International Ionizing Radiation Metrology

The Role of a National Measurement Institute to Meet Challenges in Radiation Technologies

National Institute of Standards and Technology
U.S. Department of Commerce

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International Metrology in a Thimble

NIST

Precise measurements

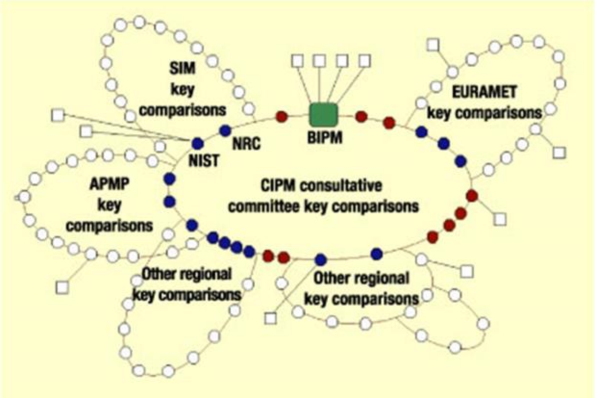
- Overcome technical barriers
- Enable world trade
- Serve as the foundation for various scientific and societal activities

Metrology

The science of *measurement*,
embracing both experimental and
theoretical determinations
at any level of *uncertainty*
in any field of science and technology.

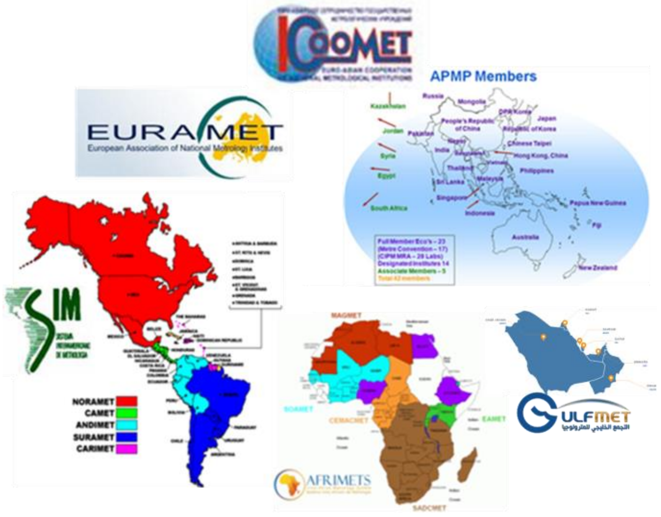
Convention du Mètre/Meter Convention

- Signed in Paris in 1875 (17 nations, now 64)
- Basis of international agreement on units of measurement



CIPM MRA (40 original signers, now 101 + 150 DIs)

- Open, transparent and comprehensive scheme
- Reliable quantitative information on comparability of national metrology services
- Technical basis for wider agreements (international trade, commerce and regulatory affairs)
- Mutual recognition of national measurement standards, certificates



"Consultative committees:" metrology in sound, length, mass, electricity/magnetism, time, thermometry, photometry, chemistry, and ionizing radiation (CCRI)

Consultative Committees on Ionizing Radiation

Section I

Section III

Section II

CCEMRI established 1958 (CCRI in 1997)

Activities

- Definitions of quantities and units
- Standards for x-ray, γ-ray, charged particle and neutron dosimetry
- Radioactivity measurement and SIR
- Advice to CIPM regarding IR standards
- Planning of international measurement comparisons

Technical support to BIPM on their ionizing radiation program

Input to CCRI Strategy

Sections I (M McEwen), II (L Karam) and III (A Zimbal)

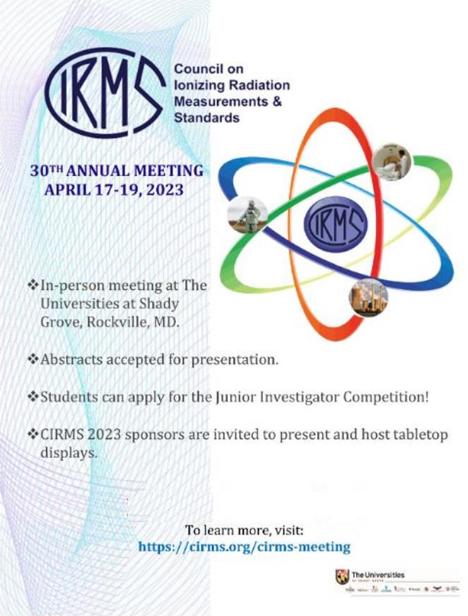
International Structure
Players, Partners and Products

Metrology not done *in vacuo*

- User and stakeholder communities (needs)
- Collaborators (technologies)
- International partners (trade)
  - Regional Metrology Organizations (RMOs)
  - SIM MWG 6 (Canada, US, Mexico, St. Kitts and Nevis, Brazil, Uruguay, Argentina, Chile)
- Measurement comparisons (techniques)
- BIPM Ionizing Radiation Department

Calibrations and measurements, testing

Certificates (supporting QA, accreditation, auditing, etc.)



United States Department of Commerce
National Institute of Standards and Technology

NVLAP®

Certificate of Accreditation to ISO/IEC 17025:2005

NVLAP LAB CODE: 200948-0

Thermodata Corporation
Whitewater, WI

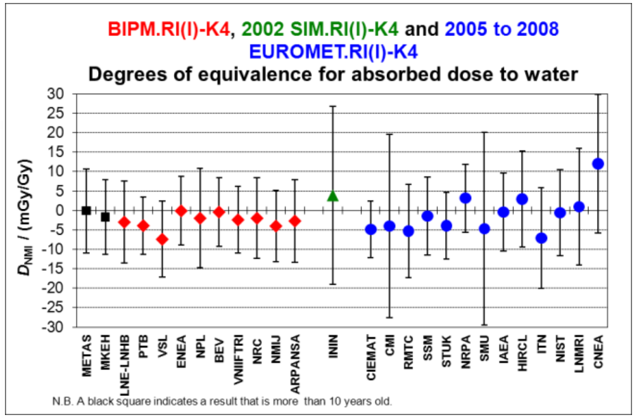
is accredited by the National Voluntary Laboratory Accreditation Program for specific services, listed on the Scope of Accreditation, for:

Calibration Laboratories

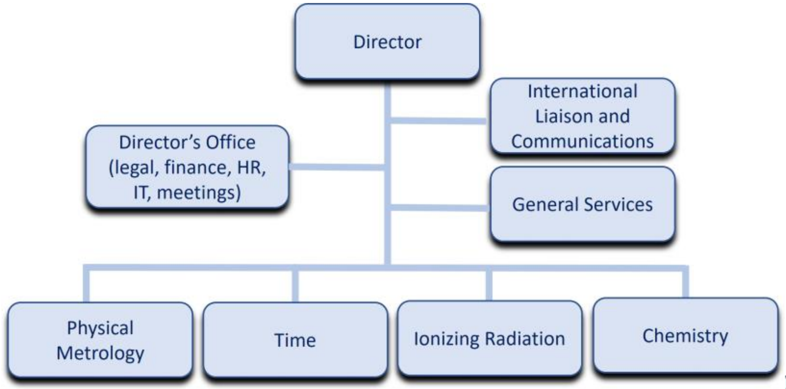
This laboratory is accredited in accordance with the recognized International Standard ISO/IEC 17025:2005. This accreditation demonstrates technical competence for a defined scope and the operation of a laboratory quality management system (refer to joint ISO-ILAC-IAF Communique dated January 2009).

2015-04-01 through 2016-03-31
Effective Dates

For the National Voluntary Laboratory Accreditation Program



The Bureau International des Poids et Mesures (BIPM)
The Hub of the Wheel



BIPM IR staff in front of the Marie Curie building

Ensuring world-wide uniformity of measurements and their traceability to the SI

Authority of the Meter Convention (diplomatic treaty)

Operations

- Consultative Committees
- Own laboratory Work
- Measurement-related research
- Comparisons, Calibrations
- Supervised by CIPM

Ionizing Radiation

- Activity
- Dosimetry

Traceability With Confidence

NIST

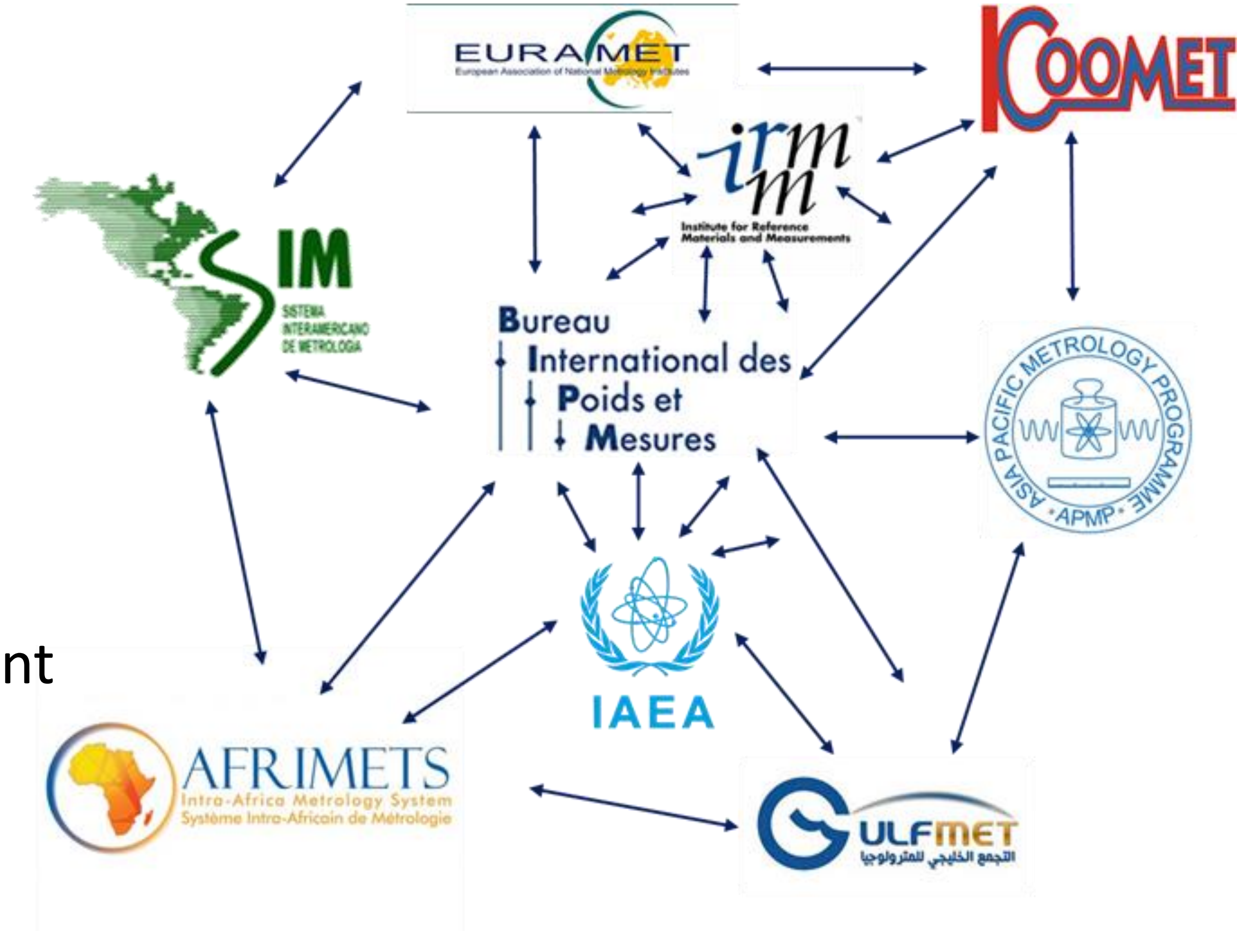
Primary methods

Traceability

- Metrology for the user communities
- Measurement assurance programs
- Sources calibrated primary methods

Watching the watchers

- NMIs and the BIPM
- CIPM MRA [calibration and measurement capability (CMC) claims]
- Comparisons



Calibration and Measurement Capabilities (CMCs)

Equivalence of Measurements

Calibration or Measurement Service			Measurand Level or Range			Measurement Conditions/Independent Variable		Expanded Uncertainty				Reference Standard used in calibration		Comparisons supporting this measurement/ calibration service	Services Administration			
Quantity	Instrument or Artifact	Instrument Type or Method	Minimum value	Maximum value	Units	Parameter	Specifications	Value	Units	Coverage factor	Level of Confidence	Standard	Source of traceability		NMI Service Identification	Service Category	NMI	Comments
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
air kerma rate	ionization chambers (other dose/rate instruments in special tests)	Calibration in air against national standard	9E-09	3E-02	$Gy\ s^{-1}$	x rays, 10 kV to 50 kV	Conform to ISO 4037/1 (2000)	1	%	2	95 %	free-air chambers	NIST	Rapport BIPM-99/05 (1999) J Res NIST 104, 135 (1999) Draft report for Metrologia Technical Supplement on BIPM.RI(I)-K2 2003	SIM-RAD-NIST-1001	1.6.4	NIST	29 W-anode beam qualities; 11 Mo-anode beam qualities; 6 Rh-anode beam qualities; see http://ts.nist.gov/ts/htdocs/230/233/calibrations/ionizing-rad/x-gamma-ray.htm#46010C for list.

