Improving the Mechanical Stability of a Standard Capacitor

S. S. Moodley, Will van den Berg, and C. S. Veldman

***Abstract*—CSIR, National Metrology Laboratory of South Africa, had manufactured 10-pF ultra-low expansion quartz capacitors that had been in use since the early 1970s. Although the capacitors were extremely stable and had low temperature coefficients of capacitance, they were susceptible to mechanical shock. The development of a standard capacitor with improvements to increase its robustness is presented. Results of the transportability test show that the design has improved the mechanical stability of the capacitor.**

***Index Terms*—Capacitance, capacitor, mechanical stability, shock, testing, vibration.**

I. Introduction

THE Krypton lamp was the basis for the national standard for length in South Africa during the early 1970s [1]. Attempts to change the basis for the national standard for length involved intercomparisons between the wavelengths of the Krypton and the Helium-Neon Stabilized Laser. An interferometer was built incorporating, inter alia, closely spaced (0.1 mm) 10-pF capacitors that acted as detectors. [2]. The Optical Interferometry Section of CSIR, National Metrology Laboratory (CSIR-NML), began the development of 10-pF reference capacitors around 1973. The primary purpose of the capacitors was to act as stable references for the capacitors used in the interferometer. Subsequent to the discovery of the stability of the ultra-low expansion (ULE) capacitors, their purpose extended to the maintenance of the measurement standard for capacitance in South Africa. This was achieved by using a stable 10-pF ULE capacitor as a transfer standard that was hand-carried and calibrated abroad [3]. The value of these capacitors over approximately 25 years has proven to be stable (with the relative capacitance drift lower than 0.3×10^{-6} per year). During 1999, a project was initiated to improve the mechanical stability of the capacitors after two capacitors were damaged during transit, while being transported as separate airfreight packages at the beginning of an international intercomparison [4]. The assembly of a capacitor of improved design was completed in April 2001 and the capacitor was subjected to various tests to determine its robustness.

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II. Original Design

A. Electrodes

Approximately ten capacitors were manufactured during the 1970s and were of concentric cylinder form. Silver, gold and chromium were used as plating material. The process of evaporating chromium onto the electrode form was relatively unsuccessful. The silver coating was found to diffuse into the substrate. Differences between the two coefficients of thermal expansion of the materials, i.e., that of the silver (approximately 17×10^{-6}/K) and that of the ULE quartz ($(0 \sim 30) \times 10^{-9}$/K between 0 °C and 50 °C), would cause breakage of the electrodes. Gold was the most successful material of the plating material. The gold was painted on and fired at approximately 900 °C.

B. Dielectric

The dielectrics used were nitrogen (N_2) and vacuum. The vacuum was difficult to maintain in the early capacitors and eventually was lost.

C. Construction Details

The capacitor consisted of three major components viz., the quartz/ULE component, an inner container and an outer container that have been described in detail in [5].

1) ULE Component: The ULE component consisted of two pieces of quartz that are referred to as the "inner" plate and the "outer" plate (Fig. 1). Once the gold had been fired on the ULE substrate, two slits were ground defining the effective length, L, of the inner plate, as depicted in Fig. 1. Corresponding slits were made on the outer plate. The slits were ground, using a diamond wheel cutter of 0.1-mm thickness. Once the inner plate and outer plate were assembled, the two sections of the quartz fused due to the gold coating and this ensured proper contact. The tapered sections of both plates ensured a tight fit. Glass-metal feed-throughs ensured access to the electrode surfaces through gold-lined tunnels in the ULE monolithic substrate. The ULE component was then suspended in a container that is referred to as the "inner container."

2) Inner Container: The inner container was made of extruded stainless steel (SS 316) pipe. Glass-metal feed-throughs were fixed onto the lid. These ensured access to the electrodes on the ULE component. Beryllium-copper contact strips ("finger springs") were attached to the cylindrical section, lid and bottom of the inner container. The lid and bottom were fixed to the inner container by plasma welding. The inner container was housed in a container that is referred to as the "outer

