Radioactive sources in ionizing radiation metrology: applications and the potential for alternative technologies

Report of the CCRI Task Group on Radioactive Sources and Alternative Technologies (CCRI-RS-TG)

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1. Introduction

1.1 Background

The use of any technology must balance risks and benefits, and this challenge is very clear in applications of ionizing radiation where the known risks of exposure have to be appropriately managed, enabling safe use. National and international bodies have developed extensive regulatory, control and monitoring mechanisms to ensure that the benefits are maintained while risks are minimized. Elimination of risk is rarely possible, without elimination of the technology/application but there is a general imperative to investigate ways of continually reducing risk while managing any impact on activities. An added concern in recent years in regard to ionizing radiation applications is the potential security implications for malicious use of radioactive sources. Accidental dispersals of radioactive material may cause contamination to the environment and individuals in the vicinity causing harm and fatality to humans and animals [IAEA, 2001; IAEA; 2006]. The safety and security of radioactive substances is a key activity of the International Atomic Energy Agency as evidenced through its publication of safety standards [IAEA, 2014], but addressing the malicious use of radioactive sources has been an area of increasing activity in many countries over the last two decades. One consequence of this is that National Metrology Institutes (NMIs) and Designated Institutes (DIs) of member states have implemented additional controls on the use, storage and transport of radioactive sources used in ionizing radiation metrology.

In the United States, the Office of Radiological Security (ORS) within the National Nuclear Security Administration (NNSA) of the Department of Energy (DOE) is tasked with promoting the adoption and development of non-radioisotopic alternative technologies in applications of ionizing radiation. As part of its activities the ORS sponsored a committee of the joint National Academies of Science, Engineering and Medicine (NASEM) to look at this issue and a report was published in June 2021 [NASEM, 2021]. The committee took a very wide view on applications of ionizing radiation, looking at radiation therapy, industrial processing (including sterilization), radiography, radiobiology and other medical applications, and calibration laboratories. An extensive set of recommendations were provided across these applications but only one referred to calibration laboratories, relating to the use of Cs-137 within the framework of radiation protection dosimetry. It is worth exploring this specific application since it relates directly to one of the missions of the Consultative Committee for Ionizing Radiation (CCRI) to the BIPM. The CCRI, through its activities, aims to enable all users of ionizing radiation to make measurements with confidence at an accuracy that is fit for purpose.

Cs-137, in the form of CsCl has been used in various applications since the beginning of the nuclear energy in the 1950s. By far the largest use of Cs-137 sources is in blood irradiators, located in hospitals, and other medical facilities. Blood irradiators are used to treat blood used for patient transfusions, to prevent transfusion-associated graft-versus-host disease (TA-GvHD) [NASEM, 2021]. Multiple cesium-137 sources with activities up to 185 TBq (5 kCi[1]) are used to deliver a uniform dose to a volume of blood. This activity of source is considered Category I, based on the International Atomic Energy Agency (IAEA) categorization system [IAEA, 2005]. CsCl is a powder, which is encapsulated for use in such irradiators. If the encapsulation is broken then the high activity material can be relatively easily dispersed, representing a safety and security hazard. In 2014 the NNSA-ORS initiated the "The Cesium Irradiator Replacement Project" (CIRP) with the goal of eliminating blood irradiation devices that use Cs-137 in the form of cesium chloride by December 31, 2027 [NNSA, 2021]. The project provides financial incentives towards the purchase price of a new non-radioisotopic device as well as the removal and disposal of Cs-137 irradiators used specifically for blood irradiation, and many centres have begun the process of installing systems that use x-ray tubes to deliver the required dose.

The NASEM report, recognizing the endpoint of the NNSA-ORS program (i.e., complete elimination of CsCl sources from the market), recommended that calibration laboratories investigate alternatives, although in this case no non-radioisotopic alternative was identified. In response to the NASEM report, and specifically this threat to the international radiation protection dosimetry framework based on Cs-137 sources in the form of CsCl, the CCRI formed a task group to look at the role of radioactive sources in ionizing radiation metrology and the potential options for non-isotopic alternatives. The task group drew representatives from NMIs/DIs from all three sections of CCRI as well as experts from the IAEA and the radioactive source manufacturers community, with the aim of providing a metrology-specific perspective on this critical topic. It is important to emphasise that this Task Group's terms of reference are significantly different from that of the NASEM expert committee, in that the strategic mandate is to "ensure that a robust international system of standards and calibration capabilities within the field of ionizing radiation can be maintained and disseminated." Conserving the integrity of the well-established network of primary, secondary and tertiary calibration laboratories around the world is paramount, ensuring that the necessary accurate measurements underpin all uses of ionizing radiation in environmental, medical and industrial fields.

[1] Although Bq is the SI unit of activity of radionuclide sources, Ci is routinely used by source manufacturers and is therefore also provided for readability).

The NASEM report is not the sole focus of, nor reason for, this report. National and international regulations on the transport, installation, use and disposal of radioactive sources are impacting the operational activities of NMIs and DIs, in terms of the types of sources/irradiators that can be used, the time between re-sourcing, and the operational life of irradiators. Discussions within the CCRI community have highlighted numerous incidents where regulation has negatively impacted an ionizing radiation metrology facility, with perhaps the most visible being the closure of the BIPM's Cs-137 laboratory and subsequent transfer of air kerma realization and dissemination to the IAEA dosimetry laboratory[2].

1.2 Starting assumptions for the Task Group activity and report

As noted above, this report is an expert perspective on the role of radioactive sources in the international system of measurement under the CIPM MRA [CIPM, 1999]. It provides the historical context and describes the current situation for the three sections of the CCRI:

I: photons and charged particles (dosimetry);
II: radionuclide metrology;
III: neutron measurements.

This report is not intended to be a comprehensive literature review, references are provided as examples to give the reader additional context.

Although the intention is to identify currently-available or potential future alternatives to radioactive sources for ionizing radiation metrology, the Terms of Reference of the Task Group (https://www.bipm.org/en/committees/cc/ccri/wg/ccri-rs-tg) do not include the investigation of alternative paradigms for the dissemination of primary quantities nor the development of alternative formulations of the documentary standards employed by end-users.

The future needs for ionizing radiation metrology are explored with the starting point being that accuracy and precision in the maintenance and development of primary standards in the three sections, and the dissemination of such standards through calibration services (CMCs) must not be negatively impacted. The history of metrology, across all measurement areas, is also one of continually lowering uncertainties and expanding applications to meet end-user requirements. This underlying trend is the primary guide when considering how ionizing radiation metrology is realized.

2. Metrological needs for ionizing radiation metrology

NMIs and DIs disseminate the following SI quantities for the measurement of ionizing radiation (the primary ones are given in the table):

[2] The realization/dissemination is carried out by BIPM staff using the IAEA's Cs-137 radiation field.

Table 1 – 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}

Note that in various documents and applications, older quantities - Curie (Ci), Roentgen (R) , rad/rem – are still found.

