BUREAU OF INDIAN STANDARDS
DRAFT FOR COMMENTS ONLY
Not to be reproduced without permission of BIS or use as Standard
Doc No.: PGD 26 (25508) WC-Draft
May 2024

विशेष प्रकाशन मसौदा

भारत में मीट्रिक प्रणाली की अत्याधुनिकता पर एक अपडेट

Draft Special Publication

An Update on The State of The Art of Metric System in India

Weights and Measures Sectional Committee, PGD 26	Last date for Comment: 31 May 2024

Doc No.: PGD 26 (25508) WC-Draft
May 2024

भारत में मीट्रिक प्रणाली की अत्याधुनिकता पर एक अपडेट पर एक मोनोग्राफ, 2024

A MONOGRAPH
on

An Update on the State of the Art of Metric System in India, 2024

(An update on the SP4 : 1969 Metric change in India)

by

Shanay Rab[1], V. K. Jaiswal[2], D. D. Shivagan[2], Goutam Mandal[2], Ashutosh Agarwal[3], Sanjay Yadav[4], D. K. Aswal[5], and Venu Gopal Achanta[2]

[1]School of Architecture, Technology, and Engineering, University of Brighton, United Kingdom
[2]CSIR-National Physical Laboratory (CSIR-NPL), New Delhi, India
[3]Department of Consumer Affairs, Krishi Bhawan, New Delhi
[4]Independent and Formerly with CSIR-National Physical Laboratory, New Delhi, India
[5]Bhabha Atomic Research Centre, Mumbai, India

भारतीय मानक ब्यूरो
BUREAU OF INDIAN STANDARDS

FOREWORD

This Special Publication, 'An Update on the State-of-the-Art of Metric System in India' is an update to the SP4 : 1969 Metric change in India. The text of this publication finalized by the Weights and Measures Sectional Committee had been approved by the Production and General Engineering Division Council.

It contains recent developments and global perspectives about the metric system. The recent international decision on the redefinition of the SI base units based on fundamental constants and quantum standards, as well as its implications, finalized in 26th CGPM, are briefly discussed. By elucidating the modern metric system, it ensures alignment with international standards set by the BIPM and aims to disseminate these capabilities nationwide. It also provides a comprehensive overview of the current status of the SI unit system and initiatives for the establishment of redefined quantum standards in India.

ABOUT BUREAU OF INDIAN STANDARDS

Bureau of Indian Standards (BIS) is the National Standards Body of India established under the BIS Act 2016 for the harmonious development of the activities of standardization, marking and quality certification of goods and for matters connected therewith or incidental thereto. BIS has been providing traceability and tangibility benefits to the national economy in a number of ways – providing safe reliable quality goods; minimizing health hazards to consumers; promoting exports and imports substitute; control over proliferation of varieties, etc through standardization, certification and testing.

ABOUT SP4 : 1969 'METRIC CHANGE IN INDIA'

SP4 is the first authoritative narrative of India's transition to the metric system and the decade that followed. It delves into the challenges faced during this monumental shift in the country's measurement system, mirroring experiences across diverse regions. SP4 encapsulates India's journey through Metric Change, offering invaluable insights for both developing and advanced nations engaged in similar endeavours.

SP4's comprehensive scope spans various disciplines, encompassing basic standards, metrology, railways, shipping, civil aviation, posts, telegraphs, telephone services, construction, and engineering industries. Its meticulously documented content establishes it as the definitive reference work of its time on this subject.

Through first-hand accounts, SP4 illuminates the historical, legislative, educational, and public relations dimensions of this bold experiment. Whether a specialist seeking in-depth analysis or a lay reader intrigued by this transformative era, SP4 serves as both inspiration and a blueprint for emulation.

CONTENTS

PREFACE

Metrology, the science of measurement, has played an indispensable role in the development of human civilization. From ancient civilizations to the modern era of advanced technology, the quest for precise and standardized measurement has been a constant pursuit. It acts as a pivotal role across a spectrum of human activities, spanning various sectors including industry, commerce, regulatory frameworks, defence, environment, education, scientific inquiry, food production, transportation, healthcare, and overall quality of life. Its essence lies in establishing and maintaining measurement standards, calibrating instruments, and employing measurement techniques to address challenges and enhance processes. Categorized into three distinct domains, metrology encompasses scientific or fundamental metrology, applied or technical metrology, and legal metrology.

Accordingly, precise and accurate measurements play a crucial and significant role in every aspect of human endeavour, from scientific discovery to industrial innovation, relies fundamentally on the accuracy and consistency of measurement standards. As the world becomes increasingly interconnected and interdependent, the need for a universally accepted system of measurement has never been more pressing. The International System of Units (SI) stands as a beacon of uniformity and coherence in this quest for precision, serving as the lingua franca of measurement across borders, disciplines, and cultures.

The present monograph sets the stage for a comprehensive exploration of the SI unit system, tracing its historical evolution, legislative frameworks, recent developments, and global implications with special reference to the state of the art of the metric system in India. From the aftermath of the French Revolution to its modern-day redefinition based on fundamental constants of nature, the SI system embodies humanity's collective quest for precision, standardization, and scientific progress. At the heart of the SI unit system lies the General Conference on Weights and Measures (CGPM), the apex body responsible for maintaining and updating the SI through deliberations, resolutions, and international cooperation. Recent meetings of the CGPM, such as the 26th and 27th sessions, have witnessed landmark decisions and paradigm shifts in the definition of fundamental units, paving the way for a new era of metrological excellence and innovation. Moreover, the SI unit system extends far beyond mere standards and definitions; it embodies a philosophy of precision, rigor, and universal applicability. From the laboratory bench to the factory floor, from the classroom to the marketplace, the SI units serve as the common currency of measurement, facilitating communication, collaboration, and commerce in a globalized world.

Still, the journey towards a harmonized, universally accepted system of measurement is not without its challenges. Cultural differences, historical legacies, and technological advancements pose formidable obstacles to standardization and interoperability. Moreover, emerging fields such as quantum metrology, nanotechnology, and artificial intelligence demand innovative approaches to measurement and calibration, challenging traditional notions of precision and accuracy. As we embark on this exploration of the SI unit system, let us reflect on its profound significance to human civilization. From the smallest subatomic particles to the vast expanse of the cosmos, from the microscale of cellular biology to the macroscale of planetary systems, the SI units provide a common language to understand and quantify the mysteries of the universe.

This monograph invites readers on a journey of discovery and enlightenment, as we delve into the intricacies, complexities, and wonders of the SI unit system. Through historical narratives, legislative frameworks, recent developments, and global perspectives, we aim to unravel the mysteries of measurement and celebrate the timeless quest for precision in a world of infinite complexity and wonder. The present document provides valuable resource material elucidating the modern metric system for ensuring that the primary/national measurement standards of India not only align with international equivalences established at the International Bureau of Weights and Measures (BIPM) but also disseminate these measurement capabilities to stakeholders nationwide. This document is poised to become an essential reference for science and engineering graduates, postgraduates, researchers, scientists, regulators, policymakers, and entrepreneurs alike. Its narrative employs a motivational tone, emphasizing that India's measurement capabilities meet international standards. The authors extend their gratitude to all the colleagues and students of CSIR-NPL, past and present, whose contributions and endeavours are included in this monograph and sincerely acknowledge them.

Shanay Rab,
V. K. Jaiswal,
D. D. Shivagan,
Goutam Mandal,
Ashutosh Agarwal,
Sanjay Yadav,
Venu Gopal Achanta,
and D. K. Aswal
Authors

1. ABSTRACT

The metric system is an international decimal system of weights and measures that was adopted in the 1790s with the slogan for measurement units "for all times, for all people". It is based on the metre for length and the kilogram for mass. The historical development of this system has resulted in the formation of *The International System of Units (SI)*. The SI system stands as a pinnacle of uniformity in measurement. Serving as a common system across borders and disciplines, the SI fosters global collaboration and facilitates communication in an increasingly interconnected world. This SI unit system is considered the heart of any measuring system and is placed at the top of the unbroken metrological traceability chain. It also acts as a foundation of modern science and technology and plays an important role in international trade and commerce.

For the implementation of the metric system in India, the Government of India enacted the *Standards of Weight and Measure Act* in 1956 to ensure uniform standards for weights and measures throughout the country which are traceable to the SI units. The CSIR-National Physical Laboratory (CSIR-NPL) i.e. the National Metrology Institute (NMI) of India is responsible for the realization, establishment, custody, maintenance, up-gradation, and dissemination of globally compatible national standards of measurement under the Legal Metrology Act and subsequent Legal Metrology (National Standards) Rules. To boost the industrial growth and Indian economy, it becomes even more inevitable as India strives to achieve the success of various government initiatives, such as 'Atma Nirbhar Bharat' (Self-Reliant India), 'Make in India,' 'Digital India,' 'Skill India,' 'Vocal for Local,' etc. Despite the universal appeal of SI system, achieving harmonization in measurement faces challenges stemming from cultural diversity, historical legacies, and emerging technologies. Fields like quantum metrology and nanotechnology demand innovative approaches to measurement, challenging traditional paradigms of precision.

This monograph takes the readers to travel through a concise journey into the intricacies and curiosities of the SI unit system. Through a bit historical insights, legislative frameworks, recent developments, and global perspectives, it aims to unveil and introduce the recent developments in metric system. The recent international decision on the redefinition of the SI base units based on fundamental constants and quantum standards, as well as its implications, finalized in 26th CGPM, are briefly discussed. The resolution of the 27th CGPM on the extension of SI unit prefixes is also discussed. By elucidating the modern metric system, it ensures alignment with international standards set by the BIPM and aims to disseminate these capabilities nationwide. With a motivational tone, it emphasizes India's adherence to global measurement standards, making it an essential reference for various stakeholders. The monograph also provides a comprehensive overview of the current status of the SI unit system and initiatives for the establishment of redefined quantum standards in India.

Keywords — Metrology; Metric system; SI units; Traceability; NMI

2. INTRODUCTION

Since the dawn of civilization, people have been measuring things. The oldest known standardized systems of weights and measures appear to have been developed between the 4^{th} and 3^{rd} millennia BC among the ancient peoples of Egypt, Mesopotamia, Elam (in Iran), and the Indus Valley. According to early Babylonian and Egyptian accounts, length was first measured using the forearm, hand, or finger, and time was measured using the periods of the sun, moon, and other celestial bodies. Mostly for agriculture, construction, and trade, the earliest civilizations required measurement. Thus, the early standard units may have been limited to a single community or small region with their own length, area, volume, and mass standards according to the knowledge and feasibility. These systems of measurement were frequently tied to a single field of application only [1-8].

Standardized weights and measures became increasingly important as manufacturing technologies and the scale of trade between the countries grew across the globe. As a result, the requirement of each country for precise and reliable measurements is becoming more inevitable. The precision and accuracy of measurements made during the manufacturing/process have a major impact on technological advancement. Only global harmonization of units and a uniform system, as well as compatibility of measuring standards and interchangeability of laboratory results, make this possible [9-12]. The accurate and precise measurements through strong metrological infrastructure are essentially required to achieve the following objectives:

a) To ensure that all producers and manufacturers, including farmers, receive the correct payments for their produce and all consumers get the correct quantity of goods.

b) To develop and deploy appropriate metrological methods for industry, support product innovation, process improvement, and quality assurance.
c) To ensure that the components and finished products meet regulatory requirements, documentary standards, and specifications.
d) To meet consumer and industrial quality expectations, including product value/price and reliability.
e) To reduce fraud by controlling the pre-packed goods/commodities.
f) To make sure the correct measures of bulk raw material are exported to get the correct price. It also helps governments to collect correct taxes on exports.
g) To use metrological controls to help improve the economic conditions of all concerned and assist in poverty reduction.
h) To achieve global acceptability of measurements and test results to remove technical trade barriers.
i) To facilitate international trade and contribute to inclusive economic growth, access to opportunities for Small and Medium-sized Enterprises (SMEs), and a level playing field for developing economies.

