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AN INTERNATIONAL COMPARISON OF HIGH VOLTAGE CAPACITOR CALIBRATIONS

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ABSTRACT

The suitability of a commercially available, compressed-gas-insulated, high voltage capacitor for precise measurement of ac voltages has been examined by national laboratories in the U.S.A. and Canada. The voltage, temperature, and pressure dependences and the mechanical stability of the capacitor were determined. It was found that by taking proper precautions the device is competitive with other methods. As a result of this research, it was also found that high voltage capacitance measurements at the two laboratories involved are in agreement.

INTRODUCTION

The measurement of electric power and energy at high voltage requires a precise means for scaling those voltages down to acceptable metering levels. For most practical purposes, this role has been adequately fulfilled by the inductive voltage transformer and more recently by the coupling capacitor voltage transformer. For more precise applications however, as for example, the calibration of the foregoing two devices, and for laboratory investigations, a more accurate divider employing gas-dielectric capacitors is commonly used.

In this paper the results of an interlaboratory investigation of the stability and accuracy aspects of a compressed-gas, high voltage capacitor are given. The purpose of the investigation was twofold: (1) to assess the accuracy and stability capabilities of such capacitors for use in precision and metering-type dividers; and (2) to conduct a comparison of the high-voltage measurement capabilities of the two participating national standards laboratories: the High Voltage Measurements Section, National Bureau of Standards (NBS) of the United States and the Power Engineering Section, National Research Council (NRC) of Canada.

AC HIGH VOLTAGE RATIO DEVICES

The Inductive Voltage Transformer

The inductive voltage transformer (potential transformer) is perhaps the most stable device for the accurate reduction (scaling) of high voltages for measurement purposes. Among its advantages are nearly permanent ratio stability with time, very low output impedance and low temperature dependence. The ratio is affected slightly by the applied voltage, but this dependence can be compensated if the transformer is calibrated over the range of operating voltages. Voltage transformers developed for commercial applications have exhibited ratio stabilities better than 0.01% [1]. Such transformers are routinely used in power/energy metering from relatively low voltages of several hundred volts to the EHV level of 500 kV. Except as reference standards to calibrate other transformers, they are generally not prevalent as measuring instruments in high voltage testing laboratories. Presumably relatively high cost, large and heavy construction and infrequent need for the highest accuracies impede their more general acceptance as high voltage dividers.

The Capacitive Divider

In general high voltage laboratory applications, dividers are usually constructed from capacitors insulated with solid-liquid materials, e.g., oil and paper or synthetic materials. Such dividers are not shielded against stray capacitances and thus their ratios could be influenced by nearby objects. Depending on the divider current, accuracies of the order of 0.1% to 1% are possible. A special type of a capacitive divider, combined with a resonating inductor to reduce its output impedance, is employed in permanent power/energy metering installations of EHV systems. The capacitor usually serves a dual role - as a voltage divider and a coupling capacitor for communications signals. Hence, the device is known as a coupling-capacitor voltage transformer (CCVT).

A more sophisticated instrument, available in most high voltage laboratories, is the compressed-gas-insulated high voltage capacitor. Regarding accuracy, it has many advantages over its counterparts having solid-liquid insulation. The capacitor is completely shielded and thus unaffected by proximity to other objects. The commonly used dielectric materials - nitrogen, carbon dioxide and sulfur hexafluoride - are very stable substances. The electrode geometries are more stable than those in oil-paper capacitors or their synthetic substitutes. The gas-insulated capacitor has practically no dielectric loss, tan δ being typically less than 5 parts per million (ppm). Such a capacitor is indispensible in accurate bridge circuits for measuring dielectric losses. In spite of its potential for high accuracy however, the gas-insulated capacitor is not used in dividers for general laboratory applications, except in specialized situations. It is also not used in power and energy metering systems.

A disadvantage of the gas-insulated capacitor is its small capacitance, typically of the order of 100 pF, which produces a high output impedance in a divider and substantial burden dependence. With the currently available operational amplifiers, this difficulty can be overcome by combining the divider with an amplifier which then supplies the power to the load. In fact an "active voltage transformer" based on a high voltage capacitor, an amplifier and a low voltage output transformer, is conceptually feasible. Such a device, incorporating a laboratory-type

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capacitor, could be a very accurate and versatile divider. An active transformer containing an outdoor-type-capacitor, either a separate unit or one constructed as a part of the coaxial bus of a gas-insulated substation, can lead to an instrument for power and energy metering.