These quantities are macroscopic and are either characterizations of a radioactive source/field or, in the case of kerma and dose, measures of the interaction of ionizing radiation with matter. This means that dissemination of all the quantities in Table 1 requires both measurement standards and radiation fields. Depending on the sub-quantity (e.g., air kerma for medium-energy x-rays, ambient dose equivalent for thermal neutron beams) the radiation field may be due to a radioactive source or could be electrically generated. In addition, it is important that the radiation fields used in the operation of primary standards and dissemination of such standards to users should be similar to the radiation fields at the point of use in the specific application.

Metrology is an activity that takes place over extended periods of time, in that client calibrations may be several years apart, so it is essential that primary and secondary standards maintained by NMIs/DIs are not only accurate but stable over long time periods. One of the simplest ways to monitor detector performance is through the provision of a reference with a known output against which the detector response can be monitored. An analogue in electrical measurements would be a standard cell and for ionizing radiation metrology the decay of radioisotopes provides a predictable output over many years (timescale determined by the half-life of the specific isotope).

As a result of these two requirements – appropriate calibration fields and reference outputs for long-term monitoring, radioactive sources are used within the activities of all three sections of the Consultative Committee on Ionizing Radiation (CCRI) – sections covering radiation dosimetry, radionuclide metrology and neutron measurements. It is obvious, but worth stating explicitly, that radionuclide metrology has as its focus radioactive sources but these fundamental issues of radiation metrology still apply and have an impact on detector design and operation.

3. Current status of the maintenance, development and dissemination of standards

3.1 Role of radioactive sources

Radioactive sources have been a critical component of ionizing radiation metrology since the discovery of radium. Many NMIs/DIs have records of the first radium standards from the Commission Internationale des Étalons de Radium and authorised by Curie, Rutherford and Meyer, if not the actual sources themselves. The early realization of the role sources play in metrology has the consequence that they are embedded in the infrastructure of primary standards and the only major changes over the last century has been the move from certain source types (e.g., radium) to others (Co-60, Cs-137), for both safety and operational reasons. Long-lived radioactive sources as reference fields have also imprinted a timescale for measurement standards, allowing reliable measurements on the same detector for several decades. Measurement techniques within all three sections of CCRI have a similar basis to those of 50 years ago, indeed some primary and secondary standards are of a similar age, particularly Free-air chambers, reference-class ion chambers and well-type chambers. Radioactive sources provide easy-to-use, stable reference fields for maintaining these standards, and therefore we have the current situation where the primary standard and its associated reference field (check source is another common term) needs to be viewed as a combined system. In some cases, the source becomes the *de facto* standard. For example, the calibration of equipment used for radiation protection purposes, e.g., survey instruments, personnel dosimeters, is performed using a calibrated radiation field [IAEA, 2000; Lee and Burgess, 2014].

It is also important to note the precision possible in monitoring measurements using radioactive sources. If the half-life is known accurately (the case for the sources used for this purpose in NMIs/DIs), and geometry of source is fixed (i.e., sealed source in a known and repeatable geometry) then the radiation field intensity at the point of the measuring instrument is predictable with a standard uncertainty < 0.02%. [e.g., Boutillon and Peroche, 1993; Ratel, 2007; McEwen and Taank, 2017]

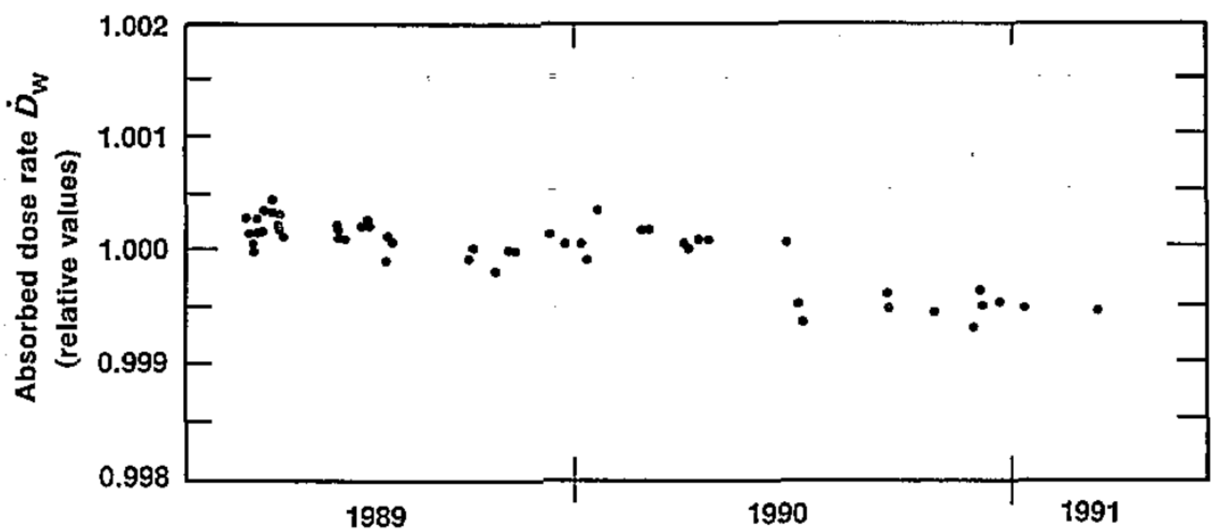

Figure 1. Figure 5 from Boutillon and Peroche (1993) showing the stability of the BIPM ionometric standard of absorbed dose to water. The dose rate is corrected for the half-life of Co-60, illustrating the temporal drift in the chamber response (< 0.05% per year).

Electrically-generated radiation beams will be discussed in detail below but, in general, such devices have not been designed with metrology applications in mind, so they tend to have a variable output (sufficiently stable for end-user applications, but not necessarily at the level of precision required for metrology) and obsolescence impacts their use over longer periods. [e.g., Luketina and Greig, 2004; Wang *et al*, 2025].

