Capacity Building & Knowledge Transfer

Specific Guidelines for Comparisons and CMCs in Ionizing Radiation

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Bureau International des Poids et Mesures

Outline

- Ionizing Radiation in the Economy
- Consultative Committees on Ionizing Radiation
- International Measurement Comparisons
- Claiming Capabilities (CMCs)

Capacity Building & Knowledge Transfer

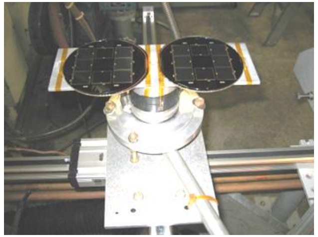
Ionizing Radiation in the Economy

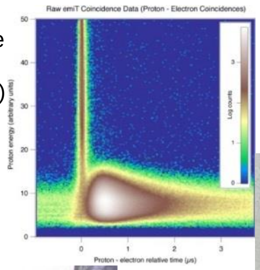
Bureau International des Poids et Mesures

Ionizing Radiation Measurements Impact Most Industries

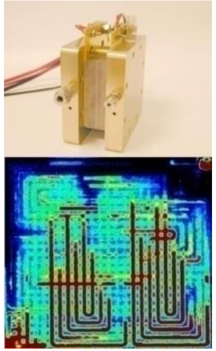
- Fundamental science and research
- Health care
- Manufacture and Industry
- Energy and the environment
- Security and protection
- International metrology
- National regulators
- Secondary calibration labs (e.g., SSDLs) and accreditation bodies

Radiation hardness testing for space-bound solar panels



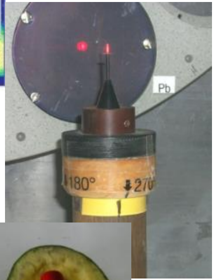


Search for time reversal violation (emiT) in polarized neutron decay

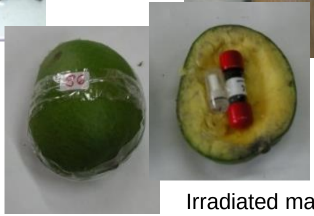


Neutron tomography to “see” inside a working fuel cell

Detectors for first responders)



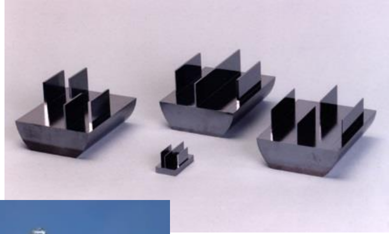
Calibration of brachytherapy seeds

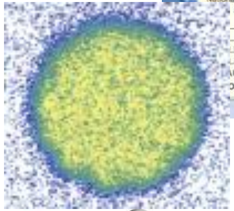
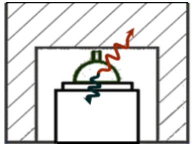
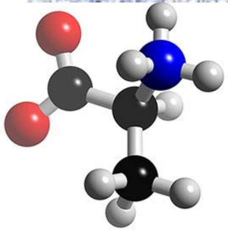
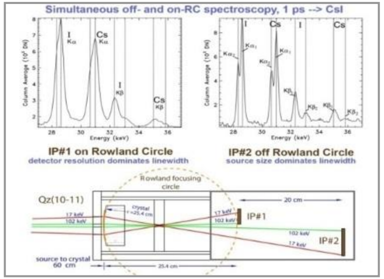


Irradiated mangos to permit importation (pest control)

Research in Measurement Science
Supporting the NMI Function

- Neutron Science
  - Interferometry
  - Neutron tomography
  - Neutron spectrometry
- Radionuclide metrology
  - Standardization and sources
  - Impurities
  - Extraction methodologies
- Radiation dosimetry
  - Accelerators
  - Materials interactions and data
  - Calorimetric methodologies

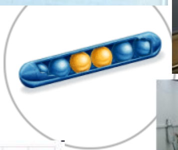


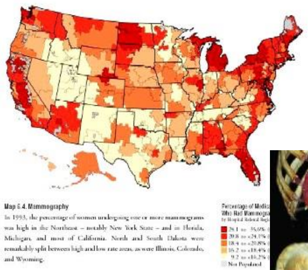






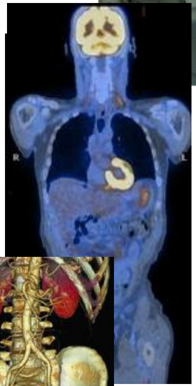
Medicine and Healthcare

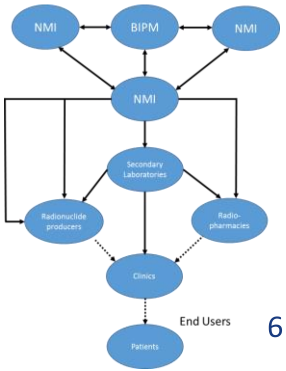
Powerhouse in the Clinic

- Theoretical dosimetry
  - Codes and models
  - Dose mapping
- Safety and Efficacy
  - Brachytherapy
  - External beam
  - X-ray calibrations (inc. mammography)
- Quantification and Pharma
  - Medical imaging (CT, PET)
  - Vaccine development
  - Traceability to meet regulations
- Innovation for Personalized Medicine
  - Nuclear medicine
  - Peptide/protein analysis







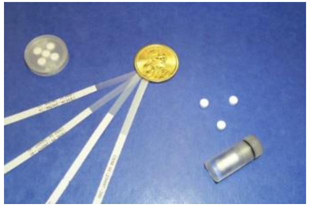


Enabling Industry and Manufacturing

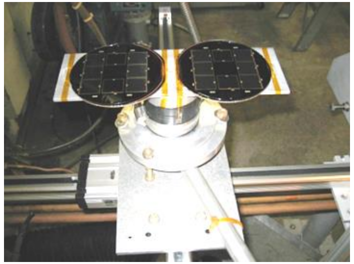
Assuring Quality

- Radiation Processing
  - Accelerator facilities
  - High dose dosimetry
  - Dosimeter materials
- Sterilization Techniques
  - Medical device sterilization
  - Measurement assurance
- Manufacturing
  - Radiation hardness testing
  - Materials processing
  - Neutron imaging (seeing inside a closed box)

Crosslinking of electrical cable surface



Alanine films & pellets

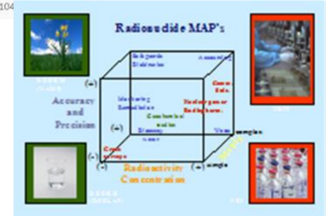


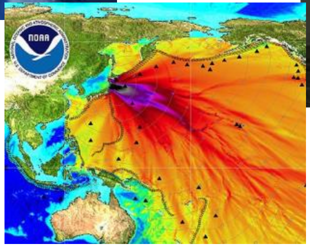
Sterilization process

Energy and Environmental Stewardship

Monitoring for Safety

- Environment and Safety
  - Nuclear power, security
  - Natural and manmade
- Expertise
  - Neutron fluence, cross section
  - Radiochemistry
  - Low and ultralow level measurements
  - Complex matrices
- Measurement assurance
  - Protocols, methods
  - Transfer dosimetry and calibrations
  - Proficiency evaluation
  - Measurement traceability



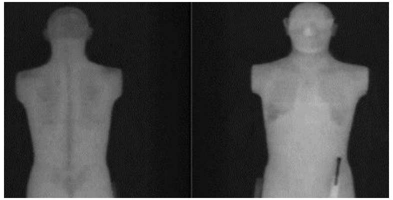


NIST low-scatter neutron calibration facility

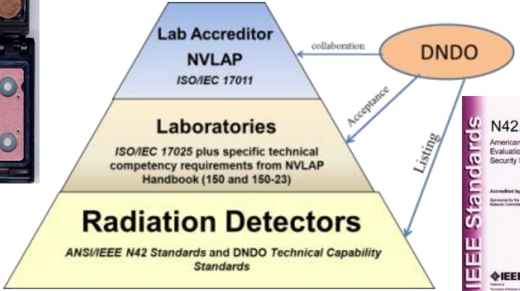
Security and Protection
Confidence and Informed Policy

