New Fused-Silica-Dielectric 10- and 100-pF Capacitors and a System for Their Measurement

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Abstract—New instruments have been designed to bring to standards laboratories the improved accuracy of capacitor calibrations developed by the National Bureau of Standards. The new 10- and 100-pF reference standard capacitors, based upon an NBS design, use a fused-silica dielectric with gold electrodes to provide the time and voltage stability required for calibrations to parts in 10^7. To maintain the capacitor temperature constant to within 0.01 °C, one model of the capacitors is designed for use in an oil bath, the other model is fitted with a new, stable, thermostatically controlled air bath. The system to measure these capacitors with a precision of parts in 10^8 consists of a bridge, detector, and oscillator. For these special measurements and for the general calibration of a wide range of capacitors, the new transformer-ratio-arm bridge has 12 capacitance decades and a range of 10 μF–10^{-7} pF, and five conductance decades and a range of 10^3–10^{-10} μmho. The new phase-sensitive detector and power oscillator provide high sensitivity to bridge imbalance over the frequency range 10 Hz–100 kHz.

NEW instruments have been designed to bring to standards laboratories the improved accuracy of capacitor calibrations developed by the National Bureau of Standards. Higher accuracy in the transfer and storage of the unit of capacitance has been provided by the construction of 10- and 100-pF reference standards with the proved mechanical and electrical stability of fused-silica dielectric. A new transformer-ratio-arm bridge has been built to meet the needs for high precision in the intercomparison of these standards and for high accuracy in the calibration and measurement of a wide range of other capacitors. It supplies the required extended ranges of capacitance and conductance, and the extended sensitivity, particularly when used with the complementary new phase-sensitive detector and power oscillator.

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Fused-Silica Capacitors

The design of the new 10- and 100-pF standards is based upon the development at NBS by Cutkosky and Lee [1] of a 10-pF capacitor with the time stability and small variations due to voltage change or shock that permit calibration to parts in 10^7. The dielectric material used for such stability is a special grade of fused silica. It has the further advantages of low losses and low frequency dependence of its dielectric constant in the audio-frequency range.

Design

The first modifications of the NBS design for commercial production had electrodes applied to the dielectric substrate with the configuration shown in Fig. 1. In such a design, the gaps can either be ground with a diamond wheel after the substrate has been coated with silver or gold or be masked out during the coating process. In both cases the definition of the edge of the gap is not great, and this could cause dependence of the capacitance on voltage applied if there were isolated particles of metal connected to guard or electrodes by electrostatic forces. Adjustment of capacitance is done by grinding away material, recoating, and testing; as many as three adjustments could be necessary and the time involved in doing this would considerably increase the cost of production. Another slight disadvantage of the design is that the direct capacitance is not completely within the fused silica but includes capacitance from the top of an electrode through the gap to the other electrode. Therefore, motion

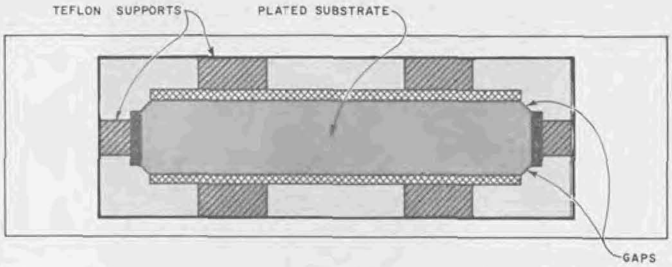

Fig. 1. Fused-silica capacitor, first design. Main electrodes are crosshatched; guard electrode is in solid black.

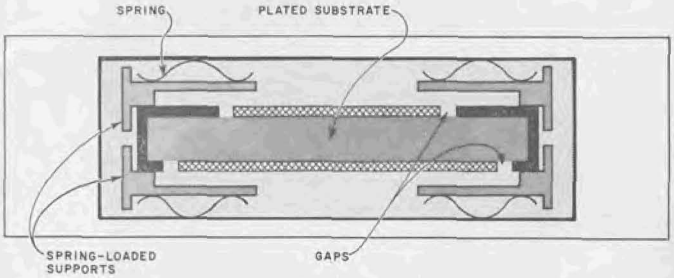

Fig. 2. Fused-silica capacitor, second design. Only thickness of substrate changes between 10- and 100-pF element.

of the substrate in the cell, changing the relative position of guard and electrode in the vicinity of the gap, would change the direct capacitance.