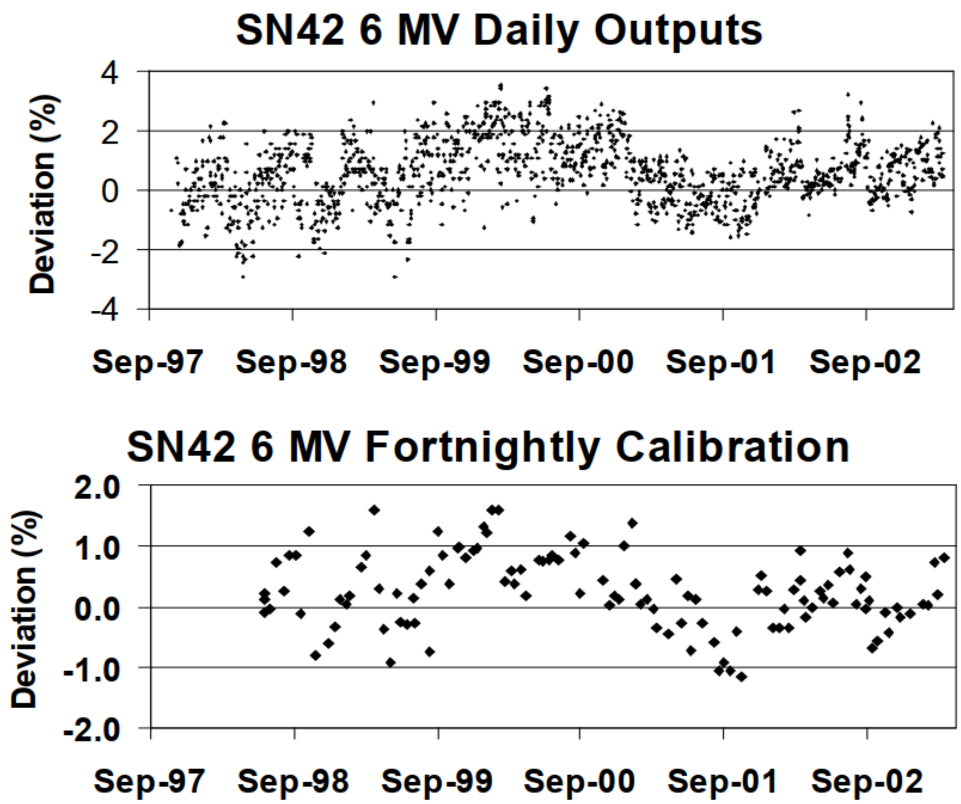

Figure 2. Figure 1 from Luketina and Greig (2004) showing the stability of the output of a clinical linear accelerator over a period similar to the Figure above for Co-60. The fortnightly calibration is more rigourous than daily checks hence a reduced spread on results. This level of performance is consistent with data obtained from NMIs operating clinical linear accelerators.

3.2 Radionuclides used in ionizing radiation metrology

A large number of radionuclides are currently used across the activities of the CCRI. The list below refers to actual use in the NMI laboratories for the maintenance, development and dissemination of standards, the end user communities supported by these activities use a much wider range of isotopes.

Table 2 – radionuclides of relevance to the various CCRI Sections

CCRI Section	Critical radionuclides*	Energy (keV)	Activity (Bq)
I – dosimetry of x-rays, photons, charged particles	Co-60, Cs-137, Sr-90, Ir-192, I-125, Pd-103, Am-241	20 keV to 1.33 MeV	Up to ~ 400 TBq
II – radionuclide metrology	Ra-226, Ho-166m, Cs-137		
III – neutron measurements	Am-241 (as Am-Be), Cf-252	Broad energy spectra up to 15 MeV	Up to ~1000 GBq for Am-Be and ~100 GBq for Cf-252

* Not a comprehensive list, the most important and/or most commonly-used radionuclides are listed here. Absence does not imply any judgement on its current or future relevance for ionizing radiation metrology.

From a safety perspective, the sources are, in all cases, encapsulated. The use of these sources is restricted to a small number of trained users, and all facilities are regulated, have required training for staff, approved safety procedures, routine audits, policies to account for all nuclear material, and operations occur under authorized licences issued by national nuclear regulatory agencies. From a security point of view, facilities that are authorized through licenses to conduct business using radioactive sources meet strict requirements to ensure that access of non-authorized personnel is prohibited, achieved through such measures as 24/7 CCTV monitoring, motion sensors, restricted areas, biometrics, *etc.*, laid out in audited security procedures. Regulation worldwide is generally very consistent, with most of the regulators in this field following the International Basic Safety Standards [IAEA, 2014].

3.3. Relevance to end users of current standards development and dissemination

Developments in applications of ionizing radiation (and associated new technologies) have, in general, timescales of decades, rather than few-year cycle seen in other fields such as communications, IT and biotechnology, and significant infrastructure (both in terms of equipment and normative standards) has been built around specific radioactive sources. These include Cs-137 in radiation protection, Am-Be in neutron measurements, Ra-226 in radioactivity, and Co-60 in radiation processing. Assumptions of the continued availability of these radio-isotopes appears to be built into sector-wide strategies (e.g., Co-60 for radiation processing) [iiA, 2025]. Maintenance and development of standards and dissemination of calibration services based on the same radio-isotopes would therefore seem appropriate as being "fit for purpose".

The one exception is perhaps radiation therapy, where new treatment techniques (and associated technologies) have appeared on a timescale of 5-to-10 years over the last two decades. Examples include novel delivery systems, proton and heavy ion therapy, electronic brachytherapy, and MR-linacs (Fiorino *et al*, 2020). Despite this rapid change in technology, the reference fields provided by NMIs for radiation therapy are predominantly delivered using

Cobalt-60 irradiators, and international organizations, such as the IAEA and AAPM, which provide guidance documents, continue to select Co-60 as the calibration field for dosimetry protocols for external beam radiation therapy [IAEA, 2024; Muir *et al*, 2024]. Indeed, the continued used of Co-60, an obsolete technology from the perspective of state-of-the-art radiation therapy delivery, has provided the necessary stable dosimetry basis for disseminating absorbed dose standards in radiation therapy, across the range of treatment modalities. International clinical audits exercises (as carried out by the IAEA and IROC-Houston [Izewska and Andreo (2000), Kry *et al*, 2019]), as well as comparison programs for NMIs/DIs [www.bipm.org/kcdb] have clearly demonstrated this, ensuring that the outcomes of new methods are not biased by errors in device calibration. Furthermore, stakeholder input during recent CCRI meetings has stressed the importance and reliability of the current framework using radioactive sources for ensuring the safe use of ionizing radiation in cancer therapy

The vast majority of routine calibrations of radiation protection devices carried out for the nuclear industry are performed using radionuclide sources. This is due to the large volume of personal and area survey instruments used to monitor the workforce and the facilities which can more easily and economically be performed by primary and secondary standards labs with a radionuclide source than using an accelerator or reactor facility. The recently revised ISO standards for neutron reference radiation fields (ISO, 2021; ISO, 2023) reflect this dependence on radionuclide sources for routine testing of devices, with accelerator and reactor facilities specified for a more specialised type testing of the energy response of a device.

4. The extent of the problem for metrology

4.1 Cs-137

Cs-137 (predominantly in blood irradiators and research irradiation systems) is one of the four main radioisotopes that are the focus of the NNSA-ORS activities to replace radioactive sources in ionizing radiation applications (the others being Co-60 for radiation processing, Ir-192 for industrial radiography, and Am-241 for well-logging [ORS presentation 9-Mar-2023]). Although the elimination of Cs-137 irradiators for use in metrology as described above is not a focus of the NNSA-ORS, the reduction in demand for Cs-137 sources, as a result of the replacement program for other applications, will have a direct impact on the supply of Cs-137 sources for calibration irradiators and therefore affect the metrology community.

Many NMIs and DIs worldwide (as well as Secondary Standard Dosimetry Laboratories, (SSDLs) within the IAEA/WHO SSDL network and other secondary calibration laboratories) make use of Cesium-137 irradiators to establish national standards for the quantity air kerma[3] in support of radiation protection and homeland security measurements/calibrations. Such measurements and calibrations are critical to the safety and security of radiation workers at nuclear power plants, hospitals, national and international agencies, emergency responders, soldiers, patients and the public at large. It is estimated that radiation detection instruments and dosimeters numbering in

[3] Similar in concept to 'absorbed dose to air'

the millions are traceable to the air kerma standards for Cs-137 established by each NMI in each country.