The metric system, also known as the SI system, is the foundation of modern science and technology and plays an important role in international trade and commerce. Metrology and the metric system are intricately connected, and the metric system provides the standardized units of measurement used in metrology.

According to the Vocabulary of Metrology (VIM) document, metrology is delineated as the science of measurement and its practical applications. This encompasses both theoretical frameworks and practical methodologies for measurement, irrespective of the uncertainty involved and the specific field of application. Metrology is commonly categorized into scientific or fundamental metrology, industrial or applied metrology, and legal metrology. The accurate measurement permeates into our daily lives, influencing various facets of existence. The economy of a state hinges on its manufacturing prowess, which in turn affects global trade, contingent upon the international comparability of manufactured goods. Measurements hold sway over virtually every aspect of life, encompassing health, nutrition, transportation, communication, commerce, economy, and defence. For a society to attain global relevance, ensuring the international comparability of measurements is imperative. Inaccurate measurements can precipitate erroneous decisions, potentially yielding grave repercussions. Thus, the integrity of measurements stands as a cornerstone for informed actions and sustainable progress.

Metrology can be classified into three main types based on its application and purpose. Scientific metrology primarily focuses on ensuring measurement compatibility by conducting research and development in measurement standards. This involves the maintenance and dissemination of standards, typically overseen by organizations like the International Bureau of Weights and Measures (BIPM) and national metrology institutes (NMIs). Industrial metrology, on the other hand, is geared towards optimizing measurements for practical applications in manufacturing processes. It encompasses both theoretical and practical aspects, ensuring the quality and accuracy of manufactured components and products. Through testing and calibration, industrial metrology ensures the correctness of measuring instruments, contributing to improved product quality and supporting manufacturing and trade activities. Legal metrology is essential for ensuring the legitimacy of measurements, in compliance with statutory requirements and laws governing measurements. These requirements stem from the need to safeguard public health and safety, protect consumer rights, facilitate taxation, preserve the environment, and promote fair trade practices. Competent bodies oversee the enforcement of legal metrology standards to uphold these statutory requirements and ensure the integrity of measurements in various sectors. Figure 1 shows the classification of metrology.

FIG. 1 SUBFIELDS OF THE METROLOGY

The history and modern development of the metric unit system are described in the subsequent sections.

3. BACKGROUND OF METRIC UNIT SYSTEM

Historically, the origins of the metric system can be found in the 17th century in England. With the increasing momentum of scientific advancement and the ever-greater necessity of worldwide collaboration during the Age of Enlightenment, the lack of proper standards of measurement became an increasing challenge. However, it was only in France that the concept of the metre was found suitable to cultivate. The French scientists of the late 18th century created the first practical version of the metric system, driven by growing frustration with the chaos that had previously existed in the country with hundreds of thousands of units of measurement varying from village to village due to a lack of unified national standardization. It was made with the aim of being "for all people, for all time". As a result, this system was defined logically and abstractly, without reference to authority, tradition, local custom, or human anatomy. This system was concerned with the mathematical relationships between the measured values, tying them all together with a simple set of units taken from nature; for example, the metre was originally 1/10,000,000 of the distance between the north pole and the equator, measured along the Paris meridian, and the kilogram was the mass of one cubic decimetre (or litre) of water [2, 7, 13-14].

By the mid-19th century, France's metrication had been largely completed. The utility of the metric system had become generally recognized by the end of the century, and it had become the official measurement system of practically all of continental Europe. Especially, its utility in science and international commerce had become impossible to ignore by the late 19th century, and representatives from seventeen leading nations signed the *Treaty of the Metre* (Metre Convention) in 1875, establishing the metric system as the uniform international standard of measurement for the first time. The participating countries were given the metre and kilogram prototypes to use in establishing their national standards. The *Treaty of the Metre*, signed there, established a permanent laboratory known as the International Bureau of Weights and Measures (BIPM) in Sèvres, near Paris, to keep international standards, inspect national standard copies, perform metrological research and created two international bodies General Conference on Weights and Measures (CGPM) and International Committee for Weights and Measures (CIPM) to oversee systems of weights and measures based on them. Throughout the 20th century, metric units became increasingly popular. The precision with which the units were specified was improved because of advancements in measurement technology. For example, the second (s) was redefined from 1/86,400 of the mean solar day to "the period of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium-133 atom". Further, instead of being defined by a physical prototype, a platinum-iridium bar that was originally intended to be one metre long, the metre was defined as the length travelled by light in a vacuum in 1/299 792 458 s. For this definition of the second and precise definition of the speed of light in a vacuum, 299 792 458 m/s, was taken [15-17].

The introduction of the International System of Units, generally known as the SI unit system, in 1960 was the most significant milestone in the evolution of the metric system in the 20th century. The earlier CGS (centimetre-gram-second) and technical (or "gravitational") metric systems were rendered obsolete by this rationalized version of the metre-kilogram-second (MKS) system. The newly formed SI unit system in 1960 consisted of six "base units": the metre, kilogram, second, ampere, degree kelvin (later called "kelvin"), and candela, as well as 16 other units derived from the base units. Later in the 20th century, the mole was added as a seventh base unit, along with six other derived units. The detailed status of the present SI unit system is described in the next section.

4. REDEFINITION AND CURRENT STATUS OF SI UNIT SYSTEM

As discussed earlier, modern metrology has its roots in the French Revolution and the SI unit system was first introduced in 1960 at the 11th CGPM meeting. The kilogram remained the sole SI base unit specified by a physical artifact when the metre was redefined in 1960. Since then, various significant and extraordinary studies have gone into developing the SI unit system and connecting it to truly invariant quantities in terms of natural constants or fundamental constants [2, 7, 12, 18-20].

More importantly, in 2007 at 23rd meeting of the CGPM mandated the CIPM to explore the adoption of natural constants as the basis for all units of measure, rather than the artifacts that were in use at the time [21-22]. Since then, a lot of research work has been carried out throughout the world to redefine the SI unit system in terms of fundamental constants discussed later on. The progress towards the revision of the SI units was well documented in the resolution, unanimously adopted by 60 member states of CGPM from across the globe [23].

5. RECENT DEVELOPMENTS IN SI UNIT SYSTEM THROUGH THE 26TH AND 27TH CGPMS

Recent years have witnessed significant developments in the SI unit system, driven by the deliberations and decisions of the General Conference on Weights and Measures (CGPM), the supreme authority responsible for maintaining and updating the SI.

5.1 Resolutions During The 26th CGPM

The 26th CGPM convened in November 2018, marked a historic milestone with the redefinition of four fundamental units of measurement: the kilogram, ampere, kelvin, and mole. This paradigmatic shift towards redefining units in terms of fundamental constants of nature, such as the Planck constant (h) and the elementary charge (e), represented a quantum leap in the quest for precision, stability, and universality in measurement standards. The redefinition of the kilogram, in particular, replaced the artifact-based definition with the Planck constant, ensuring the long-term stability and reproducibility of the kilogram across different measurement laboratories worldwide. One of the notable developments was the adoption of the revised International System of Units, known as the SI Brochure 9th edition, which incorporated the latest updates and recommendations for SI units and their usage. The revised SI Brochure aimed to provide clarity, consistency, and guidance to metrologists, scientists, engineers, and policymakers navigating the complexities of measurement standards and practices in the 21st century.

The outcome of this long process has been the approval by the CGPM at its 26th meeting in November 2018 which came into force on 20th May 2019 (World Metrology Day) in the form of the SI redefinition [24]. All 7 definitions defining base units of the SI unit system are included in Table 1 [12, 23]. A detailed discussion on the realization of these base units can be found in various articles [2, 7, 12, 20, 25-28]. The kilogram, ampere, kelvin, and mole - four of the seven SI base units - were redefined by assigning fixed numerical values to the Planck constant (*h*), the elementary electric charge (*e*), the Boltzmann constant (*k*), and the Avogadro constant (N_A), respectively. Physical constants had previously established the second, metre, and candela, and their definitions had only to be corrected. The revised definitions attempted to improve the SI without altering the value of any unit, ensuring that the measurements remained consistent. The linkage of these constants with SI base units is shown in Figure 2.

FIG. 2 SI LOGO WITH DEFINING CONSTANTS (CREDIT: BIPM)

Table 1 Definition of SI Base Units Based on Constants [23]

Base Quantity	**Name**	**Symbol**	**Definition**
Length	metre	m	It is defined by taking the fixed numerical value of the speed of light in vacuum *c* to be 299 792 458 when expressed in the unit $m \cdot s^{-1}$, where the second is defined in terms of the caesium frequency $\Delta\nu_{Cs}$.
Mass	kilogram	kg	It is defined by taking the fixed numerical value of the Planck constant *h* to be $6.626\ 070\ 15 \times 10^{-34}$ when

			expressed in the unit J·s, which is equal to $kg{\cdot}m^2{\cdot}s^{-1}$, where the metre and the second are defined in terms of *c* and $\Delta\nu_{Cs}$.
Time	second	s	It is defined by taking the fixed numerical value of the caesium frequency $\Delta\nu_{Cs}$, the unperturbed ground-state hyperfine transition frequency of the caesium-133 atom, to be 9 192 631 770 when expressed in the unit Hz, which is equal to s^{-1}.
Electric Current	Ampere	A	It is defined by taking the fixed numerical value of the elementary charge *e* to be $1.602\ 176\ 634 \times 10^{-19}$ when expressed in the unit C, which is equal to A·s, where the second is defined in terms of $\Delta\nu_{Cs}$.
Temperature	kelvin	K	It is defined by taking the fixed numerical value of the Boltzmann constant *k* to be $1.380\ 649 \times 10^{-23}$ when expressed in the unit $J{\cdot}K^{-1}$, which is equal to $kg{\cdot}m^2{\cdot}s^{-2}{\cdot}K^{-1}$, where the kilogram, metre, and second are defined in terms of *h*, *c* and $\Delta\nu_{Cs}$.
Amount of Substance	mole	mol	One mole contains exactly $6.022\ 140\ 76 \times 10^{23}$ elementary entities. This number is the fixed numerical value of the Avogadro constant, N_A, when expressed in the unit mol^{-1} and is called the Avogadro number. The amount of substance, of a system, is a measure of the number of specified elementary entities. An elementary entity may be an atom, a molecule, an ion, an electron, or any other particle or a specified group of particles.
Luminous Intensity	candela	cd	It is defined by taking the fixed numerical value of the luminous efficacy of monochromatic radiation of frequency 540×10^{12} Hz, K_{cd}, to be 683 when expressed in the unit $lm{\cdot}W^{-1}$, which is equal to $cd.sr.W^{-1}$, or $cd.sr.kg^{-1}.m^{-2}.s^3$, where the kilogram, metre and second are defined in terms of *h*, *c* and $\Delta\nu_{Cs}$.

5.2 Resolutions of 27th CGPM

The 27th CGPM convened from November 15th to 18th, 2022, at the Palais des Congrès in Versailles, France, reaffirmed its commitment to promoting the widespread adoption of the SI unit system through international cooperation, capacity building, and awareness-raising initiatives. Recognizing the importance of metrology in addressing global challenges such as climate change, healthcare, and sustainable development, the CGPM emphasized the role of metrology as a catalyst for innovation, quality assurance, and economic prosperity. Furthermore, the 27th CGPM underscored the need for continued research and development in metrology to address emerging measurement challenges and opportunities in rapidly evolving fields such as quantum metrology, nanotechnology, and artificial intelligence. By fostering collaboration between scientific communities, metrology institutes, and industry stakeholders, the CGPM aims to accelerate technological innovation and facilitate the adoption of cutting-edge measurement techniques and standards in diverse sectors of the economy. During this landmark event, the CGPM adopted seven pivotal resolutions [29]:

1) Addressing evolving needs in metrology to meet the challenges of a dynamic global landscape.
2) Responding to the impact of global digital transformation on the International System of Units (SI).
3) Extending the range of SI prefixes to accommodate advancements in measurement technology and precision.
4) Examining the use and future development of Coordinated Universal Time (UTC) to ensure its relevance and accuracy in contemporary society.
5) Exploring the future redefinition of the second to enhance precision and consistency in timekeeping standards.
6) Encouraging universal adherence to the Metre Convention to promote international cooperation and harmonization in metrological practices.
7) Allocating resources to the International Bureau of Weights and Measures for the period spanning 2024 to 2027, facilitating its essential role in maintaining global standards and promoting metrological excellence.