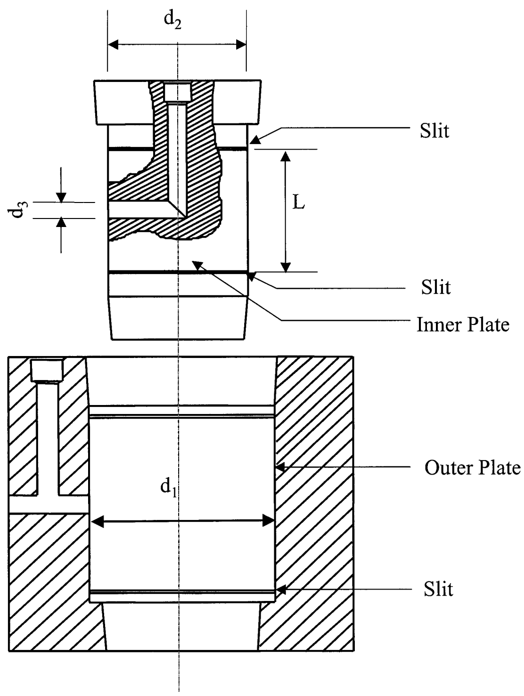

Fig. 1. Inner and outer plates of the ULE component.

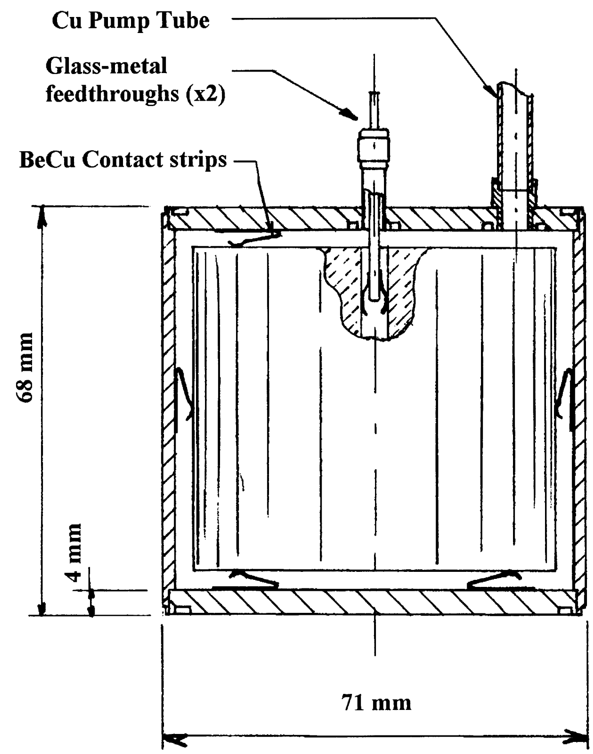

Fig. 2. Inner container showing the ULE component, glass-metal feedthroughs, pump tube, and the BeCu contact strips.

container." This was processed once the inner container was out-gassed at 90 °C over 24 h and infused with the dielectric. The inner container was essentially the same as was designed previously and can be seen in Fig. 2.

3) Outer Container: The outer container was machined out of aluminum and was cylindrical in shape. The top of the inner container had been fixed to the top of the outer container via an aluminum screen. This was of particular importance since this eliminated any vertical movement of the inner container with respect to the outer container. High frequency coaxial connectors were affixed to the top of the outer container. The space between the inner container and the outer container (sides and bottom) were packed with low-density foam.

4) Calculation of Capacitance: The capacitance value C was calculated using (1)

$$C = \pi\varepsilon_0\varepsilon_r \left\{ \frac{\left[d_2 L - \left(\frac{d_3}{2}\right)^2\right]}{d_1 - d_2} \right\} \tag{1}$$

where ε_0 and ε_r are the permittivity of vacuum and permittivity of dry nitrogen, respectively. The effect of the holes drilled to connect the electrodes to the glass-metal feedthroughs needed to be taken account. The surface area mapped by this hole i.e., the term $(d_3/2)^2$, was removed from the effective surface area of the inner plate. The capacitance of the capacitor fabricated to improve the mechanical stability was estimated using (2) [6]

$$C \approx \frac{2\pi\varepsilon_0\varepsilon_r L}{\ln\left(\frac{r_0}{r_i}\right)} \tag{2}$$

where $2r_o$ ($2r_o = d_1 \approx 35$ mm) and $2r_i$ ($2r_i = d_2 \approx 30$ mm) were the inner diameter of the outer plate and the outer diameter of the inner plate, respectively (Fig. 1). The effective length of the inner plate L was approximately 27 mm.

