

Original Article

Design and Performance Evaluation of a High-Precision Cryogenic Calibrator for Low-Temperature Industrial Applications

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Abstract - Accurate cryogenic calibration from -196 °C to +50 °C is a critical requirement for environmental monitoring, medical diagnostics, aerospace, superconductivity, materials science and the development of cryogenic instruments. The most accurate method is fixed-point calibration according to the International Temperature Scale of 1990 (ITS-90), but it requires skilled personnel, expensive fixed-point cells and time-consuming procedures, limiting it to some national metrology institutes. Comparison calibration is more practical for routine use, but the comparison sources are generally limited by refrigeration constraints to approximately -80 °C, or if Liquid-Nitrogen (LN₂) cooled systems are used to attain milli-kelvin accuracy near -196 °C, they are large, expensive and limited to a single fixed point. The literature does not report any system that combines the full -196 °C to +50 °C coverage, sub-0.05 °C uncertainty and portability in one compact unit. This combination gap is the particular problem addressed here. The design of a Low-Temperature Calibrator (LTC) for operation from -196 °C to +50 °C with a target thermal stability and axial uniformity of ±0.02 °C and a corresponding target expanded measurement uncertainty of ±0.05 °C, consistent with GUM and IEC 60751 practice, is described in this work. The proposed design incorporates several sensor wells, radiation shielding, a metal isothermal comparison block, multizone thyristor-controlled heating, an LN₂ cooled insulated enclosure, automatic data logging and an easy-to-use HMI. Since this is a design and methodology study, the reported values are design targets, not measured results, and immediate follow-on work is planned to fabricate and experimentally validate a prototype. If validation is successful, the approach is expected to improve the accuracy, efficiency and accessibility of industrial cryogenic temperature calibration over current single-point or laboratory-only systems.

Keywords - Axial uniformity, Cryogenic systems, Dry block calibrator, Liquid nitrogen baths, Low-Temperature Calibration, Thermal stability.

1. Introduction

1.1. Thermodynamic Industrial Principles

Temperature perception began as a qualitative sense of hot and cold and was progressively formalized into quantitative thermodynamic scales through the development of thermometry. Early scales were arbitrarily defined but were later refined to anchor on reproducible fixed points, such as the freezing and boiling points of pure substances. The current worldwide temperature scale is the International Temperature Scale of 1990 (ITS-90), which defines fixed points and interpolation methods for the realization of temperature scales (Tew Jr, 2015) (Radebaugh, 2016). Temperature is conceptually related to how much kinetic energy the particles constituting a system have. The measurement of temperature is a thermodynamic one. The Zeroth Law of Thermodynamics introduces the concept of thermal equilibrium and the

existence of an empirical temperature. The Kelvin scale is an absolute thermodynamic temperature scale, based on the triple point of water, which has been set to 273.16 K (Radebaugh, 2016). The measurement principles are based on different physical properties which are dependent on temperature, namely: electrical resistance, thermoelectric voltage and thermal expansion. Each sensor type converts a change in temperature into an electrical signal (e.g. resistance or voltage) that can be measured and related to a temperature value by established physical laws or any empirical correlations. Precise temperature control is also critical for industrial applications as it affects quality of products, efficiency of the process and associated safety. For instance, Industrial Platinum Resistance Thermometers (IPRTs) are designed to bear harsh conditions, such as mechanical shock, vibration, and aggressive chemical environments, while continuing to



provide accurate measurements (Pearce, 2021). Temperature sensing is important for chemical reactions, food processing, energy generation and manufacturing. Automated systems are usually linked to local area networks and offer continuous monitoring and maintenance functions for temperature instrumentation from a remote place (Pearce, 2021). The ability to accurately control thermal conditions directly affects economic viability and reliability of operation in a wide range of areas.

1.2. Operation in Cryogenic Temperatures

All temperature and heat transfer phenomena are governed by the laws of thermodynamics. These laws are of great importance in the science of cryogenics. The Third Law of Thermodynamics says you cannot reach absolute zero (0 K) in a finite number of steps. It illustrates the increasing difficulty of cooling as you go toward absolute zero.

In practical cryogenic systems, like the one we are considering here, operating at around 77 K, both the First Law (conservation of energy) and the Second Law (entropy and the direction of heat transfer) are relevant. Heat always flows from a high temperature region to a low temperature region. Any actual process of cooling is irreversible, and it reduces the efficiency of the process. The thermodynamic properties of liquid nitrogen, such as the boiling point, latent heat of vaporization, and specific heat of the vapor, are important for the cooling efficiency and the lowest attainable temperature (Misek & Dominec, 1982).