5.3 SI Unit Prefixes

As previously highlighted, the universally recognized system of measurement units is the International System of Units (SI). SI prefixes are employed to create decimal multiples and submultiples of SI units, ensuring that numerical values remain universally understandable, ideally falling within the range of 1 to 100.

The use of prefixes traces back to the French Revolution when the metric system was initially introduced in 1795, covering a limited range of orders of magnitude between 0.001 and 1. The introduction of micro (μ) and mega (M) prefixes occurred in 1935, followed by their formal inclusion alongside other prefixes in 1960. By 1991, the system expanded to encompass multiples and submultiples ranging from 10^{-24} (yocto or y) to 10^{24} (yotta or Y). As scientific progress necessitated access to a broader range of orders of magnitude, the range of available SI prefixes continued to expand. The advent of modern computing further popularized the usage of SI prefixes, particularly in data science, as evident in terms like gigabytes (GB) and terabytes (TB). With the exponential growth of scientific needs and online data, there arose significant interest in expanding the range of SI prefixes to accommodate evolving requirements [30-31].

To address this challenge, the international scientific community voted to broaden the spectrum of prefixes within the International System of Units during the 27th CGPM in November 2022. This decision allows for the inclusion of four new prefixes for global measurement indication, thus aiding in the prevention of the use of "unofficial" prefix names in technical writing practices. The updated SI unit system has undergone an update to incorporate new prefixes: ronto and quecto for minuscule quantities, particularly relevant in fields like quantum physics, and ronna and quetta for colossal magnitudes, such as the vast volumes of data stored on internet servers. Table 2 lists the SI unit prefixes after the update.

Table 2: SI unit prefixes

Name (symbol)	**Scientific Notation**
quetta (Q)	10^{30}
ronna (R)	10^{27}
yotta (Y)	10^{24}
zetta (Z)	10^{21}

exa (E)	10^{18}
peta (P)	10^{15}
tera (T)	10^{12}
giga (G)	10^{9}
mega (M)	10^{6}
kilo (k)	10^{3}
hecto (h)	10^{2}
deca (da)	10^{1}
Base	10^{0}
deci (d)	10^{-1}
centi (c)	10^{-2}
milli (m)	10^{-3}
micro (µ)	10^{-6}
nano (n)	10^{-9}
pico (p)	10^{-12}
femto (f)	10^{-15}
atto (a)	10^{-18}
zepto (z)	10^{-21}
yocto (y)	10^{-24}
ronto (r)	10^{-27}
quecto (q)	10^{-30}

5.4 Possible Future of The Second

As previously stated, the 27th General Conference on Weights and Measures (CGPM) made the decision to redefine the second within the International System of Units utilizing optical clocks. Presently, the international standards community is actively engaged in the process of implementing this new standard, with the aim of finalizing the adoption by 2030 [32-33].

The popularity of optical clocks surged following the advent of the femtosecond frequency comb. A femtosecond frequency comb is a laser source characterized by a spectrum comprising a series of discrete, evenly spaced frequency lines. These combs facilitate researchers in gauging the frequencies of optical instruments against the established frequency standard of the caesium atom. Consequently, this process delineates the precise correlation between the frequencies of optical clocks and microwave clocks. With the aid of a frequency comb, it becomes feasible to directly tally the 'ticks' of an optical atomic clock, which emerges as a pivotal component in the development and assembly of clocks functioning within the visible range of the electromagnetic spectrum. Presently, they already exceed the accuracy of today's finest caesium clocks by a factor of 100. Thus, optical clocks offer a significant advancement in timekeeping technology, providing unprecedented levels of precision and stability that make them increasingly preferable over traditional caesium clocks for many scientific and technological applications.

5.5 Some of The Other Significant Recent Developments at the BIPM and the OIML

Some of the recent activities held at BIPM and OIML reflect commitments to advancing metrology, standardization, and global cooperation in the field of weights and measures. Through initiatives such as the redefinition of the kilogram, promotion of international collaboration, enhancement of measurement uncertainty frameworks, and facilitation of mutual recognition arrangements, these organizations contribute to the integrity, reliability, and harmonization of measurement standards worldwide [34].

The BIPM has been actively promoting international collaboration through initiatives such as the Global Metrology Network (G-Met), which facilitates the exchange of knowledge, expertise, and best practices among national metrology institutes (NMIs) and regional metrology organizations (RMOs) worldwide. G-Met fosters capacity building, research collaboration, and technical assistance to address global challenges in metrology.

The BIPM continues to refine and standardize methodologies for evaluating measurement uncertainty through the Guide to the Expression of Uncertainty in Measurement (GUM). This framework provides guidelines and recommendations for quantifying and expressing uncertainties in measurement results, promoting consistency and comparability in metrological practices [35].

With the increasing digitization of measurement instruments and processes, the BIPM may undertake initiatives to develop standards, guidelines, and best practices for digital metrology. This could include addressing challenges related to data integrity, interoperability, cybersecurity, and traceability in digital measurement systems. Implementing the CIPM "Grand Vision" for the SI Digital framework will require the BIPM to add new capabilities that enable the Digital Transformation of the BIPM databases and services so that they will be machine-readable. Activities in the Work Programme will support the digital transformation through the creation of a digital hub in which BIPM, RMO, and NMI data can be accessed in a form that meets the FAIR data principles. As this field of activities evolves and expands it is foreseen that there will be several iterations and revisions to ensure that the facilities meet stakeholder needs [36-41].

The CBKT Programme initiated in 2014 has been widely welcomed and has become a pillar supporting both national and regional metrology activities. It has a highly appreciated portfolio that continues to expand. The activities of the BIPM CBKT "Remote-learning" initiative have been extended by the addition of e-learning capabilities. The e-learning platform started in 2022, was expanded to enable it to host material from interested RMOs. The CBKT activities will continue realizing their significant role some additional capabilities are being proposed [42-43].
The OIML has made significant strides in strengthening the Mutual Acceptance Arrangement (MAA), a multilateral agreement that facilitates the mutual recognition of measurement standards and conformity assessment procedures among member states. The revised MAA enhances transparency, confidence, and market access for products and services traded internationally.

Recognizing the transformative potential of digitalization and smart technologies in metrology, the OIML has initiated efforts to develop guidelines, recommendations, and standards for digital measuring instruments, software, and data exchange protocols. These initiatives aim to ensure the accuracy, reliability, and interoperability of digital measurement systems in diverse applications [44].

The OIML continues to prioritize capacity building and training programs to enhance metrological competence and infrastructure in developing countries and emerging economies. Through workshops, seminars, and technical assistance initiatives, the OIML promotes the adoption of international metrological standards and best practices, thereby facilitating trade facilitation and economic development.

The OIML has initiated actions towards the e-Learning concept and accordingly, OIML has constituted a committee on e-Learning and other online training. The Committee will work in consultation with the DTG, the CEEMS AG, the OIML-CS MC, and the RLMO RT, taking into account the OIML G 23:2022 Guide to the use of online technologies [45].

6. HISTORY AND STATUS OF THE METRIC SYSTEM IN INDIA

The history of the metric system in India is marked by a journey of gradual transition from traditional indigenous measurement systems to the adoption of international standards. India's metrication efforts gained momentum, signaling a commitment to align with the simplicity, coherence, and universality of the metric system. Over the decades, legislative reforms, educational initiatives, and technological advancements have propelled India towards the widespread adoption of metric units in various sectors. Today, the metric system stands as the cornerstone of measurement practices in India, underpinned by legislative frameworks, which mandate the use of metric units for trade, commerce, and education. The status of the metric system in India reflects a landscape characterized by significant progress, yet nuanced challenges. While metric units are widely used and taught in educational institutions, traditional units persist in certain cultural contexts and informal transactions, highlighting the need for ongoing awareness campaigns and cultural sensitization. Moreover, efforts to promote metrication in rural areas and among marginalized communities remain a priority for enhancing economic development, market access, and standardization. Despite these challenges, India's commitment to the metric system as a cornerstone of modernization, standardization, and global integration underscores its resolve to embrace precision, efficiency, and interoperability in measurement practices.

6.1 Historical Background

The earliest evidence of measurement systems in India is from the early Indus Valley civilization, with the earliest examples dating from the 5th millennium BC. In modern history, prior to metrication, the Indian government followed the British imperial system, which was codified in the *Indian Weights and Measures Act of 1870*. Many other indigenous systems, on the other hand, were in use in other parts of the country, and this was a constant source of contention among government officials and the general population. India's journey towards metrication dates back to the mid-20th century. The Indian Parliament adopted the metric system of weights and measures in December 1956 with the Standards of Weights and Measures Act, which went into force on October 1, 1958. The Government of India passed the Indian Currency Act in 1955 to implement decimal coinage in the country [46-48]. The new system of coins became legal tender in April 1957, where the rupee consists of 100 paise. Pair the customary units with their approximate metric units. Choose the units used for measuring capacity in the Metric System. In April 1962, all other systems were banned. This process of metrication is called "big-bang" route, which was to simultaneously outlaw the use of pre-metric measurement, metricate, reissue all government publications and laws, and change the education systems to metric. However, the process faced challenges due to the coexistence of multiple systems of measurement and the widespread usage of traditional units in everyday transactions. The adoption traces its roots to the colonial era, where the British Empire imposed its imperial units on land steeped in diverse indigenous measurement systems. This hegemonic imposition, however, sowed the seeds of discontent, as indigenous systems persisted alongside imperial measures, reflecting the resilience of cultural identity amidst colonial subjugation.

The winds of change began to blow with India's struggle for independence in the 20th century. The quest for freedom from colonial yoke paralleled a quest for liberation from the shackles of imperial measurement. Visionaries like Mahatma Gandhi envisioned a post-colonial India liberated not only politically but also culturally and intellectually. The call for Swadeshi, or indigenous self-reliance, resonated not only in the realm of economics but also in the sphere of measurement, sparking a renaissance of traditional measurement systems rooted in local customs and practices.

The momentum towards metrication gained traction in the aftermath of independence in 1947. The newly independent nation, led by visionary leaders like Jawaharlal Nehru, recognized the imperative of modernization and rationalization in every sphere of governance. The establishment of the Indian Standards Institution (ISI) in 1947 marked a watershed moment, laying the groundwork for the standardization of weights and measures on indigenous terms.

The Metrication Act of 1956 emerged as a cornerstone in India's journey towards metric enlightenment. Enacted under the visionary leadership of Prime Minister Jawaharlal Nehru, this legislation aimed to gradually transition from imperial units to the metric system, aligning India's measurement practices with global standards. However, the process of metrication was not merely a top-down imposition but a participatory endeavour, engaging stakeholders from diverse sectors to navigate the complexities of transition.

Despite the legislative impetus, the path towards metrication was fraught with challenges. The coexistence of multiple systems of measurement, entrenched cultural practices, and the sheer diversity of India's linguistic and regional landscape posed formidable obstacles to uniform adoption. Traditional units persisted in everyday transactions, reflecting the enduring legacy of indigenous knowledge systems amidst the tide of modernity.

In the ensuing decades, India's march towards metrication continued unabated, buoyed by legislative reforms, institutional frameworks, and grassroots advocacy. The Legal Metrology Act of 2009 emerged as a bulwark of regulation, providing a robust legislative framework to govern weights and measures across diverse sectors. From education to healthcare, industry to transportation, the metric system permeated every facet of Indian society, fostering standardization, interoperability, and efficiency.