CHARACTERISTICS OF THE COMPRESSED-GAS CAPACITOR

There are several sources of instability in gas-insulated capacitors which have to be considered. The capacitance value is affected by temperature, the temperature coefficients being of the order of 20 ppm/°C. In an environment with rapid temperature fluctuations, corrections cannot be made because the temperature of the capacitor itself is not known. In divider applications the differential temperature coefficient is of interest. If the two capacitors in a divider have temperature coefficients of opposite sign, the resultant temperature coefficient will be enhanced. Such a situation will occur if a gas-insulated capacitor, which has a positive coefficient, is combined with a capacitor having polystyrene as the dielectric.

The physical handling of the capacitor can also alter the geometry of the electrodes and change the capacitance. Three types of capacitor construction are illustrated in Figs. 1(a), (b) and (c).

Fig. 1(a) depicts a much-used compressed-gas capacitor design pioneered by Schering and Vieweg. To achieve immunity from proximity effects, it is customary to introduce a guard electrode to shield the low-voltage electrode from stray fields. Fig. 1(b) shows a more recent design which allows higher voltages than can normally be achieved with a Schering-Vieweg capacitor [2]. In this scheme, the outer metal tank is raised off ground both literally (by means of an insulating pedestal) and electrically (by being connected to the low voltage tap of an adjacent voltage divider). Again, a guard electrode (not shown) must be interposed between the low and intermediate voltage electrodes to render the capacitance insensitive to effects of nearby objects. Another novel design, shown in Fig. 1(c), incorporates a capacitive voltage divider as an integral part of the overall structure. The resulting precision capacitor is somewhat sensitive to proximity effects [3] because the low voltage electrode can not be perfectly guarded.

The inner electrode supports of all these designs are generally cantilever tubes or rods. Such supports are inherently more flexible and liable to permanent deformation than those which anchor at both ends. Precision capacitors have been designed, however, which can be shipped horizonally and will operate at very high voltages [4].

Eccentricity in the electrode alignment will cause an unbalanced electrostatic force which will aggravate the eccentricity and increase the capacitance. This capacitance increase is a quadratic function of the applied voltage. While these changes are usually small - of the order of 10 to 20 ppm - changes of about 100 ppm have been observed [5].

The possible application of gas-insulated capacitors in precision and metering-type dividers motivated a thorough investigation of the characteristics which could contribute to capacitor instabilities. Additionally, there was a need to compare the high voltage measurements capabilities of national standards laboratories.

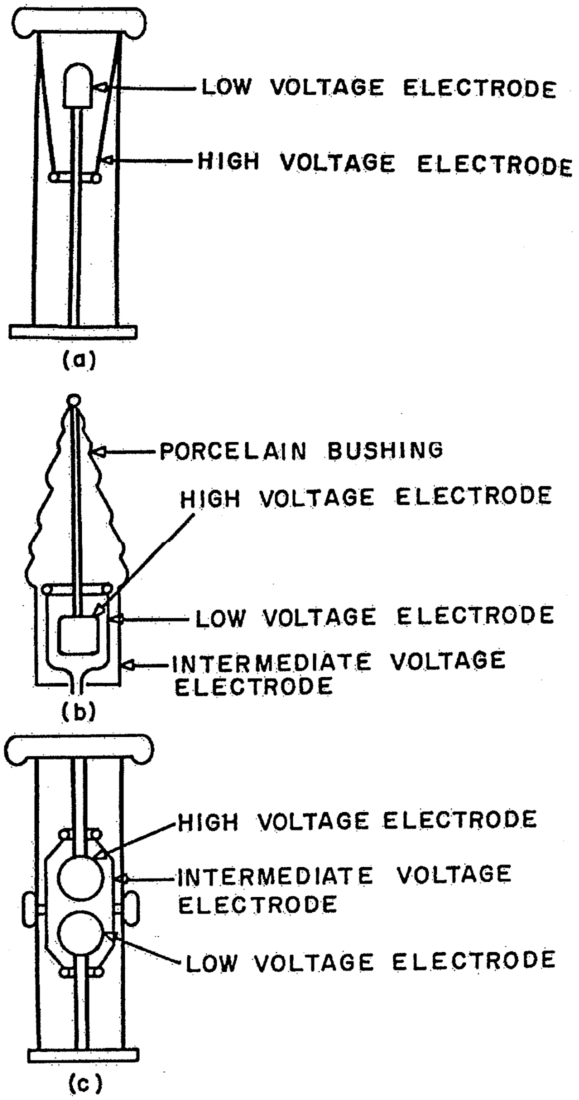

Fig. 1. Three types of compressed-gas capacitor are shown. a) is the traditional Schering-Vieweg design; b) and c) are more recent devices. Guard electrodes are not shown.

