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A Study on the Thermal Hysteresis of Traveling Inductance Standards

Luca Callegaro, *Member, IEEE*, Vincenzo D'Elia, Martina Marzano, Massimo Ortolano, M. Florian Beug, and Harald Bothe

***Abstract*— The international equivalence of measurement standards and of the calibration and measurement capabilities of National Metrology Institutes is demonstrated through international intercomparisons. The comparison CCEM-K3.2018 "Inductance at 10 mH and 1 kHz" is under preparation. To verify the uncertainty claims of the participant institutes, traveling standards of an unprecedented level of stability are required. INRIM and PTB characterized several General Radio (GenRad) 1482 inductance standards versus large temperature steps that may occur during air carrier transportation. This work reports on the thermal hysteresis manifested by these standards, which may impact on the uncertainty of the reference value of the CCEM-K3 and other future international and interlaboratory comparisons.**

***Index Terms*— Calibration, inductance measurement, international system of units, measurement uncertainty, metrology.**

I. Introduction

The Consultative Committee for Electricity and Magnetism (CCEM) of the International Committee for Weights and Measures (CIPM) has identified *electrical inductance* as a *key quantity*, at the specific value of 10 mH [1]. For key quantities, CCEM organizes key comparisons (KCs) to sustain the worldwide compatibility of measurements in agreement with the mutual recognition arrangement (MRA) [2]. At present, the comparison CCEM-K3.2018 "Inductance at 10 mH and 1 kHz" is running and is in its organizational stage.

Traveling standards employed in KCs must be stable against time, mechanical shocks, and variations in the environmental parameters occurring during travels.

Long-term effects of large temperature changes on inductance standards, occurring during transportation by carrier, are of particular concern for international comparisons. To the best of authors' knowledge, only Shemet et al. [3] briefly mention, without data, the existence of such effects.

We report, in this article, the outcome of a systematic investigation of the effects of wide temperature reductions on the inductance of metrology-grade standards. These temperature reductions aim to simulate the effects of air transportation. Some preliminary data were reported in [5].

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II. GenRad 1482 Inductance Standards

The most popular series of metrology-grade inductance standards is the General Radio (GenRad) 1482, originally developed in 1952 [4] and still commercially available at the time of writing. These standards are composed of a copper winding over a nonferromagnetic core, embedded in a soft insulating material (cork granulate). Electrically, they are configured as three-terminal impedances (high terminal H, low terminal L, and shield G). Fig. 1(a) shows the appearance of a GenRad 1482 inductance standard, and Fig. 1(b) shows a drawing of its cross section.

The specified inductance temperature coefficient of the GenRad 1482 standards is 30×10^{-6}/K. The dc resistance of the standard has a temperature coefficient of 3.94×10^{-4}/K, approximately that of pure copper [6].

III. Stability

A. Previous Studies

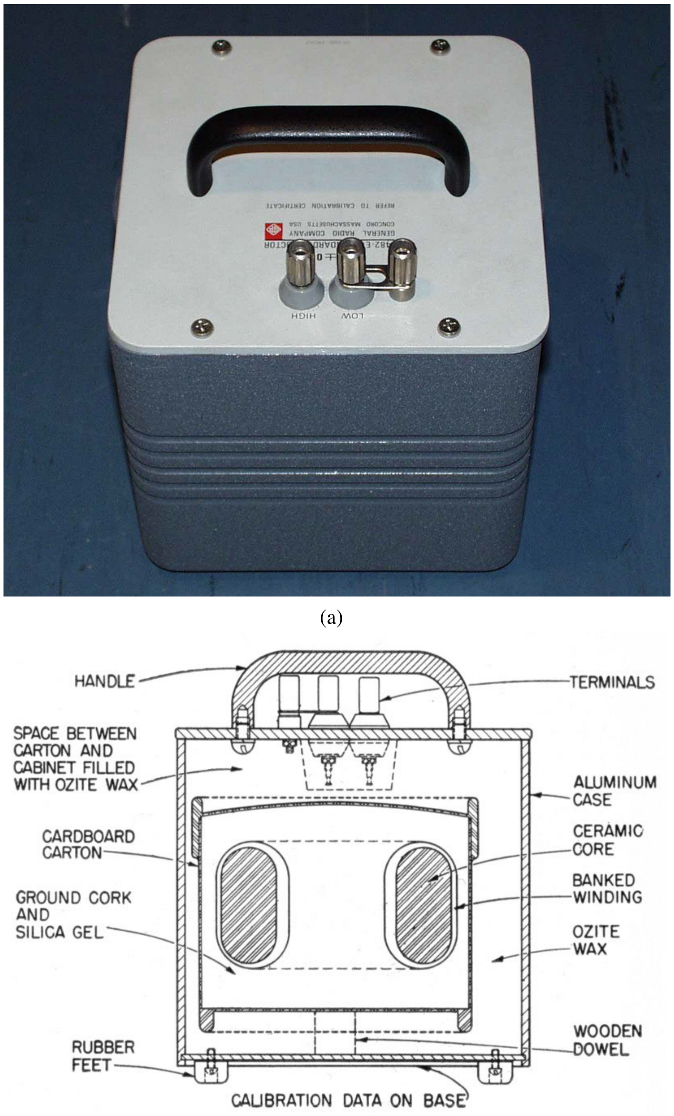
National Metrology Institutes maintain their national standard of electrical inductance by periodic calibration of a set of artifact standards, often GenRad 1482 inductors, but the outcome of these calibrations is typically unpublished.