As India stands on the cusp of the 21st century, the historical perspective of metrication serves as a poignant reminder of the nation's resilience, adaptability, and quest for self-determination. From the colonial imposition of imperial measures to the resurgence of indigenous knowledge systems, India's journey towards metric enlightenment embodies a tapestry of cultural evolution, legislative innovation, and societal transformation. As the nation strides confidently into the future, the lessons of history illuminate the path towards a metrically harmonized, globally competitive India.

6.2 Brief About The Indian Legislative Framework

The metric system in India is underpinned by a robust legislative framework aimed at ensuring uniformity, accuracy, and fairness in weights and measures across diverse sectors. At the heart of this framework lies the Legal Metrology Act of 2009, a comprehensive legislation that governs all aspects of weights, measures, and weighing and measuring instruments throughout the country. Enacted with the vision of modernizing India's measurement practices and aligning them with international standards, the Legal Metrology Act of 2009 replaces the outdated Weights and Measures Act of 1976. This landmark legislation not only consolidates and updates existing laws but also introduces innovative provisions to address emerging challenges in a rapidly evolving economic landscape. Central to the Legal Metrology Act is the establishment of the Legal Metrology Department, entrusted with the responsibility of enforcing metrological standards and regulations across the nation. This department serves as the custodian of metrological integrity, ensuring compliance with prescribed standards, specifications, and procedures in the use of weights, measures, and measuring instruments. The Act mandates the use of the metric system as the primary system of measurement for trade and commerce. Metric units, based on the International System of Units (SI), serve as the standard benchmarks for all transactions, promoting consistency, interoperability, and compatibility with global markets.

The Act requires manufacturers, packers, importers, and sellers of goods to register themselves with the Legal Metrology Department and obtain appropriate licenses for weighing and measuring instruments. This ensures traceability, accuracy, and reliability in commercial transactions, safeguarding consumer interests and promoting fair trade practices. The Act empowers authorized officers of the Legal Metrology Department to inspect, verify, and stamp weighing and measuring instruments to ensure their accuracy and compliance with prescribed standards. Regular inspections and audits are conducted to deter fraudulent practices and maintain the integrity of measurement systems.

The Act incorporates provisions to protect consumer rights and interests, including the right to receive accurate and transparent information about the quantity, quality, and price of goods and services. Any deviations from prescribed standards or deceptive practices are subject to stringent penalties and legal sanctions. The Act emphasizes the importance of capacity building, training, and awareness programs to enhance compliance with metrological regulations and foster a culture of measurement accuracy and transparency among stakeholders. In addition to the Legal Metrology Act, other relevant legislations, such as the Standards of Weights and Measures (Enforcement) Act, 1985, and the Consumer Protection Act, 2019, complement the regulatory framework, providing additional safeguards and mechanisms for ensuring the integrity of measurement systems and protecting consumer interests.

6.3 The National Metrology Institute (NMI)

The National Metrology Institute (NMI) stands as the vanguard of metrological excellence in India, entrusted with the mission of advancing scientific knowledge, technological innovation, and industrial competitiveness through the promotion and dissemination of precise and reliable measurement standards. Established by the National Measurement System (NMS) framework, the Indian NMI i.e. CSIR-National Physical Laboratory (CSIR-NPL), New Delhi serves as the apex body for metrology in the country, providing leadership, guidance, and technical expertise to diverse stakeholders across government, industry, academia, and society. At the heart of NMI's mandate lies the pursuit of accuracy, traceability, and consistency in measurement standards, underpinned by a relentless commitment to scientific rigor and international best practices. NMI operates state-of-the-art metrology laboratories equipped with advanced instrumentation, calibration facilities, and reference materials, enabling the calibration, testing, and certification of a wide range of measuring instruments and artifacts with unparalleled precision and reliability. Central to NMI's role is the establishment and maintenance of primary measurement standards across various physical quantities, including length, mass, time, temperature, pressure, and electrical units. These primary standards serve as the bedrock of India's metrological infrastructure, providing traceability to international standards and ensuring the uniformity and accuracy of measurements across diverse sectors of the economy. In addition to its calibration and measurement services, NMI plays a pivotal role in research and development initiatives aimed at advancing metrological science and technology. Through collaborative research projects, partnerships with academic institutions, and participation in international metrology forums, NMI contributes to the development of cutting-edge measurement techniques, methodologies, and instrumentation, fostering innovation and technological advancement in critical sectors such as healthcare, manufacturing, energy, and the environment.

As the apex metrology institution in India, NMI serves as a hub of knowledge dissemination and capacity building, offering training programs, workshops, seminars, and consultancy services to professionals, researchers, and industry practitioners. These initiatives aim to enhance metrological awareness, competency, and infrastructure across the country, empowering stakeholders to meet the evolving challenges of a dynamic and interconnected global economy. Furthermore, NMI actively engages in standardization activities, collaborating with national and international standards organizations to develop and harmonize measurement standards, protocols, and guidelines. By aligning with global best practices and standards, NMI facilitates interoperability, compatibility, and mutual recognition of measurements, thereby enhancing India's competitiveness in international trade and commerce. In conclusion, the NMI epitomizes India's commitment to excellence in measurement science, technology, and standards. Through its multifaceted roles in calibration, research, training, and standardization, NMI plays a pivotal role in driving innovation, quality assurance, and industrial competitiveness, thereby contributing to the nation's socioeconomic development and global standing in the 21st century.

6.4 International Linkages

At the international level, India signed the *Metre Convention* in 1957. The Convention is a diplomatic treaty that gives authority to the CGPM, CIPM, and the BIPM to act in matters of world metrology, particularly concerning the demand for measurement standards of ever-increasing accuracy, range, and diversity, and the need to demonstrate the equivalence between national measurement standards. The CSIR-NPL, the NMI of India became a member of CGPM after signing the Metre Convention The laboratory is also a founder member of the Asia-Pacific Metrology Programme (APMP), the Regional Metrology Organization (RMO) for the Asia-Pacific Region. CSIR-NPL is a leading laboratory in the country having the responsibility to implement and strengthen the metrological infrastructure in the country. It is mandated to establish and maintain National Standards of Measurements for the benefit of the nation, to improve them continuously by research, and to realize units based on the International System. Its metrological research and development activities are oriented, implemented, and executed through 7 main divisions namely, Physico-Mechanical Metrology Division, Electrical and Electronics Metrology Division, Environmental Sciences and Biomedical Metrology Division, Advanced Materials and Device Metrology Division, Bhartiya Nirdeshak Dravya (BND): Indian Reference Materials Division, Indian Standard Time Metrology Division and the Directorate consisting of Quality Management System (QMS), Centre for Calibration & Testing (CFCT), Intellectual Property Rights (IPR), Human Resource Development (HRD), Planning, Monitoring and Evaluation (PME), Business Development Group (BDG), etc. [49-52].

Since 1999, India has been a signatory to the CIPM Mutual Recognition Arrangement (MRA). CIPM MRA is the framework through which NMIs demonstrate the international equivalence of their measurement standards and the calibration and measurement certificates they issue. The outcomes of the arrangement are the internationally recognized (peer-reviewed and approved) Calibration and Measurement Capabilities (CMCs) of the participating institutes. Approved CMCs and supporting technical data are publicly available in the BIPM Key Comparison Data Base (KCDB) [53].

The MRA is in response to the growing need for an open, transparent and comprehensive system to give users reliable and quantitative information on the compatibility of national metrology services and to provide the technical basis for the wider agreement for international trade. Since 2003, the laboratory has implemented a QMS as per ISO/IEC 17025 for metrological activities. Since 2022, the laboratory has also implemented a QMS as per ISO 17034 for BND. The metrological activities are peer-reviewed from time to time to fulfil the requirements of the CIPM MRA [9, 54].

The *Legal Metrology Department (LMD)* serves as the custodian of metrological integrity and regulatory enforcement in India, ensuring fairness, accuracy, and transparency in weights and measures across diverse sectors. Established under the Weight and Measurement Act, the department operates under the auspices of the Ministry of Consumer Affairs, Food and Public Distribution, and plays a pivotal role in upholding standards, regulations, and enforcement mechanisms related to metrology. At the core of LMD's mandate lies the regulation and enforcement of legal metrology laws, encompassing the verification, stamping, and enforcement of weighing and measuring instruments used in trade and commerce. Authorized officers of the LMD conduct regular inspections, audits, and verifications to ensure compliance with prescribed standards, specifications, and procedures, thereby safeguarding consumer interests and promoting fair trade practices. Moreover, the LMD is entrusted with the task of promoting metrological awareness, education, and capacity building among stakeholders, including manufacturers, traders, consumers, and regulatory authorities. Through outreach programs, workshops, and training initiatives, the department fosters a culture of measurement accuracy, transparency, and compliance with legal metrology regulations.

One of the key linkages of the Legal Metrology Department is with the International Organization of Legal Metrology (OIML), a global intergovernmental organization dedicated to harmonizing legal metrology practices and standards across countries. India, as a member of the OIML since 1957, actively participates in its activities, contributing to the development and adoption of international standards, guidelines, and recommendations in legal metrology. The partnership between the Legal Metrology Department and OIML facilitates knowledge sharing, capacity building, and technical cooperation in legal metrology, enabling India to align its metrological practices with global best practices and standards. Through its participation in OIML Technical Committees, Working Groups, and General Assemblies, India engages in discussions, exchanges of experiences, and collaborative initiatives aimed at addressing emerging challenges and promoting mutual recognition of measurements in international trade.

Furthermore, the adoption of OIML recommendations and standards by the LMD enhances the interoperability, compatibility, and harmonization of legal metrology practices across borders, facilitating trade facilitation, market access, and consumer protection. By aligning with international norms and standards, India strengthens its position as a responsible global player committed to quality, fairness, and transparency in weights and measures.

In conclusion, the LMD serves as a cornerstone of metrological regulation and enforcement in India, ensuring compliance with legal metrology laws and promoting consumer protection in trade and commerce. Its linkage with the International Organization of LMD underscores India's commitment to global cooperation, standardization, and harmonization in metrology, thereby contributing to the nation's economic growth, competitiveness, and integration into the global marketplace.

6.5 Present Status SI Unit System

As previously stated, India signed the *Metre Convention* in the year 1957. Dr. K. S. Krishnan, the then Director of the CSIR-NPL, signed the convention on behalf of the Indian Government. Following that, in 1957, BIPM provided CSIR-NPL Copies No. 57 and No. 4 of the National Prototypes of the Kilogram (NPK) and the National Prototype of the Metre, made of platinum-iridium (Pt–Ir), respectively, to realize the SI base units the 'kilogram' and the 'metre.' This was a pivotal moment in the development of the SI unit system in modern India. Since then, CSIR-NPL has held measurement standards for base units and derived units. It also enables traceability to a variety of national businesses, as well as the environment and biomedical instruments, for the above-mentioned characteristics. It also produces the Bhartiya Nirdeshak Dravya (BND®), recognized as Indian reference materials [2, 9, 12, 52].

In the existing system, CSIR-NPL has established 6 (kilogram, meter, kelvin, second, ampere, and candela) out of the 7 SI base units. The mass standard is based on the National Prototype of the Kilogram (NPK); length is based on the speed of light; time is established through the caesium clock; temperature is realized through the triple point of water; luminance is determined through classical radiometry and photometry and current is based on the Josephson voltage and quantum Hall resistance. Further, for the realization of the mole, the research group at CSIR-NPL is working to prepare primary gas standards by gravimetric method. Figure 3 shows the current mode of realization of SI units in India [2, 12]. A brief summary of all the SI units and their current status is described in the subsequent sections.