- *Delineated* by quantity of interest, range of measurement, measurement conditions, uncertainty
- *Supported* by approved quality system
- *Validated* through comparisons, other published results
- *Evaluated* by sister NMIs
- Searchable on KCDB at https://www.bipm.org/kcdb/

Initially, synonymous with “Best Capability Measurement” used in accreditation

In 2008, BIPM, ILAC and RMOs agreed to a clarified, common, annotated definition:

“A CMC is a calibration and measurement capability available to customers under normal conditions

(a) as published in the BIPM key comparison database (KCDB) of the CIPM MRA; or

(b) as described in the laboratory’s scope of accreditation granted by a signatory to the ILAC arrangement”

Critical Role for Inter-NMI Comparisons

NIST

Key component of CMCs

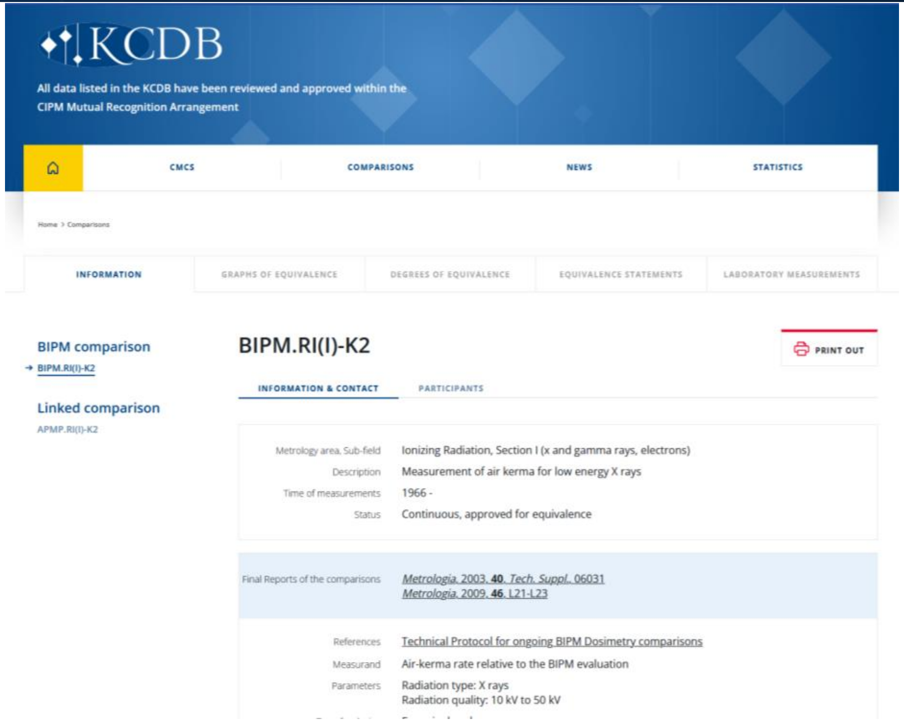
- Guidance on uncertainty expectations (uncertainty budget is crucial)
- Aid in review process
- Published results improve metrological rigor
- Key and supplementary both useful

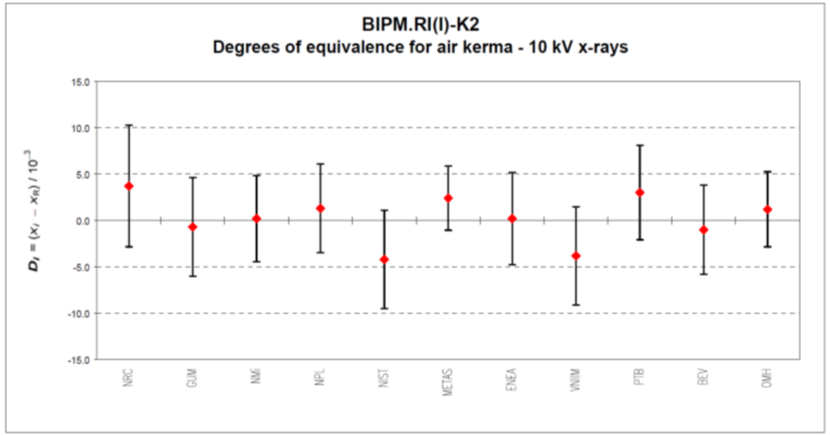
Allows improvements in methods

Contributes to planning for future comparisons (optimizing resources)