Specifically, answers were sought to the following questions: What are the overall stability limitations of a laboratory-type, SF_6-filled capacitor? How much instability is contributed by each of the significant factors such as temperature and gas density variations, mechanical handling and voltage dependence? What are reasonable means for controlling these influences? What are the capabilities of the participating laboratories for precise measurement of high voltage capacitances? What should be the procedures for periodically verifying the capacitance value and the general stability of the instrument?

The above characteristics were investigated by extensive measurements on a commercial laboratory-type capacitor both at NBS and NRC. The capacitor was of recent design and therefore likely to incorporate the newest technological advances.

INVESTIGATIVE PROCEDURES AND TECHNIQUES

General Approach

This investigation had a dual purpose - to thoroughly investigate those characteristics which affect the accuracy and stability of the capacitor and to compare the results of the two laboratories, thereby assessing their precision measurement capabilities. First, a series of measurements were performed at NBS. Then the capacitor was depressurized and shipped in a station wagon to NRC. There the measurements were repeated and the capacitor was shipped back in a similar manner. The measurements were again repeated at NBS to determine whether the parameters had changed during the shipment.

The measurements at both laboratories involved the determination of capacitance and dissipation factor (base values) at low voltage and common temperature and pressure conditions as well as the voltage, temperature and gas density dependence of these parameters. The effect of handling was investigated by tilting the capacitor and measuring capacitance at various tilt angles. Also the capacitor was exposed to its fair share of normal handling during transport between NBS and NRC.

NBS Measurements and Instrumentation

The base value, temperature and gas density dependence were determined by measurements against a low voltage (500 V rms) standard capacitor, which, in turn, was calibrated against the national standard to ±10 ppm accuracy. For voltage dependence measurements the NBS high voltage standard capacitor [6] was employed. The unique feature of this capacitor is its insignificant voltage dependence - less than 3 ppm between low voltage and 200 kV - which is achieved by very rigid electrodes and supports and careful construction. Its voltage dependence was evaluated by a series of involved electro-mechanical experiments. The long-term stability of this capacitor was not relied upon. Whenever required, its capacitance value was determined by a comparison with the low voltage standard capacitor.

The capacitance ratios were measured with a transformer-ratio-arm bridge based on a current comparator [7]. For a measurement, the same voltage is applied to two capacitors and the resulting currents are passed in two windings of a three-winding transformer (current comparator) to produce opposing magnetomotive forces. The number of turns in the windings is adjusted for the ampere-turn balance as detected by the null condition in the third winding. The outstanding feature of the current comparator is negligible non-linearity, well below 1 ppm, enabling the comparison of currents over several orders of magnitude. The accuracy of this bridge for capacitance ratio measurements is also high. The actual current ratio corresponds to the reciprocal of the turns ratio to within 1 ppm.

For pressure measurements accurate commercial gauges were employed. In the measurements before the capacitor was shipped to NRC, an instrument measuring the pressure above atmospheric to a precision of ±0.1 psi (±0.7 kPa) was used.* This was not entirely satisfactory and a gauge with ±0.02 psi (±0.1 kPa) precision was obtained for the measurements after the capacitor was returned.

For investigation of the effects due to mechanical handling, the capacitor was mounted on a hinged platform. Such a mount enabled tilting of the capacitor to any angle between the vertical and horizontal positions.

Besides the normal filling with SF_6, NBS performed pressure dependence measurements with carbon dioxide and helium fillings. The gases used were commercially obtained and of technical grade.

NRC Measurements and Instrumentation

The NRC base values, and the temperature and gas density dependences, were measured at 700 Vrms against both low voltage and high voltage 1000-pF gas-dielectric capacitors, and also at 10 kVrms against the high voltage capacitor. No significant differences were noted between the results obtained with either of the two references or the two applied voltages. The base values of the references were determined by comparison with the Canadian national standard with an uncertainty of not more than 10 ppm. In addition the NBS and NRC low voltage reference capacitors were intercompared and the closing error between their two calibrations found to be within 2 ppm.