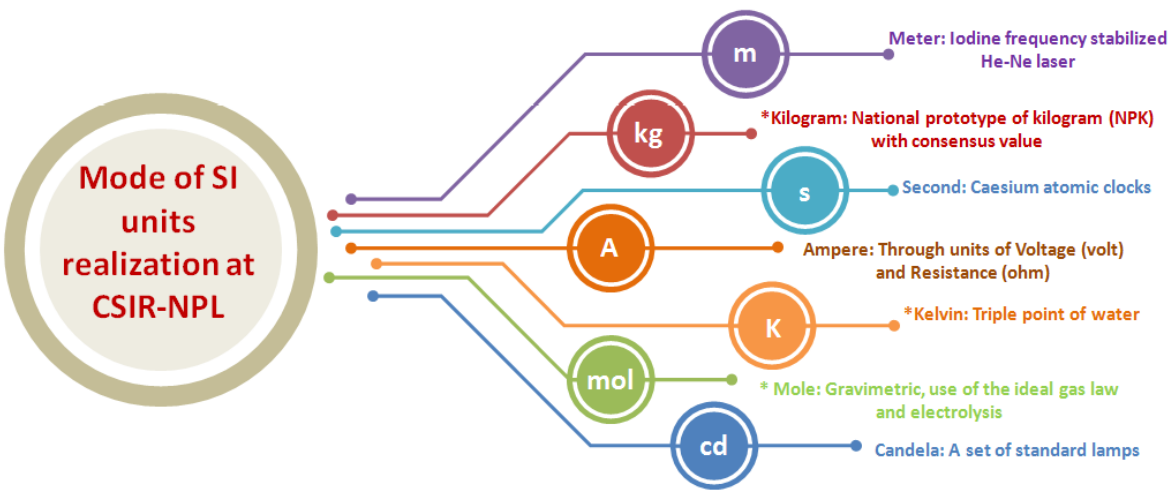

FIG. 3 MODE OF SI UNIT'S REALIZATION AT CSIR-NPL; *RESEARCH GROUPS ARE FOCUSED ON ESTABLISHING THE REDEFINED SI UNITS

6.5.1 *Status of The Unit of Meter*

In India, measurement services of length began in 1953 under its weights and measures division at CSIR-NPL, with one of the primary mandates being the realization of the unit of length. The National Prototype of Metre (figure 4) was provided by BIPM to CSIR-NPL in 1957, and a set-up for realizing the SI unit of length i.e. metre was established. The definition of the metre was revised in 1960 based on the Kr lamp; CSIR-NPL has also begun research on the Kr lamp in order to realize the SI unit of metre. CSIR-NPL has conducted research on laser frequency stabilization and developed iodine frequency-stabilized lasers indigenously [55-57].

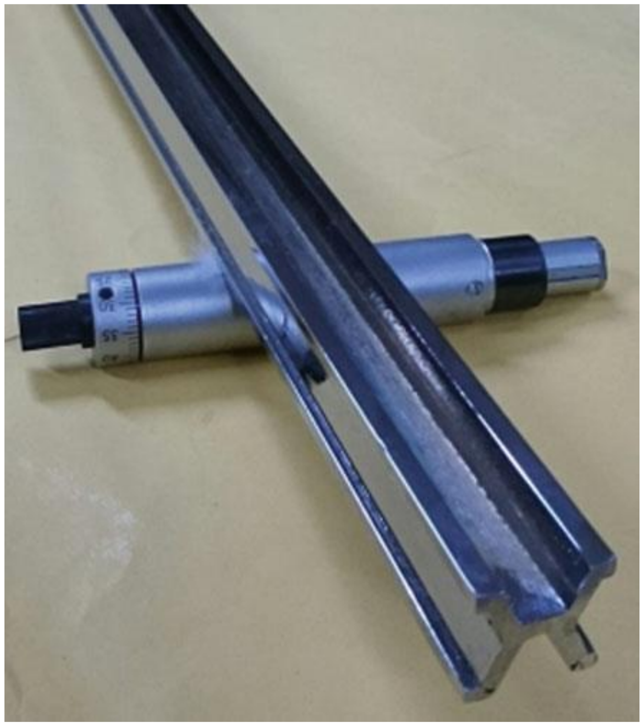

FIG. 4 THE NATIONAL PROTOTYPE OF THE METRE (COPY NO. 4) AT CSIR-NPL [55]

In 1983, the definition of the metre was again revised based on the speed of light in the vacuum as measured by iodine stabilized He-Ne laser. CSIR-NPL already planned on achieving it with its own primary laser. During this time, international efforts were underway to link the optical frequency standard to the temporal frequency standard. The number of lasers working at various wavelengths were frequency stabilized.

The iodine-stabilized He–Ne laser operating at 633 nm (474 THz) is the most commonly used laser to realize the SI unit of length because it is easy to use and is accurate up to 10^{-11}. It is used to calibrate commercial displacement measuring interferometer systems. CSIR-NPL maintains an iodine-stabilized He–Ne laser as a primary standard (figure 5) for the realization of the metre with a relative uncertainty of 2.5×10^{-11}.

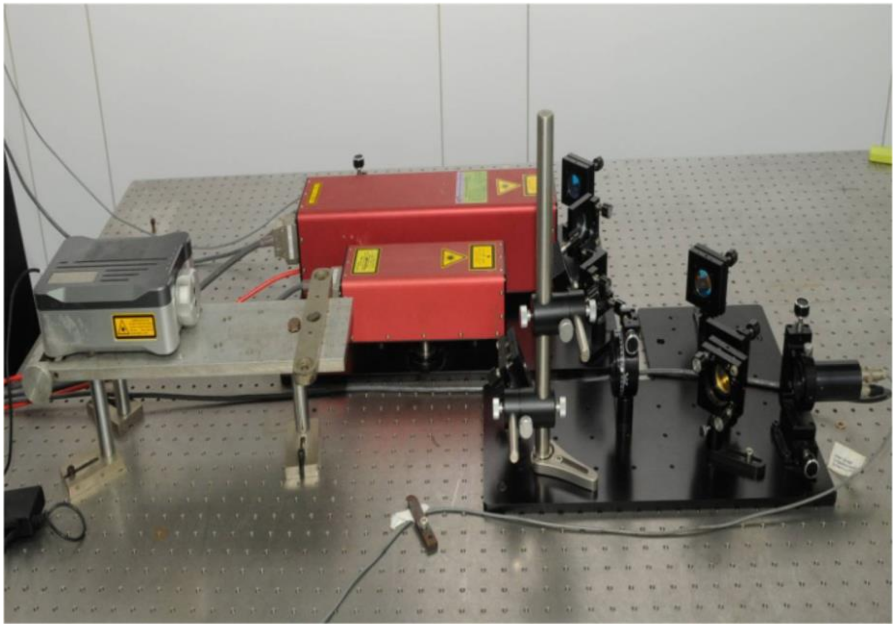

FIG. 5 IODINE ($^{127}I_2$) FREQUENCY STABILIZED HE-NE LASER [55]

Aside from the primary standard, the laboratory has state-of-the-art instruments such as the Gauge Block Interferometer, Displacement Measuring Interferometer (for linear, angular, straightness, and flatness of bed measurements), Flatness Measuring Interferometers for optical flats, etc., Length Measuring Machine, Coordinate Measuring Machines, Gauge Block Comparators, Autocollimators, and other SI-traceable instruments.

6.5.2 *Status of The Unit of Mass*

The National Prototype of the Kilogram, copy No. 57 (NPK-57), which was provided by the BIPM in 1957 after its first calibration in 1955 at BIPM, is kept at the CSIR-NPL (figure 6). Its material and characteristics are identical to those of the International Prototype of the Kilogram (IPK). So far, the BIPM has recalibrated NPK-57 in 1985, 1992, 2002, 2012 and 2022. The mass value of NPK-57 is disseminated to other CSIR-NPL mass standards ranging from 1 mg to 2,000 kg, as well as derived quantities such as pressure, vacuum, force, torque, hardness, ultrasonic, fluid flow, gas, environment, biomedical, BND, etc. [2, 12, 58-60].

FIG. 6 NATIONAL PROTOTYPE OF THE KILOGRAM (NPK-57) [58]

As described earlier, variations identical to those found with official copies of IPK were reported for NPK 57 after careful analysis of the periodic calibration certificates of NPK 57. Table 3 shows the variations in mass (NPK 57) values and associated measurement uncertainty [2, 58]

Table 3 Mass Values of National Prototype of The Kilogram (NPK-57) After Recalibration at BIPM

Year of calibration	**Mass Value**	**Combined Standard Uncertainty (*k*=1)**
1955	1 kg - 0.054 mg	Not provided
1985	1 kg - 0.022 mg	± 0.008 mg
1995	1 kg - 0.036 mg	± 0.002 3 mg
2002	1 kg - 0.044 mg	± 0.005 mg
2012	1 kg - 0.051 mg	± 0.007 mg

2014 *	1 kg - 0.087 mg	± 0.003 mg
2020 **	1 kg - 0.087 mg	± 0.021 mg
2022	1 kg - 0.058 mg	± 0.021 mg

**Revised value after extraordinary calibration carried out by the BIPM using IPK.*
***Revised uncertainty after calculation of the consensus value of the kilogram after redefinition.*

Recently, CSIR-NPL has successfully demonstrated a 'Kibble Balance' of 1 g (figure 7) for determining the Planck constant [61-62]. For the realization of the revised definition of the unit of the mass, efforts are going on towards the development of 100 g 'Kibble Balance' first and later on 1 kg in coming years. Until then, the mass traceability chain will be established using NPK-57, which has been the national standard in India since 1957, with the addition of consensus values in the uncertainty quantification.

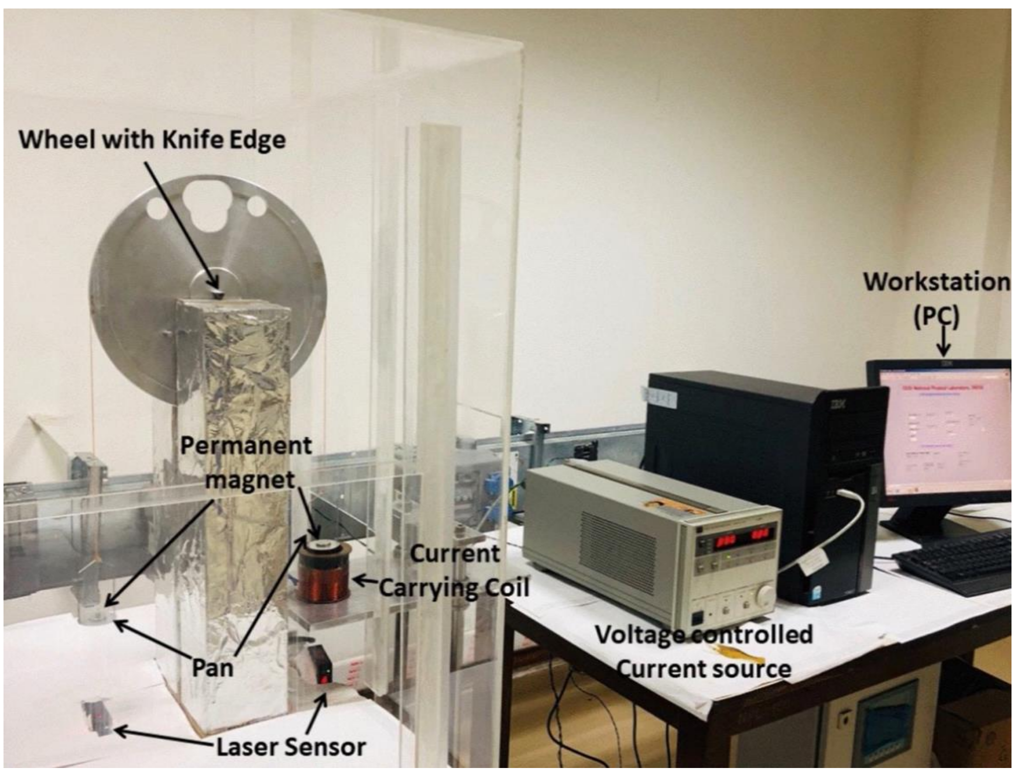

FIG. 7 KIBBLE BALANCE SYSTEM AT CSIR-NPL FOR 1 G MASS REALIZATION

6.5.3 *Status of The Unit of Time*

The transition frequency between two hyperfine levels (i.e. |F= 4|mf = 0 and |F = 3|mf = 0) of natural Cs-133 atoms is used to define SI second. This definition of SI second is realized in practice using Cs atomic fountain primary frequency standard (FS). India's first-ever caesium fountain primary frequency standard was designed, developed, and assembled indigenously at CSIR-NPL, as shown in Figure 8.