Long-term stability observations are reported in [7], [8], and [9]. The stability after mechanical impact is reported in [8] and [10].

B. Past Comparisons

In the framework of the Metre Convention, a number of inductance comparisons were organized in the past, by both the CCEM and the regional metrology organizations. The key comparisons reported in the KC database (KCDB) [11] are CCEM-K3 (1989–1994[1]) [12], EUROMET.EM-K3 (2006) [13], and SIM.EM-K3 (2013–2015) [14]. EURAMET organized two supplementary comparisons (at the level of 100 mH), EUROMET.EM-S20 [15] and EURAMET.EM-S26 [16]. Two informal comparisons, one between INRIM and the Czech Technical University in Prague (CTU) [17] and one between PTB and the Technical Research Centre of Finland Ltd., Centre for Metrology (MIKES) [18], were also carried out.

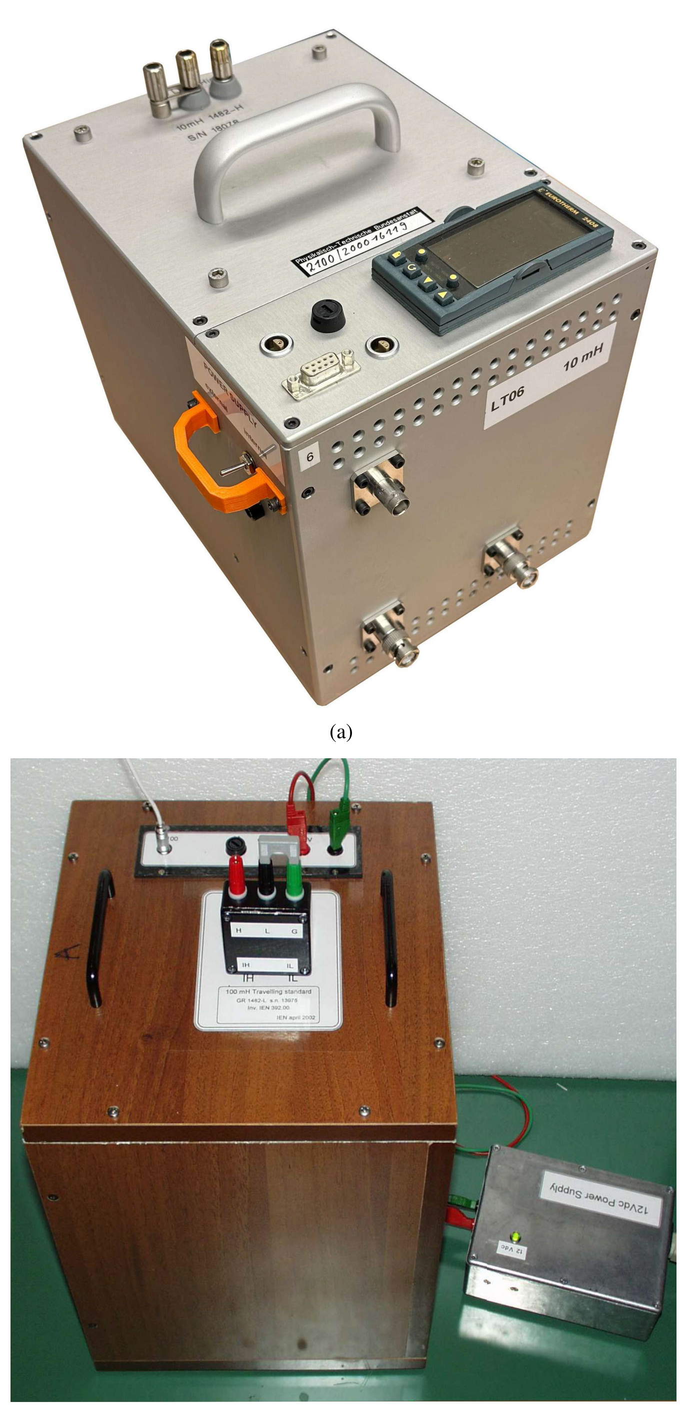
[1]The reported period is that of circulation of the standard.