- Decontamination
  - Biological organisms
  - Irradiation of Mail
- Radiation protection
  - Dosimetry
  - Calibrations
  - Measurement Assurance
- Homeland security
  - X-ray screening (explosives detection)
  - Rad/nuc and neutron (SNM) detection
  - Nuclear forensics
  - Standards and testing
  - SRMs and calibrations

TLD badges on PMMA phantom



Card with TLD chips



American National Standards Institute

Committees on Ionizing Radiation

International Metrology in Ionizing Radiation

- Potentially 193 (~membership in the UN) countries need ionizing radiation measurements (particularly for medical applications and worker protection)
- CIPM MRA lists 102 signatories (as of 25 October 2017)
- Fifty one signatories (37 with or preparing designated labs) support ionizing radiation measurements

Examples from SIM	Institute	Field of Ionizing Radiation Measurements
Argentina	CNEA*	Dosimetry, Radioactivity
Brazil	LNMRI/IRD*	Dosimetry, Radioactivity, Neutrons
Canada	NRC-INMS	Dosimetry, Radioactivity, Neutrons
Chile	CCHEN**	Awaiting designation (all services)
Mexico	ININ*	Dosimetry, Radioactivity, Neutrons
St. Kitts and Nevis	SKNBS*	Facilities to be developed (Dosimetry)
Uruguay	MIEM-LSMRI*	Dosimetry
USA	NIST	Dosimetry, Radioactivity, Neutrons

*Designated or **Planned to be Designated

Note Red text denotes measurements but no published CMCs
Faint Red denotes pending designation or facilities

Consultative Committees on Ionizing Radiation

- 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 ionizing radiation program
- Input to CCRI Strategy
- Sections I (M. McEwen), II (L. Karam) and III (V. Gressier)

Sections of the CCRI (from meetings of 2015)

CCRI Guidance Documents on Comparisons and CMCs

In Addition to the Various CIPM MRA General Documents

- Rules on Completing CMCs in Ionizing Radiation: https://www.bipm.org/utils/common/documents/jcrb/IR_CMC_Rules.pdf
- Classification of Services in Ionizing Radiation: https://kcdb.bipm.org/appendixC/RI/RI_services.pdf
- Validity of Ionizing Radiation Comparisons under the auspices of the CIPM MRA: https://www.bipm.org/utils/common/pdf/CC/CCRI/CCRI_Validity_of_IR_Comparisons.pdf
- Special Issues of *Metrologia*, esp. Vol. 52 (#3, 2015) on *Uncertainties in Radionuclide Metrology*
- CCRI publications, including guidance and strategy documents: https://www.bipm.org/en/committees/cc/ccri/publications-cc.html

Services in Ionizing Radiation

Current State (since 2000)

- Expertise
- Facilities
  - Primary
  - Secondary
- Meeting regulations
- Measurement traceability
- Working with RMO and NMIs

Branch	Quantity	Medium	Source	Radionuclide
1 Dosimetry	1 Absorbed dose/rate to air 2 Absorbed dose/rate to water 3 Absorbed dose/rate to graphite 4 Absorbed dose/rate to tissue 5 Absorbed dose/rate to other materials 6 Air kerma/rate 7 Reference air kerma rate 8 Ambient dose equivalent/rate 9 Directional dose equivalent/rate 10 Personal dose equivalent/rate, penetrating 11 Personal dose equivalent/rate, superficial 12 Air kerma length product 13 Air kerma area product 14 X-ray tube voltage		1 Other 2 Electrons 3 Beta radiation 4 X-ray, 10 kV to 50 kV 5 X-ray, 50 kV to 420 kV 6 Photons, high energy 7 Co-60 8 Cs-137 9 Ir-192 10 Am-241 11 Co-57 12 I-125 13 Pd-103	
2 Radio-activity	1 Activity 2 Activity per unit mass 3 Activity per unit area 4 Activity per unit volume 5 Surface emission rate 6 Surface emission rate per unit area 7 Emission rate per unit solid angle 8 Emission rate 9 Efficiency of γ-ray spectrometers (vs energy) 10 Efficiency of ionization chambers 11 Efficiency of contamination monitors	1 Other 2 Gas 3 Liquid 4 Solid 5 Aerosol 6 Ref. material: other 7 Ref. material: foods 8 Ref. material: water 9 Ref. material: biological materials 10 Ref. material: soils/sediments 11 Ref. material: flora 12 Ref. material: building materials	1 Single-radionuclide source 2 Multi-radionuclide source 3 Kx-rays	Xx-00
3 Neutron Measurements	1 Emission rate 2 Emission anisotropy 3 Fluence 4 Fluence rate 5 Ambient dose equivalent 6 Ambient dose equivalent rate 7 Personal dose equivalent 8 Personal dose equivalent rate 9 Absorbed dose to water 10 Absorbed dose rate to water 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		1 Other 2 Monoenergetic neutrons 3 Thermal neutron distribution 4 Wide energy range neutrons 5 Cf-252 source 6 Cf-252 source, D_2O moderated 7 Am-241/Be-9 source 8 Am-241/B source 9 Am-241/Li-7 source 10 Am-241/F-19 source	

Services in Ionizing Radiation

Proposed by SIM (2017)

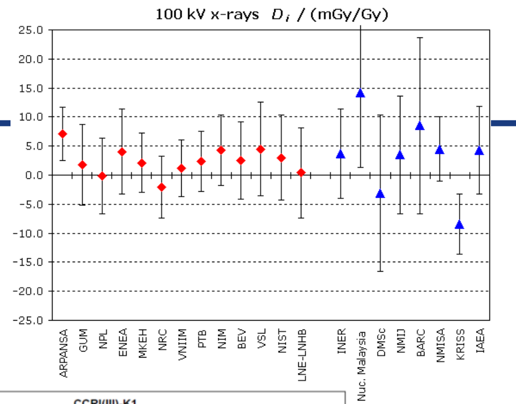
Branch	Quantity	Medium	Source	Radionuclide
1 Dosimetry	1 Absorbed dose/rate 2 Kerma/rate 3 Reference kerma rate 4 Ambient dose equivalent/rate 5 Directional dose equivalent/rate 6 Personal dose equivalent/rate 7 Kerma length product 8 Kerma area product 9 X-ray tube voltage	1 Other material 2 Air 3 Water 4 Graphite 5 Tissue: superficial 6 Tissue: penetrating	1 Other 2 Electrons 3 Beta radiation 4 X-ray, 10 kV to 50 kV 5 X-ray, 50 kV to 420 kV 6 Photons, high energy 7 Co-60 8 Cs-137 9 Ir-192 10 Am-241 11 Co-57 12 I-125 13 Pd-103	
2 Radioactivity	1 Activity 2 Surface emission rate 3 Emission rate 4 Efficiency of γ-ray spectrometers (versus energy) 5 Efficiency of ionization chambers 6 Efficiency of contamination monitors	1 Other 2 Gas 3 Liquid 4 Solid 5 Aerosol 6 Reference material: other 7 Reference material: foods 8 Reference material: water 9 Reference material: biological materials 10 Reference material: soils/sediments 11 Reference material: flora 12 Reference material: building materials	1 Single-radionuclide source 2 Multi-radionuclide source 3 Kx-rays	Xx-00
3 Neutron Measurements	1 Emission rate 2 Emission anisotropy 3 Fluence/rate 4 Ambient dose equivalent/rate 5 Personal dose equivalent/rate 6 Absorbed dose/rate	1 Other material 2 Air 3 Water 4 Graphite 5 Tissue	1 Other 2 Monoenergetic neutrons 3 Thermal neutron distribution 4 Wide energy range neutrons 5 Cf-252 source 6 Cf-252 source, D_2O moderated 7 Am-241/Be-9 source 8 Am-241/B source 9 Am-241/Li-7 source 10 Am-241/F-19 source	