The energy of the gamma-ray emitted from Cs-137 (662 keV), and the simplicity of the decay scheme for this isotope, makes it ideal as a representative field for instrument testing and calibration. Cs-137 has therefore been the central element in the basis for radiation-protection dosimetry around the world for more than five decades [ISO (2019); IAEA (2000); NCRP (1991)]. Cs-137 is therefore a standard field for both measurement and normative standards and an example where a specific nuclide is embedded in the wider measurement system than simply the collection of calibration laboratories.

At present, there is no commercially available electrically-generated radiation beam that can reliably reproduce such a energy spectrum and provide the remarkable stability of output over decades that is a primary characteristic of a radioactive source.

4.2 Co-60

Co-60 plays the fundamental role in radiation therapy dosimetry that Cs-137 plays for radiation protection. Almost all dosimetry protocols worldwide are based on a Co-60 calibration of an ionization chamber. This is the case, even though the demand for Co-60 as a radiation source for radiation therapy has diminished, where linear accelerators have become the primary treatment modality. Co-60 teletherapy units are still operated in many countries [httsp://dirac.iaea.org] and niche devices, such as the Elekta Gammaknife, provide state-of-the-art radiation beams for specific treatments. Co-60 is also the reference field for measurements in radiation processing and radiation sterilization [e.g., McEwen *et al*, 2022]. Scaling factors [e.g., Anton *et al*, 2013; Mainegra-Hing and Rogers, 2006] are used to convert dosimeter response in other radiation beams to the response in Co-60.

Therapy-level sources (> 1000 Ci) are another of the sources that the ORS has identified as higher risk (and therefore a focus for removal). This level of activity is that typically used for therapy-level instrument calibrations in NMIs, DIs, SSDLs, *etc*. Very large sources (≥ 100 kCi) are used in radiation sterilization with many thousands of such sources used in radiation sterilisation plants worldwide. Co-60 irradiators are used to sterilize approximately 25 billion single-use medical devices per year, representing around 30% of all such items [iAA, 2025]

4.3 Ra-226

Radium-226 is a key check-source that is used in the monitoring of equipment for radionuclide metrology. The long-half life and stability of these sources means that systems can be monitored over decades, as shown in Ratel (2007)

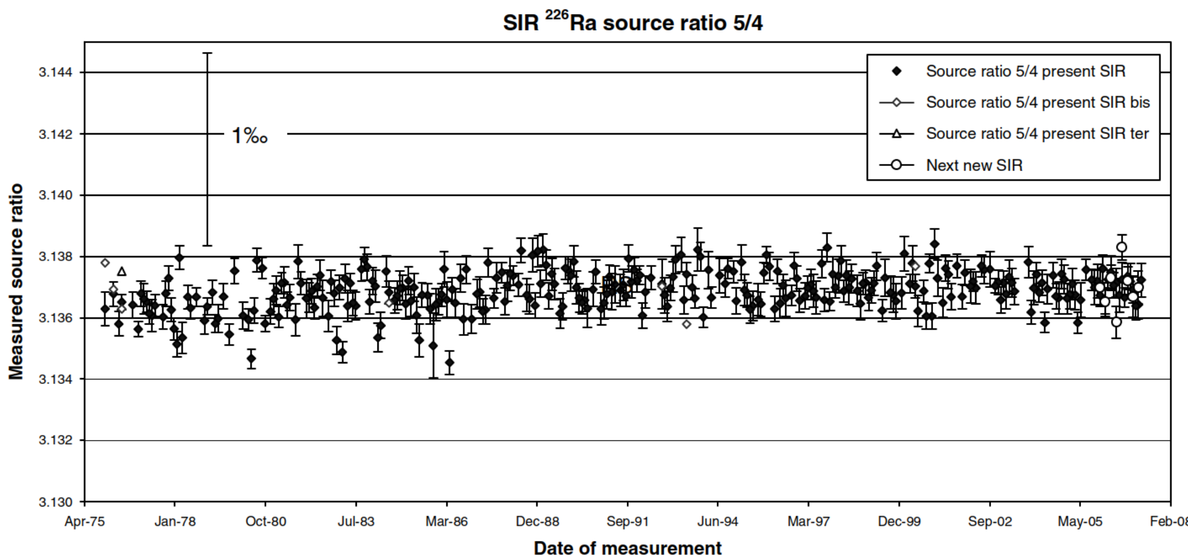

Figure 3. Figure 1 from Ratel (2007) showing the performance of the BIPM SIR using the same Ra-226 check sources over a period of more than 30 years.

Although very suitable as a check source, the age of such Ra-226 sources and concerns about helium pressure build-up (due to alpha decay) leading to potential failure of the glass encapsulation has meant that some laboratories have been required to disposes of these sources. Lifetime limits of 10-15 years have also been put on new sources, which negatively impacts long-term monitoring of detectors.

4.4 Am-241

Radionuclide neutron sources are of fundamental importance to neutron metrology as reference standards which allow quantities such as neutron dose equivalent and neutron fluence to be realized in laboratories around the world. They are also used as the source of neutrons in many standard thermal neutron reference fields in many NMIs, surrounded by a moderating material such as graphite or polyethylene. Am-Be neutron sources (consisting of a compressed mixture of Am-241 in oxide form and beryllium) are very commonly used for these applications due to their long half life compared to Cf-252 (432.6 years vs 2.647 years), high neutron yield and well-characterised energy spectrum. The long half-life of Am-241 is well-suited to metrology since the stability of instruments can be verified over a period of decades by making repeat measurements with the same reference source, invaluable for quality assurance. In addition to being employed as a neutron source, the photon emissions in the 30-60 keV range make it useful as a source for low-energy radiation protection calibrations [Bass *et al*, 1992]. As stated for other sources, there is currently no electrically-generated neutron source that can reliability provide the stability of output and longevity that is a primary characteristic of a radioactive source.