(a)

(b)

Fig. 1. Appearance and construction of a GenRad 1482 inductance standard. (a) GenRad 1482 toroidal inductance standard. The three binding posts H, L, and G allow the inductor to be configured as a two-terminal or three-terminal impedance standard. (b) Cross section of a GenRad 1482 inductance standard. Source: [4, Fig. 3] ©General Radio Historical Society.



(a)

(b)

Fig. 2. Examples of thermostated inductance standards employed during international intercomparisons. (a) Temperature-controlled enclosure for 1482 standards, developed by PTB. This specific item includes the 10 mH standard with serial no. 10 878 tested in this work. (b) Temperature-controlled 100 mH inductor, based on a 1482 standard, developed by INRIM. The standard can be configured as two-terminal, three-terminal, or four-terminal pair impedance.

All these comparisons were performed using GenRad 1482 inductors (Section II) as traveling standards. To reduce the dependence over ambient temperature, dedicated temperature-controlled enclosures were developed [19]; examples of these enclosures are shown in Fig. 2.

In comparisons performed more than 20 years ago, it was possible to transport the standards with the temperature control turned on [12], [13]. With modern air transportation regulations, this is no longer possible. Air cargo temperature can be as low as a few degree Celsius [20] for several hours. The existence of possible thermal hysteresis effects on the inductance standards is, therefore, of concern and deserves investigation.

IV. Measurements at INRIM

INRIM performed measurements on a GenRad10 mH 1482-H, serial no. 16617, bought for the purpose of this work on the secondhand market. The measurements were performed at a frequency of 1 kHz and a current of 10 mA, using a fully-digital four-terminal-pair bridge [21]. The reference impedance was a Tinsley 100 Ω ac–dc resistor. The measurement relative standard uncertainty is 4.8 μH/H (coverage factor $k = 1$), an improvement with respect to the published

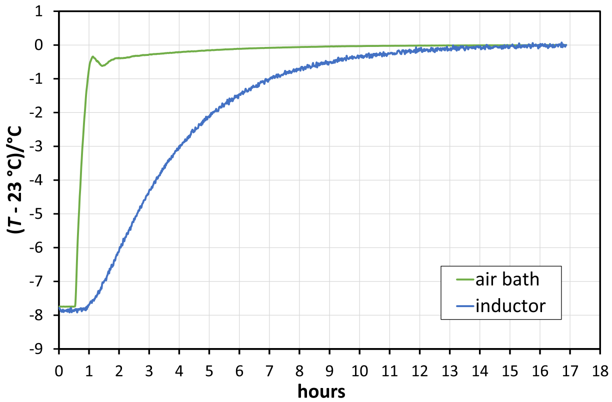


Fig. 3. Temperature evolution of the air bath (green) and of the winding (blue) after a positive step of the air bath temperature setting. A negative step (not shown) has similar time constants.

INRIM Calibration and Measurement Capabilities (18 μH/H, $k = 2$), which are related to an older calibration system [22].

A. INRIM, 10 mH: First Cooling Event

The standard was placed in a thermostated air bath (Kambic TK-190 US) at 23.00 °C for 70 days and then cooled to 15.00 °C for six days. Afterward, the standard was heated back to 23.00 °C.