Fig. 2 shows the design used to try to alleviate the problems first encountered. Since the electrode areas are not equal and the capacitance is defined mostly by the area of the smaller electrode, only one gap is now crucial.

The substrate is now held between spring-loaded supports, which are shaped so that even if the substrate moves, the guard in the vicinity of the gap remains the same. In this design the electrodes and guard are in the same plane on each face, and photoetching techniques can be used both to generate the gaps and to adjust the capacitance by changing the area of an electrode. These techniques have proved more predictable and reliable than any grinding technique used with the first design.

Construction

Fig. 3 shows two coated and etched substrates. The coating consists of $\frac{1}{2}$ mil of pure gold. The thin substrate for the 100-pF unit is 30 mils thick, while the thick substrate for the 10-pF unit is 300 mils thick. Both have a diameter of 2.727 inches. Once the capacitance has been adjusted to ± 100 ppm of nominal value, the element is placed in a brass holder shown in Fig. 4. Contact to the electrodes is made by gold-coated phosphor-bronze springs. Fig. 5 shows the holder ready to be placed in a stainless-steel container and the assembled and sealed cell. This container is welded shut, evacuated, baked, back-filled with dry nitrogen, and sealed; connections to the capacitor are made via glass-to-metal feed-throughs.

The dielectric constant of fused silica has a temperature coefficient of approximately 10 ppm/°C, and to make meaningful measurements at the part in 10^7 level one has to know the temperature to within 0.01°C. This can be

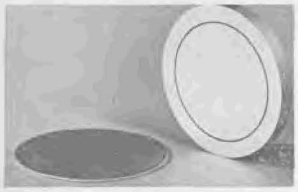

Fig. 3. 10- and 100-pF elements.

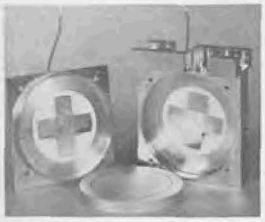

Fig. 4. Brass holder for 10-pF capacitor.

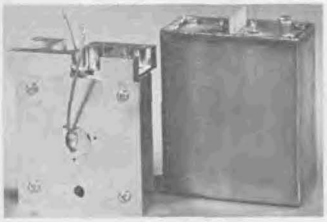

Fig. 5. Brass holder and sealed stainless-steel container in which it is mounted.

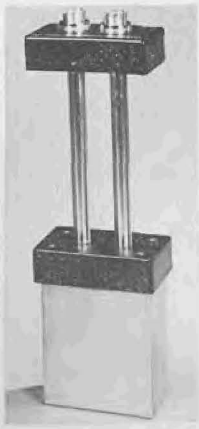

Fig. 6. Complete fused-silica capacitor, oil-bath version.

accomplished in an oil bath, and Fig. 6 shows the oil-bath version of the capacitor. The GR874 connectors have been raised 6 inches above the capacitor to allow connection above the oil level and have been gold-plated for lower contact resistance. The capacitance element is not symmetrical and to keep track of the connections, the larger electrode is connected to the connector marked *H* while the smaller electrode is connected to the one marked *L*. The simple measurement of this capacitor in an adequate oil bath is, however, complicated by the additional precision apparatus required to make the accurate temperature measurements needed in order to define the capacitance value. For that reason, an air bath was developed that can provide one or twoc apacitors with their own environment and, therefore, eliminate temperature measurements except in the case of highest accuracy. The air bath, shown opened in Fig. 7, is thermostatically controlled at a nominal 30°C and has a long-term stability of 0.01°C; it changes by less than 0.01°C for a 6°C change in ambient temperature and is controlled by a 12-volt system, thereby allowing the use of batteries during transportation. The gold-plated GR874 locking connectors, in the normal position on the front panel in Fig. 7, can be moved to the rear of the instrument for use in a relay rack.