International measurement comparisons

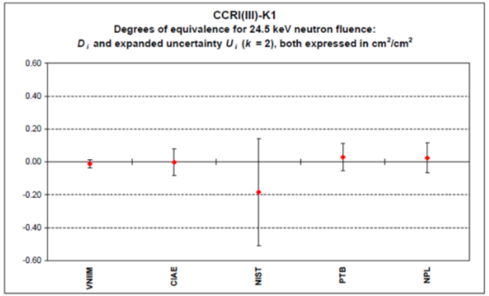
Role of Comparisons in Ionizing Radiation Metrology

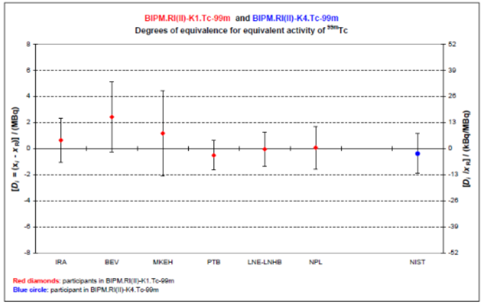
- Can be a major component of CMCs
  - Results give guidance on uncertainty expectations, useful for CMC review (neat package of results)
  - Demonstrates metrological rigor
  - Key and supplementary both serve (supplementary particularly in radioactivity because of variety of reference materials)
- Experience can lead to improvements in methods
- Planning for future comparisons can optimize resources
- Successful participation can support “equivalency”
- KCs in ionizing radiation tend to repeat every 10-15 years; SCs tend to be one-time exercises
- Opportunity to interact beyond the RMO [RMO comparisons with outside participants, CCRI (all 3 sections), and BIPM] as ionizing radiation is a smallish community

Comparisons in Ionizing Radiation
Interacting with Other NMIs/DIs



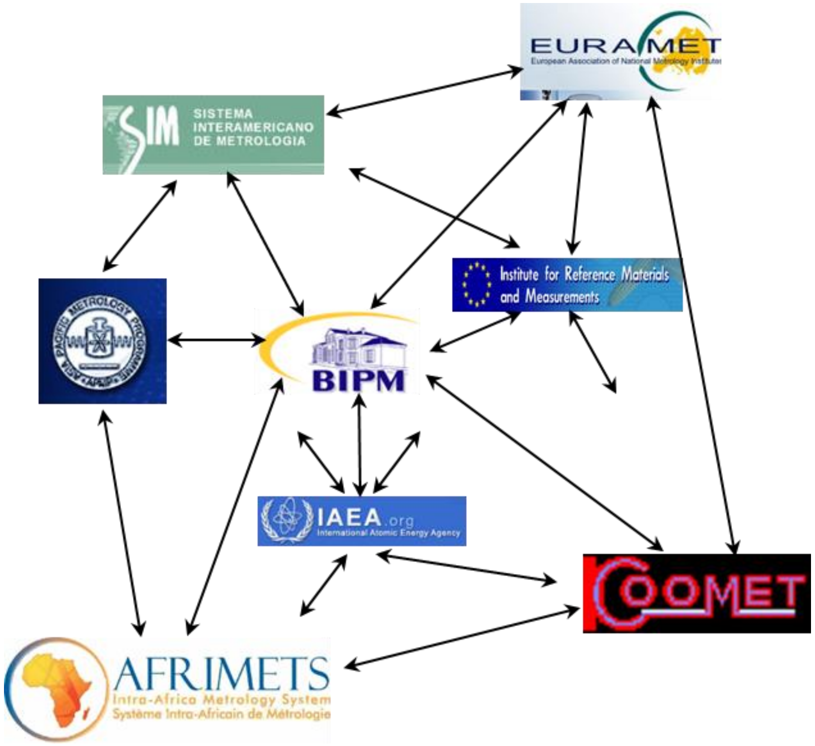
- Currently listed in the KCDB
  - 62 comparisons in x and gamma rays, & electron measurements (dosimetry); many support SSDLs
  - 29 comparisons in neutron measurements (fluence, fluence rate, emission rate, ambient dose, survey meter)
  - 140 comparisons in measurement of radionuclides (radioactivity); issues with transporting sources
- Comparisons in ionizing radiation include
  - RMO (often with participants from other RMOs), CCRI (all 3 sections), and BIPM
    - Absorbed dose to 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
    - Variety of radionuclides for health, security, metrology, environmental protection; single and multiple
  - Many matrices (from solutions to solids to dirt)
  - KCs tend to repeat every 10-20 years; SCs tend to be one-time exercises





Choosing Comparisons
CC, RMO and Interlaboratory

- Establishing (reestablishing) capability
- Optimizing coverage of CMCs
- Meeting regulatory/legal and other stakeholder support



- Regulatory/transport controls
- Limited material
- Customs (half life issues)

Difficulties for Ionizing Radiation Metrology Comparisons

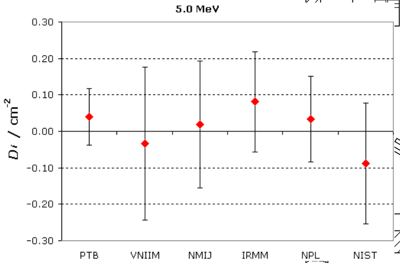
- Transport (including customs), safety, and security of radioactive sources can be problematic (esp. for radioactivity, neutrons)
- Delays (again, customs) lead to increased uncertainties due to radioactive decay (effectively reducing the amount of sample)
- Some facilities are unique or near-unique
- Solutions often depend on movement of the measurement tool rather than the measurand
  - In ***dosimetry***, 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)
  - In ***neutron*** measurements, CCRI(III)-K11 (neutron fluence) required access to a reactor (not available at most NMIs/DIs, which brought their measurement devices to all measure the same neutron field at one reactor)
  - In ***radioactivity***, 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 110 minutes are measured (see upcoming slide)

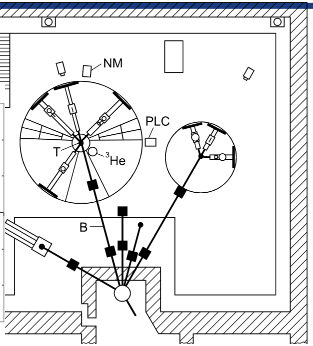
Neutron Comparisons

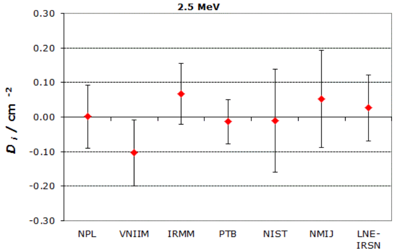
Centralized Facility to Optimize Resources

- Neutron key comparisons CCRI(III)-K11
- Status
  - 10-year comparison
  - Single-center's beams
  - Germany, Russia, EU-JRC, Japan, UK, USA, China
  - Participants' instruments in the same neutron fields
- Planned to update to replace 8 previous comparisons (including K10; 0.144 MeV, 1.2 MeV, 5.0 MeV and 14.8 MeV)
- Source-based (Cf-252) ambient dose equivalent (rate) meters in ISO Reference Fields supplementary comparison being planned

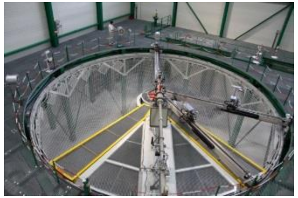
K10 in 2001 at the PTB, Braunschweig







K11 in 2011 at the LNE-IRSN, Cadarache (AMANDE accelerator)



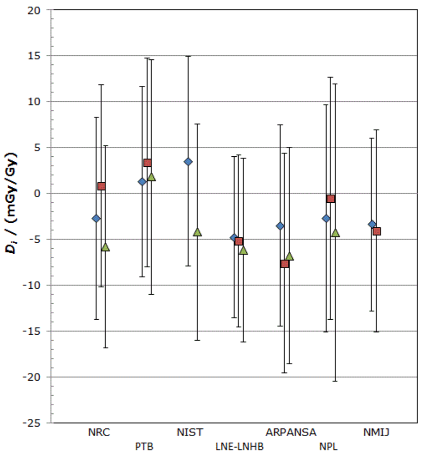
4 beam energies of neutron fluence (27.4 keV, 565 keV, 2.5 MeV, and 17 MeV)