5. Outlook for radioactive sources – availability and regulatory challenges

- Cs-137 – this radionuclide is reprocessed from spent fuel (Cs-137 is a fission product of uranium) and the current situation appears to be as noted above, that with the demand for blood irradiators declining, there is little commercial incentive to maintain ongoing capabilities for re-processing, separation and subsequent high activity source manufacture. The long half-life of Cs-137 (~ 30 years) provides a potential time-buffer for existing calibration laboratories, but this does not address the needs of new laboratories, particularly impacting developing economies, and regulatory issues related to irradiator licencing could have an effect earlier (e.g., 10-15 year timeline). The NASEM report suggested that vitrification of sources should be investigated, as this reduces the security risk. Although vitrification is practicable [Dash *et al*, 2008], the issue remains one of supply.
- Co-60 – supply of Co-60 is not a bottle neck for metrology, given the large supply needs of the industrial irradiation sector and new initiatives to increase production at various sites worldwide. The challenge is likely to be more on cost, which appears to be due to transport and safety regulations. However, looking at the overall costs for obtaining, maintaining and use of the radionuclide irradiators with their sources these costs still are lower than the costs for alternatives. The major costs for radionuclide irradiators are at initial costs and during source changes (which is also when service of the irradiator is performed). The servicing of these irradiators is performed periodically and far less frequently than for electrically-generated sources. Co-60 is also now being an alternative high dose rate brachytherapy source of choice, especially in LMICs[4], where importing Ir-192 sources can be a challenge.
- Ir-192 – this isotope continues to be the source of choice for high dose rate brachytherapy procedures. The short half life (around 73 days) is an operational challenge, both in terms of the requirement for regular replacement and the challenges, in some countries, related to the customs clearance of radioactive material. A significant advantage of Ir-192 HDR brachytherapy over other irradiation devices is the small footprint, with reduced requirements for space, radiation shielding and electrical power consumption.
- Obtaining new high-purity Ra-226, to replace obsolete sources for radionuclide metrology, is challenging and therefore alternatives are being considered. The BIPM has collaborated with the LNHB in France to develop Ho-166m sources with the necessary activity and purity, and long-term characterisation of these sources is in progress. One challenge is that there is limited half-life data available for Hm-166m, which impacts the accuracy of decay calculations. The challenges here appear to be technical, rather than production/regulation.
- Recent geo-political events have placed increased pressure on the supply lines for sources, including Am-241. Over recent years, Russia has emerged as the primary, and in some cases, the only, producer. Currently, though, Am-241 is also produced in the USA, and supply is therefore not an issue. Demand from the oil exploration and production industry means a stable basis for source manufacturers.
  There are safety and security concerns associated with using high activity sources in remote locations without the typical controls present in a laboratory setting and the NNSA-ORS

[4] Low and Middle Income Countries

program, therefore, has identified Am-241 as a target radionuclide for elimination. Considerable effort is ongoing into developing D-T accelerator-based sources as replacements for Am-Be sources.

- Cf-252 is readily available but can only be produced in a high flux reactor, of which there are only currently 2 worldwide (Oak Ridge in the USA and Dimitrovgrad in Russia). The cost of producing Cf-252 is extremely high and continues to increase. Although there is less of a security risk associated with Cf-252 sources compared to Am-Be sources, the price and short half-life is likely to further restrict their use for metrology in the short to medium term.
- It is not expected that security/regulatory/transport concerns will impact low activity sources, such as those used in LDR brachytherapy. In addition, source production of, for example, I-125 is via accelerators, and therefore is not dependent on nuclear reactors or processes that could be impacted by current or anticipated regulatory efforts.
- The rapid increase in the application of radiopharmaceutical therapies has the potential to change the narrative around radioactive sources. The benefits of radionuclides such as Cu-67, Lu-177, Ra-223, Ac-225 are being raised in both scientific publications and media news releases, and this could well lead to increased understanding of the importance of radioactive sources in health, and hence metrology.
- Shipping of radionuclide sources by air is also becoming increasingly difficult. Certain airlines no longer carry radioactive freight and countries can impose restrictions on the container dose rates that can be carried by a passenger aircraft (e.g,. the US limit of a TI of 3). The containers used to ship large neutron and gamma sources often cannot be security screened at an airport by x-rays due to their shielding and so may require the consignors to have special security measures in place at their site. These factors are particularly problematic when an international comparison exercise is being conducted and a radionuclide source has to be sent to many NMIs, causing the measurement phase to last for many years.
  It is worth explicitly stating that transport issues are independent of the source activity. Shipping low-activity samples between laboratories (e.g., in submitting samples to the BIPM SIR) can involve significant paperwork and multiple agencies, which can critically impact the value of the exercise, particularly for short half-life sources.

6. Possible alternatives and directions for future research.

6.1 Outline of the challenge

One significant advantage of radioactive sources is that the intensity of the produced radiation field can be easily tuned to the specific requirement by adjusting the contained activity, independently of the emitted energy. In contrast, both the intensity and energy of a radiation field produced by a non-radioisotope alternative can be varied in real time but there is no inherent stable value of either parameter. When considering alternative technologies, it is important to recognize what attributes of a source-based radiation field are required. It is often very tempting to try to develop a comprehensive system that can meet multiple applications, but in many of the cases identified in Table 2 something much simpler may be preferable.

However, any solution must not only be technologically suitable, it must also pass some cost-benefit test as well and be accessible by all economies. This is not a straightforward exercise since there is little or no data in the literature and any analysis is likely to be situation-specific so no attempt is made here to contrast radioactive source irradiators with alternatives. There is literature in the radiation therapy field [Lievens *et al*, 2003; Carlone *et al*, 2023; REFs] that could be translated to a metrological setting, but, again, it is not straightforward given the very different operation models for a cancer centre and a calibration laboratory.

In this section, possible technologies – existing, or in development – are discussed and the role they can play in ionizing radiation metrology is explored. The aim is to identify what technology could be used in place of radioactive sources, and the research required to arrive at a point where such a substitution could be considered. The framework of international metrology means that such a disruptive change would require collective action for successful implementation, preceded by significant parallel running of radioisotope-based and alternative technology radiation sources to establish performance metrics. In addition, once a validation is completed, documentary consensus standards would need to be developed to address these changes for the multiple radiation protection, medical and industrial applications for which the alternative technology is being considered prior to any implementation.

It should be noted that end-users of ionizing radiation in some applications have not had easy access to radioactive sources for several years (e.g., in radiation therapy, where Co-60 irradiators have been eliminated in favour of linear accelerators). In such situations stability monitoring of detectors is still required and published recommendations require regular comparison of a suite of detectors, ideally with different measurement principles, operational modes and failure pathways [e.g., IAEA, 2023]. This requires additional equipment and procedures and increased staff time to execute properly, and is not such a simple test of detector response. This is an example of an alternative approach that is not necessarily equivalent to that using a radioactive source. Quantifying the "appropriateness" of an alternative or defining "equivalent" is a further challenge, but is an essential step to ensure that there is no significant loss in performance if/when a source is replaced by some alternative.

The technology described below is not comprehensive since the task group has not the time or resources for such a detailed review, but is an expert opinion on possibilities. It is also important to recognize that metrology is a complete system, not just the radiation beams. Any change may require parallel changes detectors used, in documentary standards and, possibly, regulations, which could lead to knock-on changes in national and international guidelines and therefore would need a clear and comprehensive communications strategy. Finally, the cost of maintaining radioactive source irradiators is often given as a reason for adopting alternatives, but any change will require significant funding to allow for a comprehensive adoption of new systems within a realistic timeline.

