UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

(FSME-13-002, January, Program, Radium-223)

January 10, 2013

ALL AGREEMENT STATES

NOTICE OF LICENSING DECISION ON RADIUM-223 DICHLORIDE (FSME-13-002)

Purpose: To inform Agreement States that the U.S. Nuclear Regulatory Commission (NRC) has issued a licensing decision on the medical use of radium-223 dichloride ($^{223}RaCl_2$) under 10 Code of Federal Regulations (CFR) Part 35 Subpart E, "Unsealed Byproduct Material – Written Directive Required". No action is required.

Background: $^{223}RaCl_2$ is currently an investigational radiopharmaceutical undergoing clinical trials in the United States. It is not yet approved by the U.S. Food and Drug Administration. $^{223}RaCl_2$ is being developed by Algeta ASA (Algeta) and will be commercialized, pending approval, under a global agreement with Bayer Pharma AG (Bayer). The intended application for $^{223}RaCl_2$ is for the treatment of skeletal metastases in advanced, castration-resistant prostate cancer. Radium-223 naturally self-targets bone metastases by virtue of its properties as a calcium-mimic and kills tumor cells by highly localized short-range alpha irradiation. $^{223}RaCl_2$ has the potential to be the first therapeutic radiopharmaceutical being administered primarily for its alpha emissions.

Discussion: NRC staff carefully reviewed the radiation safety aspects of the medical use of $^{223}RaCl_2$ to determine if the radiopharmaceutical should be licensed under Title 10 of the Code of Federal Regulations (10 CFR) Part 35, Subpart E, "Unsealed Byproduct material – Written Directive Required" or 10 CFR 35 Subpart K, "Other Medical Uses of Byproduct Material or Radiation From Byproduct Material". The Advisory Committee on the Medical Uses of Isotopes (ACMUI) evaluated the medical use of $^{223}RaCl_2$ and submitted a report recommending regulation under 10 CFR Part 35, Subpart E. See Enclosure 1. Bayer also submitted data and responses to questions from NRC staff for consideration. See Enclosure 2.

In addition to the data and responses provided by Bayer, NRC staff reviewed technical information obtained during meetings and other correspondence with Bayer and Algeta representatives. NRC staff's current understanding is that unit dosages of $^{223}RaCl_2$ will be shipped to clinical trial sites from Algeta's manufacturing facility in Norway. Bayer further indicated that at some future date it may ship multi-dosage vials to the United States for commercial distribution of unit dosages to medical use licensees. The current methods of distribution (unit doses) preclude the need for end users to manipulate $^{223}RaCl_2$. NRC staff also discussed and evaluated issues related to such matters as activity measurements, contamination surveys, long-lived contaminants, radon volatility, patient release criteria, training, available dosimetry information, and administrative procedures before reaching its licensing decision.

Based on available information, NRC staff agreed with the ACMUI recommendation and determined that licensing under 10 CFR Part 35, Subpart E is appropriate because the medical use of $^{223}RaCl_2$ is similar to other commonly used beta and photon-emitting therapeutic radiopharmaceuticals. The staff has also determined that under current regulations, physicians who are approved for the use of any beta emitter or any photon-emitting radionuclide with a photon energy less than 150 keV under 10 CFR 35.390, "Training for Use of Unsealed Byproduct Material for which a Written Directive is Required," or 10 CFR 35.396, "Training for the Parenteral Administration of Unsealed Byproduct Material Requiring a Written Directive," can be authorized for the medical use of $^{223}RaCl_2$.

If NRC becomes aware of future developments related to the production, distribution, or medical use of $^{223}RaCl_2$ that may negatively impact radiation safety, NRC staff will consider revisiting this licensing decision for any additional actions.

If you have any questions regarding this correspondence, please contact me at (301) 315-3340 or the individual named below.

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Enclosures:
1. ACMUI Report on Licensing for Radium-223 Dichloride, November 20, 2012
2. Radium-223 Dichloride: Bayer Responses to NRC Questions, November 8, 2012

Nuclear Regulatory Commission (NRC)
Advisory Committee on the Medical Uses of Isotopes (ACMUI)
Report on Licensing for Radium-223 (^{223}Ra) Dichloride
November 20, 2012

Subcommittee Members

Darice Bailey, Susan Langhorst, Steven Mattmuller, Christopher Palestro, Orhan Suleiman, Bruce Thomadsen, James Welsh, and Pat Zanzonico (Chair)

Charge

To provide recommendations on licensing of radium-223 (^{223}Ra) dichloride ($^{223}RaCl_2$).