Absorbed Dose to Water (BIPM.RI(I)-K6)

BIPM Calorimeter to NMIs

- SI traceability with Co-60
  - NMI > 1.5 % (transfer > 2 %)
  - BIPM standard for comparisons and calibrations > 1 %
- SI traceability with Photon Beams
  - More direct for clinic than Co-60
  - Ensures measurement traceability
  - Provides confidence in measurement
  - Supports CMCs
  - Satisfies legislation

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**



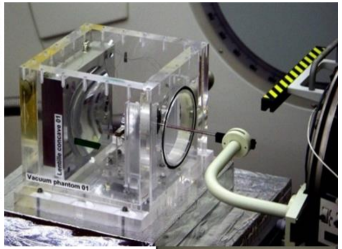
Patient doses 5 % ➡ improve cure, reduce complications

- requires 3 % for reference beam cal
- hospital dosimeter cal must be < 2.5 %
- > 5 % investigation initiated
- > 10 % incident reported
- > 20 % serious incident / accident

- Well-characterized LINAC for dissemination (not available at all NMIs)
- PTB (Germany), NIST (USA), LNE-LNHB (France), NRC (Canada), ARPANSA (Australia), METAS (Switzerland), NPL (UK), VSL (Netherlands), NMIJ AIST (Japan), MKEH (Hungary), NIM (2016)
- Next: KRISS (2017), ENEA (2018); begin re-comparisons
- Results given as ratios with a combined standard uncertainty

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**

BIPM calorimeter mounted on the patient couch of the NIST clinical accelerator

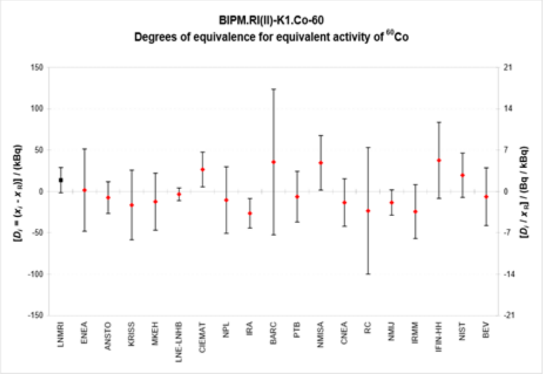


Close-up of BIPM primary standard graphite calorimeter on CLINAC (BIPM u_i = 3.4 10^{-3} from 6 to 20 MV)

The International Reference System (SIR)

Ongoing Comparisons in Radionuclide Metrology

- Continuous key comparison for gamma-ray emitters (established 1976)
- Indicated as BIPM.RI(II)-**K1**.nuclide
- Highly stable (740 ind. results, 67 nuc.)
- Lab submits source, (absolute) activity (method used), full uncertainty budget
- BIPM measures source and determines activity (based on IC current from Ra-226)
- Result is equivalent activity (A_e)
- Most recent result used in DoE
  - Often linked to other comparisons (for DoE)
  - Only SIR results go into KCRV

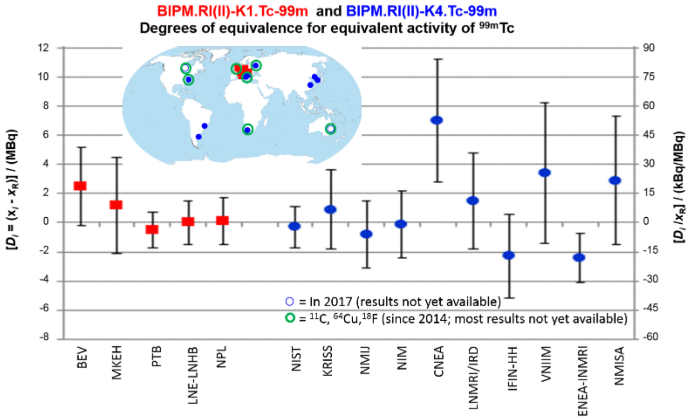


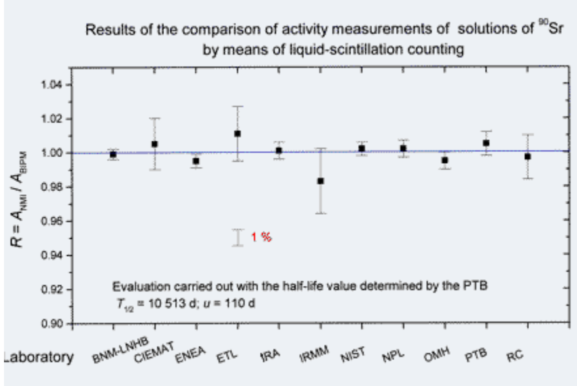
Black square dates pre 1990
Right-hand axis shows approximate values only.

Metrological Challenges

SIR for the Very Short Lived and Non-Gamma-Ray Emitters

- Increased customs controls inhibit exchange of sources
- SIR geographically fixed
- Solution proposed by CCRI(II): take instrument to the source (SIRTI)
  - Well-type Na(Tl) crystal calibrated against SIR
  - Nb-94 source to monitor stability
  - Comes with BIPM expertise ☺
  - Primary & SIRTI measurements at host
  - Initial exercise: BIPM.RI(II)-K4.Tc-99m (linked to BIPM.RI(II)-K1.Tc-99m)
  - Expanded to F-18, Na-22; eventually to C-11
- Other plans for SIR: extension to beta-particle measurements





Radionuclide Measurement Method Matrix

Shining the Light Far

- Categorized by
  - Radiation-type
  - “Primary” measurement method
- Degree of difficulty color-coded
- CMC support by comparisons results
- In general, results using one primary method can not support claims (for the same nuclide) by another method
- Secondary methods not grouped
- Uncertainties are NOT benchmarks, but are “reasonable” to expect (for CMC reviewers’ aid)

Nr	Nuclide	4P-BP/AP-PC/PP/LS-GR-NA/GH-CO/AC	4P-XR/AE-PC/PP/LS-GR-NA/GH-CO/AC	4P-AP-LS-00-00-HE	4P-BP/AP/XR/AE-NA/CS-00-00-HE	4P-PH-NA-00-00-HE	4P-BP/AP-PP-00-00-HE* (*nuclides emitting beta or alpha particles, accompanied by emission of gamma ...)	4P-XR/AE-PP-00-00-HE	SA-AP-PS-00-00-00	4P-BP-PC/PP/LS-GR-NA-CT/AT	4P-AP/BP/PH/AE/XR-LS-00-00-CN	4P-BP-LS-00-00-TD** (**pure-beta emitting nuclides only)	4P-AP/BP/PH/AE/XR-LS-00-00-TD*** (***all not pure-beta emitting nuclides)	4P-BP-PP-00-00-HE**** (****pure-beta emitting nuclides only)	4P-BP-PC-00-00-IG	??-XR/AE/PO-??-00-00-??	??-GR-??-00-00-??	4P-??-PC/PP/LS-??-NA/GH-CO/AC/CT/AT (DS)'	4P-??-LS-00-00-CN/TD (DS)'	4P-??-PP-00-00-HE (DS)'	SA-??-PS-00-00-00 (DS)'	4P-??-PC-00-00-IG (DS)'	
16	Ca-41										6					3							T
17	K-42	1					2				2												T
18	Ca-45									2	2	2		2									T
19	Sc-46	1					1.5				3												T
21	Sc-47	0.6					1.5				3												T
22	Cr-51		1								3												L
23	Mn-52		1.5								2												T
25	Fe-55							6			3		2			4							T
26	Mn-56	0.7				2	2				2		2										T
27	Co-56		0.8			0.4					3		3										T
28	Co-57		1					3			2		2										T
35	Ga-67		2			2												2	3				T
38	Se-75		2															2	3				T
39	As-76	1																	2				T
40	Br-82	1																	2				T
41	Sr-85		1																3				T
42	Kr-85														2								
43	Rb-86	1.2					2												2				T
	Rb-87																		1.4				
44	Sr-87m					3											3						
45	Y-88		0.8			1.5													1.5				G
46	Sr-89									2		1		2					0.6				T

