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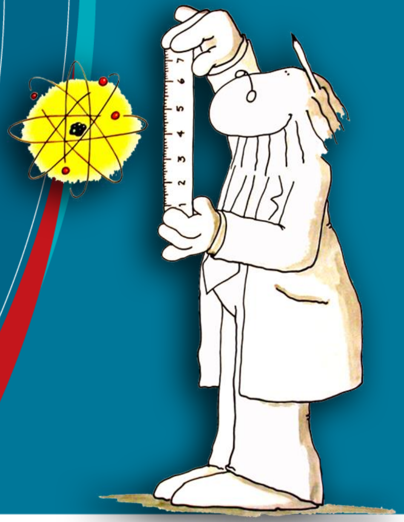
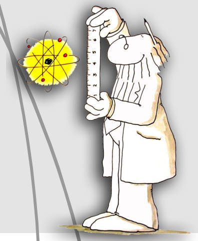
The role of radioactive sources in (inter)national ionizing radiation metrology

Malcolm McEwen, April 2021

Chair, CIPM Consultative Committee on Ionising Radiation

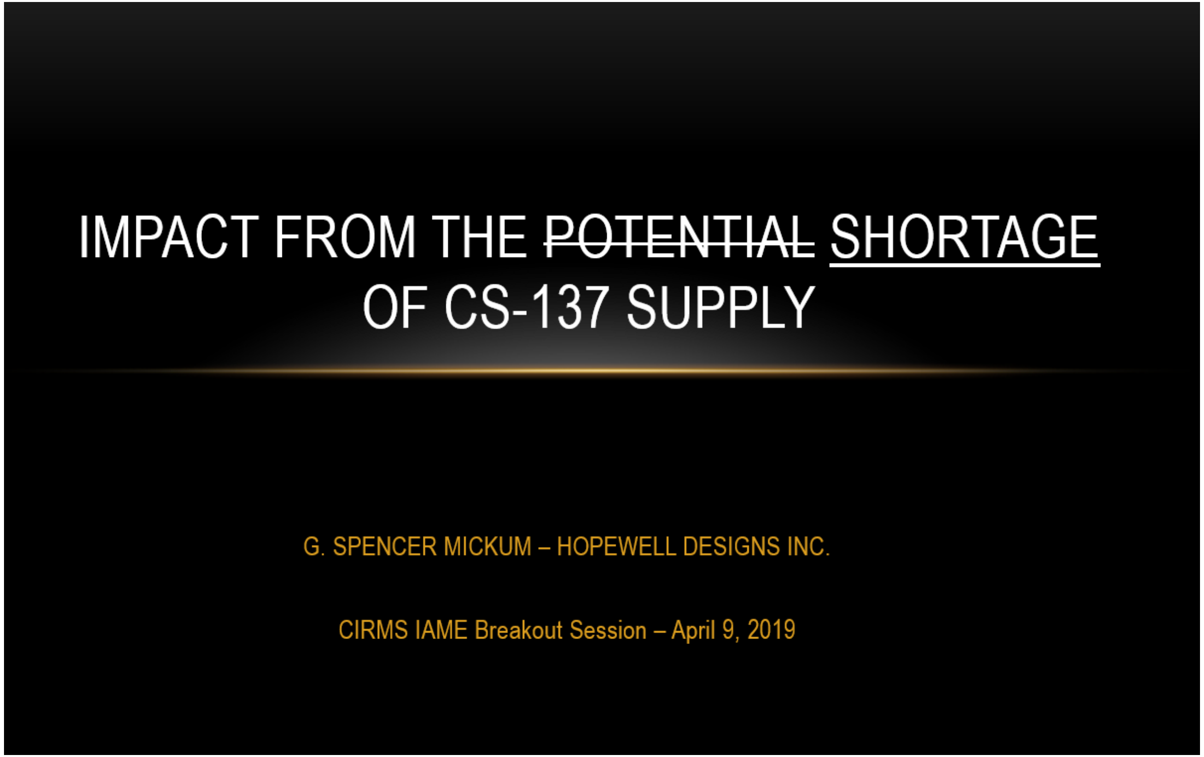


Outline

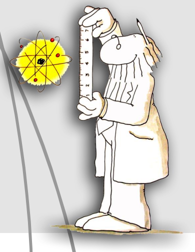


- The current situation
- Disruption to the status quo
- A brief look at alternatives
- Some ‘intermediate’ thoughts

A primary driver for this activity



Let’s start at the very beginning: Quantities and Units



Quantity	Unit
Air kerma / air kerma rate	Gy
Absorbed dose / doserate	Gy
Dose equivalent and related quantities	Sv
Absolute activity	Bq
Fluence / fluence rate	m^{-2} / $m^{-2}\ s^{-1}$

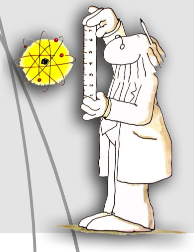
These quantities are

a) macroscopic

b) characterizations of a radioactive source/field or measures of the interaction of ionizing radiation with matter.

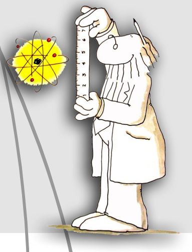
Therefore: dissemination of all these quantities requires both measurement standards and radiation fields.

So how many sources?