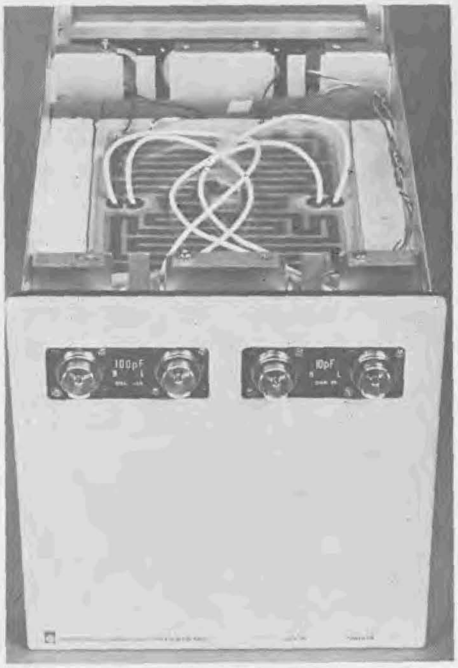

Fig. 7. Air bath for capacitors. Pattern on inside box is etched heater covering all six sides.

Performance

The evaluation of the fused-silica capacitors was difficult because standards and measuring equipment capable of the required accuracy and resolution are not available. This equipment had to be developed concurrently with the capacitors.

It was found that the voltage dependence of a fused-silica capacitor is a good indicator of its quality, and it is the first test made on a new unit. The capacitance change has to be less than one part in 10^8 when the voltage applied is changed from 50 to 150 volts.

Frequency dependence and dissipation factor are directly related to the dielectric and were evaluated by comparison with two types of air capacitors. It was found that the frequency dependence was 4 ± 4 ppm between 1 and 10 kHz and the dissipation factor was also 4 ± 4 ppm at 1 kHz.

The effects of mechanical and thermal shocks were investigated. Oil-bath versions were dropped at different angles from heights of several inches; the capacitance did not change by more than one part in 10^7. The capacitors were also cycled between 0 and 50°C and the hysteresis effect was less than 4 ppm; however, some of this change might not be real but due to changes of temperature in the oil bath.

As for long-term stability, it could only be checked indirectly, and the difference between two capacitors in an air bath was not more than one part in 10^7 during one year of observation.

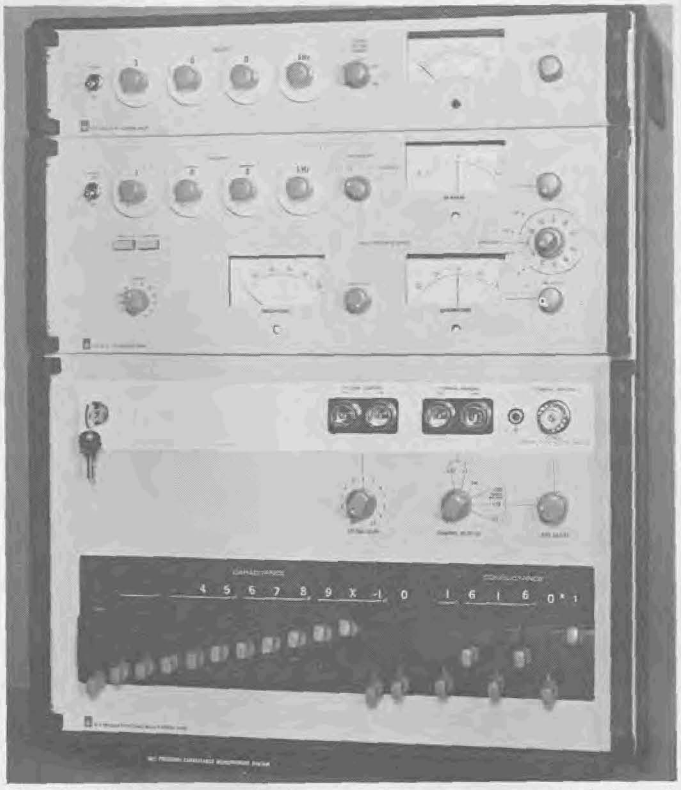

Fig. 8. Precision capacitance measurement system, consisting of, from top to bottom, oscillator, detector, and precision capacitance bridge.

System

One consequence of the improved quality of the new capacitors is that both the tests required to demonstrate their stability and the calibrations to be made in their ultimate use as standards require more precision than that to be found in the measurement systems of most laboratories. The need for such measurements during the development of the capacitors led to the extension of the range and quality of our measuring instruments. The result is the new capacitance-measuring system shown in Fig. 8, consisting of an oscillator, a detector, and a precision capacitance bridge. The design of this system has two main objectives: in particular, to provide the precision that permits intercomparisons of the new capacitors to parts in 10^8 in the frequency region near 1 kHz; in general, to provide high direct-reading accuracy in the measurement of a wide range of capacitance at audio frequencies.