For the voltage dependence measurements, the NRC reference was a commercial 500 kV, 50-pF gas-dielectric capacitor, tilted in such a way that the force of gravity deflected the low voltage electrode to be in exact concentricity with the high voltage electrode, thus making the capacitance between them voltage independent. The degree of tilt (about 11 degrees off vertical) and its direction were determined by searching for the condition of minimum capacitance which coincides with the condition of zero voltage dependence. The NRC arrangement, with the reference capacitor on the left, and the capacitor under study on the right, is shown in Figure 2.

The capacitance ratios were measured with a current comparator bridge, similar but earlier in design to the NBS bridge. The pressure gauge was the same as the first used by NBS.

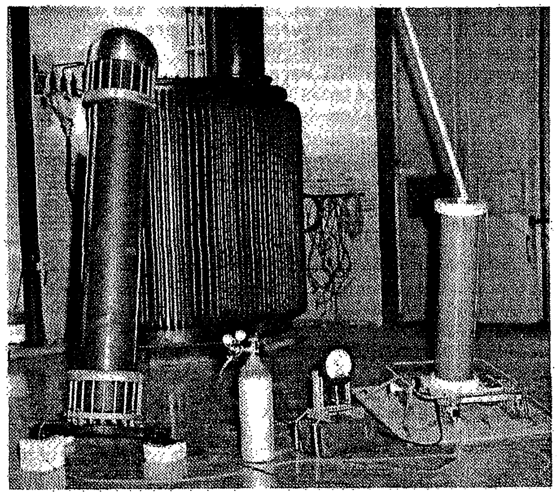

Fig. 2. Experimental set-up at NRC, Canada. Test capacitor is at right.

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*1 MPa = 145.038 psi. Since the SI pressure unit is still unfamiliar to many, pressures both in SI and English units are presented.

EXPERIMENTAL RESULTS

The compressed-gas capacitor chosen for study is of commercial manufacture, measuring approximately 1.5 m in height and 0.3 m in diameter. Its design is of the Schering-Vieweg type (Fig. 1(a)). When filled with SF_6 to an absolute pressure ≥0.35 MPa (≥50 psia) it is rated for 200 kV rms service. Internally, the capacitor consists of two guarded low voltage electrodes concentric with a high voltage electrode. The nominal capacitances between the low voltage electrodes and the high voltage electrode are 20 pF and 100 pF. External circuitry allows selection of either capacitance separately or both in parallel.

Voltage Dependence

Voltage coefficients were determined for each capacitance. The test capacitor was filled with SF_6 to a pressure of ∿0.45 MPa (∿65 psia). Both at NBS and NRC the 20-pF capacitor was found to have a voltage dependence of

$$C_V = C_0 \ (1 + 32 \times 10^{-17} \ V^2)$$

where V is the rms voltage applied and C_0 is the capacitance at low voltage. The applied voltage ranged from 10 kV to 200 kV. It can be seen that the change in capacitance with voltage is less than 15 ppm over the entire range of energizing voltage.

The voltage dependence is still smaller at the 100-pF setting. Measurements at NRC and NBS both showed capacitance changes of less than 3 ppm over a range of 200 kV. Such changes are within random errors.

Temperature Coefficient

The NBS laboratory facility includes a large enclosure in which temperature may be varied from 10 °C to 50 °C. The capacitor was filled with SF_6 to a nominal pressure of 0.45 MPa (65 psia). After being placed in the enclosure, the capacitor was maintained for 24 hours at constant ambient temperature to attain equilibrium conditions at each of the two temperature extremes before measurements were made. The capacitance measurements at 50 °C, 10 °C and room temperature (22.8 °C) were found to lie on a line whose slope is 23.4×10^{-4} ppm/°C (Fig. 3).

At NRC no special temperature chamber was available. Nevertheless the ambient laboratory temperature could be varied from 10 °C to 24 °C. Even so, the measurements made at NRC confirm the temperature coefficient found at NBS.

Only the temperature coefficient at the 100-pF setting was determined. Accurate knowledge of the temperature coefficient is essential if ambient laboratory temperature changes during the course of measurements or from day to day. By using the temperature coefficient all measurements can be corrected to a single temperature.