6.2 Kilovoltage x-ray systems

Kilovoltage systems would appear to have the greatest potential as a high stability radiation source, due to the simplicity of operation, long lifetime of the x-ray tubes used in NMIs, and the ability to accurately control the input parameters (anode current and tube voltage). The BIPM have reported excellent repeatability in air kerma measurements for medium energy x-rays (generating potential ≤ 300 kV) in the provision of Key Comparison BIPM.RI(I)-K3 [see http://bipm.org/kcdb]. More detail is provided here to extend the discussion. Burns reports a typical standard deviation of repeat air-kerma determinations smaller than 0.03%. The x-ray system delivers four standard beam qualities and measurements on the same day show strong correlations, indicating that only intensity is varying, not energy. Over longer timescales ≥ ten years, slow drifts in the measured air kerma rate are seen exceeding 0.1%, again with correlations between the different beam qualities. A meta-analysis of secondary standard calibrations over 30 years indicated no significant variation in the BIPM primary standard Free Air Chamber at the 0.03% level, suggesting that the drift in air kerma rate was due to the x-ray tube.

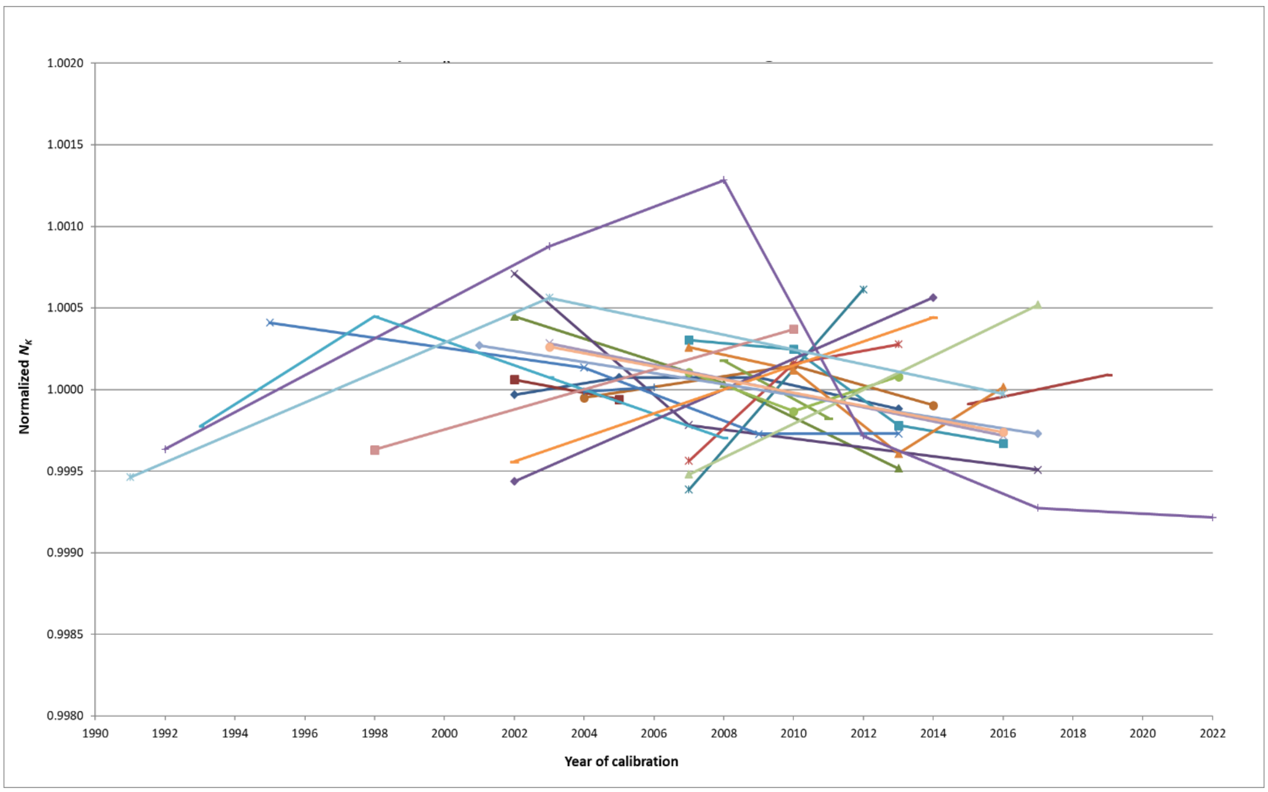

Figure 4. Summary of calibration data determined using the same x-ray tube and primary standard over a period of ~30 years. Data supplied by the BIPM. Combining all the data leads to the conclusion that the long-term drift (~0.1 %) is due to the x-ray tube, rather than the primary standard.

As noted above, the relevance of a reference or calibration beam to that of the end use is an important factor and energy response changes between different beams must be considered. Detector stability in one beam does not necessarily equate to the same level of stability in another. The experience of the task group members is that performance differences (e.g., due to detector construction) are exacerbated at low photon energy, suggesting even lower uncertainties might be possible for Cs-137 (photon energy = 662 keV) or Co-60 (photon energy = 1250 keV). However, this assumes that kV x-ray tube performance is independent of the applied voltage, which is likely to be optimistic for 600 kVp and above.

Significant effort has been put into the BIPM system to deliver this level of stability but there is nothing in the technology that could not be reproduced in other laboratories with similar equipment. The issue of equipment failure remains for any electrically-generated radiation beam. Radioactive sources have long lifetimes and rarely exhibit un-signalled catastrophic failure. X-ray tubes, in contrast, can fail without warning and re-establishing reference beams is a significant effort. Duplicate systems would likely have to be operated to ensure continuity.

As noted above, replacing Cs-137 irradiators for radiation protection measurements and calibrations requires a device that can produce a photon energy around 662 keV. This is in a region between x-ray tubes and linear accelerators. Before WWII, a lack of other options led to the construction of very high energy x-ray tubes (up to ~ 1 MV kVp) [Charlton *et al*, 1940; Innes, 1948]. A number of NMIs are currently looking at higher-energy kV x-ray tubes, although commercial systems are not available above ~ 500 kVp [Zhao *et al*, 2020; Ishii *et al*, 2022]. To achieve energies closer to Cs-137 can be obtained with different technologies - Van der Graff generators can produce electron energies up to 2 MeV [Barnard *et al*, 1956], but such devices are challenging to maintain, and generally cannot be controlled at the same level as is possible for a kV x-ray tube. Recently, researchers at the LNHB in France [Bordy *et al*, 2019] have investigated generating kV x-rays using an electrostatic accelerator, which may offer a route to a ‘Cs-equivalent’ photon beam.

6.3 Electron linear accelerators and proton accelerators

The same approach as applied to kV x-ray tubes can be considered for higher-energy electron and proton accelerators. If one can measure both the total current in the emitted beam and the energy of the radiation then one has a standardized output that could be used as a reference field. Faraday cups and calibrated toroidal monitors are finding increasing applications and could potentially become more accurate and more widespread [Schüller *et al*, 2017; Renaud *et al*, 2025, Rawat *et al*, 2025]. Whether the output can be controlled at a fixed output using such devices is not clear. Normalization for intensity fluctuations is a more likely operating mode, which could still be useful.