The boiling point of LN₂ varies with pressure, so knowledge of vapor-liquid equilibrium is essential if the boiling point of LN₂ is to be used as a reference or control point. Accurate and traceable temperature metrology at cryogenic temperatures requires the use of special sensors and techniques. Temperature sensors commonly used are Standard Platinum Resistance Thermometers (SPRTs), silicon diodes and thermocouples. SPRTs are extensively used as primary standards due to their high accuracy and stability. Silicon diodes are sufficiently sensitive and can be used in a wide temperature range. Thermocouples are versatile, but usually not as accurate as SPRTs or diodes. Such sensors need to be calibrated by comparing their measurements to a traceable reference standard in a controlled cryogenic environment. Uncertainty analysis is an important part of the temperature metrology, since it includes factors like sensor calibration, thermal gradients and errors in the measurement system (Estacio, 2019).

Comparison calibration is a practical method for traceability propagation. In this method, sensors are tested against a pre-calibrated reference standard in a thermally stable environment. This was forthwith continued with improvements in cryostat design, electronic instrumentation and better knowledge of heat transfer and materials behavior at low temperatures, leading to the refined calibration systems

available today, including those using metal blocks for thermal equilibration (Ballico and Freund, 2011). Superconductivity is a field of cryogenic thermometry, which is intrinsically thermometry-dependent, and refers to the disappearance of electrical resistance in some materials at a critical temperature (T_c). Accurate determination of T_c, critical magnetic fields (H_c) and critical current densities (J_c) are important for characterization of superconducting materials and for comprehending their basic physics. High-temperature superconductors are operated at relatively warm cryogenic temperatures (e.g. above 77 K, the boiling point of liquid nitrogen), but still require precise temperature control and measurement for optimal synthesis of the materials and fabrication of devices.

Cryogenic technologies are of great importance in the aerospace industry, mainly in rocket propulsion systems with Liquid Hydrogen (LH₂) and Liquid Oxygen (LOX) propellants. Accurate temperature monitoring of these cryogenic fuels during storage, transfer and in engine operation is vital for optimum performance, safety and efficiency. Infrared detectors in space-based telescopes and Earth observation satellites are usually cooled to cryogenic temperatures to reduce thermal noise and improve sensitivity.

Furthermore, cryosurgery and cryopreservation of biological tissues and cells require precise temperature control in the cryogenic range to achieve specific therapeutic effects or to ensure long-term viability of samples (Ballico & Freund, 2011). The liquefied gas industry, involved in the production, transport and storage of Liquefied Natural Gas (LNG), nitrogen, oxygen, argon and helium, makes widespread use of cryogenic thermometry. For instance, custody transfer of LNG requires very precise temperature (and density) measurements to ensure fair trade. Also, reliable temperature monitoring is required for safe handling of large quantities of cryogenic materials to prevent over-pressurization or embrittlement of materials.

Temperature control and measurement are crucial elements for experimental design and reproducibility in scientific research. The precision of temperature control is of great importance in analysis in the fields of materials, medical, spacecraft, chemical, pharmaceutical and environmental sciences. Experiments in superconductivity, quantum physics and space simulation are also significant at cryogenic temperatures (Radebaugh, 2016).

As for the low temperature sensors, the accuracy and calibration process are very stable and important for the reliability of test results (Pal et al., 2017). The temperature range of -200 °C to +50 °C is important for many reasons. The boiling point of liquid nitrogen at normal room pressure, -196 °C, is a convenient and often used cooling medium. The +50 °C point includes ambient and normal operating temperatures for most of the equipment.

1.3. Temperature Sensors Criteria and Calibration Concepts

Temperature is measured with a variety of sensors, each based on a different physical principle. Thermocouples measure the voltage generated by the difference in temperature of two dissimilar metals. RTDs, such as Industrial Platinum Resistance Thermometers (IPRTs) and Standard Platinum Resistance Thermometers (SPRTs), are based on the principle that metals have a predictable change in electrical resistance with temperature (Silke Augustin, 2023). In a semiconductor thermistor, the resistance changes a lot and nonlinearly with temperature. Infrared sensors detect the thermal radiation emitted by an object to give temperature readings without contact. The accuracy depends on the emissivity of the surface.