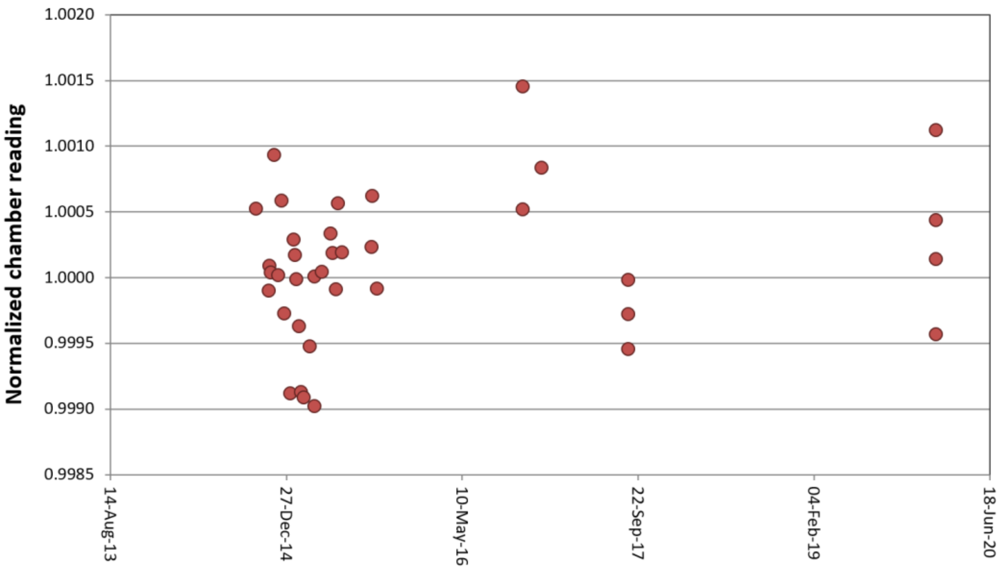
CCRI Section	Critical radionuclides	Energy	Activity
I – dosimetry of x-rays, photons, charged particles	Co-60, Cs-137, Sr-90, Ir-192, I-125, Pm-147, Pd-103, Am-241	20 keV to 1.33 MeV	Up to ~ 400 TBq
II – radionuclide metrology	Most of them!		Generally low
III – neutron measurements	Am-241 (as Am:Be), Cf-252	10 eV to ~ 2 MeV	~ 1E6 n/s

Key Activity:
Maintenance of standards



NMIs play the long game – they need reproducibility over years, ideally decades.

How do you monitor performance of measurement standards?



Sr-90 check source

Simple, self-shielded geometry

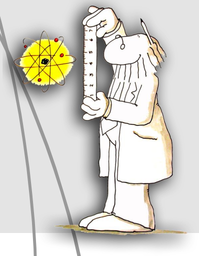
Low activity

Sources are really, really good!

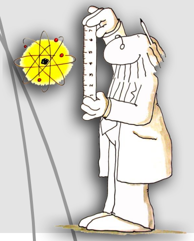
So what’s the issue?

- ORS has identified several iostopes that are priorities for elimination from widespread use
- These all have application in calibration laboratories
- Even if primary standards and calibrations are not the focus for this activity, security and/or availability issues are likely to have an impact

` **NOT JUST USA!**



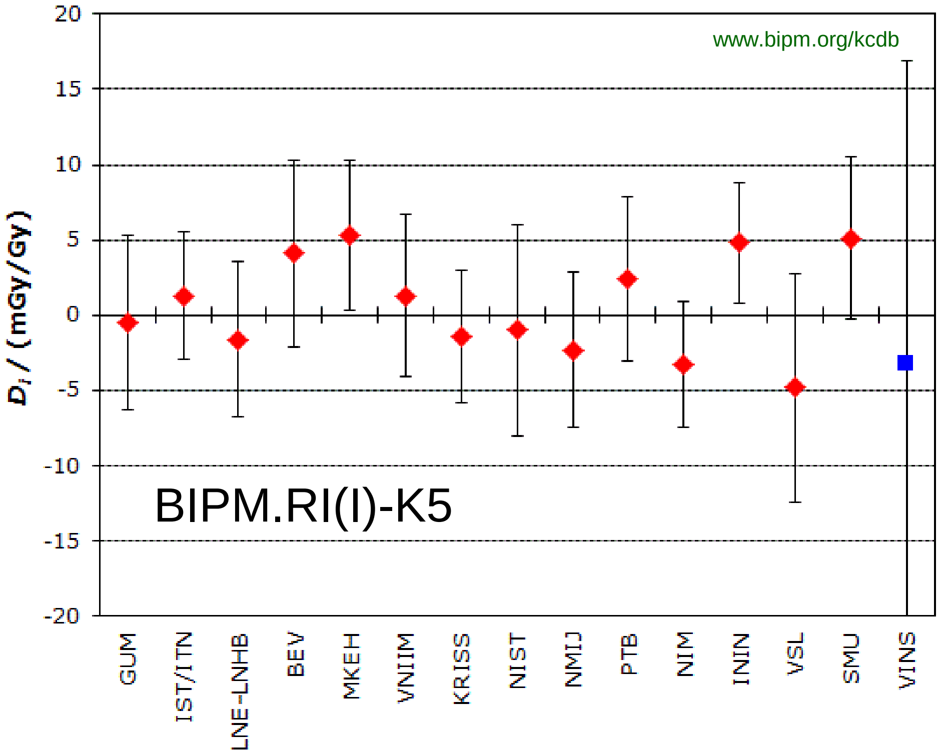
Impact?
An example: Cs-137



Cs-137 is very attractive as a reference field for radiation measurements:

- Single photon energy
- Energy is relevant to various applications
- Long half-life
- Available in suitable activity levels

An example: Cs-137

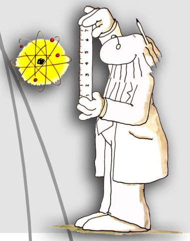


Laboratories from Europe, North America, Central America, Asia

Global acceptance and relevance

BUT it's also widely used in blood irradiators, which are being eliminated/replaced

Implications of international standardization on Cs-137



International standardization means:

1. Cs-137 is one of the agreed beams in which detectors are compared

2. Cs-137 becomes a beam that is required for detector characterization and performance specification

3. Significant knowledge and procedures built upon the assumption of the availability of Cs-137 radiation fields

INTERNATIONAL STANDARD

ISO 4037-2

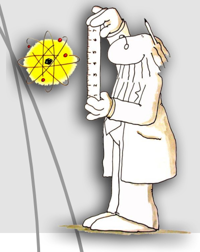
Radiological protection — X and gamma reference radiation for calibrating dosemeters and doserate meters and for determining their response as a function of photon energy —

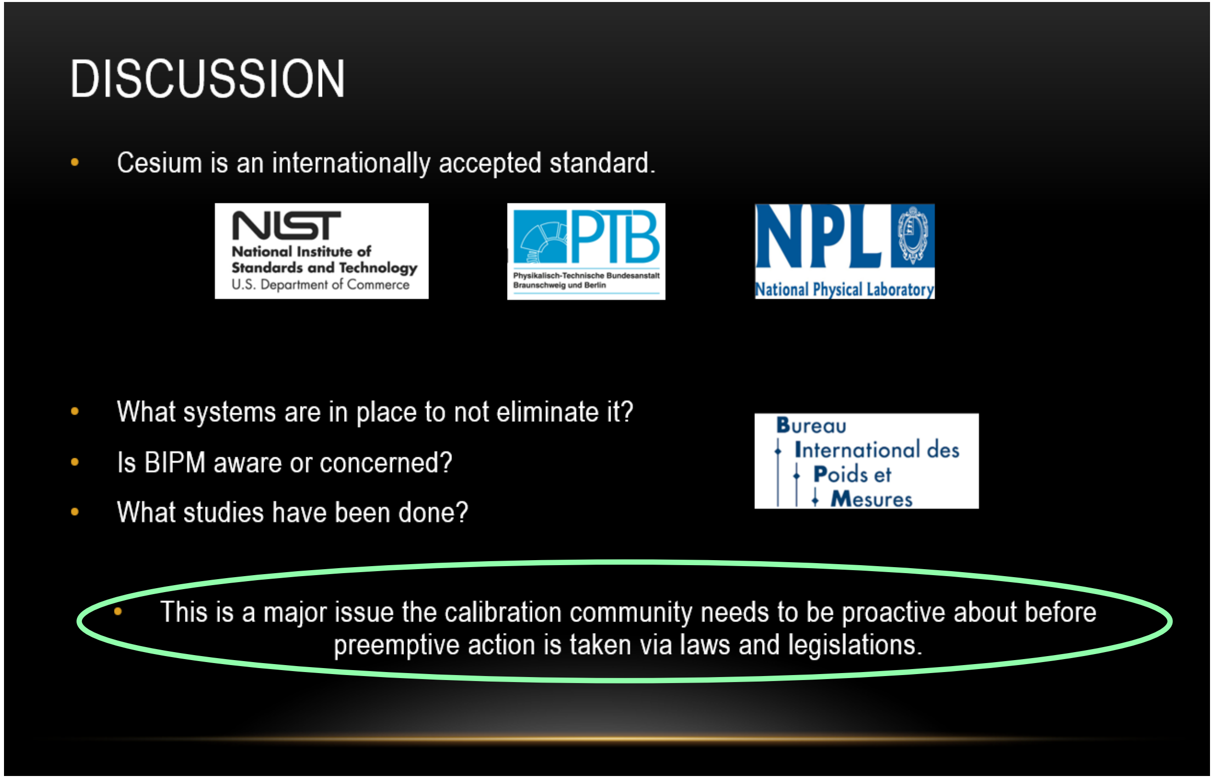
Part 2:

Dosimetry for radiation protection over the energy ranges from 8 keV to 1,3 MeV and 4 MeV to 9 MeV

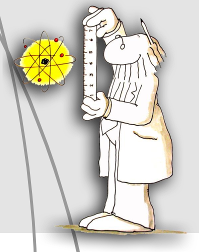
Infrastructure, specifications, procedures

Back to Spencer’s 2019 presentation





CCRI Task Group formed 2022



The CCRI is the primary forum for ionizing radiation metrology at the international level

Took us a few years but we are now engaged!

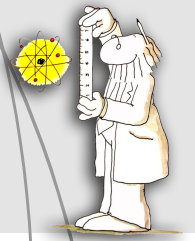
Task group draws representatives from NMIs/DIs from all three sections of CCRI (dosimetry, radioactivity, neutron measurements)

Also experts from the IAEA and the radioactive source manufacturers community

Aim: to provide a metrology-specific perspective on this topic.