Gas Density (Pressure) Dependence

The actual capacitance value assumed by a compressed-gas capacitor depends directly on the dielectric constant of the insulating gas. The dielectric constant is itself a function of gas density. One speaks usually of the pressure dependence of a capacitor, but the gas-density dependence is more apt. It is true, of course, that at constant temperature the density of a gas contained in a given volume is uniquely determined from the pressure via a thermodynamic relationship and pressure is a much more easily measured variable than density. This should not, however, obscure the fact that density is the physically important variable.

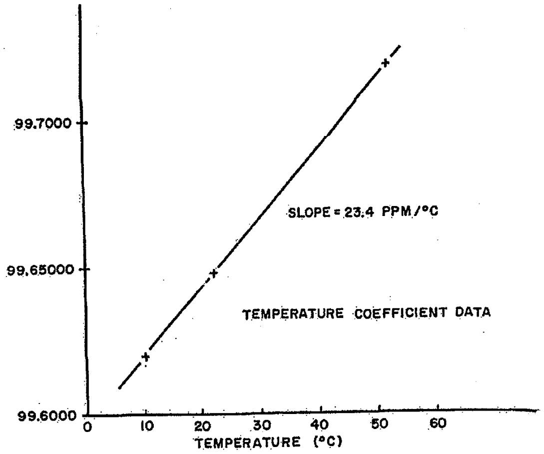

Fig. 3. Temperature dependence of test capacitor.

In the Appendix to this paper it is shown that the theoretical pressure coefficient of an SF_6-filled capacitor at constant temperature is ∿150 ppm/psi (∿22 ppm/kPa) at normal operating pressures. This number ignores all effects other than gas density and assumes the volume of the capacitor is pressure independent. Even neglecting these other effects, it is apparent (and well-known) that SF_6 compressed-gas capacitors will have severe pressure coefficients due to the characteristics of the gas itself. Therefore one has need of a rather sensitive pressure gauge in order that imprecision not introduce scatter in capacitance measurements. For instance, a gauge which reads to a precision of ±0.05 psi (±0.3 kPa) will allow a spread in capacitance of order ±10 ppm at a given pressure setting.

The results of the pressure coefficients measured with the capacitor filled with SF_6, CO_2 and He are shown in the Appendix. The data show that the pressure coefficient of the capacitor is satisfactorily explained by effects of the insulating gas alone. No changes in capacitor dimensions with pressure need be invoked to explain the observed behavior.

Mechanical Stability

The capacitor is designed for operation in the vertical position as explained in the introduction. Transport in a horizontal position was unavoidable between laboratories, however. Ground transportation was used and no extraordinary precautions were taken to insulate the capacitor from mechanical shocks in transit. Despite this treatment, the value of capacitance as measured at given conditions of temperature and gas pressure changed by only 35 ppm between NBS and NRC. On its return to NBS, the capacitance returned to within 7 ppm of its initial base value. This agreement is satisfactory when one considers that it can be accounted for by uncertainties in measurement of pressure and temperature at the two laboratories. No hysteresis in measured capacitance was tilted from vertical to horizontal and back to vertical (Table 1). As may be seen from Table 1, the change in capacitance from vertical to horizontal is a function of tilting axis. Only two axes were studied. The capacitor was shipped horizontally after being tilted about the axis labeled "B" in Table 1.

Table 1

Axis A

Tilt angle from the vertical (radians)	Normalized capacitance at tilt angle
0.00 (vertical)	1.000000
0.26	1.000016
1.38	1.000022
0.65	1.000065
1.57 (horizontal)	1.000158
0.63	1.000059
0.00	0.999998

Axis B

Tilt angle from the vertical (radians)	Normalized capacitance at tilt angle
0.00 (vertical)	1.000000
0.38	1.000006
1.67	1.000019
1.57 (horizontal)	1.000067
0.60	1.000014
0.00	1.000001

The capacitor was tilted from vertical to horizontal and back to vertical. The tilting was carried out about two arbitrarily chosen axes at right angles to each other. Tabulated values are listed in the sequence in which measurements were made. Hysteresis is seen to be negligible.

CONCLUSIONS

This investigation demonstrated that a properly designed compressed-gas high voltage capacitor is capable, without extraordinary precautions, of moderately high accuracies of 0.01% to 0.1%. If recalibration, even at low voltage, is feasible, an order of magnitude higher accuracy is possible. In SF_6-insulated capacitors the most serious influence on the capacitance value results from the gas density variations. The effect is, however, entirely predictable from theoretical considerations. Other influences are either negligible or readily controllable. Both laboratories participating in this investigation are capable of calibrating high voltage capacitors to at least 10 ppm accuracy. The obtained values agree within the stability limitation of the capacitor.