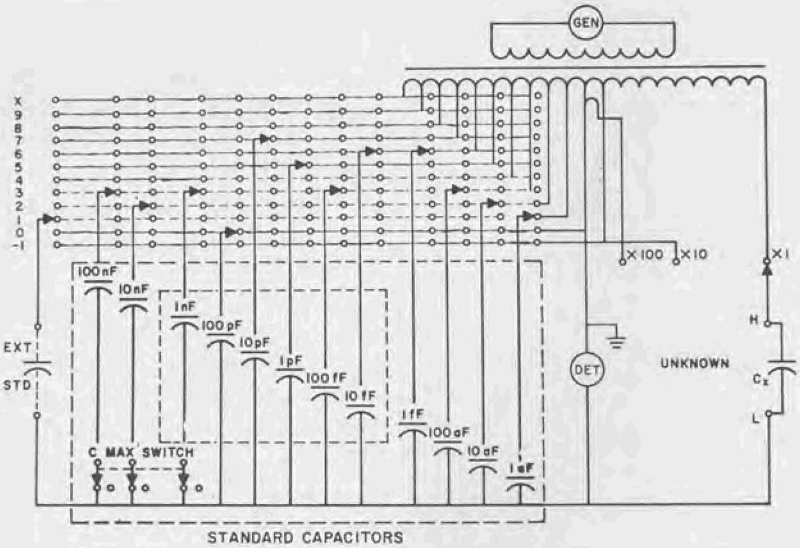

Fig. 9. Simplified bridge circuit for capacitance measurement.

Bridge

The new bridge designed to meet these objectives uses the basic transformer-ratio-arm-bridge circuit of previous precision bridges [2], [3]. The essential components for capacitance measurements are shown in the simplified circuit of Fig. 9. The three-winding ratio transformer consists of a 200-turn primary on a high-permeability tape-wound toroidal core, 2.7 × 3.5 × 0.5 inches, over which is a copper shield; for the ratio arms, two symmetrical 200-turn secondary windings tapped every 20 turns made by winding 20 turns of a 20-wire cable around the toroid. The maximum voltage to which the transformer can be driven is 150 volts at 1 kHz and is proportional to frequency.

Each capacitance decade has a fixed standard capacitor that can be connected to any one of 11 taps on one transformer secondary to give the decade steps from 10 through 0 to −1. To provide 12 decades of capacitance, the bridge has 12 internal standard capacitors, 100 nF–1 aF. When the upper three capacitors are not needed, they can be disconnected, one at a time in sequence, by the C_{max} switch to reduce the shunt capacitance across the detector and, thereby, to increase the sensitivity of the bridge to imbalance for maximum resolution. The capacitors are of three types: sealed low-loss mica-dielectric capacitors for 100 and 10 nF; sealed air-dielectric capacitors, with Invar plates for low-temperature coefficient, 1000 pF–10 fF; and air-dielectric three-terminal trimmer capacitors for the remaining four decades. For the thermal stability required in precision intercomparisons, the upper eight internal standards are mounted in a compartment that has sufficient thermal insulation from the bridge cabinet to provide a time constant of 6 hours for changes in the ambient temperature of the bridge. A constant-temperature oven for these capacitors, similar to that designed for the new reference capacitors, was considered, but the large size and cost of an oven with sufficiently constant temperature made the use of thermal lagging preferable in this bridge.

The range of unknown capacitance that can be balanced by the 12 bridge decades is 100 nF–0.1 aF. Two multipliers of 10 and 100 for these decades are provided by taps at 20 and 2 turns on the unknown side of the ratio transformers, so that the range can be extended upward to 10 μF. The direct-reading accuracy of the bridge is determined primarily by the temperature coefficients of the internal standards. When the coefficient is of the order of 2 ppm/°C, as in the 1-nF, 100-pF, and 10-pF standards, the accuracy can be as good as 10 ppm at 1 kHz when the room temperature is held to ±1°C of the temperature at which the bridge was calibrated. When the other standards, with coefficients of the order of 15 ppm/°C, are required for the first significant figure in the balance, the accuracy must be reduced to about 50 ppm. The bridge accuracy is maintained to frequencies well below 100 Hz, but is limited eventually by the reduced sensitivity to imbalance caused by the lower output-voltage limit of the transformer, e.g., 1.5 volts at 10 Hz. Accuracy at frequencies well above 1 kHz and for capacitance less than 1 nF is limited by residual impedances in the transformer windings and in the bridge wiring and decreases approximately in proportion to the square of frequency to about 0.5 percent at 100 kHz. At high capacitance and high frequency, the errors from transformer and wiring impedances in series with the unknown cause a further reduction in accuracy.