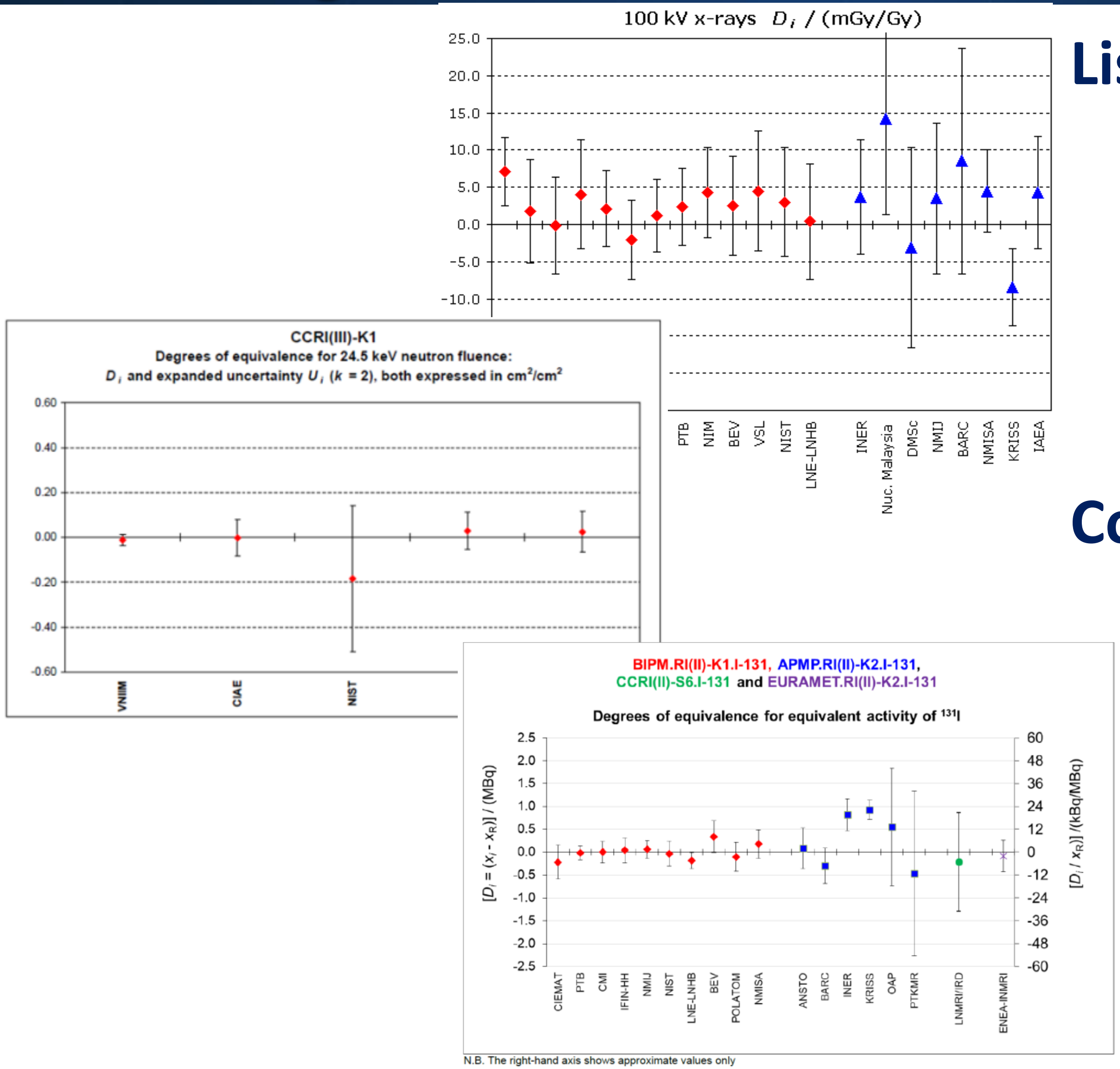
Successful participation to support “equivalency”

Find them all at https://www.bipm.org/kcdb/





Comparisons in Ionizing Radiation
Providing Confidence in Our Measurements



Listed current in the KCDB

- 69 comparisons in x and gamma rays, & electron measurements (dosimetry); many support SSDLs
- 34 comparisons in neutron measurements (fluence, fluence rate, emission rate, ambient dose, survey meter)
- 150 comparisons in measurement of radionuclides (radioactivity); issues with transporting sources
- NIST active in 110 of current and active comparisons

Comparisons in ionizing radiation

- RMO (often with participants from other RMOs), CCRI (3 sections), and BIPM
  - Absorbed dose in water, absorbed dose rate for beta, air kerma (low and med energy, Co-60), personal dose equivalent
  - A variety of neutron energies to support various applications
  - Various radionuclides for health, security, metrology, environmental protection; single and multiple
- 80 % are bilateral with BIPM
- KCs tend to repeat every 10-20 years; SC tend to be one-time exercises

Challenges for Ionizing Radiation Comparisons

And Overcoming Them

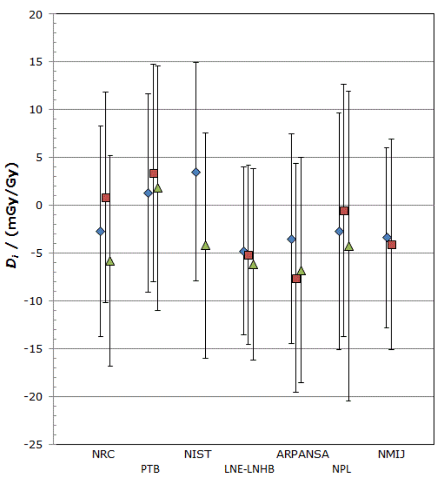
Transport (including customs), safety, and security of radioactive sources can be problematic (esp. for radioactivity, neutrons)

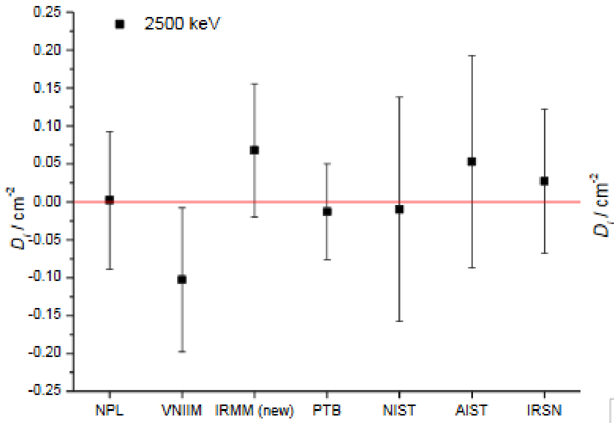
Delays (again, customs) lead to increased uncertainties due to radioactive decay (effectively reducing the amount of sample)

Some facilities are unique or near-unique

Solutions often depend on movement of the measurement *tool* rather than the *measurand*

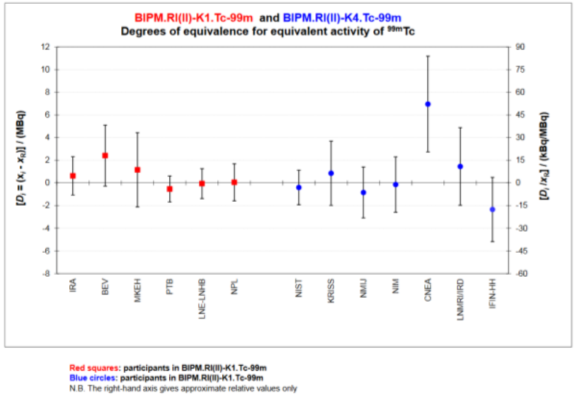
BIPM.RI(I)-K6 (absorbed dose to water from high-energy photon beams) requires access to a linear accelerator (not available at the BIPM, which transports its graphite calorimeter transfer device to other NMIs/DIs to measure the absorbed dose to water on the host's linac)