FIG. 8 CAESIUM FOUNTAIN CLOCKS AT CSIR-NPL [9]

The best measured fractional frequency uncertainty of the fountain is 2.5×10^{-15}, which is about 1 s in 30 million years. India is among only 9 countries to develop the Cs fountain clock in the world and is recognized by BIPM as India's primary frequency standard. With this clock, CSIR-NPL has successfully contributed to the International atomic timescale (TAI).

The CSIR-NPL, commonly known as the Timekeeper of the Nation, is responsible for realizing, maintaining, and disseminating Indian Standard Time (IST). UTC (NPLI) is generated by the primary NPL's Timescale,' which is traceable to the Coordinated Universal Time (UTC) given by BIPM via satellite links. IST is implemented at CSIR-NPL with the help of a timescale system that includes a bank of five caesium (Cs) atomic clocks and two active Hydrogen masers. These ultra-stable clocks are accurate to one second over a period of about three lakh years. At present, IST is traceable to UTC with a systematic link measurement uncertainty of ±2.8 nanoseconds (ns) [63-66]. Figure 9 shows the measurement uncertainty in time realization by some of the leading countries. Recently, during the year 2022, the measurement uncertainty is further improved to below ±2.0 ns.

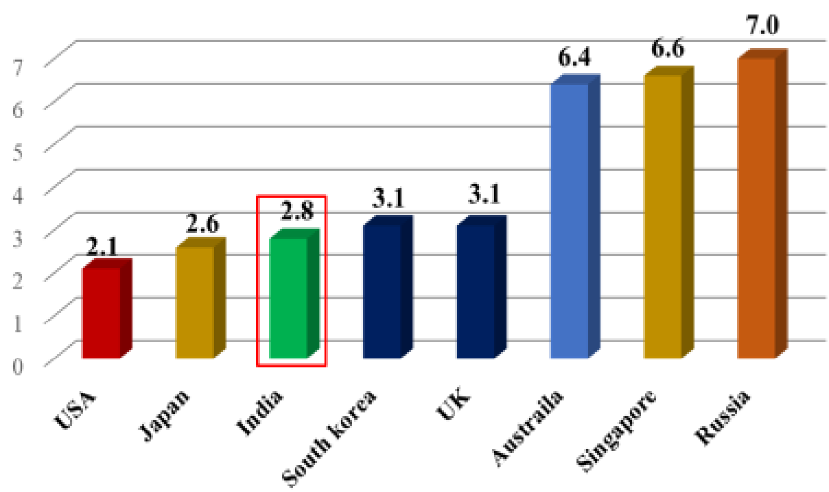

FIG. 9 A COMPARISON OF THE MEASUREMENT UNCERTAINTY OF PRIMARY TIME SCALE GENERATING IST WITH THAT FROM OTHER LEADING COUNTRIES

Furthermore, the laboratory conducts some outstanding research and development on primary atomic clocks. In 2011, the CSIR-NPL first Cs fountain clock became operational, with an accuracy of a few parts in 10^{-15}. A laboratory working group has just begun constructing a more accurate clock (10^{-17}) based on a single trapped Ytterbium ion at optical wavelengths.

6.5.4 *Status of The Unit of Current*

The earlier SI definition of ampere was abstract and difficult to realize, where the magnetic effect of current was measured. Instead, the ampere was being realized using the well-known Ohm's law, A = V/Ω, and using practical realizations of the SI-derived units of the volt V and the ohm Ω, based on the Josephson voltage standards and Quantum Hall Resistance Standards, respectively. At CSIR-NPL, the primary Josephson voltage standard was realized in 1985. The primary Quantum Hall Resistance (QHR) was established at CSIR-NPL in 2003 after the Quantum Hall Effect (QHE) was internationally adopted for the realization of resistance standards. Since then the quantum electrical standards have been effectively disseminated by CSIR-NPL for the users. Figure 10 depicts the traceability chart to show the linkage of various electrical quantities at CSIR-NPL.

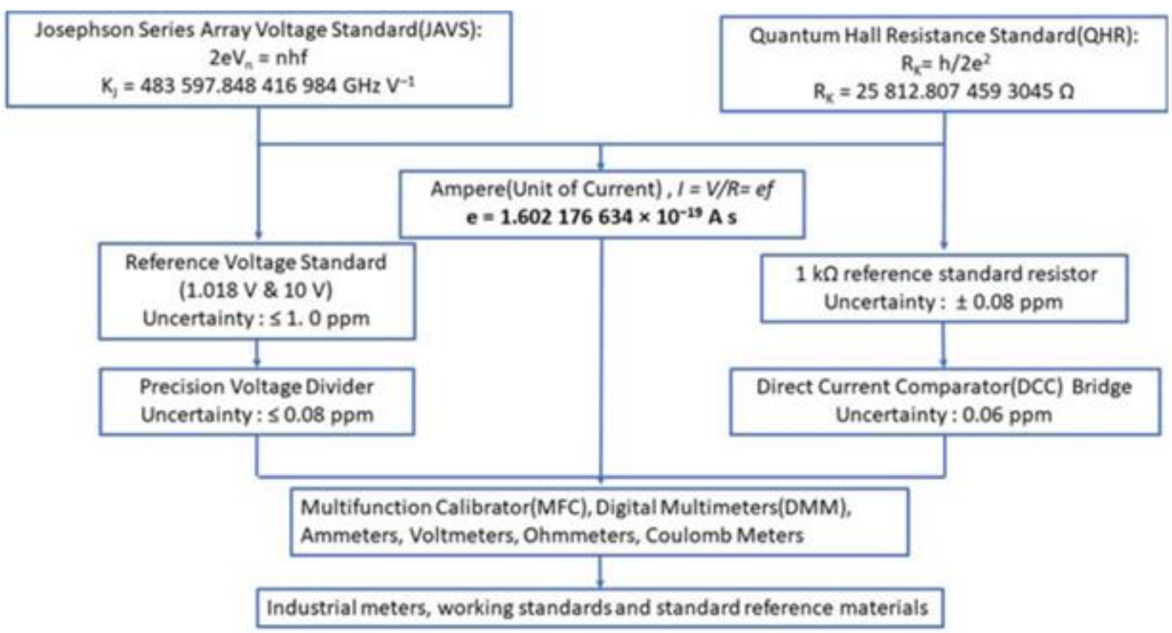

FIG. 10 TRACEABILITY CHART FOR THE ELECTRICAL QUANTITIES LINKING WITH JVS AND QHR AT CSIR-NPL [9]

For the redefined SI, the realization methods are separated conceptually from the definitions so that the units based on fundamental constants can be realized independent of place and time. Mise-in-pratique (MeP) [67] for all such redefined SI units has been given along with the methods of primary standards for the realization and dissemination. Now there is no single preferred method for realization.

For the definition of the unit of Ampere, there are primarily two methods of counting electrons. The first is single-electron tunneling (SET), in which coulomb blockage is proven and controlled based on a bias frequency (*f*) in a quantum dot structure, and the second is based on a superconducting phenomenon called quantum phase slip. The CSIR-NPL working group is now focusing on quantum phase slip in superconducting films and nanowires. For fabrication and electrical transport measurement of thin films and nanowires, the group has state-of-the-art growing facilities such as ultra-high vacuum RF (magnetron) sputtering systems, Focused ion beam induced deposition, and low-temperature measurement systems such as the physical property measurement, a SQUID based magnetic property measurement system, and a dilution refrigerator system, etc [68-69].

6.5.5 *Status of The Unit of Temperature*

The unit of thermodynamic temperature, kelvin (K), was defined based on the triple point of water (TWP) prior to the redefinition of the SI unit system (TPW, 273.16 K). The TWP-based definition of kelvin was adopted in 1967. TPW cell No. 31 was given by BIPM to CSIR-NPL in the 1970s, for the practical realization of kelvin. In the 1990s CSIR-NPL successfully developed the in-house TPW cell with triple distilled de-ionized water and used it along with the other ITS-90 defined fixed points to realize the temperature scale. Presently TPW CMC is based on the realization of 3 TPW cells [70-73]. Figure 11 shows the TPW realization standard facility at the laboratory.

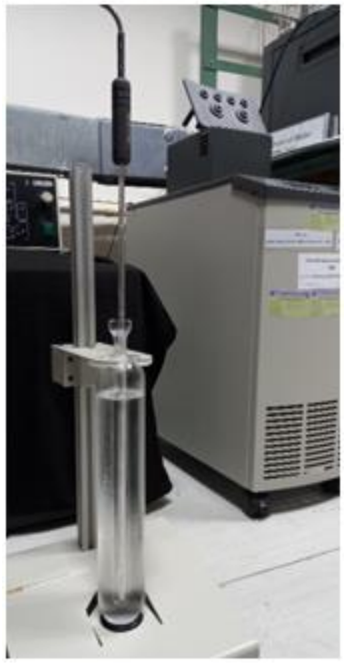

FIG. 11 TRIPLE POINT OF WATER REALIZATION FACILITY AT CSIR-NPL

TPW is still based on the material-dependent property when it comes to dissolved impurities and water isotopes. At the BIPM level, attempts have been made since 2007 to redefine the kelvin based on the Boltzmann Constant (k) by setting its numerical value to provide a material independent definition, which is presently in effect from May 20, 2019. There are numerous equations of state-based methods for achieving this. The most precise of which is acoustic gas thermometry, which involves measuring the velocity of sound in a high pure monoatomic gas to estimate the value of the Boltzmann constant at the triple point of water temperature (273.16 K). Figure 12 shows the 3D model of the Acoustic Resonator, Pressure Vessel, and Vacuum vessel for the development of the Acoustic Gas Thermometry setup.

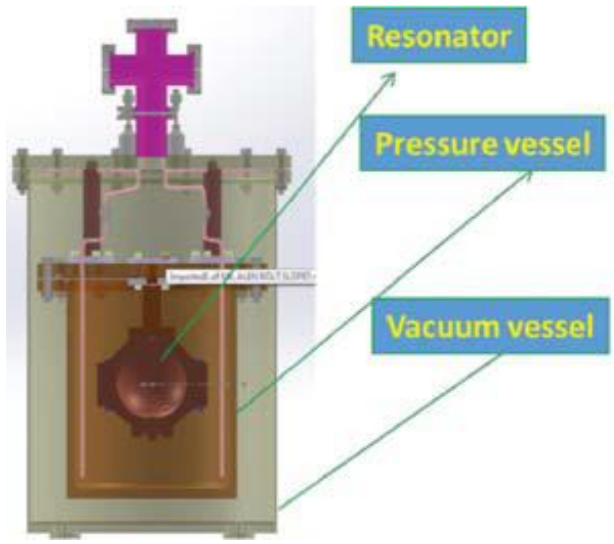

Fig. 12 Design of Acoustic Resonator, Pressure Vessel and Vacuum Vessel for The Development of Acoustic Gas Thermometry Set-Up At CSIR-NPL

Further, it is necessary to establish this acoustic gas thermometry primary standard at CSIR-NPL by designing, developing, and fabricating a copper quasi-spherical cavity acoustic-microwave resonator in India and by in-house collaborations of temperature, acoustic, microwave, pressure, dimension, and gas metrology groups.

6.5.6 *Status of The Unit of Amount of Substance*

The realization of the mole in all forms of chemical entities is done in chemistry utilizing a number of fundamental methods of measurement in terms of substance concentration (mol/m^3), substance content (mol/kg), or substance fraction (mol/mol). Gravimetric, ideal gas law and electrolysis are three extensively used ways of realizing the mole. The CSIR-NPL is working on the realization of the mole by gravimetrically preparing Reference materials. Similarly, primary gas standards are determined using the gravimetric method, with moles expressed in mol/kg or mol/mol. The laboratory is also managing an inter-laboratory initiative for the planning, development, and dissemination of various “Indian Reference Materials” also known as BNDs [74-75].