Rationale

- Radioactivity CMCs are nuclide specific
- Currently in excess of 1000 *different* combinations (quantity/nuclide/matrix) in CMCs
- Comparison results (quantity/nuclide/matrix) valid for “limited” time (eventually will be 10 years)
- Need to cover more than 1 quantity/nuclide/matrix with each comparison
- Primary methods of radionuclide metrology can be grouped according to nuclide characteristics and behavior
- In principal, one comparison could support dozens of CMCs at a time (shining the light further)

Strategizing Radioactivity Comparisons

All Labs are Welcome to Participate

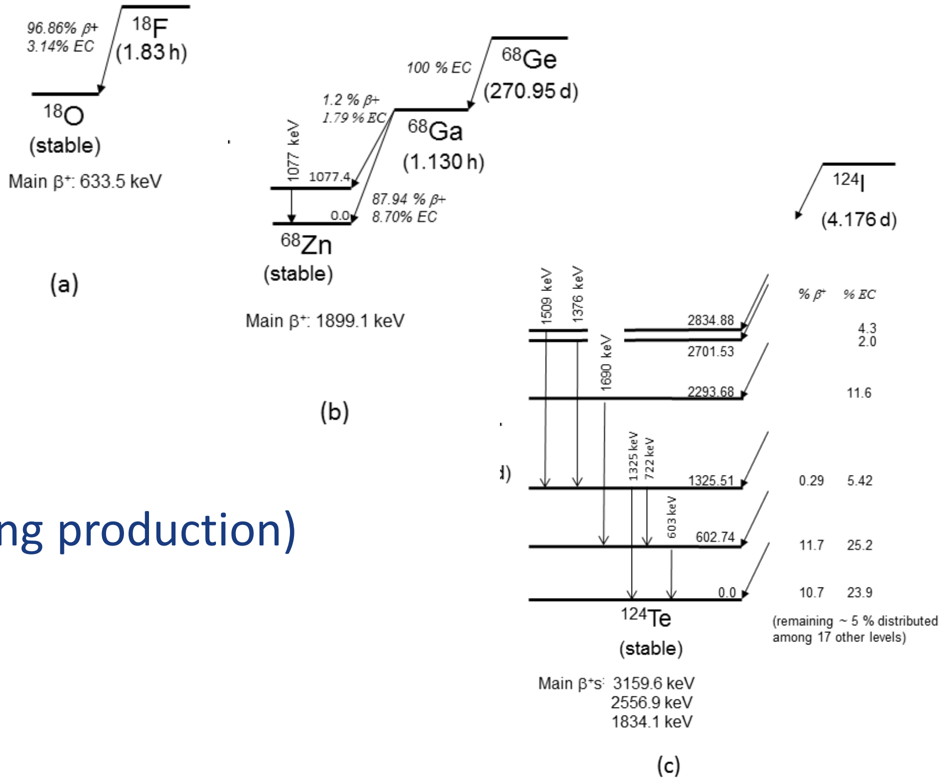
- MMM necessary, but not sufficient
  - Does not cover matrix-based sources (soil, water, biologicals, etc.)
  - Does not cover secondary methods (important for smaller and environmental labs)
- Sources
  - Sometimes become available unexpectedly (saving money)
  - Sometimes are hard to get
  - Sometimes are hard to transport
- External (stakeholder) requests may alter priorities (plan is flexible beyond 3 years)

Application	Nuclide (Example)	Year	Pilot Lab
MMM	^{222}Rn	2016	LNE-LNHB
MMM	^{223}Ra	2017	NPL
MMM	^{133}Xe	2018	LNE-LNHB
MMM	^{109}Cd	2019	BIPM
ERM (Env, Rea, Mon)	^{229}Th	2020	TBD
Medical	(^{123m}Te, ^{192}Ir,)	2021	TBD
Gas	(^{41}Ar, ^{85}Kr)	2022	TBD
Calibration/Tracers	(^{3}H, ^{51}Cr, ^{152}Eu,)	2023	TBD
Industrial	(^{60}Co, ^{65}Zn, ^{241}Am)	2024	TBD
ERM	(^{40}K, ^{210}Po, ^{235}U)	2025	TBD
Medical	(^{123m}Te, ^{192}Ir)	2026	TBD

Proposed CCRI(II) 10-year Plan for Key Comparisons (K2)

A Word on Uncertainties in IR Measurements

- Measureand-dependence
  - Decay of source
  - Impurities
  - Matrix
- Method-dependence
  - Power feed and environment
  - Instrumentation and model
  - Sample preparation
- "Darkness"
  - History of the source (including production)
  - Environmental influences
  - Laboratory practice
  - ??? (but NOT distance to Sol)



Determining the KCRV in IR Measurements
Assigning Uncertainties to a Constantly Changing Value

- Previously: arithmetic mean (presumes equal weight)

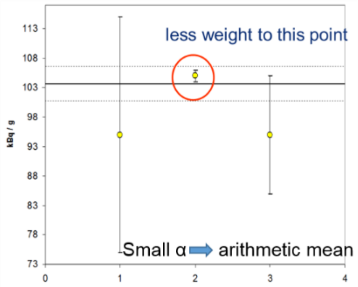
$$x_{\mathrm{ref}} = \sum_{i=1}^{N} w_i x_i$$

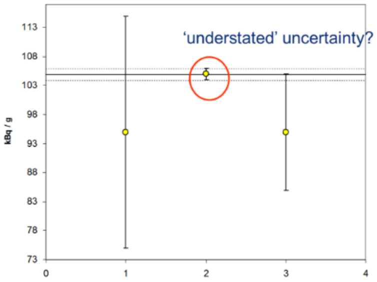
- CCRI(II): KCRV Determination Method ($KCRV_{Det}$)
  - Balance among efficiency (accuracy), robustness (resistance), and reliability (confidence)
  - Expansion from Mandel-Paule (interlab variance) [seeing the forest from a tree]
  - Full use of information in uncertainty budget
  - Transition between α=0 (arithmetic mean) & α=2 (MP)
  - Maintains scientific-technical judgment (and normalized error test)
- Gives KCRV and associated uncertainties
- Labs' native uncertainties used for Degrees of Equivalence
- CMC may have tighter uncertainty than KCRV

$$w_i = u^2(x_{\mathrm{ref}})\left[\left(\sqrt{u_i^2 + s^2}\right)^{\alpha} S^{2-\alpha}\right]^{-1}$$

$$S = \sqrt{N \cdot \max(u^2(\bar{x}), u^2(x_{\mathrm{mp}}))}$$

S = typical uncertainty per datum (max arithmetic or M-P unc)





If α=2, Mandel-Paule mean

Optimal solution for relatively small datasets

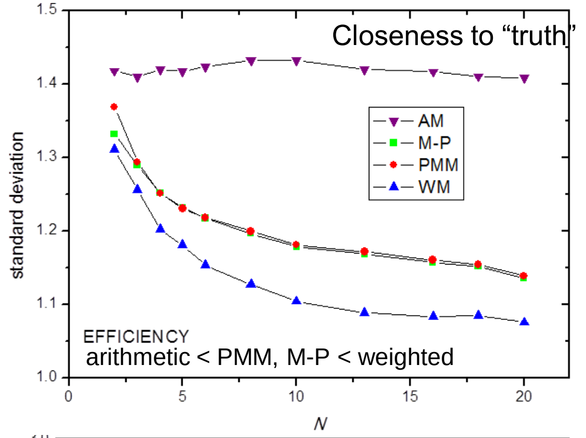
- Data quality is variable
- Measurement uncertainties are informative
- Uncertainties tend to be understated
- Data seem consistent, but are not
- Very good for "imperfect" data
- Less influenced by unknown outliers with "low" unc.