Off-the-shelf clinical accelerators have, over the last 2 decades, demonstrated good performance and reliability, meeting the needs of NMIs/DIs for calibrations for megavoltage radiation therapy [see BIPM.RI(I)-K6 on http://bipm.org/kcdb]. Some accelerators are more stable than others, and different manufacturers’ devices have been shown to demonstrate different stability behaviours (e.g., short-term random variations compared to systematic drifts over the longer-term) [e.g., Grattan and Hounsell, 2011]. Linear accelerators are predominantly viewed as a replacement for Co-60 although recent work from the NMIJ (Japan) has looked at a producing a photon beam closer to the energy of Cs-137 [Ishii *et al*, 2023).

Proton accelerators, as used for radiation therapy or physics research, tend to be more complex devices that electron linear accelerators, and therefore it might be expected that stability would be worse than seen for e-linacs. However, results from one group (Rana *et al*, 2019) suggest that somewhat better stability is possible, at least over a period of months. One of the challenges in assessing alternatives is that stability data is somewhat sparse in the literature for many electrically-generated sources. However, all the data reviewed for this report showed stability that cannot be considered as equivalent as that of a radioisotope-based radiation field.

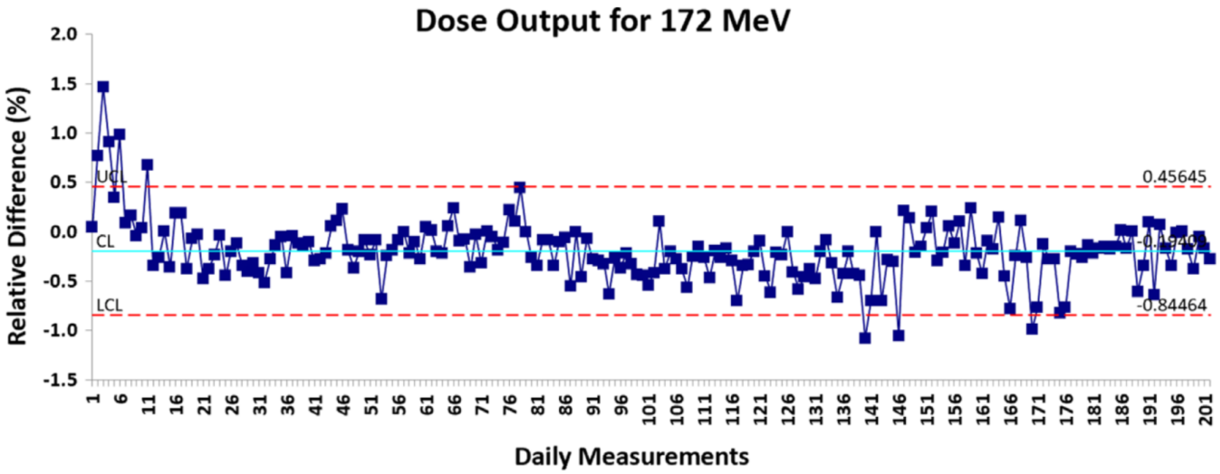

Figure 5. Figure 9 from Rana *et al* (2019) showing reproducibility of the output over a period of more than 6 months.

Proton accelerators are also used to produce quasi-monoenergetic neutron fields for calibration and type testing of devices (Nolte and Thomas, 2011a). Accurate monitoring of the neutron output is essential, both in terms of energy and fluence Nolte and Thomas, 2011b) and a monitoring of the beam current alone is not sufficient to determine the neutron output. A well-characterised and maintained facility can perform many of the same functions as a radionuclide source, particularly in the case of simulated workplace fields (Lacoste et, 2011), but they are regarded as being complementary rather than replacing sources due to the significant cost and effort required to characterise, run and maintain such a facility. As a result, they are only located in a small number of NMIs.

6.4 D-D and D-T generators

Compact neutron generators using either the DD (deuterium-deuterium) or DT (deuterium-tritium) reaction are commonly used in applications such as oilwell logging, detection of dangerous materials, neutron activation analysis and neutron radiography. DD and DT neutron generators produce relatively monoenergetic neutrons with energies of approximately 2.5 MeV and 14 MeV respectively. The lower energy of the DD generator is closer to that obtained from radionuclide neutron sources so they have been used as replacements for certain applications Weinmann-Smith *et al*, 2025; McElroy and Cleveland, 2017). Others have modified the spectra from DT generators by placing material around the generator to replicate that from a radionuclide source (Mozhayev *et al*, 2024; Haslip, 2001).

The paper by Piper *et al* (2017) discusses the advantages and disadvantages of using neutron generators to replace Cf sources for dosimetry and instrument calibration. One major disadvantage of a neutron generator is the limited lifetime of 1000 to 2000 hours (IAEA, 2012) after which time the target or the entire tube needs to be replaced. They also require regular operation to maintain good performance and a monitoring system is required in order to correct for variations in the output in the short and long term. The level of characterization required for a neutron generator is much higher than that for a radionuclide source where the emission rate and anisotropy can be determined by measurements with a manganese bath and a neutron detector (Roberts *et al,* 2011). The physical size of a neutron generator presents challenges in determining the neutron output by primary methods, so a series of fluence and spectrometric measurements are required.

6.5 Lower-risk radioactive sources

With current technologies, elimination of radiation sources would lead to increased uncertainties in primary standards and calibration services. Although regulatory bodies tend to be focused on elimination, it is worth considering if it is possible to replace something higher risk (e.g., CsCl powder, Ra-226) with something lower risk (e.g., vitrified Cs-137 sources, Ho-166m*).* The challenge in this is partnering with organizations with the expertise to develop such alternative source types or configurations.

Related to this is the idea of extending the lifetime of sources, and/or using lower activity sources. In this situation, decaying sources are not replaced but the irradiators are maintained in use. Many NMIs/DIs already work with such a process, continuing to make measurements beyond 1, 2, and even 3 half-lives (Ir-192 is an obvious example, where the short half-life of 74 days means that source replacement is not realistic on the ideal one-half-life timescale). Primary standards may require a higher activity source but alternative monitoring systems may allow linkage back to a primary measurement while minimizing the added uncertainty in the dissemination of calibration services. Measurement techniques could possibly be developed to allow source activities below a level of concern/focus for regulatory bodies. Figure X shows the dissemination of well-chamber calibration coefficients for a single Ir-192 source over almost 7 half-lifes (~ factor 100 change in intensity). The uncertainty in measurements at the lowest source activity is not significantly different from measurements with a newly-installed source.