CCRI(III)-K11 (neutron fluence) required access to the right accelerator (not available at most NMIs/DIs, which brought their measurement devices to all measure the same neutron field at one accelerator)

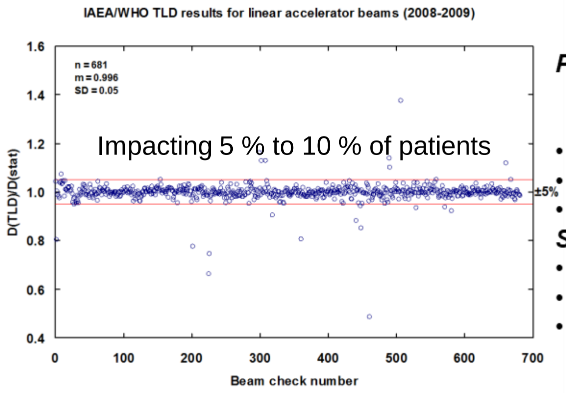
BIPM.RI(II)-K4 (activity of solution) measures very short-lived (hours) sources, with no time to ship; BIPM transports its traceable chamber to the host labs, where sources with half lives as short as 20 minutes are measured



Measurement Traceability for High-Energy Photons

Metrology to Support Clinical Accelerators

Relative uncertainties (%) for dissemination (Co-60 to LINAC)	
Traceability (Co-60) of national standard for the NMI	0.4
Long-term stability of NMI national standard	0.1
Beam quality conversion, k_Q	1.0
Combined standard uncertainty	**1.1**
Expanded uncertainty (k = 2)	**2.2**



Expanded Uncertainty at k = 2

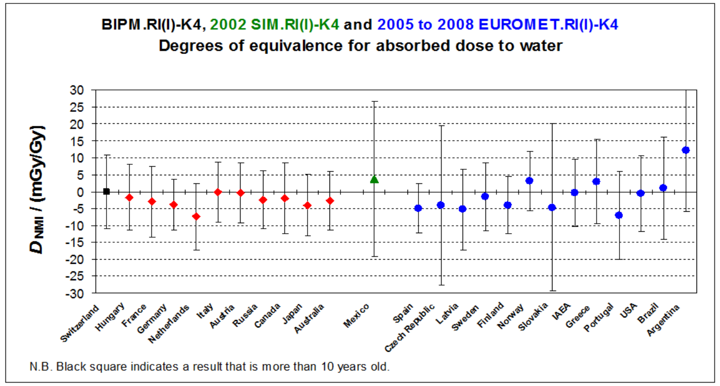
Patient doses 5 % - maximize cure; minimize complications

- *requires 3 % for the reference beam calibration, thus*
- *hospital dosimeter calibration better than 2.5 %*

- *> 5 % - investigation initiated*
- *> 10 % - incident reported*
- *> 20 % - serious incident / accident*

SI traceability

- *NMI secondary/working standard > 2 %*
- *NMI national standard > 1.5 %*
- *BIPM standard for comparisons and calibrations > 1 %*



Snapshot of degrees of equivalence for ^{60}Co absorbed dose to water from BIPM or RMO comparisons.

Measurement challenges to safety

- Variety of rad types (protons, photons, electrons)
- Dose mapping
- Dose to normal tissue control
- Dose to clinicians (radiation protection)

Metrological needs

- Absorbed dose in tissue
- Confidence in user dosimetry

Measurement standards for accelerator-based photons

- More direct for clinical beams than Co-60
- Ensures traceability (confidence, CMC claims, regulatory compliance)
- Widespread among NMIs

On-Site Comparisons at NMIs
BIPM.RI(I)-K6, Absorbed Dose to Water

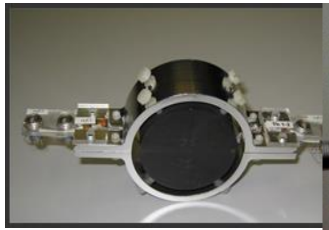
CCRI ~2005 request to BIPM

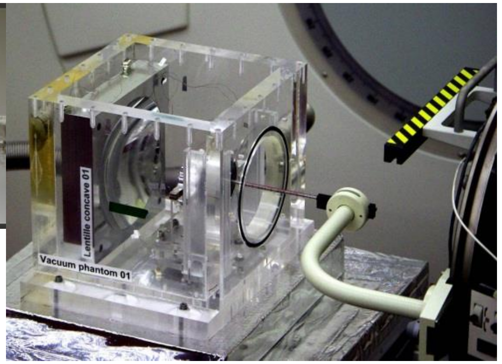
- Primary standard to establish KCRV for MV beams
- No accelerator at BIPM
- Comparison run with travelling primary standard (and BIPM staff) to validate NMI primary standard

Disadvantages

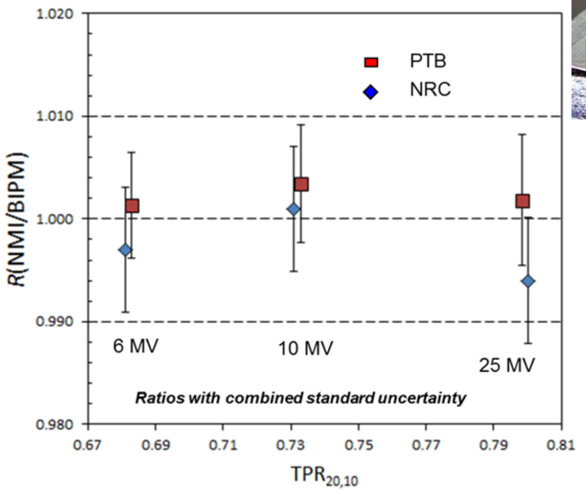
- Not all NMIs have required accelerator
- 3/4 of BIPM staff also travelled, 3 weeks at a time (reducing staff at BIPM)
- Risk of damage, loss of primary standard
- Inconsistencies among participant facilities
- No capacity to calibrate secondary standards

Since 2017, contract in place with near-by DOSEO facility for more permanent arrangement





*BIPM primary standard graphite calorimeter being set up in NIST accelerator beam (***BIPM u_i = 3.4 10^{-3} from 6 MV to 20 MV)**



Relative uncertainties (%) for dissemination (Direct LINAC)	
Comparison of NMI standard (MV) at the BIPM	0.4
Long-term stability of NMI national standard	0.1
Combined standard uncertainty	**0.4**
Expanded uncertainty (*k* = 2)	**0.8**