Fig. 3 shows the temperature evolution in the air bath and in the winding, the latter monitored by measuring the inductor dc resistance. The delay due to the limited heat exchange from the surface to the bulk of the inductor is evident.

Fig. 4(a) shows the evolution of the inductance value before, during, and after the first cooldown event.

The cooling event induced a change of the inductance value of −271 μH/H, compatible with the specified temperature coefficient of 30×10^{-6}/K. After the cooling event, the inductor recovered the original value within a few μH/H, but after a few days, the inductance started to change randomly, with deviations up to 20 μH/H from the precooling value.

B. INRIM, 10 mH: Second Cooling Event

For the second cooling event, the standard was removed from the air bath and placed in the airtight container of Fig. 6, together with an environmental parameter data logger. It was then placed in a refrigerator and cooled to a temperature of 5 °C for ten days. After the cooling period, it was left to return to about 23 °C by keeping it in the airtight container: the aim was to avoid possible humidity condensation on the standard (see also Section VI). It was then removed from the cointainer and placed in the air bath for inductance measurements at 23.00 °C. After such operations and the settling of the inductor temperature, the measurements were resumed. In the 112 days between the last measurement performed after the first cooling event, Fig. 4(a), an unmonitored shift of +48 μH/H occurred.

Fig. 4(b) shows the evolution of the inductance value before, during, and after the second cooldown event. The standard recovers, in some days, the precooling value within a few μH/H; the strong shift as after the first cooling event, Fig. 4(a), is no longer observed.

V. Measurements at PTB

PTB performed measurements on two different standards

1) A GenRad10 mH 1482-H (serial no. 18078) standard. It is permanently housed in the temperature-controlled enclosure shown in Fig. 2(a), maintained at 26 °C with a stability better than 10 mK [18].
2) A GenRad100 mH 1482-L (serial no. 01279) standard.

The measurements were performed with the PTB Maxwell-Wien bridge [23] at a frequency of 1 kHz and currents of 2.5 mA for the 10 mH standard and 1.25 mA for the 100 mH standard. The combined relative measurement uncertainty is 5 μH/H (coverage factor $k = 1$). For $k = 2$, this uncertainty corresponds to the expanded uncertainty of the published PTB's calibration and measurement capabilities (CMCs) for inductance under the given conditions.

A. PTB, 10 mH

The time evolution of the 10 mH PTB inductor is shown in Fig. 5(a).

Before the experiments, the inductor showed a good long-term stability (about 10 μH/H deviation over a 3.5-year observation period).

The first event consisted in turning off the temperature control, reducing the inductor temperature from 26 °C to 23 °C for five days. This temperature change leads to a shift in the inductance value of −90 μH/H, well in agreement with the specified temperature coefficient. The temperature control was then switched on, and the inductor recovered the value before the event within one day and maintained it in the next days; the drift after one month is less than −3 μH/H.

The second event consisted in turning off the temperature control and cooling the case to 10 °C for three days. A measurement taken immediately after the cooling shows an inductance change of −470 μH/H.

After turning on again the temperature control, the inductance stabilizes (in less than one day) to a value −6 μH/H less than the one before the cooling event. The shift is consistently maintained after the next three months.

B. PTB, 100 mH

The time evolution of the 100 mH PTB inductor is shown in Fig. 5(b). It displayed remarkable long-term stability before the cooling event (less than 10 μH/H deviation over a 11-year observation period).

The standard was cooled to a temperature of 5 °C for three days in a temperature-controlled cabinet, and then returned at 23 °C. The measurement taken immediately after cooling shows an inductance reduction of more than 500 μH/H. After seven days, the inductance recovered to a value 10 μH/H less than the one before the cooling. Subsequent measurements show that the inductor recovers its original value after 17 days and then stabilizes.

VI. Discussion

Fig. 3 shows that the thermal settling time of the inductors is around 12 h, hence short if compared to the timescale of the events observed in Figs. 4 and 5.

