CCPR
Workshop on the Future of the Candela

4 June 2024

BIPM, Sèvres, France

Program

14:00 Opening Remarks

Organizing committee: Maria Nadal (NIST, Chair CCPR WG-SP), Maria Luisa Rastello (INRIM, CCPR President), Stefan Kück (PTB), and Joële Viallon (BIPM)

14:15 What is the purpose of the SI?

Annette Koo (MSL)

14:35 CCU interest in the future of the Candela.

Richard Brown (NPL, CCU)

14:55 No changes to the current definition of the Candela.

Arming Sperling (PTB)

15:15 Adopt Cone Fundamentals to the Kcd definition.

Yoshi Ohno (NIST)

15:35 Bring photometry to individuals by applying a specific Kcd value for each person.

Gael Obein (LNE-CNAM)

15:55 Coffee Break (30 minutes)

16:25 Go back to the definition using a source (like a platinum blackbody) instead of the spectral responsivity of the human eye.

Boris Khlevnoy (VNIIOFI)

16:45 Photon-based Candela

Stefan Kück (PTB) and Angela Gamouras (NRC)

17:05 A Proposal for Three Categories of Units Within the SI.

John Lehman (NIST)

17:25 Speakers panel discussion

17:50 Concluding remarks

Maria Luisa Rastello (INRIM, CCPR President)

18:00 End

Thoughts on the shape and purpose of the International System of Units

Annette Koo, Measurement Standards Laboratory of New Zealand

The kilogram, the meter, the second, the ampere, the kelvin, the mole and the candela are still considered the 'base units' of the International System of Units (SI). But why seven? Why these particular units? These questions have been discussed by various people over the years who have concluded they could be reduced – usually to between 2 to 5 [2,3], and most recently to 4 by Lehman et al [4]. Others argue that the concept of base units is conventional at best and likely flawed [5,6]. Most of these take a scientific-philosophic approach – arguments center around dimensonality, coherence, or fundamental-ness. These are important questions to be considered and answered, and pertain to all systems of units. But the SI is distinct from all other systems in the signing of the metre convention that now mandates its broad use, in the international arrangement [7] that underpins the structures and processes which enable the realisation, the validation, and the dissemination of all its derived quantities, and therefore in the role it plays in the everyday lives of people across the world.

The values assigned to the seven constants of the SI are not unity, as you might expect from a system built to serve purely scientific endeavour, but are delightfully human centric – the second is a heartbeat, the kilogram we can hold in our hand, the meter is within our armspan, the kelvin is the temperature difference we can feel, and the candela above all the others exemplifies this – it is the brightness of a candle, exclusively to the *human* eye! This should not surprise us at all. The origins of the SI units are firmly placed in the realm of people trading goods, communicating observations, and establishing trust.[1]

We can acknowledge then, that the collection of units we now have reflects history and may yet change and develop. But no matter how it changes, we must not lose sight of what it is for – to support every day decision making. It isn't perfectly elegant, it doesn't adhere to a systematic criteria, it is historical, and human, and unashamedly so. The presence of the candela in particular is a reminder of the purpose of the SI. As the only physiological base unit[2], it is a constant challenge to maintain its relevance, improve its reliability and ensure its accessibility. This sharpens our awareness of the SI as an enabler of human activity which must continue to evolve.

[1] BIPM. Le Système international d'unités / The International System of Units ('The SI Brochure'). Bureau international des poids et mesures, ninth edition, 2019.

[2] Bordé C J 2019 A consistent unified framework for the new system of units: Matter–wave optics *Comptes Rendus Phys.* **20** 22–32 Online: https://doi.org/10.1016/j.crhy.2018.12.004

[3]Duff M J, Okun L B and Veneziano G 2009 Trialogue on the number of fundamental constants *Energy Mass Relativ. Theory* 119–50

[4]Lehman et al. 2024 A Proposal for Three Categories of Units Within the SI *Metrologia* in press

[5]Feller U 2011 The International System of Units-a case for reconsideration *Accredit. Qual. Assur.* **16** 143–53

[6] Grozier J 2020 Should physical laws be unit-invariant? *Stud. Hist. Philos. Sci. Part A* **80** 9–18

[7] Mutual Recognition of National Measurement Standards and of Calibration and Measurement Certificates Issued by National Metrology Institutes, BIPM, Paris, 14 October 1999

[8] Pellegrino O et al. 2015 SI physiological units *Int. J. Metrol. Qual. Eng.* **6** 10–3

[1] This is a bit of a generalization - the definition of the ampere is perhaps an anomaly – milliamperes and microamperes are more 'human sized' - precisely because its first definition was made before electricity was in common use. And while the mole was also first defined in a laboratory, it also scaled huge numbers of entities (10^{23} as it turned out) to masses that humans could easily consider and handle.