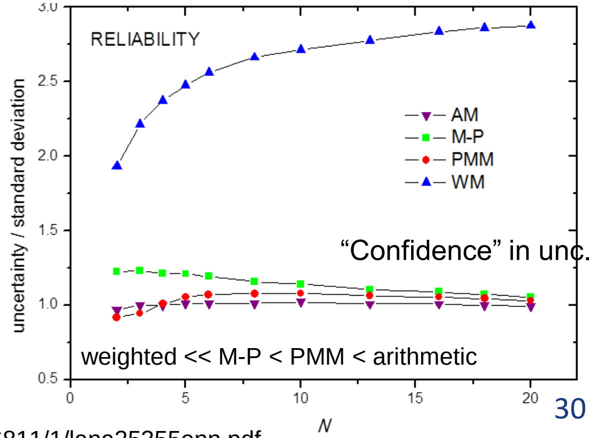
The $KCRV_{det}$ In Action*

Choosing α

Power	Reliability of Uncertainties (chance within 1 or 2 sigma)
α = 0	uncertainty variation due to error ≥ 2 times variation expected from metrological reasons
α = 0	uninformative uncertainties (arithmetic mean)
α = 2-(3/N)	informative uncertainties (trending underestimated); KCRVs
α = 2	informative uncertainties (modest error, no trend to underestimation; Mandel-Paule)
α = 2	well-defined uncertainties, consistent data (weighted mean)

Test of Estimators by Computer Simulation





*For more details, see http://publications.jrc.ec.europa.eu/repository/bitstream/111111111/26811/1/lana25355enn.pdf

Applying the $KCRV_{Det}$ to Example KCRVs

BIPM.RI(II)-K1 (SIR Results)

Radionuclide	Value $Mean_{arth}$ (old) method (NE k=4)	Value $KCRV_{det}$ (new) method (potential for wider uncertainty)
Zn-65	29 657 (67) kBq	29 694 (44) kBq
Sr-85	29 972 (42) kBq	29 975 (46) kBq
Ba-133	43 929 (67) kBq	43 906 (55) kBq
Eu-152	14 929 (27) kBq	14 919 (35) kBq
Lu-177	558.8 (2.8) MBq	560.1 (1.8) MBq

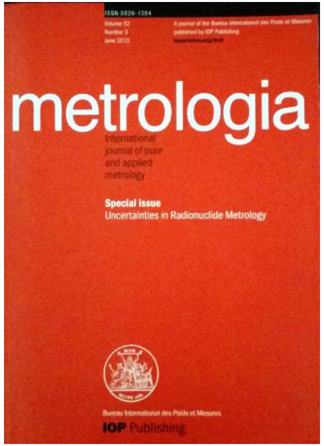
Outlier Determination

Outlier rejection based on technical grounds

CCRI(II): final arbiter to correct or exclude any data from the calculation of the KCRV

Statistical tools may be used to indicate data that are extreme

Practical Implementation of Uncertainty Analysis in Radionuclide Metrology



- *Uncertainties in Radionuclide Metrology*
- Chapters authored by expert metrologists in their field of specialization
- **52**, Number 3, June 2015 (S1-S212)
- http://iopscience.iop.org/0026-1394/52/3

CHAPTER		LEAD AUTHOR
0	Introduction	L. Karam
1	Uncertainty of nuclear counting	S. Pommé
2	Weighing uncertainties in quantitative source preparation for radionuclide metrology	V. Lourenço
3	Uncertainty of combined activity estimations	G. Ratel
4	Example of Monte Carlo uncertainty assessment in the field of radionuclide metrology	P. Cassette
5	The uncertainty of the half-life	S. Pommé
6	Uncertainties in nuclear decay data evaluations	M.-M. Bé
7	The uncertainty of counting at a defined solid angle	S. Pommé
8	Uncertainties in 4πβ–γ coincidence counting	R. Fitzgerald
9	Assessment of the uncertainty budget associated with 4πγ counting	C. Thiam
10	Uncertainty evaluation in activity measurements using ionization chambers	M.- N. Amiot
11	Uncertainties in gamma-ray spectrometry	M.- C. Lépy
12	Typical uncertainties in alpha-particle spectrometry	S. Pommé
13	Uncertainties in internal gas counting	M. P. Unterweger
14	Uncertainties in surface emission rate measurements	M. P. Unterweger
15	Uncertainty determination for activity measurements by means of the TDCR method and the CIEMAT/NIST efficiency tracing technique	K. Kossert
16	Uncertainty associated with Monte Carlo radiation transport in radionuclide metrology	F. O. Bochud
17	Determination of a reference value and its uncertainty through a power-moderated mean	S. Pommé

Implementing Comparisons in Ionizing Radiation

- "Pilot" (aka, practice) Comparisons
  - Can serve a purpose (assessing a protocol)
  - Can be expensive investment (half life, regulation on transport)
  - Rare in radioactivity and dosimetry, almost never in neutron measurements (costly)
- "On-going" comparisons support metrological infrastructure
  - SIR* to support nuclear data, efficiency curves for ionization chambers
  - Air kerma and absorbed dose to water to support regulatory requirements globally
- Special problems
  - Short sample lifetime (traveling chamber for gamma-ray-emitting sources)
  - Limited source material (sometimes, participation must be limited)
- **Do Not Be Deterred**: to pilot a comparison in ionizing radiation
  - Sketch the procedure out in advance of writing your own protocol
  - Use all available resources (protocols, guidance from experienced labs, etc.)
  - Listen to stakeholders to learn of upcoming needs

Claiming capabilities (CMCs)

CMCs in Ionizing Radiation

From KCDB, http://kcdb.bipm.org/appendixC/default.asp

- Currently over 4100 CMCs in ionizing radiation (about 1/6 of total) published
  - 1012 Dosimetry
  - 2882 Radioactivity
  - 207 Neutrons
- Generally reviewed by all RMOs
  - Wide variety of possible claims (e.g., radioactivity and reference materials) requires widely available expertise
  - Submissions reviewed to the “rules”
  - “Validation” by various mechanisms as long as they are *available to any reviewer*

earch KCDB

Calibration and Measurement Capabilities
Ionizing Radiation

Result of the search

Your selection : Dosimetry, Canada

6 summary CMC descriptions match your selection. Please select one or more CMCs, then click on 'view' to access more information.

Select	Quantity	Source	Country	NMI	RMO
☐	Absorbed dose/rate to water	Photons, high energy	Canada	NRC	SIM
☐	Absorbed dose/rate to water	Co-60	Canada	NRC	SIM
☐	Air kerma/rate	X-ray, 10 kV to 50 kV	Canada	NRC	SIM
☐	Air kerma/rate	X-ray, 50 kV to 420 kV	Canada	NRC	SIM
☐	Air kerma/rate	Co-60	Canada	NRC	SIM
☐	Air kerma/rate	Cs-137	Canada	NRC	SIM

earch KCDB

Calibration and Measurement Capabilities
Ionizing Radiation

In the CMCs uncertainty statements, the notation Q[a, b] stands for the root-sum-square of the terms between brackets: **Q[a, b] = $[a^2 + b^2]^{1/2}$**

Result of the search

Your selection : Ionizing Radiation, Neutron Measurements, Canada

Canada, NRC (National Research Council)
Complete CMCs in Ionizing Radiation for Canada (.pdf file)

Ambient dose equivalent rate. Neutron dosemeter, **8.0E-06 Sv h^{-1} to 2.0E-04 Sv h^{-1}**
Relative expanded uncertainty (k = 2, level of confidence ~95%) in %: **6**
Irradiation with calibrated neutron sources
Neutron spectrum at distance 0.3 m to 1.5 m: Am-241/Be-9 ISO 8529-3
Reference standard: Calibrated neutron source
Source of traceability: NRC
Approved on 21 October 2005
Internal NMI service identifier: SIM-RAD-NRC-3001

CMCs in Ionizing Radioactivity

Why are there ***so*** many in Radioactivity????????