Comparisons Closer to the Hub

Evolution of BIPM.RI(I)-K6

measured $TPR_{20,10}$ between 0.63 (included) and 0.71 (excluded)

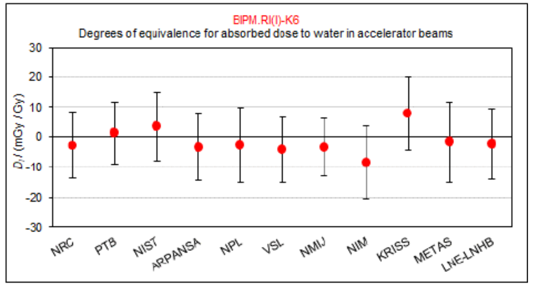


Figure 3. Graph of the degrees of equivalence with the KCRV

measured $TPR_{20,10}$ between 0.71 (included) and 0.77 (excluded)

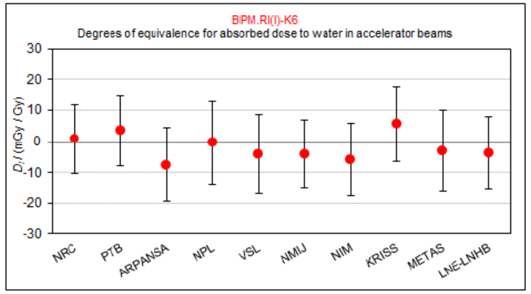
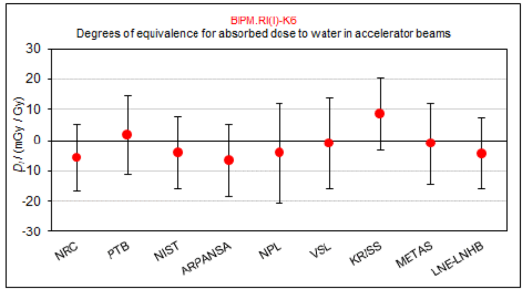


Figure 3. Graph of the degrees of equivalence with the KCRV

measured $TPR_{20,10}$ between 0.77 (included) and 0.81 (included)



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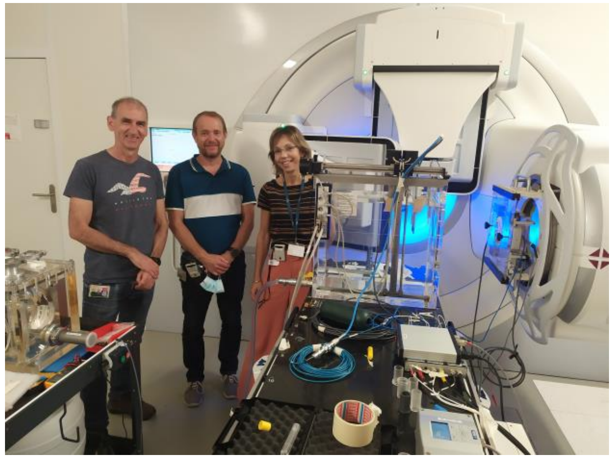


BIPM "lite" at CEA's DOSEO facility

- Fixed installation allows for improved planning and traceability for secondary standards
- Contract sets minimum number of weeks, which can be extended
- Schedule set at year start

How it works

- BIPM primary standard/equipment installed at start of each measurement period (1-2 weeks) then dismantled
- Comparisons, calibrations for the NMIs
- Improvements to the BIPM standard (R&D)

Remaining limitations

- Host facility (host schedule, LINAC mods, flexibility constraints)
- Time investment (set up/break down, QA checks, recalibration on Co-60 each time)

Measurement Traceability for Gamma-Ray Emitters
Energy, Environmental, Industrial, Medical, Security Applications

NIST

International Reference System (SIR)

- Highly stable ionization chamber
- 72 gamma-ray emitting radionuclides and counting
- Expanding to alpha and beta emitters

Comparison

- Continuous since 1976 (BIPM.RI(II)-K1.*nuclide*)
- Equivalent activity (A_e) based on IC current from one of five sealed Ra-226 sources (reference points)
  - Extremely pure
  - Sealed in 1973 in double-walled Pt-Ir tubes
  - Integrity uncertain

Challenges

- Replacement electrometers may not be adequately linear
- Regulatory pressure to remove sealed sources
- Non-source alternative need to be developed

The workhorse for radionuclide metrology, the SIR ionization chamber has served in a continuing key comparison of gamma-ray emitting radionuclides since 1976.

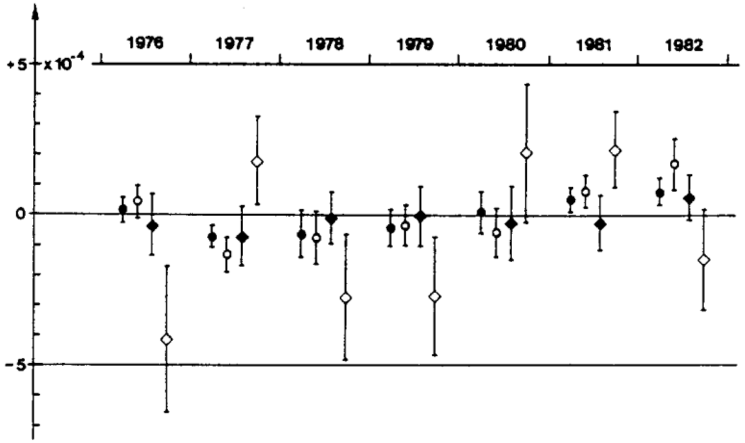


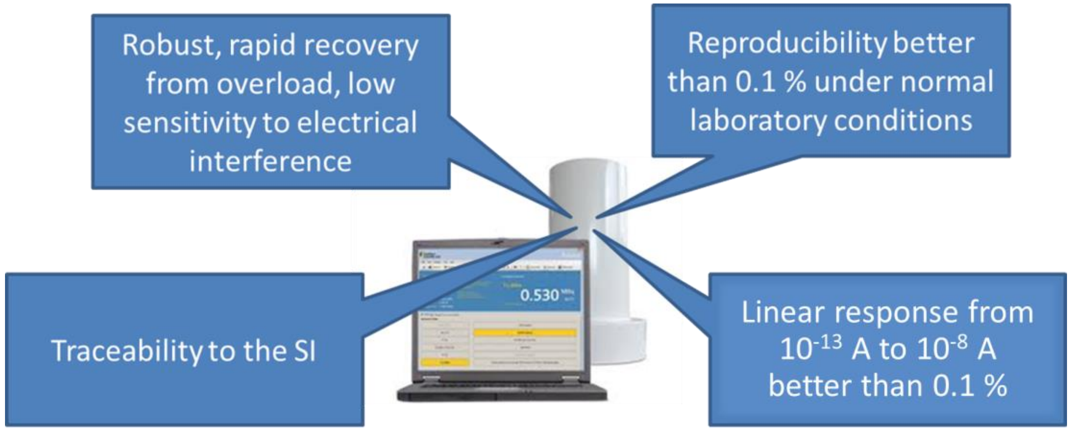
Fig. 5. Mean values and their uncertainties of periodic measurements of the ratios of reference sources, numbered 1 to 5, no. 5 being the strongest one. Relative deviations from the general mean. ● nos. 5/4, ○ 4/3, ◆ 3/2, ◇ 2/1.