Timeline: Report back to CCRI in 2023

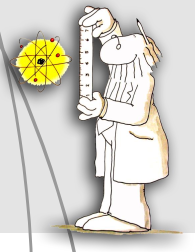
A closer look at alternatives



Within a well-integrated system change is not straightforward. Before we talk about alternatives in detail we need to look at three over-arching questions:

1) **DEFINITIONS – how to accept an alternative?**
   - **“Like-for-like” or “Fit for purpose”?**
2) **COLLATERAL – what else is impacted?**
   - **What additional costs are we willing to accept?**
3) **INERTIA – how do we implement change?**
   - **Can we make incremental changes or not?**

A closer look at some alternatives



Kilovoltage x-ray sources

Electron linear accelerators and proton accelerators

Other electrically-generated irradiation platforms

Calculational alternatives

“Zero-radiation” options

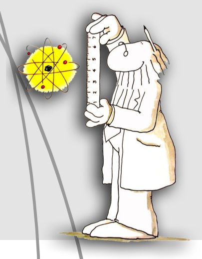
Lower-risk radioactive sources

Co-operative managed reduction (*not an alternative)*

This will focus on dosimetry standards and radiation beams

I apologize to my colleagues in radionuclide metrology and neutron measurements

A closer look at some alternatives



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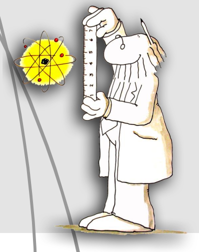
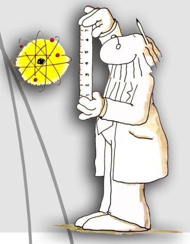
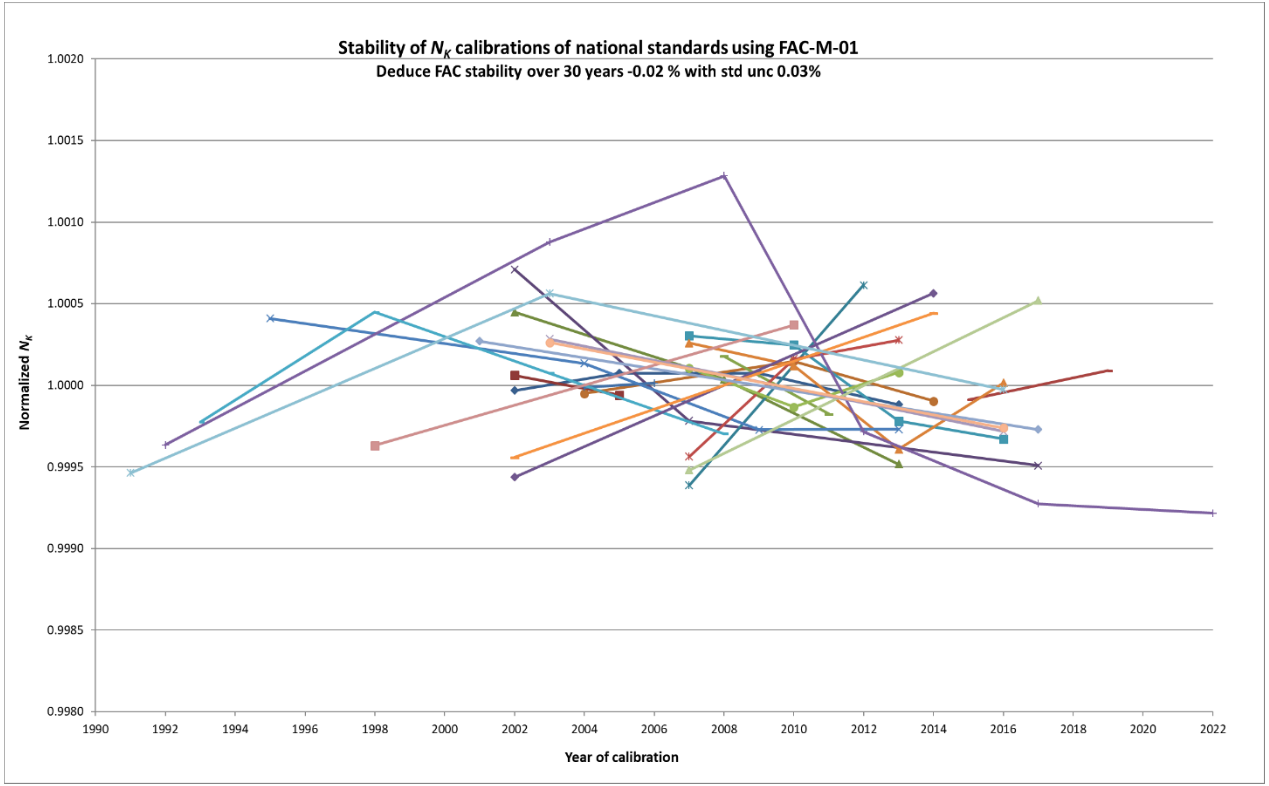
Kilovoltage x-ray sources



- ✓ kV x-ray systems have the highest level of precision reported for electrically-generated radiation
- ✓ BIPM report a typical standard deviation of repeat air-kerma determinations (days to weeks) **smaller than 0.03%.**
- ✓ Over longer timescales ≥ ten years, slow drifts in the measured air kerma rate are seen exceeding **0.1%**.
- ✓ Meta-analysis of calibration data over 30 years indicates this drift is x-ray tube, not primary standard.
- ✓ Indicates limit of performance of x-ray systems

Kilovoltage x-ray sources





- ✓ Suggests a possible candidate as a reference field
- ✓ BIPM system is specialized but can be reproduced in other laboratories

Kilovoltage x-ray sources

BUT

- Photon energy is low – maximum tube voltage ~ 300 kV, average photon energy < 150 keV. **Not representative** of most applications.
- Radiation detectors can show large energy dependencies in kV beams (depending on design)
- Interaction coefficients not precisely known at low energies – impacts theoretical conversions to higher energies

Can kV beams play a more generic reference field role?