6.5.7 *Status of The Unit of Luminous Intensity*

The realization of the SI base unit of luminous intensity i.e. candela is maintained at the CSIR-NPL using a bank of calibrated luminous intensity standard lamps that are traceable to the primary standard. Continuous participation in International inter-comparisons establishes the traceability of photometric parameters and the validation of results [76-77]. Figure 13 shows the experimental setup used for the realization of luminous intensity. Internationally at present, the luminous intensity is realized using a Primary spectral irradiance standard having a black body as the primary source where the temperature is traceable from the primary radiometer.

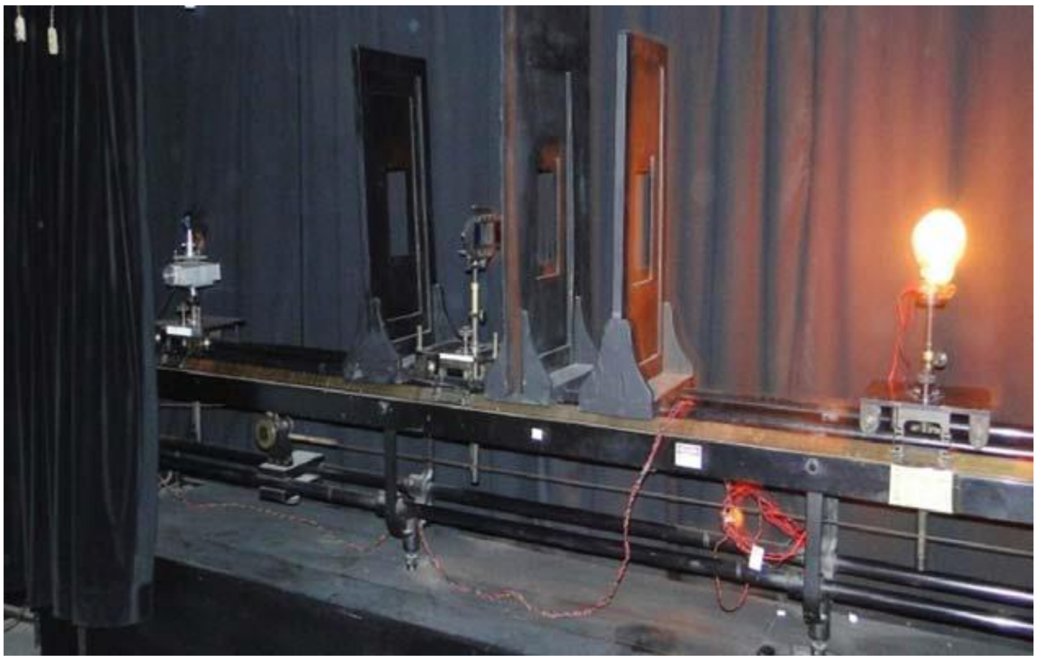

FIG. 13 EXPERIMENTAL SETUP FOR THE REALIZATION OF LUMINOUS INTENSITY AT CSIR-NPL

Other goals of the group include providing apex measurement and calibration facilities, as well as measurement traceability for various derived photometric parameters such as illuminance, detector illuminance responsivity, luminous flux, and luminance, as well as radiometric and colorimetric parameters such as spectral irradiance in the range of 280 nm to 2500 nm, colour temperature, and colour coordinates.

In recent years, the demand for LED lighting has risen dramatically and manufacturing industries have also reciprocated well by creating economic solid-state lighting devices as the international community moves toward energy-efficient lighting. Currently, photometry of LED is being pursued by different NMIs worldwide and the research group at CSIR-NPL is also pursuing LED-centered radiation metrology and is in the process of establishing calibration and testing facilities to disseminate apex level photometric scales for LED-based lightings as per national and international standards.

CSIR-NPL in collaboration with the Bureau of Energy Efficiency (BEE), Government of India has recently dedicated an *LED Photometry Laboratory* to the Nation during the 2022 metrology conclave for the calibration and testing of LED-based lighting products. Figure 14 depicts various established metrology grade systems in the laboratory. The group also plans to establish a broad range intensity realization setup and other primary setups in the near future.

FIG. 13 C-TYPE GONIOPHOTOMETER SYSTEM AND PHOTO BIOLOGICAL SAFETY TESTING SYSTEM ESTABLISHED RECENTLY AT CSIR-NPL

6.5.8 *The Changes Implemented in The Education System After the Revised SI*

In India, the adoption of the International System of Units (SI) and the metric system has led to several changes in the education system aimed at aligning curricula, pedagogy, and assessment practices with global standards of measurement. Educational authorities have revised textbooks, syllabi, and curricula across various educational levels to incorporate the principles, definitions, and standards of the SI units and metric system [78-80]. Concepts related to fundamental units such as the kilogram, meter, second, and others are taught following the revised SI, emphasizing precision, coherence, and global compatibility in measurement education. Some of the schools and educational institutions have updated laboratory equipment, measurement tools, and experimental setups to reflect the SI units and metric standards. Practical exercises and laboratory experiments emphasize the use of SI units for measurements, data analysis, and uncertainty estimation, providing students with hands-on experience in applying metrological principles in scientific inquiry. Assessment methods and evaluation criteria in science and mathematics subjects have been revised to incorporate the SI units and metric system. Students are assessed on their understanding of measurement concepts, proficiency in using SI units for calculations and problem-solving, and ability to interpret and communicate measurement results accurately. Teacher training programs and professional development initiatives have been conducted to familiarize educators with the principles, definitions, and applications of the SI units and metric system. Teachers are being equipped with the knowledge and skills to effectively teach measurement concepts, conduct laboratory activities, and assess student learning outcomes in alignment with the revised SI.

7. CONCLUSION AND A WAY FORWARD

The document presents historical perspectives on the evolution and growth of the metric system. The journey from some of the historical aspects to current revisions in the realization of the SI unit system is also briefly included. The recent developments finalized on metric system in the 26th and 27th CGPM are also highlighted. It also describes the state-of-the-art facilities at CSIR-NPL that enable the realization of SI units. Now, the SI units are realized through fundamental constants as primary metrological standards and then the measurement of units is disseminated to its stakeholders. Therefore, the realization and dissemination of the SI units are very crucial and important for international trade and industrial growth. Now, it is the responsibility of CSIR-NPL to realize SI units as per advancement and technological developments in fundamental constants wherever possible and disseminate the SI units to users and industries through apex calibration, testing, consultancy, training, etc. The importance, significance, and indispensability of metrology and the new SI system are crucial for the inclusive progress of the country. CSIR-NPL maintains the global compatibility and excellence of measurement standards through participation in international key comparisons, publishing the key comparison reports, and publishing new Calibration and Measurement Capabilities (CMCs) on the BIPM website. Therefore, the role of CSIR-NPL is extremely vital to drive the growth engines of the nation and improve the quality of life of citizens, which in turn, would save precious lives, resources, and time. The present monograph is prepared to disseminate knowledge on current advancements in the field of the metric system to readers and the general public to address one of the important responsibilities of CSIR-NPL as the NMI of the country. This document is expected to be a source of information to all the stakeholders, including metrology practitioners in calibration and testing laboratories, academicians and educators, accreditation and quality specialists, legal metrologists, administrators, and policymakers.

ACKNOWLEDGEMENT

The authors are thankful to all the CSIR-NPL colleagues and students of CSIR-NPL past and present, whose works and activities are briefly mentioned in this document.

REFERENCES

1. Aswal, D.K. Quality Infrastructure of India and Its Importance for Inclusive National Growth. *MAPAN* 35, 139–150 (2020).
2. Rab, S., Yadav, S., Garg, N., Rajput, S., & Aswal, D. K. (2020). Evolution of measurement system and SI units in India. *MAPAN*, 35(4), 475-490.
3. Shigeo Iwata, Weights and Measures in the Indus Valley, [1], (2008) 2254–2255.
4. Upinder Singh, A History of Ancient and Early Medieval India: From the Stone Age to the 12th Century Always learning, Pearson Education India; 2008.
5. A.R. Verma, National Measurement System, National Physical Laboratory, New Delhi, 1987.
6. M.R. Goyal, Unit of length measurement and speed of light in Ancient India, 2013, Available
7. Stephan Schlamminger, Redefining the Kilogram and Other SI Units, *Phys World Discov*. 2018; 1–25.
8. Jean-Pierre Fanton, A brief history of metrology: past, present, and future, Int. *J. Metrol. Qual. Eng.* 10, 5 (2019), 1-8.
9. Aswal, D. K. (Ed.). (2020). Metrology for inclusive growth of India. Springer Nature.
10. Aswal, D. K. (2020). Quality infrastructure of India and its importance for inclusive national growth. *MAPAN*, 35(2), 139-150.
11. Rab, S., Yadav, S., Jaiswal, S. K., Haleem, A., & Aswal, D. K. (2021). Quality Infrastructure of National Metrology Institutes: A Comparative Study, *IJPAP*.
12. Yadav, S., Aswal, D.K. Redefined SI Units and Their Implications. MAPAN 35, 1–9 (2020). https://doi.org/10.1007/s12647-020-00369-2
13. Whitelaw I., A Measure of All Things: The Story of Man and Measurement, Macmillan; 2007.
14. Taylor, B. (1995). Guide for the use of the International System of Units (SI): The metric system. *DIANE Publishing*.
15. Page, C. H., & Vigoureux, P. (1975). The international bureau of weights and measures 1875-1975. NASA STI/Recon Technical Report N, 75, 33282.
16. S. V. Gupta, A Treatise on Standards of Weights and Measures, Commercial Law Publishers; 2005.
17. Quinn, T. (2004). The Metre Convention and world-wide comparability of measurement results. *Accreditation and quality assurance*, 9(9), 533-538.

18. Williams, C. J. (2021). The SI from platinum to Planck: The biggest revolution in metrology since the French Revolution 1. *In New Frontiers for Metrology: From Biology and Chemistry to Quantum and Data Science* (pp. 119-130). IOS Press.
19. Reddy, William M. "Sentimentalism and its erasure: The role of emotions in the era of the French Revolution." *The Journal of Modern History* 72, no. 1 (2000): 109-152.
20. Davis, Richard S. "How to Define the Units of the Revised SI Starting from Seven Constants with Fixed Numerical Values." *Journal of Research of the National Institute of Standards and Technology* 123 (2018).
21. Milton, M. J., Davis, R., & Fletcher, N. (2014). Towards a new SI: a review of progress made since 2011. *Metrologia*, 51(3), R21.
22. Gupta, S. V. (2019). Redefining the Base Units. *In Mass Metrology* (pp. 365-384). Springer, Cham.
23. General Conference on Weights and Measures, Proceedings of the 26th meeting of the CGPM, Appendix 3. The base units of the SI (page 491-493), Accessed on April 16, 2022, Available from: https://www.bipm.org/fr/search?p_p_id=search_portlet&p_p_lifecycle=2&p_p_state=normal&p_p_mode=view&p_p_resource_id=%2Fdownload%2Fpublication&p_p_cacheability=cacheLevelPage&_search_portlet_dlFileId=30876792&p_p_lifecycle=1&_search_portlet_javax.portlet.action=search&_search_portlet_page=2&_search_portlet_operation=changePage
24. Appendix 4. Historical notes on the development of the International System of Units and its base units, Accessed 20 February 2022, Available from: https://www.bipm.org/utils/common/pdf/si-brochure/SI-Brochure-9-App4-EN.pdf
25. Stock, M., Davis, R., de Mirandés, E., & Milton, M. J. (2019). The revision of the SI—the result of three decades of progress in metrology. *Metrologia*, 56(2), 022001.
26. Newell, D. B., Cabiati, F., Fischer, J., Fujii, K., Karshenboim, S. G., Margolis, H. S., & Zhang, Z. (2018). The CODATA 2017 values of h, e, k, and N_A for the revision of the SI. *Metrologia*, 55(1), L13.
27. Rab, S., Zafer, A., Kumar Sharma, R., Kumar, L., Haleem, A., & Yadav, S. (2022). National and Global Status of the High Pressure Measurement and Calibration Facilities. *Indian Journal of Pure & Applied Physics (IJPAP)*, 60(1), 38-48.
28. Newell, D. B., & Tiesinga, E. (2019). The international system of units (SI). *NIST Special Publication*, 330, 1-138.
29. 27th CGPM: Key outcomes and documents, https://www.bipm.org/en/cgpm-2022/documents, accessed on 11 March, 2024.
30. Brown, R. J. (2019). On the nature of SI prefixes and the requirements for extending the available range. Measurement, 137, 339-343.
31. Brown, R. J. (2022). A further short history of the SI prefixes. Metrologia, 60(1), 013001.