In cryogenic applications, specialized sensors such as silicon diodes and Cernox™ are routinely used (Pal et al., 2017; Radebaugh, 2016). The choice of temperature sensor depends on the required accuracy, temperature range, environmental conditions and cost. Platinum resistance thermometers, and especially SPRTs, are highly accurate and stable, and are used as interpolation instruments in the ITS-90. IPRTs provide a trade-off between the accuracy and durability required for industrial applications, with temperature ranges from -200 °C to 650 °C (Pearce, 2021). Thermistors are very sensitive within a limited range, but not so linear. Thermocouples are very versatile over a wide range, but generally not as accurate as RTDs. Common limitations of temperature sensors are drift, hysteresis, self-heating and susceptibility to electrical noise or mechanical stress (Pearce, 2021).

To better standardize temperatures around the world, the International Committee for Weights and Measures (CIPM) created the International Temperature Scale of 1990, or ITS-90. It has fixed points corresponding to the phase changes of fourteen elements and one compound, water, over the range 0.65 K to 1357.77 K. ITS-90 offers a strong calibration framework with devices like SPRTs and helium vapor thermometers, but its complexity, cost, and reliance on rigid fixed points make it difficult to implement in practice for cryogenic applications. The infrastructure required for the implementation of ITS-90 does not favor frequent or in-situ calibrations. This creates a gap between high-precision standards and deployable solutions in the field. ITS-90 ranges from the triple point of equilibrium hydrogen (13.8033 K) to the freezing point of silver (961.78 °C) and relies on Platinum Resistance Thermometers (PRTs) that are calibrated at specified fixed points. In the cryogenic range (e.g. around 77 K), the assigned interpolating instruments are the SPRTs whose resistance-temperature relationship is determined through calibration at fixed points such as the argon triple point (-189.3442 °C), mercury triple point (-38.8344 °C), and water triple point (0.01 °C) (Silke Augustin, 2023). The comparison method is a commonly employed technique for the calibration of temperature sensors, particularly in

situations where the direct realization of fixed points on the temperature scale is either impractical or financially unfeasible. In this approach, the sensor under test is positioned in close thermal contact with a calibrated reference thermometer within an environment. After thermal equilibrium is attained at various temperature setpoints, readings from both sensors are recorded simultaneously. The accuracy of the sensor under test is evaluated by comparing its electrical output (ohms or milli volts) with the calibrated and ITS-90 traceable reference standard (Ballico & Freund, 2011). The uncertainty of calibration depends on the axial thermal uniformity, sensor thermal contact, thermal stability, and the accuracy in measurement of sensor's electrical outputs. The selection of the cooling medium and the design of the calibration chamber or cryostat are also vital for achieving the necessary temperature range and stability (Pal et al., 2017). This comparison method provides a stable thermal source that is simple, cost-effective, and fast turnaround for user-friendly industrial calibration.

Despite these advances, a specific gap remains between the milli-kelvin accuracy achievable with large, stationary cryostats at national metrology institutes and the portable, low-maintenance comparison systems needed in industrial and commercial calibration laboratories. Existing commercial dry-block and single-point LN₂ comparators typically provide either a wide temperature range with modest uncertainty or high stability at one fixed point, but not both within a single compact, portable unit spanning -196 °C to +50 °C. Addressing this specific combination gap, through the design of a Low-Temperature Calibrator (LTC), is the central problem taken up in this work and is detailed in Section 2.

2. Problem Description

A persistent gap exists between the mK-level accuracy achievable with large, stationary cryostats operated at national metrology institutes (Ballico and Freund, 2011) and the portable, low-maintenance systems required in industrial and commercial calibration laboratories. Commercial dry-block and single-point LN₂ comparators typically deliver either a wide temperature range with modest uncertainty ($\geq \pm 0.5$ °C) or high stability at a single fixed point ($\approx \pm 0.002$ °C at 77 K), but not both, and none is documented to cover the complete -196 °C to +50 °C span within one compact, portable unit. This gap between metrology-grade precision and field-deployable practicality is the specific problem the present work addresses through the design of the Low-Temperature Calibrator (LTC).

Precision low-temperature calibration, across -196 °C to +50 °C, underpins many scientific and industrial processes. Accurate temperature measurement is essential in aerospace, superconductivity research, materials science, and the development of cryogenic temperature sensors. The paper presents design, evaluation and sustainment of a cryogenic comparison calibration system with liquid nitrogen (LN₂) at a temperature range of -196 °C to +50 °C. It encompasses a

number of related fields. Precision systems like liquid-nitrogen comparators and the proposed Low-Temperature Calibrator (LTC) are state-of-the-art in the calibration of cryogenic sensors to obtain high thermal stability and uniformity. Thermal stability and uniformity, such as axial and radial uniformity and thermal stability in sub-zero temperature zones, are reviewed with a focus on minimizing calibration errors and uncertainty through optimized bath design, sensor placement and insulation strategy.