2882

*Note that mixed sources will have several lines, but are counted as a single CMC

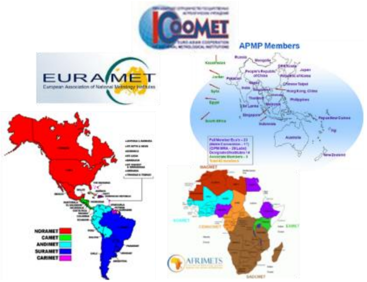
Country	RMO	CMCs in Radioactivity
South Africa	AFRIMETS	36
Australia	APMP	32
China	APMP	176
Chinese Taipei	APMP	78
Japan	APMP	217
Korea (Republic of)	APMP	189
Belarus	COOMET	30
Cuba	COOMET	63
Russian Federation	COOMET	124
Ukraine	COOMET	15
Austria	EURAMET	100
Bulgaria	EURAMET	16
Czech Republic	EURAMET	104
France	EURAMET	206
Germany	EURAMET	158
Hungary	EURAMET	78
Italy	EURAMET	13
Netherlands	EURAMET	57
Poland	EURAMET	68
Romania	EURAMET	37
Slovakia	EURAMET	37
Slovenia	EURAMET	5
Spain	EURAMET	107
Switzerland	EURAMET	21
Turkey	EURAMET	3
United Kingdom	EURAMET	116
JRC-EC	Int'l	110
Argentina	SIM	48
Brazil	SIM	96
Mexico	SIM	45
USA	SIM	497

CMCs in Radioactivity as Available on the KCDB (appendix C)

Why Are There So Many Radioactivity CMCs?

From KCDB, http://kcdb.bipm.org/appendixC/default.asp

- CMCs acknowledge customer needs
  - Each radionuclide gets its own CMC
  - Each measurement method gets its own CMC
  - “the light shines far” for comparisons, but not for CMCs (specification of radionuclide)
- Multi-nuclide source
  - Each radionuclide gets its own line
  - Entire source gets one identifier (i.e., 1 CMC)
- Comparisons organized strategically to optimize coverage



RMO	Radioactivity CMCs
SIM	686
EURAMET	1126 (+110)
COOMET	232
APMP	692
AFRIMETS	36

Ionizing Radiation, United States, NIST (National Institute of Standards and Technology) KCDB

Calibration or Measurement Service			Measurand Level or Range			Measurement Conditions/Independent Variable		Expanded Uncertainty					Reference Standard used in calibration			
Quantity	Instrument or Artifact	Instrument Type or Method	Minimum value	Maximum value	Units	Parameter	Specifications	Value	Units	Coverage factor	Level of Confidence	Is the expanded uncertainty a relative one?	Reference standard	Source of traceability	Comments	NMI Internal Service Identifier
Activity	Reference materials: biological materials, multi-nuclide source	Low-level alpha-particle spectrometry	1.0E-04	2.0E+00	Bq	Am-241	spiked synthetic feces, ~ 100 g	4	%	2	not specified	Yes	liquid scintillation counting (CIEMAT/NIST method)	NIST	Approved on 03 November 2004	SIM-RAD-NIST-2084
Activity	Reference materials: biological materials, multi-nuclide source	Low-level gamma-ray spectrometry	1.0E-02	8.0E+02	Bq	Co-60	spiked synthetic feces, ~ 100 g	4	%	2	not specified	Yes	4 pi beta-gamma-coincidence	NIST	Approved on 03 November 2004	SIM-RAD-NIST-2084
Activity	Reference materials: biological materials, multi-nuclide source	Low-level gamma-ray spectrometry	1.0E-02	8.0E+02	Bq	Cs-137	spiked synthetic feces, ~ 100 g	4	%	2	not specified	Yes	4 pi beta-gamma-anticoincidence	NIST	Approved on 03 November 2004	SIM-RAD-NIST-2084
Activity	Reference materials: biological materials, multi-nuclide source	Low-level alpha-particle spectrometry	1.0E-04	2.0E+00	Bq	Pu-238	spiked synthetic feces, ~ 100 g	4	%	2	not specified	Yes	liquid scintillation counting (CIEMAT/NIST method)	NIST	Approved on 03 November 2004	SIM-RAD-NIST-2084
Activity	Reference materials: biological materials, multi-nuclide source	Low-level alpha-particle spectrometry	1.0E-04	2.0E+00	Bq	Pu-240	spiked synthetic feces, ~ 100 g	4	%	2	not specified	Yes	liquid scintillation counting (CIEMAT/NIST method)	NIST	Approved on 03 November 2004	SIM-RAD-NIST-2084
Activity	Reference materials: biological materials, multi-nuclide source	Gas-flow proportional counter	1.0E-04	1.0E+01	Bq	Sr-90	spiked synthetic feces, ~ 100 g	4	%	2	not specified	Yes	liquid scintillation counting (CIEMAT/NIST method)	NIST	Approved on 03 November 2004	SIM-RAD-NIST-2084
Activity	Reference materials: biological materials, multi-nuclide source	Low-level alpha-particle spectrometry	1.0E-04	2.0E+00	Bq	Th-230	spiked synthetic feces, ~ 100 g	4	%	2	not specified	Yes	liquid scintillation counting (CIEMAT/NIST method)	NIST	Approved on 03 November 2004	SIM-RAD-NIST-2084

“Rules” for Acceptable CMCs
from CIPM MRA-D-04, p. 13

- Fully implemented and approved QMS
- Range and uncertainties as supported by QMS
- Documentation (infamous col. P/15) to underpin CMC claims
  - Results of key and supplementary comparisons
  - Documented results of past CC, RMO or other comparisons (including bilateral)
  - Knowledge of technical activities by other NMIs, including publications
  - On-site peer-assessment reports
  - Active participation in RMO projects
  - Other available knowledge and experience
- Note that comparisons are not always available or practical
- “International Rules for Completing the CMC Tables for Ionizing Radiation”
  - http://www.bipm.org/en/cipm-mra/cipm-mra-documents/ (“additional instructions” for RI)
  - Col. P is revised to, “Evidence supporting this measurement/calibration service”
- Interlaboratory communication is ***key***

The Good and the "Not so Good"

Preparing and Reviewing Ionizing Radiation CMCs

- Follow specific instructions
  - Determined by CCRI RMO WG on CMCs
- Any documentation to support claims
  - Available to reviewers
  - Best if peer-reviewed (publications, comparison reports, etc.) but not obligatory
  - Whatever the reviewer will accept can be valid
- Example of proper CMC in Ionizing Radiation (showing recent revisions)

International Rules for completing the CMC Tables for Ionizing Radiation

Agreed at the RMO Working Group meeting 18/9/00 and updated on 26/09/03, 24/09/04 and 21/11/06. Reviewed on 29/11/07 and no further changes made. Reviewed on 12/06/09 and corrected on 26/10/2009. Reviewed on 29 April 2010 with changes marked in red.

This document should be read together with the BIPM instructions for drawing up CMC EXCEL files contained within the JCRB Document "CMCs in the context of the CIPM MRA" (CIPM-MRA-D-04). The EXCEL templates are also available on the JCRB web site. Each submission of an EXCEL file should include a row, between the headings and the first CMC (row 3), to include the column letter A, B, etc., associated with each heading, to facilitate CMC review.

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
Calibration or Measurement Service			Measurand Level or Range			Measurement Conditions/Independent Variable		Expanded Uncertainty					Reference Standard used in calibration		List of Comparisons supporting this measurement/calibration service	Comments to be published via the KCDB	Service Administration				Feb-16
Quantity	Instrument or Artifact	Instrument Type or Method	Minimum value	Maximum value	Units	Parameter	Specifications	Value	Units	Coverage factor	Level of confidence	Is the expanded uncertainty a relative one?	Standard	Source of traceability			NMI Service Identification	Service Category	NMI	Comments	Comment on modifcation
DOSIMETRY																					
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 ray, 10 kV to 50 kV	conform to ISO 4037/1 (2000)	1	%	2	~95%	Yes	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~~; Metrologia 40, 06031 (2003) BIPM.RI(I)-K2; Metrologia 49, 06006 (2012) BIPM.RI(I)-K2	Approved on 04 November 2004	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.	Updated draft report with published reference, added most recent reference.
Air kerma rate	Ionization chambers (other dose/rate instruments in special tests)	Calibration in air against national standard	9E-09	4E-03	Gy s^{-1}	X ray, 50 kV to 300 kV	conform to ISO 4037/1 (2000)	1	%	2	~95%	Yes	free-air chambers	NIST	J Res NIST 108, 383 (2003) BIPM.RI(I)-K3	Approved on 04 November 2004	SIM-RAD-NIST-1002	1.6.5	NIST	49 W-anode beam qualities; see http://ts.nist.gov/ts/htdocs/230/233/calibrations/ionizing-rad/x-gamma-ray.htm#46010C for list.	