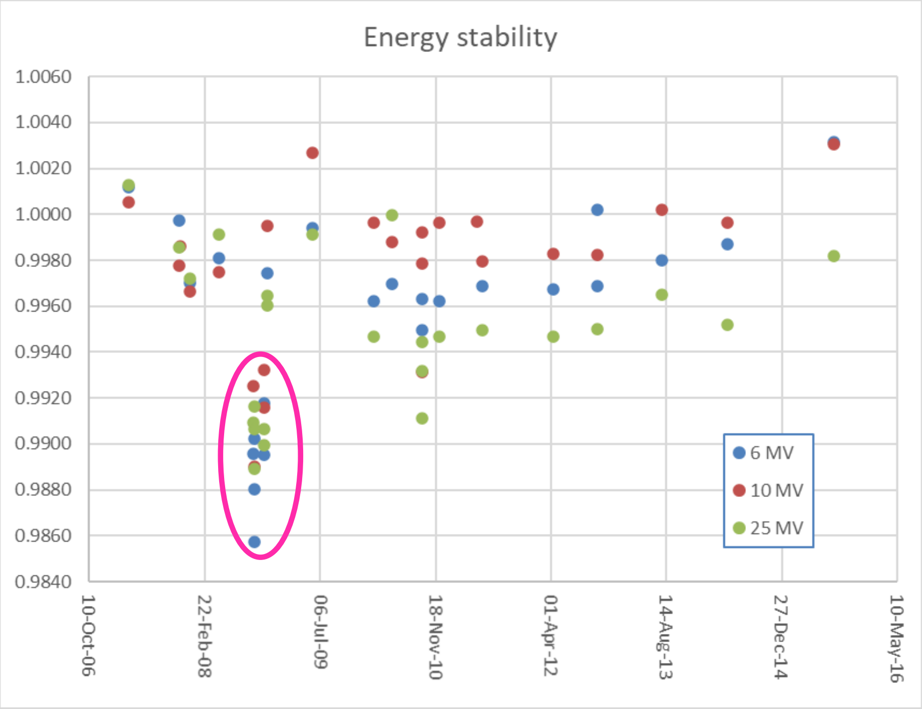
Electron linear accelerators

- ✓ Now in operation at most NMIs
- ✓ Can provide both photon and electron beams
- ✓ Energies, doserates relevant to a wide range of applications
- ✓ Many parameters can be varied in a controlled way

BIPM primary standard for clinical accelerator dosimetry

VSL water calorimeter (Netherlands) mounted on the NPL (UK) linac couch.

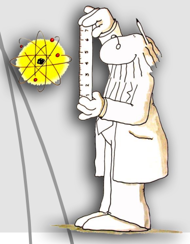
Electron linear accelerators



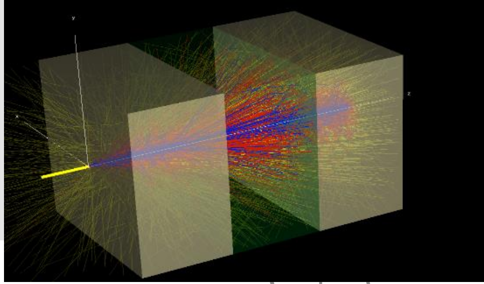
Output stability	
	Monitor cal (cGy/MU)
2017	1.0025
2019	0.9996
2020	1.0062
2021	1.0039
2022	0.9990

Not bad, but not +/- 0.1%

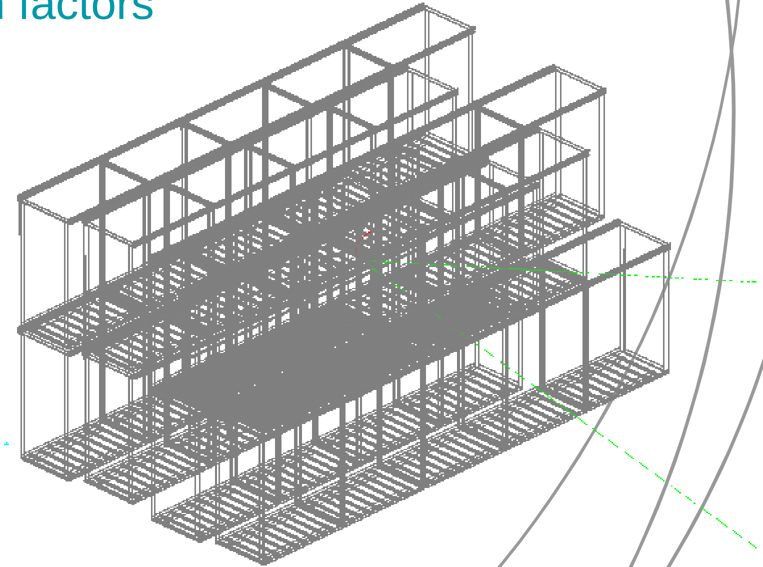
A lot of equipment to fail!