In sustainable cryogenic practice, energy-efficient system designs that minimise LN₂ consumption and environmental impact are investigated. Collectively, this study aims to design, develop, and evaluate a negative-temperature comparator capable of higher thermal stability and axial uniformity across -196 °C to +50 °C, addressing major open challenges in negative-temperature calibration while contributing to the broader field of temperature metrology.

2.1. Literature Review

Calibration at cryogenic temperature is of utmost importance to ensure the accuracy and reliability of temperature measurement in a wide range of scientific and industrial applications. Conventional approaches like fixed-point calibration against the ITS-90, while providing high accuracy, are encumbered by complexity, cost and operational limitations, particularly at cryogenic temperatures.

As a result, alternative methods, such as comparison calibration, have gained popularity due to their utility in routine and industrial applications. This review covers the progress of cryogenic calibration methods, state-of-the-art technology, limitations of current systems, and the need for more accessible and robust low-temperature calibration options. It also identifies critical research gaps that will guide the design of a novel low-temperature calibrator, which is the focus of this work.

Liquid nitrogen remains the coolant of choice for most cryogenic comparison systems, although alternative media exist (Sosnovtsev et al. 2016). It is more abundant and considerably cheaper than liquid helium, which reaches lower temperatures (4.2 K) but is scarcer and costlier.

Cryocoolers avoid cryogen handling altogether but generally offer lower cooling power and poorer temperature stability than LN₂-based baths. Dry ice and thermoelectric coolers cover only a narrow range and cannot match the accuracy of LN₂ systems. For these reasons, LN₂ continues to be widely used for thermal stabilisation of detectors and calibration equipment alike.

LN₂'s high latent heat of vaporisation makes it an efficient coolant (Ballico and Freund, 2011), though materials in contact with it must be selected to avoid low-temperature embrittlement. It can be used in open baths, but closed-loop

systems, in which flow or level is regulated to cool a calibration block, are more common in practice.

Pal et al. (2017) note that cryogenic-temperature physics often departs markedly from ambient behaviour, or shows strongly amplified effects, and that this governs both sensor choice and calibration-system design. Electron and phonon quantum-mechanical behaviour, the temperature dependence of electrical resistivity, thermoelectric effects, and semiconductor-junction properties all become significant at low temperatures. Practical scales such as ITS-90 disseminate the thermodynamic Kelvin-scale definition of temperature, and the thermometric parameter chosen for a given sensor (resistance, voltage, or capacitance) must be stable, well characterised, and sufficiently sensitive over the intended range. Among cryogenic sensor types, Platinum Resistance Thermometers (PRTs) remain the most common reference standard for their stability and reproducibility, particularly below about 13.8 K, while rhodium-iron, germanium, and carbon-glass RTDs serve lower temperatures or specialised environments.

Misek and Dominec (1982) describe how the physical properties of materials change substantially at cryogenic temperature, with direct consequences for sensor and cryostat design. The electrical resistivity of pure metals falls sharply as temperature decreases, eventually dominated by impurity and defect (residual) scattering - the mechanism exploited by metallic RTDs - while some alloys develop non-monotonic resistance-temperature behaviour at very low temperature due to the Kondo effect. Specific heat generally falls with temperature (approximately as T^3 from lattice vibrations, and linearly with the electronic contribution in metals), giving faster thermal response but greater vulnerability to small heat leaks. Thermal conductivity likewise varies strongly: pure copper and silver become excellent conductors, useful for isothermal blocks and heat sinks, whereas stainless steel and many plastics become good insulators, useful for cryostat construction. The choice of material for structural components is further limited by mechanical embrittlement at low temperature. Liquid nitrogen boils at a normal boiling point of about 77.36 K (-195.79 °C) at standard atmospheric pressure. This reference temperature is convenient and commonly used, though it varies slightly with purity and ambient pressure.

Cryogenic calibration techniques are classified into fixed-point and comparison calibrations in Tew Jr, (2015). Fixed-point methods give well-defined, highly reproducible temperatures - triple points, boiling points or superconducting transitions of pure substances - and are the main references for scale definition and dissemination, but are complex and time-consuming. Comparison methods involve calibration of a sensor under test against a pre-calibrated reference in a controlled thermal environment. They tend to be more pragmatic and flexible for routine calibration of diverse sensor types, provided the reference is well characterized, and the

comparison environment is well controlled. Many national metrology institutes maintain facilities for both, and the choice between them is made according to the required accuracy, temperature range, sensor type and available resources.