Example of “Not so Good”
Ionizing Radiation CMCs with Issues

SIM Comments on EURAMET CMCs (from)
Dosimetry and Activity (EURAMET.RI)

Reviewing Laboratory: NRC (Canada: Malcolm McEwen, malcolm.mcewen@nrc-cnrc.gc.ca; Raphael Galea, raphael.galea@nrc-cnrc.gc.ca), NIST (USA: Michael Mitch, michael.mitch@nist.gov; Michael Unterweger, michael.unterweger@nist.gov; Lisa Karam, lisa.karam@nist.gov), CNEA (Argentina: Margarita Saravi, saravi@cae.cnea.gov.ar; Amanda Iglicki, iglicki@cae.cnea.gov.ar)

NMI Service ID	Col.	Comment
EUR-RAD-MIRS/ /F-2,O-2-1001	O	Traceability is given as MKEH but in the reference comparison doc (EUROMET #738) the traceability is listed as BEV. Clarification is needed.
EUR-RAD-MIRS/ /F-2,O-2-1002 through 1004	P	Is “similar to” normal indication for Section I (dosimetry) CMCs (it is for Section II, radioactivity)? If not, please remove
EUR-RAD-MIRS/ /F-2,O-2-1003	I	The same uncertainty is claimed for this beam, which has a 300 times lower dose rate than the x-ray beam used in the reference comparison (#1001). It is surprising that there is no impact of this very low dose rate
EUR-RAD-MIRS/ /F-2,O-2-1004	R	Duplicate service ID in rows 8 (#1004) and 9 (#1004), but very different CMCs; please clarify. Renumbering may be needed.
EUR-RAD-MIRS/ /F-2,O-2-1004	N, O, P	Check entries in row 9– possibly should be the same as those in row 10 (#1005)
EUR-RAD-MIRS/ /F-2,O-2-1005, 1006	P	BIPM website indicates that EURAMET report 1177 is only in **Draft A** status, therefore can’t be used as proof of capability.
EUR-RAD-MIRS/ /F-2,O-2-2001, 2002	A, B, C	Although these are all (appropriately) the same CMC (but separate due to radionuclide), all the lines should contain all of the full information.

Example of “Not so Good”

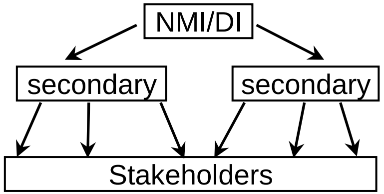
Ionizing Radiation CMCs with Issues

CIPM MRA Appendix C Calibration and Measurement Capability (CMC) Declarations

Calibration or Measurement Service			Measurand Level or Range			Measurement Conditions/Independent Variable		Expanded Uncertainty					Reference Standard used in calibration		List of Comparisons supporting this measurement/ calibration service	Administration		
Quantity/ Class	Instrument or Artifact	Instrument Type or Method	Minimum value	Maximum value	Units	Parameter	Specifications	Value	Units	Coverage Factor	Level of Confidence	Is the expanded uncertainty a relative one?	Standard	Source of traceability		NMI Service Identifier	Service Category	NMI
Personal dose equivalent rate at 10 mm depth	Dosemeter	Calibration on ISO water slab phantom against a calibrated monitor chamber free in air	0.0005	0.01	Sv/h	X-ray, 40 kV to 150 kV	ISO-4037, Narrow-spectrum Series, 50 kV to 150 kV, max. 30 mA	5	%	2	~95%	Yes	Graphite cavity ionisation chamber	MKEH	EURAMET.RI(I)-S5 (EUROMET #738)	EUR-RAD-MIRS/I[illegible]/F-2,O-2-1001	1.10.5	MIRS/IJS/F-2,O-2
Personal dose equivalent rate at 10 mm depth	Dosemeter	Calibration on ISO water slab phantom against a calibrated monitor chamber free in air	0.000001	0.003	Sv/h	Cs-137	ISO-4037 86 GBq (1. 12. 2013)	5	%	2	~95%	Yes	Graphite cavity ionisation chamber	MKEH	similar to EURAMET.RI(I)-S5 (EUROMET #738)	EUR-RAD-MIRS/I[illegible]/F-2,O-2-1002	1.10.8	MIRS/IJS/F-2,O-2
Personal dose equivalent rate at 10 mm depth	Dosemeter	Calibration on ISO water slab phantom against a calibrated monitor chamber free in air	0.000001	0.00003	Sv/h	Co-60	ISO-4037 278 MBq (1. 12. 2013)	5	%	2	~95%	Yes	Graphite cavity ionisation chamber	MKEH	similar to EURAMET.RI(I)-S5 (EUROMET #738)	EUR-RAD-MIRS/I[illegible]/F-2,O-2-1003	1.10.7	MIRS/IJS/F-2,O-2
Personal dose equivalent rate at 10 mm depth	Dosemeter	Calibration on ISO water slab phantom against a calibrated monitor chamber free in air	0.00002	0.0002	Sv/h	Am-241	ISO-4037 179 GBq (1. 12. 2013)	5	%	2	~95%	Yes	Graphite cavity ionisation chamber	MKEH	similar to EURAMET.RI(I)-S5 (EUROMET #738)	EUR-RAD-MIRS/I[illegible]/F-2,O-2-1004	1.10.10	MIRS/IJS/F-2,O-2
Air kerma rate	Dosemeter	Calibration against a calibrated monitor chamber free in air	0.0005	0.1	Gy/h	X-ray, 40 kV to 150 kV	ISO-4037, Narrow-spectrum Series, 50 kV to 150 kV, max. 30 mA	3	%	2	~95%	Yes	Graphite cavity ionisation chamber	MKEH	similar to EURAMET.RI(I)-S5 (EUROMET #738)	EUR-RAD-MIRS/I[illegible]/F-2,O-2-1004	1.6.5	MIRS/IJS/F-2,O-2
Activity per unit mass	Reference material: foods / flora	Gamma ray spectrometer, balance	20	50000	Bq kg^{-1}	K-40	Matrix bilberry, cylindrical geometry (diameter from 6 to 9 cm, height from 1 to 6 cm), density from 0,5 to 1 g cm^{-3}	7	%	2	~95%	Yes	Calibrated HPGe spectrometer, CRM (multigamma aqueous solution), set of standard weights	LNE-LNHB (Bq) MIRS (kg)	EC Interlaboratory comparison on Sr-90, Cs-137 and K-40 in wild bilberry powder, supported by CCRI(II)-S8	EUR-RAD-MIRS/I[illegible]/F-2,O-2-2002	2.2.7.2.K-40	MIRS/IJS/F-2,O-2
			1	100000	Bq kg^{-1}	Cs-137	Matrix bilberry, cylindrical geometry (diameter from 6 to 9 cm, height from 1 to 6 cm), density from 0,5 to 1 g cm^{-3}	7	%	2	~95%	Yes	Calibrated HPGe spectrometer, CRM (multigamma aqueous solution), set of standard weights	LNE-LNHB (Bq) MIRS (kg)	EC Interlaboratory comparison on Sr-90, Cs-137 and K-40 in wild bilberry powder, supported by CCRI(II)-S8	EUR-RAD-MIRS/I[illegible]/F-2,O-2-2002	2.2.7.2.Cs-137	MIRS/IJS/F-2,O-2

Reminders…

- Ionizing radiation metrology supports a vast array of industries, and legal and regulatory aims
- Measurement traceability enables international trade
- *CMCs* document capabilities to support measurement traceability
  - "Mutual Recognition" and "Equivalency" allow comparability within stated uncertainties
  - CMCs provide basis of analysis and confidence to customers
  - "Optimizing" CMCs for efficiency and practicality
- International approach (especially through *comparisons*) brings robustness and validity to measurements



Capacity Building & Knowledge Transfer

Thank You!

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Bureau International des Poids et Mesures