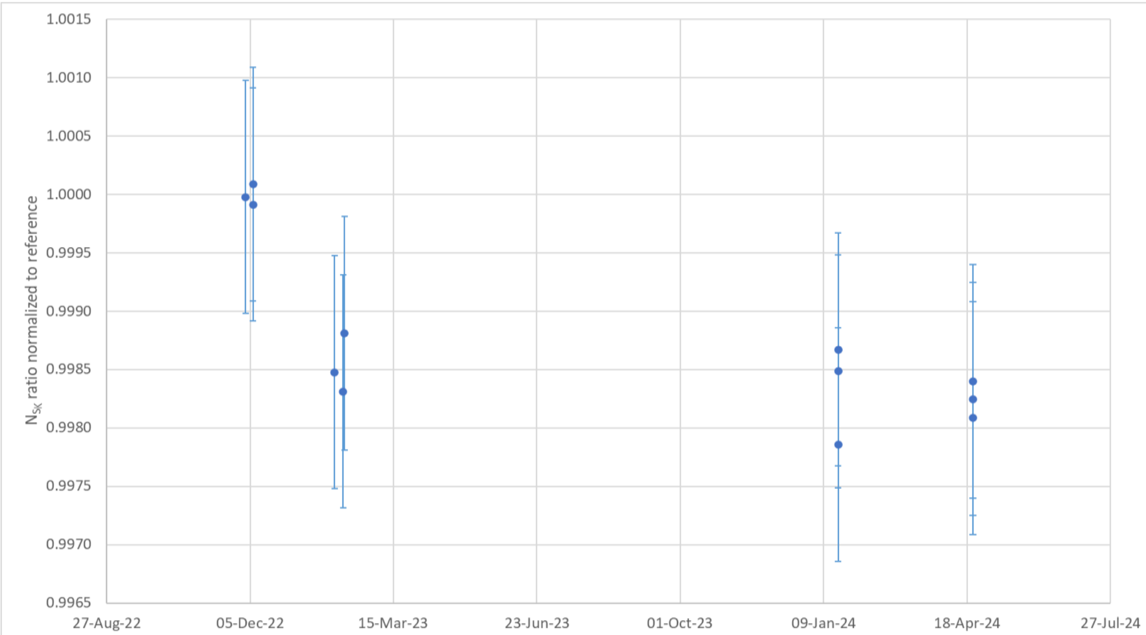

Figure 6. Stability of well-chamber calibration coefficients using a single Ir-192 source over multiple half-lifes. The calibration geometry remained constant, the only variable being the source activity. Data courtesy NRC.

An issue with extending the life of long half-life sealed sources is the problem of 'recommended working life' as defined in ISO2919 [ISO, 2012]. Some source manufacturers define a recommended working life of, for example, 15 years, for a sealed source. Some regulators insist that sources be removed from service after this period, and in many cases the Special Form status is withdrawn resulting in significantly more complex transportation requirements. In parallel with the challenge of the working life of a source, there can be regulatory limits on the working life of the irradiator itself. For complex radiation-delivery devices (e.g., HDR Ir-192 brachytherapy afterloaders) there are valid concerns related to control-system failure, radiation damage, etc., but many radioisotope irradiators are 'low-tech' electro-mechanical devices with reliable operation demonstrated over decades.

6.6 Calculational alternatives

A radical option is to consider whether sources can be eliminated altogether without a significant loss in operational performance. In this scenario the number of sources used in a calibration laboratory would be reduced by using calculated conversion factors to yield the detector response in one beam (e.g., Cs-137) based on measurements in another (e.g., Co-60). This is not a straightforward conversion and not only requires accurate validation of the procedure but increases the demands on the replacement radiation source. The latter, in particular, may not be realistic given calibration/use workloads currently reported by NMIs.

For example, the NRC (Canada) currently disseminates Cs-137 air kerma calibrations based on a theoretical conversion from a chamber calibrated in terms of air kerma in a Co-60 field [Shortt *et* *al*]. However, in this procedure, a Cs-137 field is still used for the calibration of user instruments; it would be significantly more challenging to predict the Cs-137 response of a wide range of client detectors based on measurements in Co-60, or an alternative radiation field.

Over the last two decades, the use of accurate, high resolution (spatial and temporal) simulations in ionizing radiation metrology has grown significantly, from limited determinations of correction factors to large-scale (whole facility) simulations. It is not unreasonable to extrapolate this trend and predict that simulations describing the complete radiation production process (e.g., from heated cathode to emitted x-ray beam) are possible on a 10-year timeframe. In such a scenario, the radiation output would be determined from input measurements of non-radiation quantities. Rabus *et al* [2025] provide a recent review of how metrology can be applied to medicine, which gives indications of the impact on ionizing radiation measurements.

6.7 Zero-radiation options

"Zero-radiation options" can be considered the hardware equivalent of calculational alternatives. In such scenarios, other measurement techniques are 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. Such measurements are not possible for commercial detectors but McNiven *et al* [2008], amongst others, proposed that high-resolution CT scanning could yield the sensitive volume of an ionization chamber, if accurate modelling of the electric field could be satisfactorily addressed. Non-radiation options are already in use, for example for range verification of an electrometer using current sources rather than different intensity radioactive sources. Relative measurements would seem to achievable but it would seem to be more challenging to find absolute determinations of detector response free of radiation fields.

6.8 Emerging (design-stage) devices

The discussion above addresses current technology, or devices that can be considered evolutions or extrapolations of what is available today. However, there are some experimental devices at various stages of development that could provide modes of operation closer to that of radioactive sources. The NASEM report (2021) goes into significant detail but the relatively small number of radiation devices currently available should give caution to the idea that a true equivalent source is round the corner. It would be sensible for the ionizing radiation metrology community to monitor device development and engage with developers at an early stage to maximise the metrological applicability of these emerging devices.

The concept of an accelerator on a chip was developed around 10 years ago and offers a very different accelerating structure to produce high-energy electron beams – laser-driven and miniaturized. Given the rapid development of chip-based instruments, allowing for single-particle control, one can project that it might be possible to produce very precise, in both intensity and energy, particle beams that could be ideal electrically-generated radiation sources. The literature to date (e.g., Sapra *et al*, 2020; Niedermayer *et al,* 2021) consists primarily of design studies, but Chlouba *et al* (2022) demonstrate production of an electron beam, albeit with a very wide energy spectrum.

7. Recommendations

Radioactive sources play an essential and justified role in ionizing radiation metrology. The examples outlined above show their metrological importance within different applications of ionizing radiation, both for the NMIs/DIs and the end user communities. The precision possible in the output intensity from a radioactive source is difficult, if not impossible to currently match with non-isotopic alternatives. This is particularly the case if particle energies greater than 500 keV are required (a majority of end-use applications of ionizing radiation).

However, since external pressures on the availability and operation of irradiation devices containing radioactive sources are likely to continue at current levels, if not increase, the following actions are recommended:

Recommendations – radioactive sources in metrology

- Ensure that the CCRI strategy i) reaffirms the value of radioactive sources in maintaining the worldwide IR metrology system and ii) highlights the need to ensure on-going access to calibration facilities.
- Identify state-of-the-art radiation delivery capabilities within the NMI community and expand access to this technology (i.e., duplicate what is already achievable).
- Investigate the possibility of using kV x-rays as a reference beam – acquire, collate and analyse data from multiple systems.
- Continue investigations of high-energy x-ray systems (as a potential alternative to Cs-137) and share information with community
- Support continued development of Monte Carlo radiation transport systems and investigations of 'end-to-end' simulations.
- Continue efforts to investigate how electrical systems can be used for detector characterization (e.g, the joint CCRI/CCEM group looking at well chamber relative calibration).
- Engage with radiation protection community on the future of Cs-137, identify if a roadmap for an RP system based on other radiation fields is feasible.
- Liaise with international bodies and professional associations to develop a long-term vision for dosimetry protocols.

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