A rigorous uncertainty analysis is central to any credible calibration process (Pal et al. 2017), quantifying doubt in the measurement result. Cryogenic calibration uncertainty sources are commonly grouped into Type A (evaluated statistically) and Type B (evaluated by other means - manufacturer data, prior calibration reports, or scientific judgement) contributions. Typical sources include the reference thermometer's calibration uncertainty, block temperature stability and uniformity, data-acquisition resolution, sensor self-heating from excitation current, lead-wire thermal EMF, thermal contact resistance, and interpolation error where a mathematical fit is applied to the data.

Mitigation relies on careful apparatus design (high-conductivity block materials, well-anchored leads, adequate immersion depth), tight control of the thermal environment, high-quality reference standards, appropriately low excitation currents, and disciplined procedure, with a full uncertainty budget required to state the system's Calibration and Measurement Capability (CMC). Pal et al. (2017) also report a variable-temperature insert using a copper calibration block, covering 2.2 K to 325 K with liquid helium at the low end and implicitly LN₂-compatible operation at the higher end of the cryogenic range. Comparison systems using LN₂-cooled metal blocks have been reported by several groups: the National Measurement Institute of Australia (NMIA) developed a vacuum cryostat with an oxygen-free copper block that achieved milli-kelvin-level transfer errors from -202 °C to 250 °C using controlled LN₂ flow at the lower end of the range, with gold-plated radiation shields and computer-controlled temperature stability (Ballico and Freund, 2011).

Isotech's nitrogen boiling-point comparison apparatus uses an equalising block to compare sensors against the LN₂ boiling point, with a manufacturer-reported uncertainty of the order of ± 0.002 °C (Isotech, 2011). Reports of this kind consistently emphasise thermal homogeneity within the block, minimising heat loss, and robust control as the main design challenges, alongside ensuring adequate sensor immersion and reliable LN₂ delivery. Because such systems are frequently built to a specific user's needs, no single design serves every application; the recurring lesson across these studies is the importance of thermal anchoring of leads and stable temperature control, both of which directly inform the design of the LTC proposed here. Sustainability in metrology and calibration means minimising the environmental impact and resource consumption of a measurement process while preserving its accuracy and reliability (Brandi & dos Santos, 2016). For cryogenic calibration, this translates into optimising LN₂ consumption, recovering boil-off gas where

practical, and adopting more energy-efficient cooling designs. Nitrogen itself supports this goal: it is a by-product of air separation that would otherwise be released to the atmosphere, and it is odourless, colourless, chemically inert, non-flammable, and non-explosive, making it an environmentally benign cryogenic medium (CAMEO Chemicals, n.d.).

Overall, the literature shows steady improvement in cryogenic temperature calibration, particularly across -196 °C to +50 °C, but comparison systems in this range still face open challenges in thermal stability, uniformity, scalability, and cost, and compact, user-friendly systems with traceable accuracy remain scarce in industrial settings.

As summarised in Table 1, existing single-point systems such as the Isotech apparatus and the Fluke 7196B LN₂ comparator achieve milli-kelvin stability but only at the LN₂ boiling point, while wide-range dry-block calibrators cover a broad span but with markedly higher uncertainty and no coverage below about -80 °C (Fluke Calibration, 2024a). This gap between fixed-point precision and wide-range practicality motivates the present work, which aims to develop and evaluate a low-temperature calibrator able to close it while meeting international metrology standards.

2.2. Research Gaps

The critical analysis of the existing systems and methodologies unearths the following key research gaps:

- Limited temperature stability, high uncertainty in practical setups. Non-metrology-grade systems cannot deliver the required thermal stability (± 0.02 K) and uncertainty (mK-level) owing to poor thermal control, fluctuating LN₂ flow, and environmental disturbances.
- Metal blocks: Suboptimal thermal design and gradient control. Many systems show poor thermal uniformity in the calibration block due to poor sensor contact, asymmetrical heat input and poor thermal anchoring, introducing large calibration errors.
- Absence of standardized, low-cost calibration infrastructure. There is a distinct lack of standardized, cost-effective, reproducible and user-friendly cryogenic calibration systems, especially for laboratories without access to national metrology-level infrastructure.
- Very dependent on operator skill and manual setup. Many current systems require expert knowledge for operation and maintenance, and have time-consuming setups and limited automation, making them unsuitable for routine use in industrial or multi-user environments.
- Environmental and efficiency issues in existing LN₂ systems. Existing systems exhibit high LN₂ consumption, bulky configurations and poor energy efficiency. Sustainable calibration solutions that can optimize the use of cryogen and enhance insulation are still being developed.