With respect to the use of compressed-gas capacitors in precision measurements, the following observations can be made:

1. The high pressure-dependence requires a well-sealed capacitor. If perfect sealing is not feasible, the capacitor must be equipped with accurate temperature and pressure gauges to monitor the gas density. Alternatively, the capacitor must be recalibrated before each use. A good pressure gauge (precise to 0.1 psi) would be desirable even with a well-sealed capacitor.

2. There is no evidence that increased pressure changes the geometry of the electrodes. Any observed pressure dependence was really a gas density dependence.

3. The temperature coefficient is small but could be significant if very high accuracies are required or if large temperature fluctuations are encountered. The capacitance variations with temperature can be explained by the dimensional variations of commonly used electrode materials.

   The effect of decreased gas density due to thermal expansion and the resultant increase in volume is insignificant. Even so, it is lumped into the measured temperature coefficient.

4. This capacitor (100-pF section) has no significant voltage dependence. If not mechanically abused, it can be assumed to remain free of voltage dependence. Any change in the electrode geometry and likelihood of acquired voltage dependence will be indicated by a shift in the capacitance value. In general, the voltage dependence has to be investigated only once. Even if present, it will be significant only in the most demanding applications.

5. In the absence of voltage dependence, or if it has been determined, a calibration at low voltage is sufficient. Periodic rechecks of capacitance can be performed on this basis.

6. The capacitor was exposed to a substantial amount of handling, including transport between NBS and NRC in a horizontal position. There was no evidence of a significant permanent shift in capacitance. It can be considered that this capacitor is transportable if moderate care is exercised. Obviously, this conclusion cannot be generalized to all types of gas-insulated capacitors. Each type must be evaluated individually.

Finally, it must be emphasized that this investigation dealt with one unit of one capacitor type. It should therefore not be construed that any compressed-gas capacitor will perform similarly. It is, however, believed that this unit represents what can be achieved with the present technology. Steps have been presented for a comprehensive evaluation of this type of capacitor.

APPENDIX

It has long been recognized [8],[9] that the dielectric constant of a non-polar gas obeys the following equation

$$\frac{\varepsilon_0 - 1}{\varepsilon_0 + 2} = k\rho \qquad (1)$$

known as the Clausius-Mossotti formula [10]. Here ρ is the density of the gas, ε is the dielectric constant of the gas, and k is a constant. The subscript of ε emphasizes that the relation (1) is strictly true only for static measurements though it will be assumed here to be equally valid at 60 Hz.

The capacitance of a compressed-gas capacitor in Gaussian units is the product of the dielectric constant of the gas times some function which depends on the capacitor dimensions:

$$C = \varepsilon f(x,y,z) \ . \qquad (2)$$

It is useful to introduce a new variable, δ, which is defined by the equation

$$\delta = \varepsilon_0 - 1 \,. \tag{3}$$

Therefore (1) becomes

$$\frac{\delta}{3+\delta} = k\rho \,. \tag{4}$$

Differentiating (2) with respect to pressure, one obtains

$$\left.\frac{\partial C}{\partial P}\right|_{T_1} = f\,(x,y,z)\left.\frac{\partial \delta}{\partial P}\right|_{T_1} \tag{5}$$

where possible spatial variations with pressure have been purposely neglected.

Now if the capacitance is known at a temperature T_1 and some pressure P_1, i.e.,

$$C_{T_1,P_1} = \varepsilon_{T_1,P_1}\, f\,(x,y,z) \,,$$

then equation (5) can be written as

$$\frac{\partial C}{\partial P} = \frac{C_{T_1,P_1}}{\varepsilon_{T_1,P_1}}\,\frac{\partial \delta}{\partial P} \tag{6}$$

From (4) and (6), neglecting higher order terms,

$$\frac{\partial C}{\partial P} = \left(3k\,\frac{\partial \rho}{\partial P} + 6k^2\,\rho\,\frac{\partial \rho}{\partial P}\right)\frac{C_{T_1,P_1}}{\varepsilon_{T_1,P_1}} \,. \tag{7}$$

The plan was to measure $\partial C/\partial P$ for several different gases and then compare the left side of (7) with the right side. The constants k and ε_0 can each be determined from published data as can the derivative $\partial\rho/\partial P$ [11],[12].