Calculational alternatives

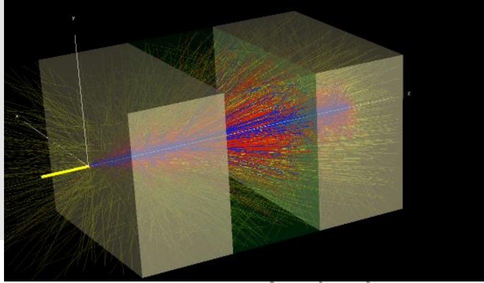


- The use of accurate, high resolution (spatial and temporal) simulations in ionizing radiation metrology has grown significantly
    - 2000 - determination of detector correction factors
    - 2023 - whole facility simulation



Courtesy Nordion

Calculational alternatives



- The use of accurate, high resolution (spatial and temporal) simulations in ionizing radiation metrology has grown significantly

  2000 - determination of detector correction factors

  2023 - whole facility simulation

- We have **consistently underestimated** the progress in computing power
- It is not unreasonable to extrapolate this trend – accurate simulations describing the complete radiation production process (e.g., from heated cathode to emitted x-ray beam) are possible on a timeframe < 10-years.
- In such a scenario, the radiation output would be determined from input measurements of non-radiation quantities.

"GPT5 – give me the dose distribution around an Am:Be neutron source of mass 5 g"

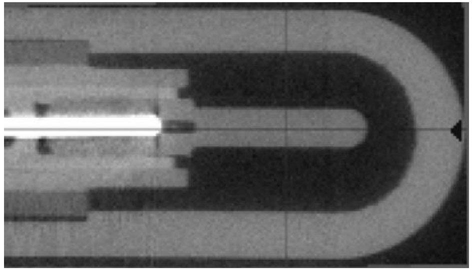
“Zero-radiation” options

Can other measurement techniques be used to replace measurements in a field from a radiation source.?

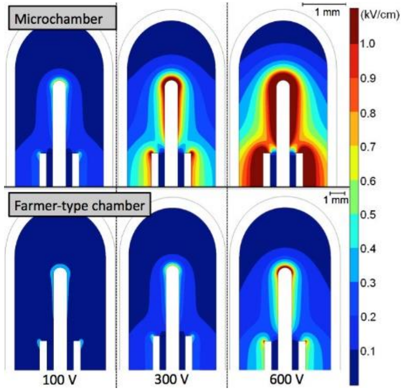
Air kerma standards are based on mechanical measurements that define the collecting mass of air. Why not all chambers?

Not a new idea – turns out I presented this idea in **2012** at CIRMS!

Micro-CT plus FE modelling of electric field can yield active chamber volume



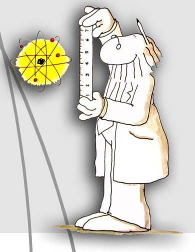
Phys. Med. Biol. 53 (2008) 5029–5043



Snow and DeWerd, *Med. Phys.* **39** (2012)

Both CT and FEM have got a lot better since then!

“Zero-radiation” options



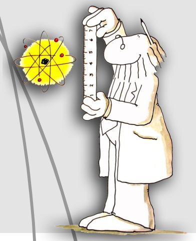
Before we get carried away, here is the conclusion from that 2012 presentation

- ➢ **An ion chamber is much more than an air volume**
- ➢ **Radiation measurements tell us about operation as well as sensitivity**
- ➢ **Only by making radiation measurements can you:**

  i. **Determine that the electrical connections are correct (polarity)**
  ii. **Confirm that components are not failing (leakage)**
  iii. **Compare response with theoretical models (recombination)**
  iv. **Really know how the device will work in its intended environment**

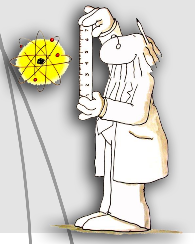
Is it really metrology if we are predicting a response?

Are there really alternatives?



Kilovoltage x-ray sources	POSSIBLE
Electron linear accelerators and proton accelerators	POOR
Other electrically-generated irradiation platforms	UNKNOWN
Calculational alternatives	POSSIBLE
“Zero-radiation” options	LIMITED
Lower-risk radioactive sources	LIMITED
Ongoing access to the sources we need	YESSSS!

Summary



Calibration laboratories may not be a focus for risk-reduction activities by regulatory bodies but capabilities are at risk.

The concept of alternatives is attractive but there is no clear replacement as a reference radiation field for ionizing radiation metrology

Electrically generated sources could play a role but need better performance or enhanced operation

Simulations will increasingly be used but barriers remain – fundamental data, absolute accuracy, applicability

There are opportunities for research!

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THANK YOU

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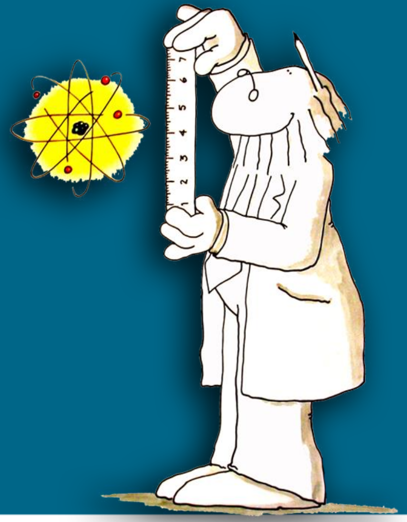
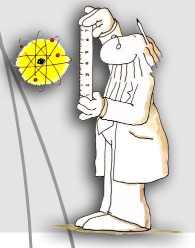
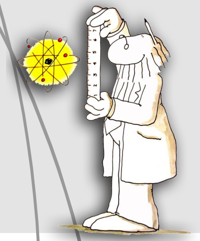


Lower-risk radioactive sources



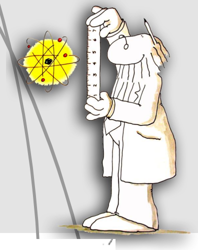
- Is it worth considering replacing something higher risk (e.g., CsCl powder, Ra-226) with something lower risk (e.g., vitrified Cs-137 sources, Hm-166*).
- The challenge in this is partnering with organizations with the expertise and enthusiasm to develop such alternative source types or configurations.
- Likely to have limited applicability

Co-operative managed reduction



- A non-alternative where NMIs huddle together sharing what decaying sources they still have while riling against the external forces that deny them access to what they need.
- Not a good scenario!
- However, the concept of source use without replacement may have a role.
- Measurement techniques would need to be developed and validated to allow accurate metrology at lower source activities potentially below a level of concern for regulatory bodies.