2.3. Comparative Positioning of the Proposed LTC

To make the specific advance of the proposed LTC explicit, Table 1 benchmarks it against representative systems discussed in the literature above. No single existing system combines full-range coverage, sub-0.05 °C uncertainty and field portability; the proposed LTC is positioned to close this combination gap rather than to improve any one axis in isolation. In particular, single-fixed-point comparators such as the Isotech apparatus and the Fluke 7196B (Table 1) achieve

markedly better short-term stability (≈ 2 mK) than the ± 0.02 °C targeted here, but only at one setpoint near -196 °C, while commercial dry-block calibrators cover a wide range but do not operate below about -80 °C and carry an order-of-magnitude higher uncertainty. The proposed LTC targets the specific combination these systems do not offer: full -196 °C to +50 °C coverage in a single portable unit at sub-0.05 °C expanded uncertainty.

Table 1. Comparative positioning of the proposed LTC against representative cryogenic calibration systems

System	Temperature Range	Reported Uncertainty / Stability	Portability	LN ₂ Consumption
NMIA vacuum cryostat (Ballico and Freund, 2011)	-202 °C to 250 °C	mK-level	Large, stationary	Continuous LN ₂ flow
Pal et al. (2017) VTI	2.2 K-325 K	High accuracy	Laboratory-only	Uses LHe for lowest range
Isotech LN ₂ boiling-point apparatus (Isotech, 2011)	Single fixed point (-196 °C)	± 0.002 °C	Bench apparatus	Fixed point only; not a full-range comparator
Fluke 7196B LN ₂ Comparison Calibrator (Fluke Calibration, 2024b)	Single fixed point (-196 °C)	≈ 2 mK stability; < 0.0004 °C uniformity	Bench-top (portable)	User-supplied LN ₂ ; consumption not specified
Commercial dry-well calibrator (Fluke Calibration, 2024a)	-25 °C to 650 °C	± 0.5 °C accuracy; ± 0.05 °C hole-to-hole	Portable	Electrical only; not rated below ≈ -25 to -80 °C
Proposed LTC (this work)	-196 °C to +50 °C (single unit)	± 0.02 °C stability / ± 0.05 °C expanded uncertainty	Portable (≤ 50 kg, ≤ 0.5 m ³)	< 10 L per calibration cycle

3. Objectives of the Study

The present research is conducted to achieve the following measurable objectives:

- The goal is high accuracy and precision, with thermal stability and axial uniformity better than ± 0.02 °C. The objective is to meet the requirements of the IEC 60751 standard for platinum resistance thermometers and temperature sensors at an expanded uncertainty of ± 0.05 °C.
- Develop a single-unit system covering the full temperature range of -196 °C to +50 °C using the comparison-calibration method, removing the need for multiple calibration setups and significantly reducing the time and complexity associated with fixed-point techniques.
- Sustainable Calibration at Cryogenic Temperatures. The aim is to develop a sustainable calibration methodology to tackle the problem of high Liquid Nitrogen (LN₂) consumption and energy inefficiency of current systems. It shows the use of liquid nitrogen as an eco-friendly coolant with the target of low boil-off losses and a low LN₂ consumption rate of less than 10 litres per calibration cycle.
- The aim is to develop a simple, safe, compact (< 0.5 m³) and portable (< 50 kg) system that closes the gap between the accuracy of the laboratory and the practical

application. This would permit in-situ calibration of high-precision temperature sensors in industrial environments and reduce reliance on central calibration facilities of industrial relevance.

- This objective is to control conduction losses and reduce temperature gradients in the calibration block, given the thermal gradient and heat-flow issues seen in metal-block designs. This reduces the risk of icing and sensor freezing during calibration, thus ensuring measurement reliability and equipment safety.

4. Proposed Methodology

The research methodology starts with the conceptual framework of a cryogenic calibration system with emphasis on the need of high thermal stability and low uncertainty. The isothermal metal block will be made of Oxygen Free High Conductivity Copper (OFHC), which has good thermal properties in the negative temperatures. It will be designed in respect of geometric optimization for better stability and uniformity. The design targets a thermal stability and axial uniformity of ± 0.02 °C, distinct from the expanded measurement uncertainty target of ± 0.05 °C defined in Section 3; both are required for precise calibration in industrial environments. The design assumes negligible radial heat leak through the insulated enclosure relative to the axial conduction path through the OFHC copper block, and a quasi-steady-state block temperature during each dwell period. Design-stage

sensitivity analysis indicates that axial uniformity is most sensitive to sensor-well contact resistance and radiation-shield emissivity, followed by block wall thickness and insulation thickness; these parameters were therefore prioritized in the mechanical design and will be verified experimentally once the fabricated prototype is instrumented. After the finalization of design, manufacturing of the isothermal metal block and insulated cryogenic chamber will be fabricated. The chamber, maybe made of stainless steel 316 or aluminum or other advanced cryogenic suitable material, to ensure efficient functioning under cryogenic conditions. The passive liquid nitrogen will be used for creating stable cooling with minimal boil-off losses and improved energy efficiency. Also, the safety requirements such as nitrogen pressure relief valves and sufficient insulation for the cryogenic equipment.