A plot of capacitance versus pressure for the capacitor under study looks like a straight line (Fig. 4), i.e., $\partial C/\partial P$ is a constant. A constant $\partial C/\partial P$ in turn implies ideal gas behavior because the second term on the right side of (7) turns out to be negligible. However if the ideal gas behavior is used to calculate the right side of (7), agreement with experiment is poor for all gases studied - SF_6, CO_2, and He. In addition, a straight line fit to the capacitance versus pressure data does not, as it should, extrapolate to the same zero-pressure value for the three gases studied. These results are summarized in Table II.

The situation is different for a quadratic fit to the capacitance data (Table III). Here $\partial C/\partial P$ contains a small though significant term linear in pressure. The effect of this term is to produce agreement in extrapolated zero-pressure capacitance values for the three gases. Also, the constant term of $\partial C/\partial P$ now agrees well with the corresponding term calculated from $\partial\rho/\partial P$ assuming ideal gas behavior. Further, the small term of $\partial C/\partial P$ linear in pressure is accounted for by calculating $\partial\rho/\partial P$ using Van der Waal's equation, which includes a correction to the ideal gas law.

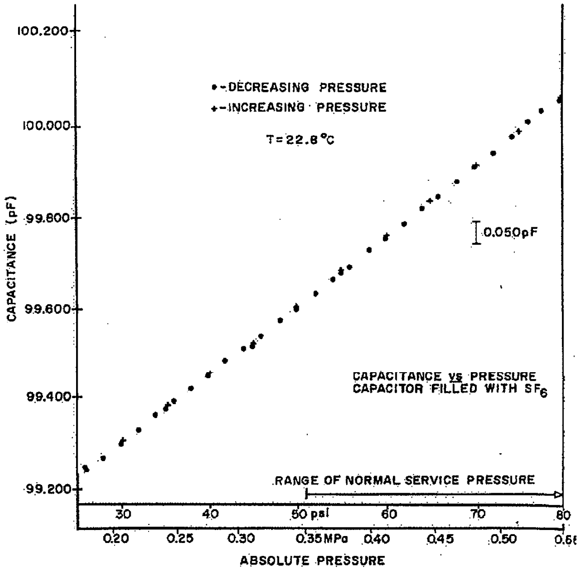

Fig. 4. Pressure dependence of test capacitor.

Table II

Comparison between ideal gas theory and experiment.

Experiment

	$\left.\frac{\partial C}{\partial P}\right\|_{T=22.8°C}$ (pF/Pa)
SF_6	$(2.202 \pm 0.004) \times 10^{-6}$
CO_2	$(0.952 \pm 0.003) \times 10^{-6}$
He	$(0.082 \pm 0.001) \times 10^{-6}$

Theory

	$\left.\frac{\partial C}{\partial P}\right\|_{T=22.8°C}$ (pF/Pa)
SF_6	2.034×10^{-6}
CO_2	0.892×10^{-6}
He	0.063×10^{-6}

	$\lim_{P\to 0} C_{EXPT}$ (pF)
SF_6	98.8474 ± 0.0015
CO_2	98.8731 ± 0.0012
He	98.8811 ± 0.0005

1 Pa = 1.45038×10^{-4} psi

Table III

Comparison between Van der Waal's theory and experiment.

Experiment

	$\left.\frac{\partial C}{\partial P}\right\|_{T=22.8°C}$ (pF/Pa)
SF_6	$(2.012 \pm 0.022) \times 10^{-6} + (5.1 \pm 0.6) \times 10^{-13}$ p
CO_2	$(0.903 \pm 0.015) \times 10^{-6} + (1.4 \pm 0.4) \times 10^{-13}$ p
He	$(0.075 \pm 0.004) \times 10^{-6} + (0.2 \pm 0.1) \times 10^{-13}$ p

Theory

	$\left.\frac{\partial C}{\partial P}\right\|_{T=22.8°C}$ (pF/Pa)
SF_6	$2.034 \times 10^{-6} + 4.1 \times 10^{-13}$ p
CO_2	$0.892 \times 10\text{-}6 + 0.8 \times 10^{-13}$ p
He	$0.063 \times 10^{-6} - 0.1 \times 10^{-13}$ p

	$\lim_{P \to 0} C_{EXPT}$ (pF)
SF_6	98.8789 ± 0.0037
CO_2	98.8807 ± 0.0025
He	98.8823 ± 0.0008

$1\ \text{Pa} = 1.45038 \times 10^{-4}$ psi

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