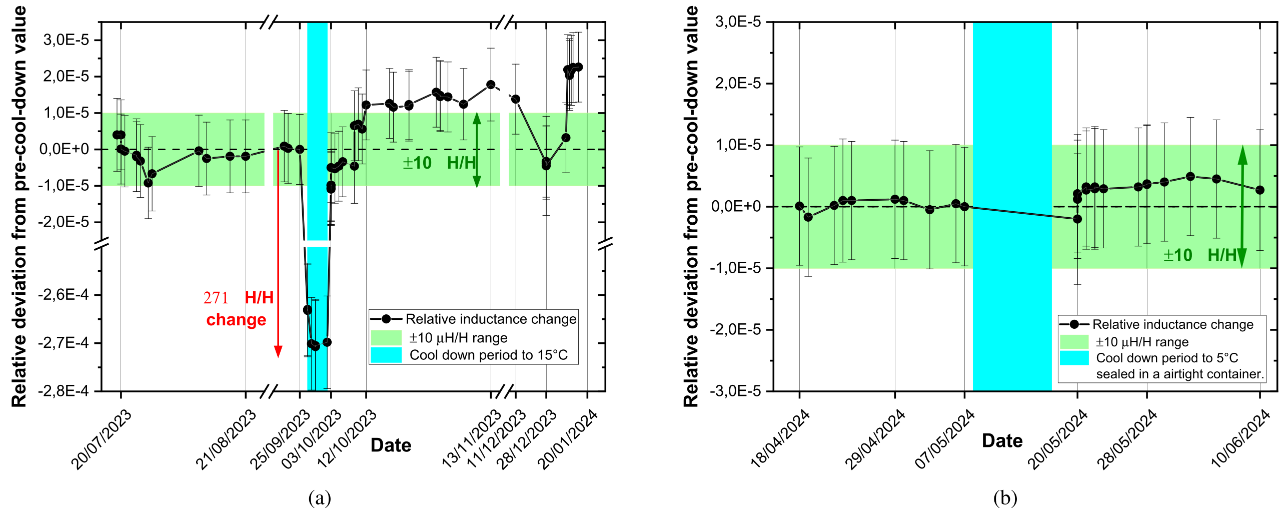


Fig. 4. Time evolution of the inductance of the INRIM 10 mH standard in the course of two different cooling events. (a) First cooling event, down to 15 °C, performed in a temperature-controlled air bath. (b) Second cooling event, down to 5 °C, performed in a refrigerator with the standard encased in the airtight container of Fig. 6. The uncertainty bars correspond to a $k = 2$ coverage factor.