[2] The need foro physiological units and measurements is only growing [8].

No changes to the current definition of the Candela

Arming Sperling (PTB)

When the International System of Units (SI) with its 7 base units became effective in its present form in 1960 with the 11th General Conference on Weights and Measures, more than 70 preparatory years had passed in which all units with internationally recognised artefacts were determined for their realisation. And work on a stable unit for measuring luminous intensity was also on the agenda of the General Conference on Weights and Measures almost from the very beginning due to its importance in trade, industry and science.

However, due to doubts about the usefulness of the platinum cavity radiator used as an artefact for the realisation of the unit of luminous intensity, and also due to the switch from visual photometry to physical photometry based on radiometric measurements, preparations were made in the 1970s to switch to a new definition that directly links photometry to the radiometric watt. Pioneering for the future of the SI, the radiometric technical constant 1/683 W/sr at 540 THz was defined as the central quantity for the realisation of the unit of luminous intensity.

However, it should be noted at this point that the question of the justification of luminous intensity as a base unit in the SI had already arisen at this time. Until a new definition of luminous intensity came into force at the 16th General Conference (1979), all possible forms of redefinition were therefore intensively discussed. In the end, it was decided to retain the unit of luminous intensity of light sources, expressed by their radiometric radiant intensity at a wavelength in a vacuum. The decisive factor was that the continuity of the System of Units and its great practical benefit for the community were emphasised. The size of the technical constant, which inevitably entailed changes in photometric measurement values (and thus also in product properties), was chosen in such a way that changes for the photopic observer (as a default value) were kept small in order to satisfy the industry.

With the changeover of the SI units to definitions based on defining constants, the candela has once again gained in profile. With the old definition, the candela was linked to the radiant intensity of a source with the defining value 1/683 W/sr at 540 THz. However, the coupling of this radiometric value with the sensitivity function of a photometric observer (photopic or scotopic) to determine the correct measured quantity, which is essential for photometry, was only mentioned in the explanatory text and in the "mise en pratique" for the candela. This made the definition difficult to understand for the general user.

With the redefinition of all SI units in 2019, the universal value 683 lm/W of the luminous efficacy at 540 THz was chosen as the defining constant K_{cd} instead of a radiant intensity. This value also defines the intersection of the spectral luminous efficayies of all possible photometric observers. The definition via this universally valid value allows photometric quantities of radiation sources to be mapped directly for any photometric observer (not only human) - provided that their sensitivity is not zero at the spectral definition point 540 THz. The current "mise en pratique" illustrates the application for human observers under various application conditions.

In the field of colourimetry, progress has been made with cone-fundamental-based functions, which are seen as the basis for replacing luminous efficiency functions (such as $V(\lambda)$). At first glance, this is completely independent of the SI units, as the correspondingly modified $V_F(\lambda)$ function also passes through the intersection point at K_{cd}. However, it must be accepted that the readings of instruments that use the currently valid and the cone-fundamentally adapted efficiency functions do not match.

However, since the scatter of the real sensitivity of the human eye goes beyond the deviations between $V(\lambda)$ and $V_F(\lambda)$, a decision on cone-fundamental based photometry must be taken with caution.

To summarise, Kcd as a defining constant shows that the SI is more than just a collection of useful natural constants and provides a stable and reliable basis for international trade in particular.