32. Dimarcq, N., Gertsvolf, M., Mileti, G., Bize, S., Oates, C. W., Peik, E., ... & Ashby, N. (2024). Roadmap towards the redefinition of the second. Metrologia, 61(1), 012001.
33. Resolution 5 of the 27th CGPM (2022), https://www.bipm.org/en/cgpm-2022/resolution-5, accessed on 11 March, 2024.
34. National Metrology Systems Developing the institutional and legislative framework, https://www.bipm.org/documents/20126/42177518/National-Metrology-Systems.pdf/3f13d88c-aef6-9c50-62dc-39fa6f48f6e9, accessed on 11 March, 2024.
35. Guide to the expression of uncertainty in measurement — Part 6: Developing and using measurement models, https://www.bipm.org/documents/20126/50065290/JCGM_GUM_6_2020.pdf/d4e77d99-3870-0908-ff37-c1b6a230a337, accessed on 12 March, 2024.
36. Rab, S., Wan, M., & Yadav, S. (2022). Let's get digital. Nature Physics, 18(8), 960-960.
37. Brown, R. J., Janssen, J. T., & Wright, L. (2022). Why a digital framework for the SI?. Measurement, 187, 110309.
38. Thiel, F. (2018). Digital transformation of legal metrology–the European metrology cloud. OIML bulletin, 59(1), 10-21.
39. Eichstädt, S., Keidel, A., & Tesch, J. (2021). Metrology for the digital age. Measurement: Sensors, 18, 100232.
40. Rab, S., Wan, M., Sharma, R. K., Kumar, L., Zafer, A., Saeed, K., & Yadav, S. (2023). Digital avatar of metrology. MAPAN, 38(3), 561-568.
41. Stock, M., Wielgosz, R., Tavella, P., Judge, S., & Milton, M. (2020). News from the BIPM laboratories—2019. *Metrologia*, 57(2), 025010.
42. Tavella, P., & Hanado, Y. (2021, August). The BIPM Capacity Building and Knowledge Transfer program on Time Scale Realization. In 2021 XXXIVth General Assembly and Scientific Symposium of the International Union of Radio Science (URSI GASS) (pp. 1-2). *IEEE*.
43. OIML BULLETIN, https://www.oiml.org/en/publications/bulletin/pdf/oiml_bulletin_july_2021.pdf, accessed on 12 March, 2024.
44. Online learning from the OIML, https://www.oiml.org/en/structure/ceems/online-learning-from-the-oiml/online-learning-from-the-oiml, accessed on 12 March, 2024.
45. Yadav, S., Mandal, G., Shivagan, D. D., Sharma, P., Zafer, A., & Aswal, D. K. (2020). International Harmonization of Measurements: Part II: International and National Dissemination Mechanisms. *Metrology for inclusive growth of India*, 83-143.
46. History of measurement systems in India, Accessed 8 March 2022, https://en.wikipedia.org/wiki/History_of_measurement_systems_in_India#:~:text=The%20history%20of%20measurement%20systems,%2C%20folk%2C%20and%20metallurgical%20artifacts.

47. Velkar, A. (2018). Rethinking Metrology, Nationalism and Development in India, 1833–1956. Past and Present, 239(1), 143-179.
48. Yadav, S., Mandal, G., Shivagan, D. D., Sharma, P., Zafer, A., & Aswal, D. K. (2020). International Harmonization of Measurements. *In Metrology for Inclusive Growth of India* (pp. 83-143). Springer, Singapore.
49. Das, M. K., & Das, R. (2022). Law and Economics of Evolution of Banking Regulation in India. *In Finance, Law, and the Crisis of COVID-19* (pp. 209-219). Springer, Cham.
50. History of measurement systems in India, Accessed on 8 March 2022, https://en.wikipedia.org/wiki/History_of_measurement_systems_in_India
51. National Physical Laboratory, The legacy continues, Diamond Jubilee Volume, Published by: National Physical Laboratory, New Delhi, 2007. Accessed on 20 March 2022 https://www.nplindia.org/wp-content/uploads/2021/10/npldjvsec-1.pdf
52. A compendium of scientific triumphs, Platinum Jubilee Volume, Published by: National Physical Laboratory, New Delhi, 2022, Accessed on 20 March 2022, https://www.nplindia.org/wp-content/uploads/2022/01/NPLCompendium2022.pdf
53. Yadav, S., Mandal, G., Jaiswal, V. K., Shivagan, D. D., & Aswal, D. K. (2021). 75th Foundation Day of CSIR-National Physical Laboratory: Celebration of Achievements in Metrology for National Growth. *MAPAN*, 36(1), 1-32.
54. BIPM Website, The Republic of India, Accessed 15 March 2022, Available from: https://www.bipm.org/en/about-us/member-states/in/
55. Mandal, G., Ansari, M. A., & Aswal, D. K. (2021). Quality Management System at NPLI: Transition of ISO/IEC 17025 From 2005 to 2017 and Implementation of ISO 17034: 2016. *MAPAN*, 36(3), 657-668.
56. Sharma, R., Moona, G., & Jewariya, M. (2020). Progress Towards the Establishment of Various Redefinitions of SI Unit "Metre" at CSIR-National Physical Laboratory-India and its Realization. *MAPAN*, 35(4), 575-583.
57. Moona, G., Kumar, V., Jewariya, M., Sharma, R., & Kumar, H. (2019). Measurement uncertainty evaluation using Monte Carlo simulation for newly established line scale calibration facility at CSIR-NPLI. *MAPAN*, 34(3), 325-331.
58. Yadav, S., Sharma, N. D., Titus, S. S. K., Jaiswal, S. K., Jaiswal, V. K., Garg, N., ... & Aswal, D. K. (2020). Physico-Mechanical Metrology: Part I: Impetus for Inclusive Industrial Growth. *Metrology for Inclusive Growth of India*, 237.
59. Ehtesham, B., John, T., Yadav, S., Singh, H. K., Mandal, G., & Singh, N. (2020). Journey of Kilogram from Physical Constant to Universal Physical Constant (h) via Artefact: A Brief Review. *MAPAN*, 35(4), 585-593.
60. Ehtesham, B., John, T. & Singh, N. Limitation of the Artifact-Based Definition of the Kilogram, its Redefinition and Realization Using Kibble Balance. *MAPAN* 36, 333–341 (2021). https://doi.org/10.1007/s12647-021-00466-w

61. Ehtesham, B., John, T., Singh, H. K., & Singh, N. (2022). Automation of Demonstrational Model of 1 g Kibble Balance Using LabVIEW at CSIR-NPL, Indian Journal of Pure & Applied Physics Vol. 60, January 2022, pp. 29-37.
62. Kumar, A., Kumar, H., Ojha, V. N., Singh, S., Moona, G., & Dubey, S. P. (2017). National Physical Laboratory demonstrates 1 g Kibble balance: Linkage of macroscopic mass to Planck constant. Current Science, 113, 381-382.
63. Poudel, N., Bhardwaj, T., Arora, P., Gupta, A., & Aswal, D. K. (2021). Indian Standard Time Dissemination Over Internet via Indigenously Designed Devices and Applications. *MAPAN*, 36(4), 711-716.
64. Vattikonda, B., Das, M., Bhardwaj, T., Panja, S., Arora, P., Gupta, A., & Aswal, D. K. (2020). Time and Frequency Metrology. *In Metrology for Inclusive Growth of India* (pp. 145-195). Springer, Singapore.
65. A. Acharya, S. Yadav, P. Arora, A. Agarwal, V. Bharath and A. S. Gupta, "Present status of primary frequency standards at NPL, India," 2016 *IEEE International Frequency Control Symposium (IFCS)*, New Orleans, LA, 2016, pp. 1-2, doi: 10.1109/FCS.2016.7546774.
66. Sharma, L., Rathore, H., Utreja, S. et al. Optical Atomic Clocks for Redefining SI Units of Time and Frequency. *MAPAN* 35, 531–545 (2020). https://doi.org/10.1007/s12647-020-00397-y
67. Practical realization of the definition of some important, BIPM Webpage. https://www. bipm.org/en/publications/mises-en-pratique/, Accessed on 3rd April 2022]
68. Bhattacharyya, B., Awana, V.P.S., Senguttuvan, T.D. et al. Proximity-induced supercurrent through topological insulator based nanowires for quantum computation studies. *Sci Rep* 8, 17237 (2018). https://doi.org/10.1038/s41598-018-35424-1
69. Singh, Manju, Husale, Sudhir, & Chaujar, Rishu, Influence of fabrication processes on transport properties of superconducting niobium nitride nanowires. *Current Science*, (2018) 114(7), 1443-1450.
70. Pant, U., Meena, H., Gupta, G., Bapna, K., & Shivagan, D. D. (2021). Improved Realization of Ensemble of Triple Point of Water Cells at CSIR-NPL. *MAPAN*, 36(3), 615-628.
71. Pant, U., Meena, H. & Shivagan, D.D. Development and Realization of Iron–Carbon Eutectic Fixed Point at NPLI. *MAPAN* 33, 201–208 (2018). https://doi.org/10.1007/s12647-018-0251-y
72. Pant, U., Gupta, G., Meena, H., Bhatt, A., Bapna, K., & Shivagan, D. D. (2021). Realization of ITS-90 Radiance Temperature Scale from 961.78° C to 3000° C at CSIR-NPL. *MAPAN*, 1-11.
73. Pant, U., Meena, H., Gupta, G., Bapna, K., & Shivagan, D. D. (2020). Development and realization of Fe–C and Co–C eutectic fixed-point blackbodies for radiation thermometry at CSIR-NPL. *International Journal of Thermophysics*, 41(7), 1-15.
74. Krishna, A., Tripathy, S. S., & Singh, N. (2022). Futuristic Role of Bhartiya Nirdeshak Dravya an Indian Reference Material on Safety and Quality of Food Products. *MAPAN*, 1-6.

75. Pant, R. P., Tripathy, S. S., Mishra, D. K., Singh, V. N., Gautam, A., Vijayan, N., ... & Singh, N. (2020). Bharatiya Nirdeshak Dravyas (BND®): Indian Certified Reference Materials. *In Metrology for Inclusive Growth of India* (pp. 925-984). Springer, Singapore.
76. S. Saha, V.K. Jaiswal, P. Sharma and D.K. Aswal, Evolution of SI base unit candela: the light perception of human eye. *MAPAN-J Metrol. Soc. India*, 35 (2020) 563–573.
77. APMP Comparison on Luminous Flux Units (APMP.PR-K4), https://www.bipm.org/documents/20126/44556018/APMP.PR-K4.pdf/9b9f5792-c680-43b1-985a-5aa9c883d5c7, accessed on 22 March, 2024NPL Policy on Metrological Traceability, https://www.nplindia.in/sites/default/files/NPL-Policy-On-Metrological-Traceability.pdf, accessed on 12 March, 2024.
78. Recommendations for Revision of SI Units and other Necessary Changes to be Incorporated in Syllabi of NCERT Text Books, NPL-Recommendations-for-Changes-in-NCERT-textbooks.pdf (nplindia.in), accessed on 12 March, 2024.
79. Recommendations for Revision of Syllabus for Metrology in Engineering Courses, NPL-Recommendations-for-Changes-in-Metrology-Related-Courses-in-Engineering-Courses.pdf (nplindia.in), accessed on 12 March, 2024.