Rytz, 1983

When Radium Will No Longer Serve

“Current” Status

- Electrometers (Townsend induction balance)
- Wide range of activities (i.e., current)
- Calibration based on radium source



Integrity and stability of the ionization chamber will always need to be checked periodically with a single source

Ho-166m as alternative source

- Longish half life (1132.6(39) years)
- Safer to handle than radium (no alphas)
- Production impacted by pandemic

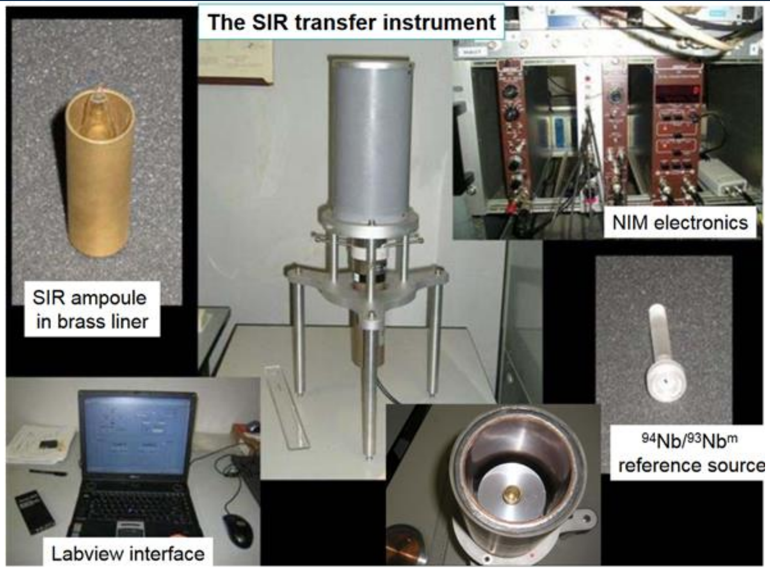
Reducing the need for sources

- Use of source is to generate a comparative current (linearity is key)
- Effort started with 2018 workshop to consider very low level electrical current measurements and standards
- New joint CCRI-CCEM task group on small current measurements for radionuclide metrology (2019)
- BIPM working on evaluating ultra stable low current amplifiers as possible solution

Expanding the Reach of the SIR
Traceability for Nuclear Medicine

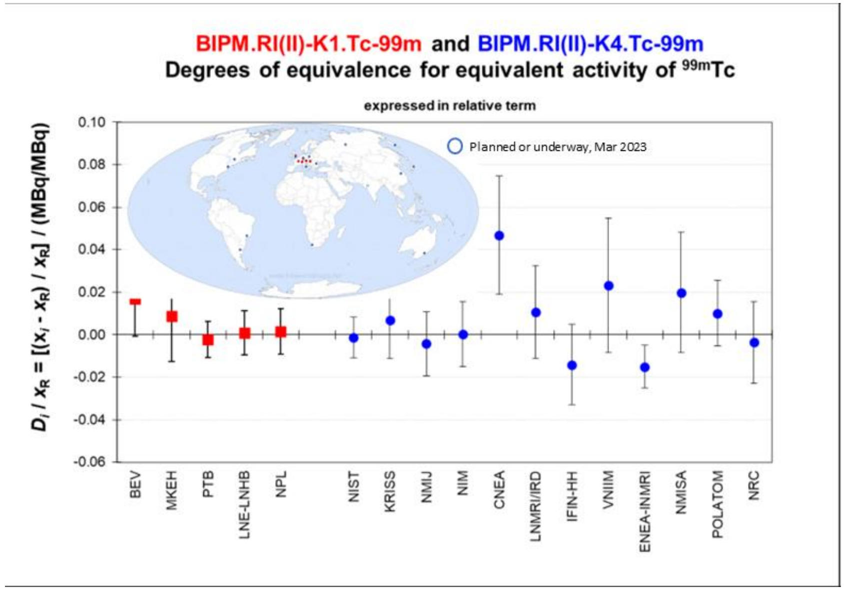
The SIRTI

- Bringing metrology for short-lived gamma-emitting radionuclides ***to*** NMIs since 2011
- “Travelling” version of the SIR (transfer instrument)
- Half lives less than a day or so
- Primary measurement at host lab



Relevant radionuclides

- Initial exercises for Tc-99m and F-18
- Evolved to C-11, Cu-64, I-123 and more to come
- Most efficient when multiple radionuclides are measured per visit

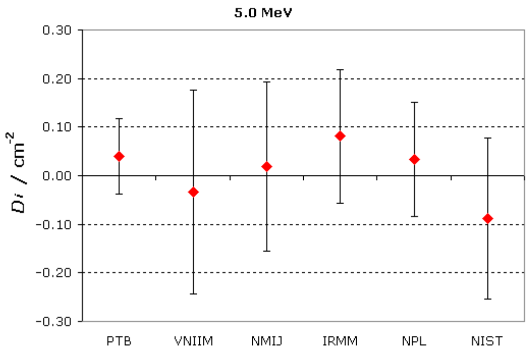


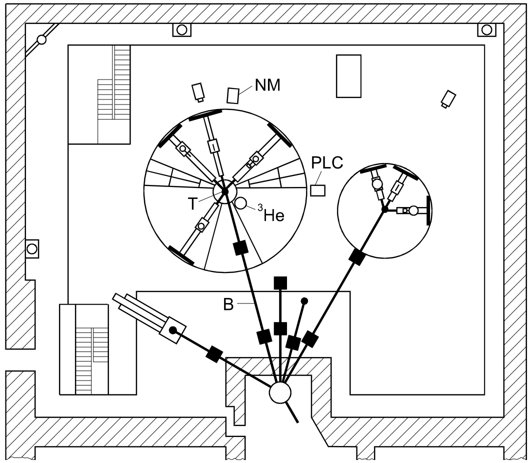
Optimizing the comparison

- Leveraged with multiple radionuclides each visit
- Pandemic impacts have accelerated a shift to remote operation (instrument sent while BIPM staff remain local and guide
- Several RMO-based systems in the works