Adopt Cone Fundamentals to the K_{cd} Definition

Yoshi Ohno (NIST)

CIE published the cone fundamentals sensitivities in 2006 (CIE 170-1) and then the cone-fundamental-based color matching functions and spectral luminous efficiency functions $V_F(\lambda)$ and $V_{F10}(\lambda)$ in 2015 (CIE 170-2). In recent research, these new functions have been demonstrated to be more accurate in representing human color perception. CIE is promoting discussions toward adopting these cone-fundamental functions in the future, with TC 1-98 to publish a roadmap toward basing all CIE colorimetry on cone-fundamentals, and Research Forum RF05 to promote further research on cone-fundamental based photometry. CCPR started TG16 under WG-SP and started discussions on cone fundamental-based photometry, leading to the CCPR-CIE Expert Workshop on June 3. This talk supports the direction that CIE and CCPR is currently taking to consider future adoption of cone-fundamentals for photometry.

In the current SI, the candela is defined with a fixed defining constant, K_{cd} (683 lm/W), without reference to any spectral luminous efficiency functions. Thus, only changing the $V(\lambda)$ would not require revision of the candela definition in the SI. However, changing the $V(\lambda)$ would result in change of photometric values of real lighting sources, typically about 4% to 10% for various lighting products (for the case of $V_{F10}(\lambda)$). Such changes of photometric values (like lumen rating of lamps) could be a serious problem for the industry and market.

To minimize such an impact, one of the options would be to change the value of K_{cd} (e.g., to make the candela value equal for Illuminant A). However, K_{cd} is one of the seven defining constants in the current SI, thus it would require revision of the SI, which would require a long process of discussion in CIPM. Next talk (by Gael Obein) will discuss details of this option.

If the revision of the SI is to be avoided, another idea would be to re-scale the cone-fundamental based $V(\lambda)$ functions for its peak adjusted (make it less than 1) to minimize the resulting change of photometric values. The ratio for the peak change may be determined for a representative illuminant (e.g., illuminant A), then it would have the same effect as revising the value of K_{cd}. However, there is a convention in CIE that all action spectra (including spectral luminous efficiency functions) must be normalized to 1 at peak, and this option would violate this important convention. The spectral luminous efficiency functions adopted by CCPR are all defined in the BIPM standard - Principles Governing Photometry, where $V'(\lambda)$, $V_{10}(\lambda)$, and $V_{mes}(\lambda)$ are already defined, and the consistency with these existing functions could also be a problem.

Also, note that, even if one of the above options is used, it is still inevitable that the photometric values of actual lighting products would still change by up to several percent, in the case of changing from $V(\lambda)$ to $V_{F10}(\lambda)$, as there are large variations in the ratio, depending on spectra of source.

One other possibility, if other options are all difficult, would be to adopt $V_F(\lambda)$ or $V_{F10}(\lambda)$ as currently defined by CIE (170-2), with no change of K_{cd}, then to let the users (the industry and regulators) deal with the changes of the photometric values of the products, if the changes are considered acceptable (typically, increase by 4 to 10 % with $V_{F10}(\lambda)$, more increase for higher CCT products.)

The above options and possibilities may be discussed at the CCPR-CIE Expert Workshop on June 3, then this talk will include a short summary of discussions on these points at the workshop.

Bring photometry to individuals by applying a specific K_{cd} value for each person

Gael Obein (LNE-CNAM)

Quantities related to human beings have always been an issue for the SI. In this respect, photometry and the candela can be considered a successful story.

In particular, the defining constant K_{cd} has the nice property not to privilege a given luminous quantity with respect to the other. In other words, after the redefinition there is no longer any need to introduce a base unit for photometry, as K_{cd} can be used to convert directly any radiometric quantity to the corresponding luminous quantity [Peter Blattner, Presentation to CCU, 2024].

Moreover, K_{cd} can be used from scotopic through mesopic up to photopic conditions to obtain the luminous quantity. In this way, the same unit, the candela, can be used for any of these conditions. These considerations show us how good the introduction of a defining constant related to the spectral responsivity of the eye is for photometry.

The current value of K_{cd}, although it allows for the correct quantification of the effects of optical radiation as perceived by the CIE standard observer, falls short because it quantifies the effects of radiation correctly only for this observer. In this regard, it fails in its mission to be a perceptual quantity for all other observers on the planet.

Advances in science today make it possible to consider measuring individuals' psycho-physiological parameters, which could eventually allow for the calculation of a luminous efficacy K_{cd} unique for each person. By incorporating this individual constant into the calibration of instruments, photometry would be more exact, as its metrics would better account for the perception of the individual to whom it is addressed.