Summary Statement and Recommendations

$^{223}RaCl_2$, currently a non-approved investigational agent undergoing clinical trials in the United States and elsewhere, represents a first-in-class, alpha particle-emitting therapeutic radiopharmaceutical. Based on relevant physical and biological considerations as well as clinical data to date, its intended indication is treatment of skeletal metastases in advanced, castrate-resistant prostate cancer, delivering high biologically effective doses to malignant cells in bone with relative sparing of hematopoietic marrow and other normal tissues. The injection volume for the body weight-adjusted dose of $^{223}RaCl_2$ (50 kBq/kg (1.35 μCi/kg)) is determined based on the vendor-supplied activity concentration in a pre-calibrated solution. Nonetheless, to minimize the probability of a therapeutic misadministration, an appropriate radioassay system (e.g., a dose calibrator) for measurement of the ^{223}Ra activity prior to its administration and the residual activity following its administration is recommended, as with any therapeutic radiopharmaceutical. This would require calibration of the radioassay system using, for example, a National Institute of Standards and Technology (NIST)-traceable ^{223}Ra standard. $^{223}RaCl_2$ does not differ significantly in terms of clinical use and management, radiation safety, and logistics from currently approved radiopharmaceuticals. Therefore, physicians already authorized to use therapeutic radiopharmaceuticals under § 35.390 or § 35.396 already have the requisite education, training, and experience to safely and effectively use $^{223}RaCl_2$. As such, licensing of authorized users of $^{223}RaCl_2$ under § 35.390 (Category (G)(3) or (G)(4)), or § 35.396(d)(2), is therefore recommended.

Clinical Background

Skeletal metastases commonly occur in many different malignancies, particularly advanced castrate-resistant prostate cancer, and are associated with severe morbidity and mortality (1). The resulting bone pain and possible fractures severely compromise the patient's quality of life and thus require effective treatment. Various non-radiotherapeutic modalities are available such as analgesics, hormone therapy, orchiectomy, cytostatic and cytotoxic drugs, bisphosphonates, and surgery, but are not universally effective (2). External-beam radiotherapy is suitable only for well-defined localized bone metastases, and extended-field radiation for more generalized skeletal disease is often accompanied by excessive toxicity (3). In the setting of widely disseminated skeletal metastases, systemic, bone-targeting radionuclide therapies have emerged as a safe, convenient, and reasonably effective palliative and therapeutic modality (4, 5). Current radiopharmaceuticals for palliation of painful skeletal metastases are exclusively beta particle emitters and include phosphorus-32 (^{32}P) sodium phosphate, strontium-89 (^{89}Sr) strontium chloride (Metastron™), yttrium-90 (^{90}Y) yttrium citrate, tin-117m (^{117m}Sn) diethylenetriamine pentaacetic acid (DTPA), samarium-153 (^{153}Sm) lexidronam (Quadramet™), thulium-170 (^{170}Tm) ethylene diamine

tetramethylene phosphonate (EDTMP), lutecium-177 (^{177}Lu) EDTMP, and rhenium-186 (^{186}Re) and rhenium-188 (^{188}Re) hydroxyethylidene diphosphonate (HEDP) (4,5). Currently approved radiopharmaceuticals for bone pain palliation include ^{32}P sodium phosphate, ^{89}Sr strontium chloride, and ^{153}Sm lexidronam, while the others remain investigational.

$^{223}RaCl_2$ (half-life: 11.43 days) is a calcium-mimetic alpha-particle emitter[1] which either avidly localizes in bone (particularly areas of active bone re-modeling typical of skeletal metastases)[2] or is rapidly excreted (6). ^{223}Ra has only short-lived radioactive progeny, radon-219 (^{219}Rn) (physical half-life: 3.96 seconds), polonium-215 (^{215}Po) (0.00178 second), bismuth-211 (^{211}Bi) (2.17 minutes), lead-211 (^{211}Pb) (36.1 minutes) and thallium-207 (^{207}Tl) (4.77 minutes) (6). The alpha emissions of ^{223}Ra and its progeny are short-range, high-linear energy transfer (LET), and high-relative biological effectiveness (RBE) radiations and should deliver highly localized, highly cytocidal radiation to metastatic cells in bone with relative sparing of the near-by bone marrow (6). In addition, ^{223}Ra and its progeny emit a number of externally countable and imageable x- and gamma-rays (81, 84, 154, and 269 keV) usable for pharmacokinetic studies, radiation dosimetry, and activity calibration (7). In principle, therefore, $^{223}RaCl_2$ potentially may provide more effective, less toxic palliation of skeletal metastases than current beta particle-emitting radiopharmaceuticals. Importantly, if approved by the US Food and Drug Administration (FDA), it would represent the very first alpha particle-emitting radiopharmaceutical in routine (i.e., non-investigational) clinical use[3] in the United States.