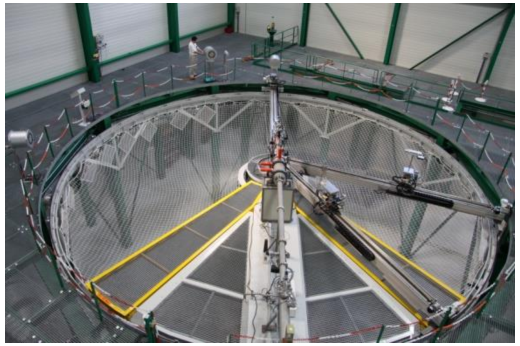
Comparisons Outside the BIPM Expertise
When NMIs Are (Mostly) on Their Own

K10 in 2001 at the PTB, Braunschweig





K11 in 2011 at the LNE-IRSN, Cadarache
- 10 participants



4 beam energies

Neutron Metrology at the BIPM

- At the BIPM until 1995 (retirement and refocus)
- Low-energy accelerator (3 MeV and 14 MeV neutrons)
- Test rig used to check ^{3}He proportional counter detectors (1992) used in comparison of neutron fluence with Bonner spheres (CCRI(III)-K1)

Responsibility for comparisons handed over to the NMIs with neutron measurement capabilities

CCRI(III) still integrated with BIPM (former chair now head of IR department)

Three general types of comparisons

- Distributed sources
- Distributed instrument (transfer device)
- Single site hosting multiple participants (accelerator-based)

Generally less frequent than in dosimetry, radioactivity

Comparison of Neutron Dose Equivalent Meters

Radiation Protection (Industry) Measurements for the Customer

Supplementary Comparisons for Neutrons

- CCRI(III)-S1 ambient dose equivalent meters (ending)
- CCRI(III)-S2 personal dose equivalent meters (started in 2022)
  - ISO neutron reference field
  - ^{252}Cf, ^{252}Cf (D_2O moderated), ^{241}Am-Be
  - DMC3000G N-detectors (MIRION Technologies)
  - PMMA or ISO water slab phantom

Importance to the user community

- Dose equivalent no longer a quantity for CMCs
- 31 CMCs for calibration of neutron personal dose equivalent have been "grandfathered"
- No recommendation in ISO 8529 parts 1-3 on method to subtract backscatter contributions of $H_p(10)$
- S2 report expected late 2025/early 2026

Set-up for CCRI(III)-S1 NIST low-scatter facility

Service Categories for Neutron Measurement CMCs

Before 2018

Quantity		Medium	Source	
1	Emission rate		1	Other
2	Emission anisotropy		2	Monoenergetic neutrons
3	Fluence		3	Thermal neutron distribution
4	Fluence rate		4	Wide energy range neutrons
5	Ambient dose equivalent		5	Cf-252 source
6	Ambient dose equivalent rate		6	Cf-252 source, D_2O moderated
7	Personal dose equivalent		7	Am-241/Be-9 source
8	Personal dose equivalent rate		8	Am-241/B source
9	Absorbed dose to water		9	Am-241/Li-7 source
10	Absorbed dose rate to water		10	Am-241/F-19 source
11	Absorbed dose to graphite			
12	Absorbed dose rate to graphite			
13	Absorbed dose to tissue			
14	Absorbed dose rate to tissue			
15	Absorbed dose to other material			
16	Absorbed dose rate to other material			

After 2018

Quantity		Medium		Source	
1	Emission rate	0	Not applicable	2	Mono-energetic neutrons
4	Fluence/rate	1	Air	3	Thermal neutron distribution
17	Absorbed dose/rate	2	Water	4	Wide energy range neutrons
		3	Tissue	11	Radionuclide sources
				12	High energy (>20 MeV) quasi-mono-energetic neutrons

Maintaining an NMI

What a New and Modernized Facility Gives NIST and the US

NIST

Old (B0017) mammography lab

New (H127-3) mammography lab

HDR brachytherapy (H108-1)

Nuclear medicine source prep (H218-2)

- Increased space to allow for expanded and additional applications
- Infrastructure improvement and reduced utility failures
- Environmental control and space for mammographic and other x-ray calibrations
- Separate facilities for source preparation, reducing risk of cross contamination and increased worker safety
- Properly shielded facility for future HDR

Disappointingly, many facilities supporting industry and radiation protection are "later"

The Punchline

Ionizing Radiation metrology is an international activity

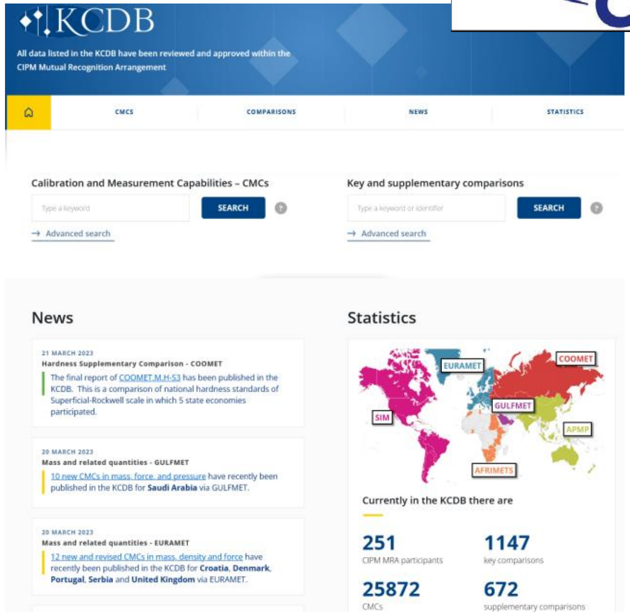
- Working to overcome technical challenges
- Enable world trade

Comparisons face their own technical challenges

- Source use
- Short half lives
- Coordination and piloting
- Relevance for customers with limited metrology resources

NMIs (like NIST) work with each other and the BIPM to meet evolving customer needs

- Metrology capabilities
- Confirmed through review of declared CMCs
- Validated through comparisons



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CCRI