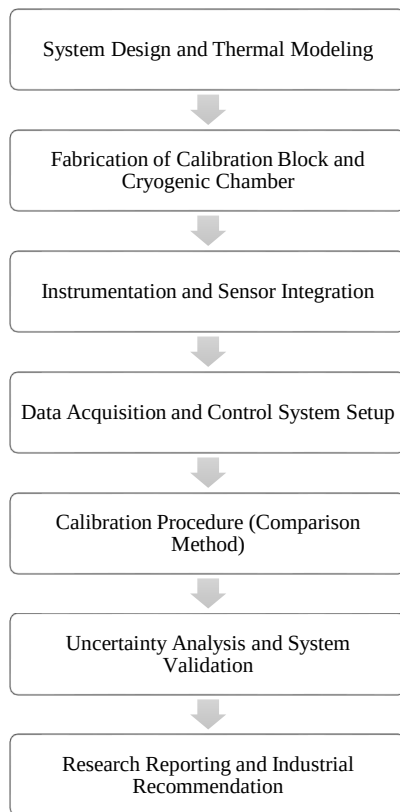


Fig. 1 Working methodology flow chart

The control instrumentation shall include a calibrated Standard Platinum Resistance Thermometer (SPRT) and Sensors under Test mounted in the isothermal metal block with minimum contact resistance. 4-wire sensors and good conductivity leads will be used to ensure accurate measurements. The control system shall be PID with thyristor and Human Machine Interface (HMI). A Programmable Logic Controller (PLC) shall be deployed to control & sequence the operations, such as real-time data logging, level control, power output and temperature display of reference sensor and sensor under test. The system shall be stabilized prior to the

recording of data. A detailed uncertainty budget, as per ISO/IEC Guide 98-3 (GUM) guidelines, shall be taken into account, including the thermal gradients, stability, uniformity and sensor repeatability. The complete system shall be validated in accordance to International Guidelines DKD-R 5-4 / Euramet cg-13.

The reference SPRT used for comparison is calibrated and traceable to a National Metrology Institute via ITS-90 fixed points. Following ISO/IEC Guide 98-3 (GUM) and the structure of DKD-R 5-1, the combined standard uncertainty will include Type A contributions, evaluated from the repeatability of readings over a minimum of three ascending and three descending cycles per setpoint and reported as the standard deviation, and Type B contributions comprising the SPRT calibration uncertainty, block axial/radial non-uniformity, data-acquisition resolution, sensor self-heating, lead-wire thermal EMF, and thermal contact resistance. Test conditions, namely the ambient temperature and relative humidity range, the LN₂ purity grade, and the dwell-time stability criterion used to confirm thermal equilibrium at each setpoint, will be recorded and stated explicitly alongside each calibration run.

At the present design stage, the repeatability, stability, hysteresis, sensor-contact effects, and complete uncertainty budget described above are targets defined by the measurement methodology rather than measured outcomes; their experimental determination, together with a quantitative thermal simulation of the isothermal block (finite-element or lumped-parameter analysis of axial temperature distribution and heat leakage), is planned as the immediate next phase of this work and will be reported once the prototype is fabricated and instrumented (see Section 5).

The calibration of the sensors is to be carried out by the comparison method according to the International Standard DKD-R 5-1 “Calibration of Resistance Thermometers”. This method consists of comparing the resistance readings of the SUTs with those of a reference SPRT traceable to ITS-90 at several carefully stabilized temperature setpoints within the desired temperature range of -196 °C to +50 °C. The calibration block is first cooled to the lowest required temperature (or slightly below) using liquid nitrogen. The temperature will then be adjusted and stabilized at each calibration point by careful control of LN₂ flow or level and block heaters operating under a PID feedback system. Potential hysteresis effects in the SUTs will be evaluated using both ascending and descending temperature sequences. The system will be given sufficient dwell time at each temperature setpoint to achieve thermal equilibrium, as evidenced by monitoring the stability and uniformity of the temperature within the calibration block. Once the steady state conditions are established, the resistance readings from both the SPRT and the SUTs will be recorded using a high-resolution data acquisition system. The data will then be analyzed to

determine the SUTs' deviation from the reference and to derive corresponding correction curves or calibration coefficients.