$^{223}RaCl_2$ has been extensively studied in patients in Europe as well as the United States (6, 8-13). Two open-label Phase-I trials (37 patients) and three double-blind Phase-II trials (255 patients) assessed radiation dosimetry, safety, and efficacy (decline in serum levels of prostate-specific antigen (PSA) and bone alkaline phosphatase (ALP) and prolongation of survival). Injected single doses varied from 5.2-252 kBq/kg (0.14-6.8 μCi/kg) body mass. Repeated treatment regimens varied in number of doses and time-dose schedule. A Phase-II clinical trial in patients with symptomatic, hormone-refractory prostate cancer showed improvement in survival, PSA levels, and ALP levels compared with placebo (i.e., no treatment), with no differences in hematologic toxicity. An international double-blind, placebo-controlled randomized trial (ALpharadin in SYMptomatic Prostate CAncer [ALSYMPCA]) was subsequently undertaken to compare $^{223}RaCl_2$ with placebo in patients with symptomatic, androgen-independent prostate cancer with skeletal metastases. The study was stratified based on ALP levels at registration, bisphosphonate use, and prior treatment with docetaxel. A total of 921 patients from 19 countries were enrolled, with overall survival being the primary endpoint. Importantly, the data demonstrated a statistically significant reduction in the risk of death for patients randomized to the $^{223}RaCl_2$ arm of the study (hazard ratio = 0.695; p = 0.00185), with a median overall survival of 14 months versus 11.2 months in the placebo arm. The overall survival benefit was seen across all sub-groups. The time

[1] Other potential clinical alpha particle-emitting, bone-seeking agents include thorium-227 (^{227}Th) EDTMP, ^{227}Th tetraazacyclododecane tetra(methylene) phosphonic acid (DOTMP), and ^{212}Bi DOTMP (4,5) but these are not as advanced in terms of clinical use as ^{223}Ra chloride.

[2] The propensity for internalized radium to localize in bone has long been recognized. For example, radium watch dial painters in the 1920s and 30s subsequently developed bone cancers and leukemias as a result of ingesting the radium-266 (^{226}Ra)-containing paint when "twirling" their paint brush tips to a fine point in their mouths. Importantly, ^{226}Ra has a much longer half-life, 1,600 years, than ^{223}Ra, a critically important factor related to its carcinogenecity in bone.

[3] The FDA's revised policy on "Expanded Access to Investigational Drugs for Treatment Use" (21 CFR Parts 312 and 316, Federal Register Vol 74, No 155 August 13, 2009) allows the use of agents such as $^{223}RaCl_2$ to be expanded to a larger population beyond compassionate use in individual patients, but such "expanded-access" use would still require compliance with the Investigational New Drug (IND) record-keeping, safety, ethical, and other requirements associated with human-subject experimentation.

to a skeletal-related event was also significantly longer for patients in the $^{223}RaCl_2$ versus placebo arm, 13.6 versus 8.4 months (p = 0.00046). The time to disease progression based on PSA and ALP levels was also significantly longer in the $^{223}RaCl_2$ arm. The patients randomized to $^{223}RaCl_2$ treatment tolerated it well. Both hematologic side-effects (grade-3 or -4 anemia, neutropenia, thrombocytopenia) and gastrointestinal side-effects (nausea, vomiting, diarrhea) did not occur with any greater frequency than with placebo. The former are related to localization of $^{223}RaCl_2$ in bone while the latter are related to its excretion through the intestines. It is noteworthy that the foregoing side-effects associated with therapeutic administration of $^{223}RaCl_2$ are hardly unique. For example, the dose-limiting toxicity associated with iodine-131 (^{131}I) iodide treatment of metastatic thyroid cancer and of radioimmunotherapy of cancer generally is most commonly myelosuppression. Nuclear Medicine physicians, Radiation Oncologists, and other physicians who administer radionuclide therapy are therefore already highly experienced in effectively managing such side-effects.

To summarize the clinical findings to date (6, 8-13), more than 1,000 prostate cancer patients have been treated with $^{223}RaCl_2$ with single and repeated treatments with significant PSA declines and prolonged survival benefit, without therapy-limiting myelotoxicity, gastrointestinal toxicity or other significant normal-tissue toxicity compared to placebo. Although not yet approved by the FDA for routine clinical use, this investigational alpha particle-emitting agent appears to be a promising bone-targeted radionuclide therapy.