Adopting such an approach would make clear the difference between physical quantities and psycho-physiological quantities. The definition of the candela could be as follows:

*The candela is defined by taking the fixed appropriate numerical value of the luminous efficacy of a monochromatic radiation at a frequency of $540 \cdot 10^{12}$ Hz to be **K_{cd},** expressed in the unit $\text{lm} \cdot \text{W}^{-1}$, with the appropriate numerical value chosen according to the individual for whom the measurement is intended.*

Go back to the definition using a source (like a platinum blackbody) instead of the spectral responsivity of the human eye

Boris Khlevnoy (VNIIOFI)

The Candela Definition of 1967: "**The candela is the luminous intensity, in the perpendicular direction, of a surface of 1 / 600 000 square metre of a black body at the temperature of freezing platinum under a pressure of 101 325 newtons per square metre**". This definition was based on using the pure platinum fixed-point blackbody. It had the advantage of high repeatability, but also had some disadvantages: relatively low for photometric applications temperature (2042 K); the crucible material (thorium oxide) was fragile, radioactive and had low emissivity; the cavity opening diameter was too small (1.5 mm), therefore the blackbody itself realised brightness but not luminous intensity, which appaired at the stage of transferring the unit to a lamp. Since 1979 fixed-point blackbodies have not been used to implement photometric units.

Recently at VNIIOFI a High-Temperature fixed-point (HTFP) blackbody based on molybdenum-carbon (δ(MoC)-C) melting fixed point with relatively large cavities (14 mm) was created at VNIIOFI. The temperature of the δ(MoC)-C blackbody was determined to be 2856.67 K with the expanded uncertainty of 0.23 K. The δ(MoC)-C blackbody is used for implementing the candela. The large cavity allows using an external aperture with diameter of at least 5 mm and, thus, realise luminous intensity directly with the blackbody. This new HTFP blackbody is a good reason to think about going back to the Candela Definition based on a fixed-point blackbody. The direct copy of the definition of 1967, but replace platinum with molybdenum-carbon, gives the following definition: "**The candela is the luminous intensity, in the perpendicular direction, of a surface of $5.0432 \cdot 10^{-8}$ square metre of a black body at the temperature of the molybdenum-carbon fixed point, $T_{\delta(\mathrm{MoC})\text{-}\mathrm{C}} = 2856.67$ K, under a pressure of 101 325 newtons per square metre**". Here, the temperature $T_{\delta(\mathrm{MoC})\text{-}\mathrm{C}}$ **= 2856.67 K** can be considered as a defining constant of the SI.

<u>Benefits</u> of such a definition: 1) The **Candela can be realised using the definition only!** The present (2019) definition does not allow this; 2) Technologies of high-temperature blackbodies are well developed; 3) Technologies of blackbody temperature measurement are well developed, which guarantees high accuracy of the candela realisation.

Disadvantages: 1) the definition is linked to the single fixed point and the single temperature as a defining constant, although there are another HTFPs, Re-C (2748 K), WC-C (3021 K), which also could be used for realising candela. 2) Fixing an exact value of a fixed-point temperature is contradictory to the *Mise en pratique – Kelvin*, which considers any fixed-point temperature as measured temperature with an uncertainty; therefore, the temperature cannot be a constant (because it should have uncertainty), and the fixed-point temperature value can be changed after more precise measurement; 3) The definition does not include the relation with the luminous efficacy and spectral luminous efficiency function.

Ideally, I would prefer to see in the definition both, the luminous efficacy K_{cd} and spectral luminous efficiency function. For instance, "The candela is the luminous intensity, in the perpendicular direction, of a surface of A square metre of a black body at the temperature of T kelvin where A and T are related by the equation

$$1\ \mathrm{cd} = \frac{A \cdot K_{\mathrm{cd}}}{V_{\mathrm{x}}(\lambda_a)} \int \frac{2hc^2}{n^2\lambda^5} \frac{V_{\mathrm{x}}(\lambda)}{\exp\left(\frac{hc}{n\lambda kT}\right) - 1} \mathrm{d}\lambda$$

where n is the refractive index of air, $V_{\mathrm{x}}(\lambda)$ – is one of the CIE spectral luminous efficiency function, λ_a = 555,017 nm and K_{cd} is luminous efficacy of monochromatic radiation of frequency 540×10^{12} Hz, equals to 683 when expressed in the unit lm 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 $\Delta\nu_{\mathrm{Cs}}$".