5. Practical Considerations and Limitations

The modular block design allows scaling to additional sensor wells for higher-throughput batch calibration without redesign of the core thermal system. Routine maintenance consists of periodic LN₂ refill, inspection of insulation/vacuum integrity, and periodic re-verification of the reference SPRT. Principal limitations of the present design are the turnaround time for a full five-point calibration cycle (approximately 8 hours), sensitivity of performance to LN₂ purity and supply reliability, and re-equilibration time when moving between widely separated setpoints; these are mitigated through the PID-based multizone thyristor control and dwell-time verification built into the control system.

As a design and methodology study, the present work reports anticipated performance derived from the design targets and comparison-calibration methodology described above, not from measurements on a fabricated unit; no prototype has yet been built or tested. Consequently, the claims regarding stability, uncertainty, portability, LN₂ consumption, energy use, and environmental benefit should be read as design targets to be confirmed experimentally, not as measured results.

Three activities are planned as immediate follow-on work and will be reported in a subsequent experimental-validation paper: (i) quantitative thermal simulation of the isothermal block to substantiate the targeted axial uniformity and heat-leakage performance; (ii) fabrication and instrumentation of a prototype, with repeatability, stability, hysteresis, and sensor-contact effects characterised over ascending and descending temperature cycles; and (iii) population of the complete GUM-based uncertainty budget outlined in Section 4 with measured Type A and Type B contributions, reported alongside a discussion of how the achieved performance compares with the benchmark systems in Table 1.

Relative to the benchmark systems in Table 1, the proposed design's principal points of difference are architectural rather than incremental: a single OFHC-copper isothermal block with multiple sensor wells and multizone thyristor-controlled heating is intended to extend milli-kelvin-class stability, currently demonstrated only at the single LN₂ fixed point by systems such as the Isotech apparatus and the Fluke 7196B, across the full -196 °C to +50 °C span within one portable enclosure, rather than requiring the wide-range, higher-uncertainty dry-block approach used in typical portable calibrators. Whether this architecture delivers the anticipated combination of range, stability, and portability in practice is precisely the question the planned prototype campaign in items (i)-(iii) above is designed to answer, and

the results will be compared quantitatively against the Table 1 benchmarks in the follow-up paper.

6. Conclusion

The aim of this work is to develop and validate a high-precision, energy-efficient and durable Low-Temperature Calibrator (LTC) capable of operating reliably in a wide temperature range (-196 °C to +50 °C). The goal is to bridge the gap between laboratory-grade accuracy and practical industrial applicability by providing a calibration system that is accurate, compact, sustainable and easy to use.

As a design and methodology study, this work reports the anticipated performance of the LTC prior to full experimental validation; fabrication and characterization of the prototype will follow, with measured results analyzed statistically (mean, standard deviation and expanded uncertainty at each setpoint, and comparison across ascending/descending cycles) and reported against the benchmarks in Table 1 in a subsequent experimental-validation paper. The following are the main anticipated results of this study:

- Attaining High-Precision Calibration with Minimal Uncertainty, the LTC system is anticipated to provide an expanded uncertainty of better than ± 0.05 °C, bolstered by thermal stability and axial uniformity within ± 0.02 °C. This performance will satisfy or surpass the calibration standards set by IEC 60751, guaranteeing dependable comparison calibration for high-accuracy Platinum Resistance Thermometers (PRTs) with sensor accuracies of ± 0.15 °C or superior.
- Streamlined, Cost-Effective, and Time-Saving Calibration across a Broad Temperature Spectrum. The Low-Temperature Calibrator LTC shall address all the calibration requirements over the entire range of -196 °C to +50 °C. The five-point calibration can be possible within 8 hours. This will significantly reduce time, cost, and complexity.
- Environment-Friendly and Energy-efficient. LTC system with Metal Block Comparison Method using passive liquid nitrogen shall function with less than 100 W of electrical energy and shall need only 10 liters of LN₂ per process cycle, thus a sustainable solution
- Compact and Portable. The LTC shall be compact (≤ 0.5 m³) and portable (≤ 50 kg), for convenience of use in field applications.
- Reduced Risks of Icing and Sensor Freezing. The LTC system will ensure that no ice formation and sensor freezing occur during the calibration process. Full details of the planned experimental-validation programme are given in Section 5.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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