Convention du Mètre

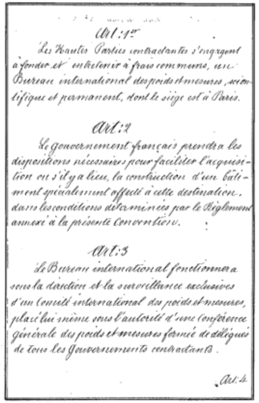


Signed in Paris in 1875 (representatives of 17 nations)

Established a permanent organizational structure for members on all matters relating to units of measurement

Created the BIPM – Bureau International des Poids et Mesures

- Intergovernmental organization (now 62 Member States)
- Under supervision of the International Committee for Weights and Measures (CIPM)
- Acts in matters of world metrology (demands for increasing accuracy, range and diversity)



Art: 1er

Les Hautes Parties contractantes s'engagent à fonder et entretenir à frais communs, un Bureau international des poids et mesures, scientifique et permanent, dont le siège est à Paris.

Art: 2

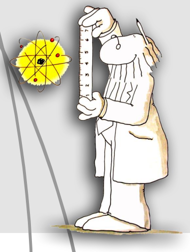
Le gouvernement français prendra les dispositions nécessaires pour faciliter l'acquisition ou s'il y a lieu, la construction d'un bâtiment spécialement affecté à cette destination, dans les conditions déterminées par le Règlement annexé à la présente Convention.

Art: 3

Le Bureau international fonctionnera sous la direction et la surveillance exclusives d'un Comité international des poids et mesures, placé lui même sous l'autorité d'une Conférence générale des poids et mesures formée de délégués de tous les Gouvernements contractants.

Art: 4

Remains the basis of international agreement on units of measurement



CIPM MRA – the next step

Mutual Recognition Arrangement

Paris: 14th October 1999

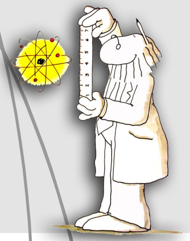
40 entities originally, now 106 (plus 152 designated organizations)

Mutual recognition of

- ✓ National measurement standards
- ✓ Calibration and measurement certificates

A legal framework that can be summarized by:
"Demonstrate science, Enable trade"

CCRI
Consultative Committee on Ionizing Radiation



Consultative committees are the primary forum for ionizing radiation metrology at the international level

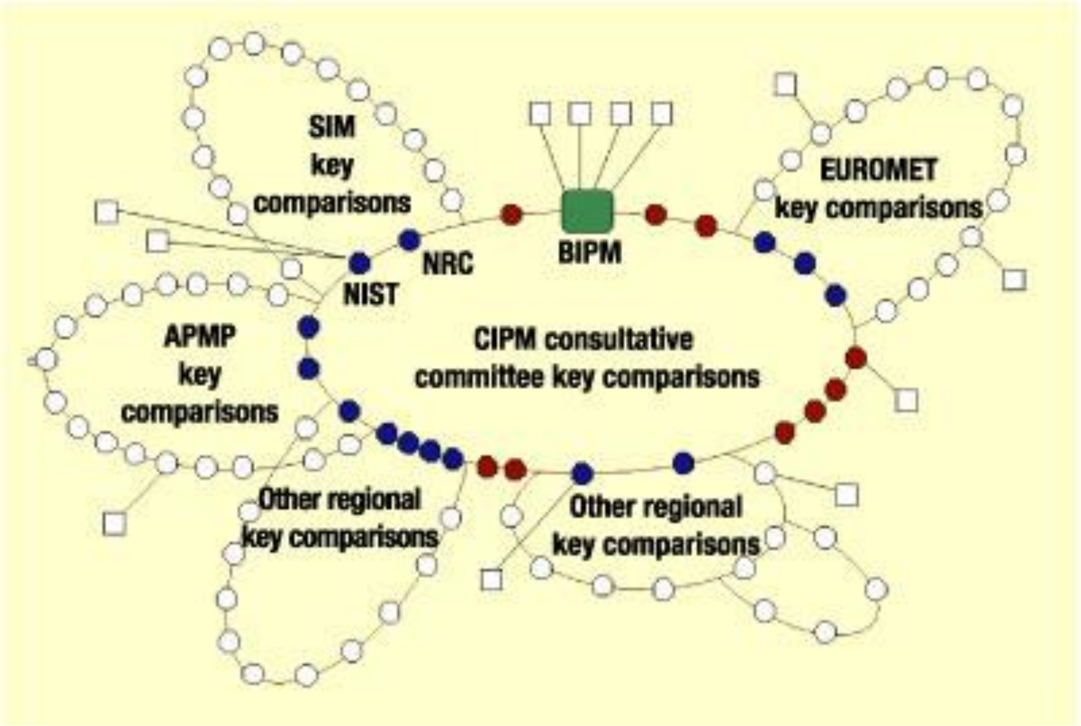
CCRI established 1958

3 sections – dosimetry, radioactivity, neutrons

Activities

- Definitions of quantities and units
- Standards for x-ray, γ-ray, charged particle and neutron dosimetry
- Radioactivity measurements
- **Approves comparisons of specific quantities to demonstrate equivalence of standards and calibration capabilities**