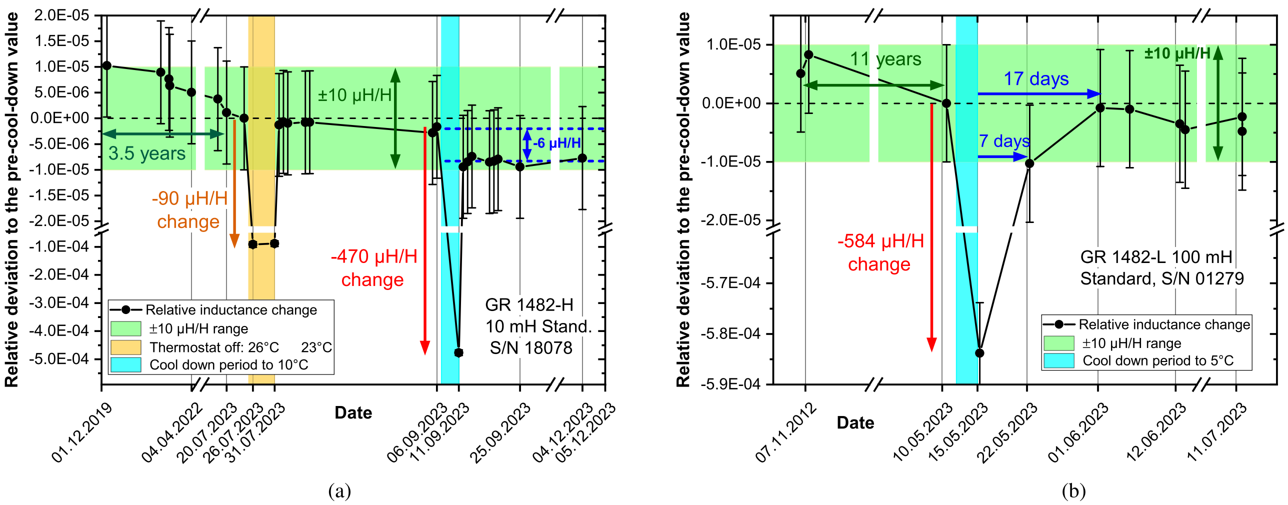


Fig. 5. Time evolution of the inductance of the PTB standards before, during, and after the temperature step events. The uncertainty bars correspond to a $k = 2$ coverage factor. (a) PTB: 10 mH. Highlighted in yellow, the shutting down the thermostat. In blue, the cooling event to 10 °C. (b) PTB: 100 mH. Cooling event down to 5 °C.

Both INRIM and PTB measurements show that the standards are relatively stable before the cooling events, and that each event induces for its duration an inductance change compatible with the specified temperature coefficient of the 1482 series.

A temperature change of only a few degrees, like that observed on the 10 mH PTB inductor when the thermostat is switched off [Fig. 5(b)], does not seem to create significant hysteresis or aftereffects. This is also consistent with INRIM previous measurements on a 100 mH thermostated inductor (not the one here reported, but characterized as traveling standard for intercomparisons [19]) and more generally with metrology laboratory practice, where some temperature cycling events over the years (e.g., due to power outages, air conditioning maintenance, etc.) are inevitable.

On the other hand, both INRIM and PTB measurements show that temperature cycles of larger amplitudes induce significant after effects, of mid- and long-term, often irreversible, in the inductance value,[2] which does not show significant aftereffects within the measurement uncertainty.

Despite being of the same type, the standards investigated show different behaviors. The INRIM 10 mH inductor, after the first cooling event, suffered a series of step changes that occurred in the following two months of observations, with a deviation up to 20 μH/H with respect to the value before the event. The second cooling event, although it reached lower

[2]INRIM experiments monitored also the inductor ac resistance, i.e., the real part of the impedance [24, Section. 1.4.3].

Fig. 6. Airtight container employed to perform the cooling event described in Section III, Fig. 4(b) to avoid possible humidity condensation effects. The yellow instrument is the environmental parameter data logger.

temperatures, does not seem to replicate the instabilities of the first event.

The PTB 10 mH inductor showed a permanent value shift of several μH/H. The PTB 100 mH inductor recovered its original value, but over a timescale of two weeks, much longer than the temperature time constant.

The inductors have been characterized as closed boxes, and the origin of the thermal hysteresis remains unknown. Most effects occur over a timescale of weeks, suggesting a mechanical creep of the wiring or—more likely—in the insulating material [see Fig. 1(b)] of the construction.

Among possible origins for such mechanical effects, one is related to the humidity content of the insulating material (ground cork and silica gel, which are hygroscopic materials). The cooling events were performed in laboratory environments, where the *relative* humidity swings over a moderate range; however, the corresponding *absolute* humidity deviations are much larger.[3] The observed phenomena occur over a timescale compatible with the need to reequilibrate the absolute humidity content of the insulating material with the environment [25]. The lack of relaxation or hysteresis phenomena in the second cooling event of the 10 mH INRIM inductor, where the airtight container prevented water exchange with the environment, is compatible with such tentative interpretation.

VII. Conclusion

The stability of inductance standards of the GenRad 1482 series, having nominal values of 10 and 100 mH, was investigated with respect to cooling events down to temperatures typical of air transportation.

The inductors had a good stability before the cooling events. After the cooling events, the inductors showed varied instabilities, in general not compatible[4] with the requirements of an international intercomparison aiming at a determination of the degrees of equivalence with uncertainty less than 10 μH/H, as expected from CCEM-K3.2018.

The origin of the observed instabilities remains unclear. There is some clue that the humidity absorbed by the insulating material that encapsulates the inductor winding might have a role.

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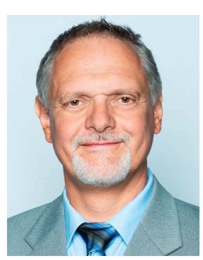

Harald Bothe was born in Goslar, Germany, in 1968. He received the Dipl.-Ing. degree in electrical engineering, specializing in communications engineering, from the University of Applied Sciences Braunschweig/Wolfenbüttel, Wolfenbüttel, Germany, in 1995.

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