Balance of the loss component in the unknown admittance is provided in this bridge by decades of conductance similar to those of capacitance, as shown in the circuit of Fig. 10. One difference is that the voltages for the decades come not from the main 200-turn secondary winding but from a separate 22-turn winding to avoid

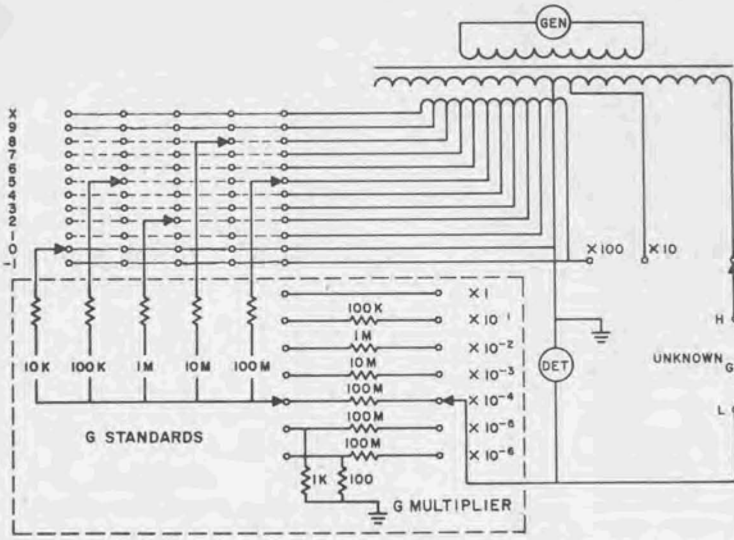

Fig. 10. Simplified bridge circuit for conductance measurement. Nominal resistor values shown are in ohms.

loading of that winding by the resistors. For the five decades there are five internal conductance standards: metal-film precision resistors for 10 kΩ, 100 kΩ, and 1 MΩ; and carbon-film resistors for 10 MΩ and 100 MΩ. For smaller conductance ranges, multipliers for these decades from 1 through 10^{-6} are provided by similar resistors connected to the decades to form T networks. For higher conductance, the multipliers of 10 and 100 from taps on the ratio-arm winding are used, as they were for capacitance. The total range of conductance is 10^{3}–10^{-10} μmho to balance unknown resistance of 10^{3}–10^{16} ohms. In the simplified diagram, nominal values of resistance are shown to indicate order of magnitude; for those resistors used as multipliers the value must be offset slightly from the indicated nominal to make the conductance of the T network correct. The resistors are adjusted to make the conductance accuracy ±0.1 percent of the reading at 1 kHz over most of the range. For small phase error, the resistors are mounted through holes in shield plates to reduce the direct capacitance across them, and trimming capacitors, not shown in the circuit, are provided to adjust capacitances to ground and, thereby, to adjust direct capacitance in the equivalent T network.