Equivalency requires a comparison



There are various ways to compare and demonstrate equivalency

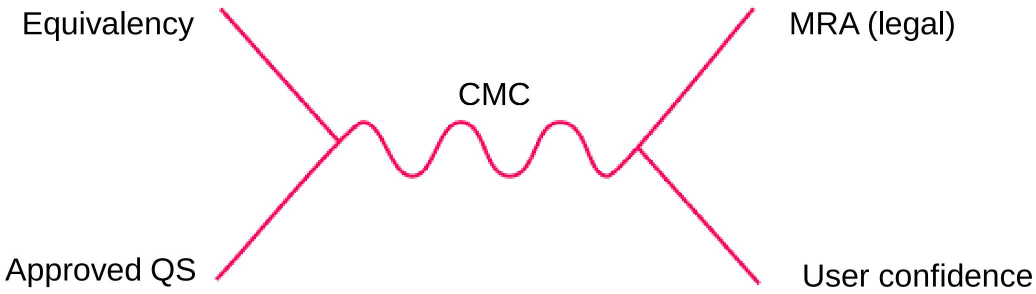
For all Ionizing Radiation comparisons a radiation field is required

Calibration Measurement Capability

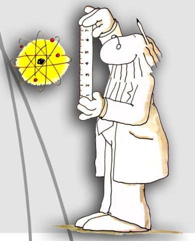
A CMC is the formal ‘proof’ that a laboratory can carry out a particular measurement

Comprises two components:

1. Demonstration of equivalency of a measurement standard with one or more other national standards
2. Demonstration of an internationally recognized quality system for the dissemination of the standard



Comparisons for dosimetry

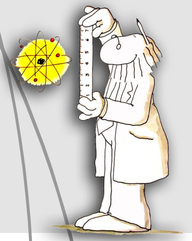


Comparison	Quantity	Energy	Year
BIPM.RI(I)-K1	Air kerma	Co-60	Ongoing
BIPM.RI(I)-K2	Air kerma	10-50 keV	Ongoing
BIPM.RI(I)-K3	Air kerma	50-250 keV	Ongoing
BIPM.RI(I)-K4	Absorbed dose to water	Co-60	Ongoing
BIPM.RI(I)-K5	Air kerma	Cs-137	Ongoing
BIPM.RI(I)-K6	Absorbed dose to water	4-25 MV (linac photons)	Ongoing
BIPM.RI(I)-K7	Air kerma	mammography	Ongoing
BIPM.RI(I)-K8	air kerma strength	Ir-192 HDR	Ongoing
BIPM.RI(I)-K9	Absorbed dose to water	50-250 keV	New

Need a different radiation field for each application

May also need a different radiation field for different beam intensities

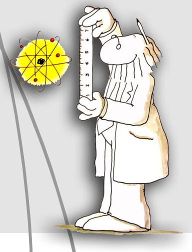
All these have been approved by the international community



Comparisons for dosimetry

Comparison	Quantity	Energy	Year
BIPM.RI(I)-K1	**Air kerma**	**Co-60**	**Ongoing**
BIPM.RI(I)-K2	Air kerma	10-50 keV	Ongoing
BIPM.RI(I)-K3	Air kerma	50-250 keV	Ongoing
BIPM.RI(I)-K4	**Absorbed dose to water**	**Co-60**	**Ongoing**
BIPM.RI(I)-K5	**Air kerma**	**Cs-137**	**Ongoing**
BIPM.RI(I)-K6	Absorbed dose to water	4-25 MV (linac photons)	Ongoing
BIPM.RI(I)-K7	Air kerma	mammography	Ongoing
BIPM.RI(I)-K8	**air kerma strength**	**Ir-192 HDR**	**Ongoing**
BIPM.RI(I)-K9	Absorbed dose to water	50-250 keV	New

Applications



An added challenge is that we also need to consider beam intensity:

A detector appropriate for radiation therapy will not have the sensitivity for radiation protection measurements (> factor 1000 difference in intensity)

Geometry is also important:

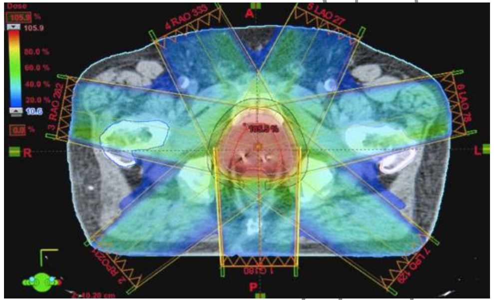
Radiation therapy uses a directed beam, radiation protection assumes a more uniform distribution

Applications beyond CCRI(I)

To demonstrate equivalence we need the right kind of detector in the right kind of radiation beam

Now we get to the physics

In radiation dosimetry we want to measure the energy deposited by a radiation beam in some material



Most often that material is the human body (radiation therapy, radiation protection)

Ideally, a radiation detector for this purpose (a dosimeter) would have a response that was energy independent

> **i.e., it would only respond to the energy deposited, not the type of beam interacting with matter**

Practical detectors are not ideal!