III. Improvements to the Original Design

A. Electrodes and Dielectric

Only gold (versus chromium and silver) was used as the plating material and dry nitrogen (versus a vacuum) was used as the dielectric.

B. Incorporation of Membrane Bellows Tubes

In the original design, the lateral movement of the ULE component relative to the inner container had been limited by the contact strips and this movement did not cause damage to the capacitors. The main cause of the damage was the vertical mechanical shock applied to the capacitor. A design that would minimize the effect of a vertical shock would improve the mechanical stability and therefore a component such as a bellows tube needed to be incorporated. Although bellows tubing is available commercially, none could be found with suitable flexibility. Special membrane bellows tubes were constructed using 0.1 mm thick stainless steel (SS 321) and plasma-welding techniques (Fig. 3). To ensure complete screening of the high and low terminals, the welds between the membranes were tested using a helium leak detector. These bellows tubes would serve two purposes *viz.*, they would provide a screen from the MUSA connectors to the lid of the inner container and also provide a mechanism to absorb the effects of any shock on the capacitor. The bellows tube could extend to 1.5 times its length in the relaxed state.

C. Vibration/Shock Damping Material

The bottom of the outer container and sides were lined with approximately 10-mm thick highly damped visco-elastic ma-

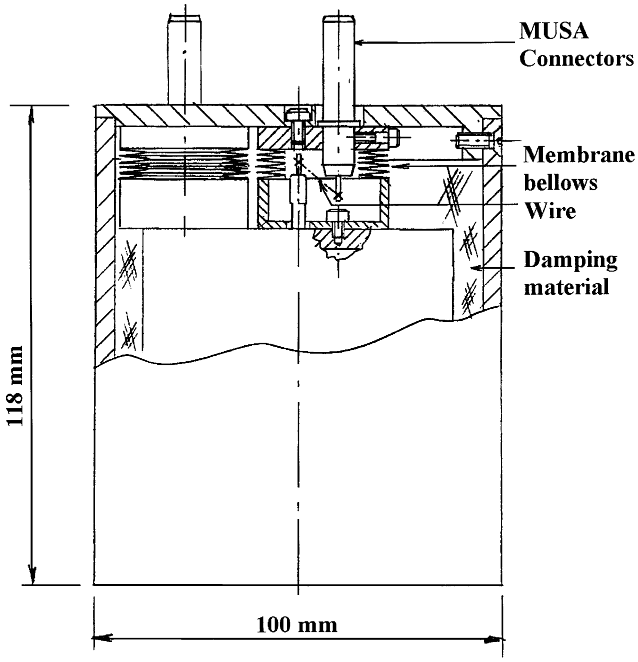

Fig. 3. Complete assembly of the capacitor.

terial, Sorbothane®. Details of the construction can be seen in Fig. 3.

IV. Testing for Mechanical Stability

A. Temperature Cycling

Subsequent to the assembly, the capacitor was subjected to temperature cycling between −20 °C and +70 °C. The temperature profile was set for four hours at either temperature with the change from one temperature to the other taking approximately 60 min. The temperature "burn in" carried out over approximately 48 h would act as an ageing mechanism and would determine any areas of weakness in any of the components used. The temperature cycling showed no effect on the capacitor value, at approximately 23 °C, to within $1 \times 10^{-6} \cdot C$.

B. Drop Test

The capacitor (weighing 2.02 kg), *without any packing material*, was drop tested twice from a height of 50 mm onto a solid surface. There was no change in the capacitance to within $0.5 \times 10^{-6} \cdot C$.

C. Vibration/Shock Test

The capacitor was mounted to shakers and was subjected to various forces and various frequencies. The parameters are given in Table I. No effect on the capacitance was noticed to within $0.5 \times 10^{-6} \cdot C$.

D. Change With Orientation

When rotated from the vertical position in 90° steps, through 360°, the maximum capacitance change noted was $0.2 \times 10^{-6} \cdot C$.