For most measurements the unknown capacitor is connected to the bridge with coaxial cables at the pair of GR874 coaxial connectors on the panel. These connectors have special gold-plated conductors to provide the low and repeatable contact resistance required by the highest precision measurements. A matching pair of connectors, connected through a decade switch to the same transformer taps used by the internal standard capacitors, permits the use of any external standard as an added decade or the direct comparison of two external capacitors. The bridge also has a two-terminal precision GR900 connector on its panel for the measurement of coaxial capacitance standards or other components fitted with this connector. The three-terminal bridge circuit measures only direct capacitance connected between inner and outer conductors of the connector, including about 2 pF inside the conductor, and excludes all capacitance to ground; neither terminal of the unknown can be grounded. Since the outer conductor (*H* terminal) as well as the case of any capacitor connected to it, is connected to the transformer winding, its impedance is low but its potential to ground could be as high as the applied oscillator voltage. To protect the operator from a dangerous shock if the oscillator voltage is high, the voltage that can be applied to the outer conductor of the GR900 connector is limited by Zener diodes in the bridge to about 35 volts. For convenience, the capacitance of the open GR900 connector can be balanced by a variable internal capacitor controlled by the zero-adjustment knob on the panel, so that the bridge decades read zero when the connector is open and then read directly the added capacitance when the unknown is connected. The selection of the type of connection to the unknown and of the multiplier for the decades is made with the terminal-selector switch on the panel. Multipliers of 1 and 10 are available when the GR874 terminals are used, multipliers of 1, 10, and 100 when the GR900 is used. A calibration position of the switch disconnects all the unknown terminals for testing and intercomparisons of the internal standards. If trimmer adjustments for the 12 internal capacitance standards are required, they can be made with ease when the cover at the upper left side of the bridge is unlocked with a key.

Detector and Generator

The output of the bridge is only a few hundredths of a microvolt when the input to the bridge is 100 volts and the imbalance is one part in 10^{8} of 10 pF. The new detector developed to extract this small signal from noise, at the high-impedance level of the bridge output, is a combination of a high-impedance low-noise preamplifier, a tuned amplifier with 130-dB gain, and two phase-sensitive detector circuits. The input impedance is that of 1 GΩ in parallel with 20 pF; the noise voltage at 1 kHz with a source impedance equivalent to the output impedance of the bridge in the measurement of 10 pF, i.e., 100 MΩ in parallel with 500 pF, is about 30 nV/root Hz. The amplifier can be tuned from 10 Hz to 100 kHz by three decade switches and a range switch. To permit easy, as well as very precise balance of the bridge, one panel meter displays the magnitude of the imbalance signal; two other meters show simultaneously the in-phase and quadrature components, which can be made to correspond to the capacitance and conductance imbalance components. Phase adjustment is provided from 0 to 360° for these signals to make the meters indicate independently the desired component. The bandwidth can be narrowed for reduction of noise, at the expense of slower response time, by adjustment of the integration time constant over five steps from 0.1 to 10 seconds. Two other panel switches provide for the insertion or removal of a line-frequency notch filter and for the choice of linear or compressed meter response. A feature of value to both the expert and the amateur user of the system is that the very sensitive input stage is so well protected by diodes that the full bridge input voltage, even 150 volts, can be applied without damage to the detector input; for example, by accidental disconnection of the unknown.

The two constant-voltage reference signals for the phase-sensitive detectors, with a phase difference of 90° and with one signal approximately in-phase with the input signal to the bridge, are obtained from the oscillator circuit of the new power oscillator in the system. A power amplifier in the instrument with up to 1.6 watts output provides a driving signal for the bridge of at least 125 volts. The frequency is adjustable over the 10 Hz–100 kHz range by controls matching those of the detector. The output voltage can be adjusted by a five-position range switch and a vernier control, and a meter indicates the voltage at the output terminals. The circuit is designed to provide a signal of low distortion, typically less than 0.3 percent, to any load impedance from an open circuit to a short circuit and is, thereby, also protected against accidental short circuits during measurements with the bridge.

All connections between the system instruments are made at coaxial terminals on the rear panels. Precautions have been taken to avoid error voltages in the system from ground loops, including, for example, the use of a coaxial choke in the internal lead from bridge to detector.

Conclusion

The new reference standard 10- and 100-pF capacitors, together with the measurement system, should facilitate the improvement of accuracy in many laboratories in the transfer and storage of the unit of capacitance. Tests during the development of these instruments and the experience of NBS with similar capacitors indicate uncertainties of the order of parts in 10^7. Further experience with production quantities of the instruments and with the problems of normal transport is certainly required to establish the effective limits of uncertainty. The new measurement system will provide good direct-reading accuracy, to 10 ppm under limited conditions, in the calibration at audio frequencies of a wide range of capacitors, from 10 μF to much less than a picofarad. The system, with resolution to 10^{-7} pF, will provide very good precision, to parts in 10^8 and beyond, in the intercomparisons of new and old standards. It may be expected to solve some measurement problems, as well as to create some, when the increased precision exposes difficulties that have heretofore been hidden from most metrologists.

References

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