Radiation Safety and Logistical Considerations

$^{223}RaCl_2$ and its progeny emit 95%, 4%, and 1% of their total radiation energy in the form of alpha particles, beta particles, and x- and gamma-rays, respectively (6). Alpha particles have very short ranges (of the order of 10 □m in bone and soft tissue) and thus present no external, or direct, radiation hazard. As long as standard universal precautions[4] are observed and internalization is avoided, alpha particles pose no significant radiologic hazard overall - despite their high LET and high RBE. Importantly, this will likewise be the case for alpha particle-emitting radiopharmaceuticals in general. Universal precautions would also safeguard against the internal radiologic hazard of the small beta-particle component among the emissions of ^{223}Ra and its progeny. X- and gamma-rays are, of course, much more penetrating than alpha- and beta-particles but are emitted in very low abundance by ^{223}Ra and its progeny, with energies comparable to those of common diagnostic radionuclides such as a technetium-99m (^{99m}Tc) (gamma-ray energy: 140 keV) and fluorine-18 (^{18}F) (511 keV). At the same time, the single-dose administered activities of $^{223}RaCl_2$, 50 kBq/kg (1.35 μCi/kg) body mass or 3,500 kBq (95 μCi) total for a 70-kg Standard Man, are several orders of magnitude lower than that of routine diagnostic radiopharmaceuticals (for which the administered activities are of the order of 370 MBq = 370,000 kBq (10 mCi = 10,000 μCi)). Thus, for such low-abundance x- and gamma-rays and such low activities, the external, or direct, radiation exposure and shielding requirements for $^{223}RaCl_2$ and its progeny are no greater than those for routinely used diagnostic radiopharmaceuticals - even though $^{223}RaCl_2$ is a therapeutic agent (14). Further, patients do not require medical confinement following $^{223}RaCl_2$ administration and may be treated on an outpatient basis.

As noted, ^{223}Ra has a physical half-life of 11.43 days; its radioactive progeny, ^{219}Rn, ^{215}Po, ^{211}Bi, ^{211}Pb, and ^{207}Tl, have much shorter half-lives, ranging from 0.00178 second to 36.1 minutes. ^{223}Ra and its progeny thus have sufficiently short half-lives for on-site decay-in-storage of radioactively contaminated waste followed by disposal as non-radioactive waste. At the same time, the x- and gamma-rays emitted by ^{223}Ra and its progeny, although low in abundance, are sufficient for assay

[4] Universal precautions (e.g., wearing of disposable gloves) constitute a method of infection control in which all human fluids, tissue etc are handled as if they are know to be infected with transmissible pathogens.

of any such waste. This can be done using conventional survey meters such as Geiger (G-M) counters - in order to verify that the exposure (or count) rates from contaminated or possibly contaminated waste are at or below background levels. Likewise, surveys of ambient exposure rates and of removable radioactive contamination (i.e., "wipes tests") associated with the use of $^{223}RaCl_2$ may be performed with instrumentation (surveys meters and well counters, respectively) already routinely available in Nuclear Medicine facilities.

$^{223}RaCl_2$ is a simple salt of radium, and not a radiolabeled molecule. It therefore requires no synthesis or other preparation by the clinical site and does not undergo any sort of chemical decomposition. Quality control procedures for determination of radiochemical purity and special storage conditions (e.g., refrigeration) are therefore not required for $^{223}RaCl_2$. As distributed by Bayer Healthcare (Pittsburgh, PA), it is provided in a crimped glass vial as an injectable isotonic solution with an activity concentration of 1,000 kBq/ml (27 μCi/ml) at calibration (15). The recommended administered activity is 50 kBq/kg (1.35 μCi/kg) body mass (15). A patient-specific volume of injectate, calculated using the following formula, is drawn directly from the vendor-provided $^{223}RaCl_2$ solution (15):

$$\text{Volume to inject (ml)} = \frac{\text{Body mass (kg) x 50 kBq/kg}}{\text{Decay factor x 1000 kBq/ml}}$$

where the decay factor is the fractional decay factor (as derived from a vendor-provided "decay factor table," for example) for the time interval from the date and time of calibration of the $^{223}RaCl_2$ to the planned date and time of administration.