TABLE I
VIBRATION/SHOCK TEST PARAMETERS

Frequency (Hz)	Acceleration m/s^2	Period (hour)	Orientation
10	2	1	Vertical
20	2	1	Vertical
40	2	1	Vertical
10	10	1	Vertical
20	10	1	Vertical
40	10	1	Vertical
10	2	1	Horizontal
20	2	1	Horizontal
40	2	1	Horizontal

E. Transportability

The capacitor was wrapped in air-bubble wrapping, placed in a cardboard box and shipped to Cape Town, South Africa, and back to Pretoria, South Africa.[1] The capacitor was measured at a SANAS-accredited [2] laboratory in Cape Town and before and after transportation at CSIR-NML. There was no indication of any damage nor any change in its value, to within $0.5 \times 10^{-6} \cdot C$. This is in contrast to the case of the two ULE capacitors that had been damaged during the intercomparison as mentioned in Section I.

V. Electrical Characteristics

The value of the capacitor was found to be 9.810 766 pF and the loss tangent 0.000 005. Although the nominal value of the capacitor was not important in this exercise, a value close to 10 pF can be achieved through extensive computer modeling of the dimensional characteristics and fine trimming by regulation of the gas dielectric properties (combination of gases and pressure) [6]. The ground conductances (G_{HG}, G_{LG}) were found to be 0.3 nS and ground capacitances (C_{HG}, C_{LG}) 74 pF and 87 pF, respectively. The temperature coefficient of capacitance was found to be $+0.4 \times 10^{-6} \cdot C/\mathrm{K}$, between 18 °C and 30 °C.

VI. Conclusion

The results of the mechanical tests show that the new capacitor design has improved the characteristics. The capacitor withstood the tests to which it was subjected and the objective of the project to improve the mechanical stability was met. CSIR-NML will further improve the design in future in order to fabricate capacitors that are within $10\ (1 \pm 100 \times 10^{-6})$ pF.

Acknowledgment

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[1]Pretoria is approximately 1500 km away from Cape Town.

[2]SANAS is the acronym for South African National Accreditation System and is the recognized accreditation body in South Africa.

REFERENCES

[1] M. McDowell, *The National Metrology Laboratory of South Africa – The First 50 Years*. Pretoria, South Africa: Nat. Metrology Lab., 1997, pp. 105–116.

[2] C. J. van der Hoeven, F. H. Muller, B. P. J. van Oorschot, and R. Turner, "Positioning of mirrors by means of capacitor probes," *J. Phys. E: Sci. Instrum.*, vol. 10, p. 1284, 1977.

[3] S. S. Moodley, B. van Oostrom, E. L. Marais, and M. L. Temba, "Capacitance intercomparison between NML (South Africa) and NPL (India) and NML (South Africa) and NMI (Netherlands)," in *CPEM Conf. Dig.*, 1998, pp. 496–497.

[4] B. van Oostrom, "International Interlaboratory Intercomparison: EA EL-24 (Capacitance) Report," Nat. Metrology Lab., Pretoria, South Africa, NML-00–0073, 2000.

[5] S. S. Moodley, C. J. van der Hoeven, and H. F. Brenkman, "The design of a 10 pF standard capacitor," *Proc. IEEE Africon Conf.*, pp. 67–70, 1999.

[6] R. D. Lee, H. J. Kim, and Y. P. Semenov, "New stable 10 pF gas-dielectric capacitors," *IEEE Trans. Instrum. Meas.*, vol. 50, pp. 294–297, Apr. 2001.

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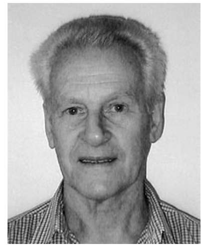

Will van den Berg was born in Amersfoort, The Netherlands, in 1935. He received the Higher Technical Diploma in physics and mechanical engineering from HTS, Eindhoven, The Netherlands, in 1982.

He worked on the development of microwave systems and nonaqueous batteries at Philips, The Netherlands, from 1958 to 1975. He joined the CSIR, Pretoria, South Africa, in 1975 as a Specialist in vacuum tube technology, vacuum testing, and joining of metals and nonmetals. During 1986, he left the CSIR to start his own company, VACTEC cc, Lynwood Ridge, South Africa. He is currently involved with the development and manufacture of inter alia, vacuum tubes, X-ray tubes, and packaging systems for special electronic devices.

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Mr. Veldman received the Aerotek Achiever award from the CSIR for developing and implementing the first laser interferometer calibration system used for accelerometer calibration in South Africa in 1998. The BIPM invited him to serve as a member of an ad-hoc committee ascertaining the need for establishing the CCAUV. He represented the CSIR-NML at the inaugural meeting of the CCAUV and currently serves as the CCAUV Rapporteur.