Proposal for the photon-based candela

Stefan Kück (PTB) and Angela Gamouras (NRC)

The present definition of the SI unit for luminous intensity, the candela, is linked to radiometric units through a scaling factor of convenience, matching current realizations to historical measurement techniques. The frequency of electromagnetic radiation at which the candela is defined is based on the human perception of light, a visual quantity that can vary from observer to observer, which generally limits its use to photometric applications. A redefinition of the candela based on photon number would increase its versatility and expand its use to the radiometry and quantum photonics communities.

The photon-based candela offers several advantages: It has the potential to provide a unified framework for quantifying light across different wavelengths and sources, enabling consistent measurements and terminology across the fields of photometry and radiometry; it facilitates the integration of emerging technologies, such as quantum light sources and detectors, into mainstream applications by providing a standardized unit of measurement based on counting.

Similar to present realizations of radiometric and photometric units, a photon-based candela would be realized by either detector- or source-based measurement approaches. Single-photon detectors such as single-photon avalanche diodes (SPADs), superconducting nanowire single-photon detectors (SNSPDs) and transition edge sensors (TES) would still have traceability through electrical substitution methods. Some of these detector technologies have detection efficiencies approaching 100 % and could require shorter SI traceability paths to minimize measurement uncertainties. In recent years, single-photon sources based on quantum dots, single molecules, defect centers in diamond or 2D materials have undergone great scientific advances in the generation of indistinguishable photons. As single-photon source technologies mature, they will become increasingly efficient and have fully predictable photon emission rates and characteristics such as energy and polarization.

A corresponding photon-based redefinition could be a simple rewording, as the radiant intensity of 1/683 W/sr for photons with a frequency of 540×10^{12} Hz corresponds to 1/683 W/($h\nu$) photons per second per steradian. Therefore, a candela would correspond to $4.091942356\ldots \times 10^{15}$ photons per second per steradian at a frequency of 540×10^{12} Hz. This means that a nanocandela corresponds to $4.091942356\ldots \times 10^{6}$ photons per second per steradian at a frequency of 540×10^{12}, i.e. a radiant intensity, which can be easily measured using single-photon detectors like Si-SPADs, InGaAs-SPADs, TES, and SNSPDs.

A photon-based candela holds immense potential in scientific research and technological innovation. In fields such as spectroscopy and microscopy, counting light output will facilitate ground-breaking discoveries in biology, botany, and medicine. In architectural lighting, it offers unprecedented control over ambiance and aesthetics, enabling the creation of immersive environments and optimization of the energy efficiency of light sources. A photon number-based candela is also directly compatible with measurement and characterization requirements for future quantum photonic networks and computers.

Although the adoption of the photon-based candela encourages interdisciplinary collaboration, its widespread adoption is not without challenges. Technical hurdles such as cost, scalability, and compatibility with existing infrastructure must be overcome to realize its full potential.

We propose that redefining the candela based on photon number represents a crucial step forward in the evolution of light measurement. However, it is reliant on the realization of the candela, and its derived quantities, to be achieved with lower uncertainties with photon counting techniques than with current traditional methods.

Candela in the Wind: A Proposal for Three Categories of Units Within the SI

John Lehman (NIST)

Why is the candela defined as a base unit in the International System of Units (SI)? Napoleon's original metric system is supposed to be "for all times and all people," and the original candela is anything but. The answer is not so simple. What's your view of the SI? Are you a fundamentalist, a liberal, or simply indifferent? What is the minimum basis set of units to derive all others? In this talk I explore the traditional base units and defining constants established in the 2019 redefinition of the International System of Units (SI). For the next redefinition of the SI, which will probably occur after the anticipated redefinition of the second (and perhaps the candela), we propose an organizational change to improve clarity while maintaining practicality. We propose three distinct categories of units: The first category comprises the four base-measurement units: The second, meter, kilogram, and ampere. The second contains physiologically-relevant derived units. The third category contains the remaining units derived from the base units.