Implicit in the foregoing dose-prescription algorithm is that the user is *not* required to assay the ^{223}Ra activity prior to its administration or the residual activity following its administration, as is typically done in Nuclear Medicine (especially for therapeutic administrations). Bayer Healthcare has asserted that measurement of the ^{223}Ra activities is *not* necessary, as the patient-specific dose corresponds to a calculated volume of the vendor-supplied solution with the vendor-specified pre-calibrated activity concentration (15). Bayer Healthcare has further asserted that such activity measurements would be potentially unreliable because (a) a setting for ^{223}Ra is not provided on currently available dose calibrators and (b) the pre-administration activity and, in particular, the residual activity would be too low (in the tens of kBq (μCi) range) to measure reliably (15). ^{223}Ra does, however, emit measurable x- and gamma-rays (7), and dose calibrators can thus be calibrated by the end user for ^{223}Ra using a National Institute of Standards and Technology (NIST)-traceable ^{223}Ra standard (16). In addition, assay of the pre-administration and residual ^{223}Ra activities, even if inexact, would help avoid potentially "catastrophic" misadministrations. By verifying that the actual pre-administration activity is consistent with the prescribed activity and that the residual activity is insignificant, clinically important over-dosing and/or under-dosing of the patient (e.g., due to mis-calibration of the vendor-supplied $^{223}RaCl_2$ solution or inaccurate drawing of the patient-specific injectate) as well as administration of an incorrect radionuclide could likely be avoided. Such activity assays would thus provide an additional level of safety at the treatment site independent of the vendor's manufacturing and calibration procedures. In a therapy setting, such redundancy, or cross-checking, is certainly prudent and is standard in Nuclear Medicine, especially in therapeutic applications. An appropriate radioassay system (e.g., a dose calibrator) for measurement of the ^{223}Ra activity prior to its administration or the residual activity following its administration is therefore recommended for the therapeutic use of $^{223}RaCl_2$.

Licensing Considerations

As noted, $^{223}RaCl_2$ represents a first-in-class - that is, an alpha particle-emitting - radiopharmaceutical. As such, it raises the issue of the appropriate NRC licensure for authorized

users of this agent. $^{223}RaCl_2$ should be licensed under § 35.300 of the Code of Federal Regulations (CFR) (Appendix 1). Within the NRC's regulatory framework, there would appear to be several different licensing options for $^{223}RaCl_2$, namely, authorized users who meet training and experience requirements under § 35.390 (Appendix 2), § 35.396 (Appendix 3), or § 35.1000 A (Appendix 4). Despite its alpha-particle emissions, $^{223}RaCl_2$ does not differ fundamentally from current routinely used therapeutic radiopharmaceuticals. Given the similarities in clinical use and radiation safety considerations (as detailed above) between $^{223}RaCl_2$ and current therapeutic radiopharmaceuticals, the use of which is authorized under § 35.390 (Appendix 2), the use of $^{223}RaCl_2$ should likewise be authorized under § 35.390. It would appear that either Category (3) or (4) in § 35.390 would be appropriate for $^{223}RaCl_2$. Category (3) applies to, "Parenteral administration of any beta emitter, or a photon- emitting radionuclide with a photon energy less than 150 keV, for which a written directive is required"; it does not explicitly include or exclude alpha-particle emitters, however. Since ^{223}Ra progeny emit beta particles as well as alpha particles, $^{223}RaCl_2$ technically might be considered a "Category (3)" radiopharmaceutical. However, even if "Category (3)" were interpreted as not applying to $^{223}RaCl_2$, Category (4), which applies to, "Parenteral administration of any other radionuclide, for which a written directive is required," would certainly apply. This same conclusion applies to § 35.396 (Appendix 3). Licensing of $^{223}RaCl_2$ under § 35.1000 (Appendix 4) is not an appropriate option as that would imply it differs significantly in terms of clinical use and management, radiation safety, and logistics from current therapeutic radiopharmaceuticals, and this is not the case. Physicians already authorized to use such radiopharmaceuticals under § 35.390 or § 35.396 already have the requisite education, training, and experience to safely and effectively use $^{223}RaCl_2$, and should not be required to provide additional training-and-experience documentation to be licensed for its use.

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Appendix 1

§ 35.300 Use of unsealed byproduct material for which a written directive is required.

A licensee may use any unsealed byproduct material prepared for medical use and for which a written directive is required that is-

(a) Obtained from:

(1) A manufacturer or preparer licensed under § 32.72 of this chapter or equivalent Agreement State requirements; or

(2) A PET radioactive drug producer licensed under § 30.32(j) of this chapter or equivalent Agreement State requirements; or

(b) Excluding production of PET radionuclides, prepared by:

(1) An authorized nuclear pharmacist;

(2) A physician who is an authorized user and who meets the requirements specified in §§ 35.290, 35.390, or

(3) An individual under the supervision, as specified in § 35.27, of the authorized nuclear pharmacist in paragraph (b)(1) of this section or the physician who is an authorized user in paragraph (b)(2) of this section; or

(c) Obtained from and prepared by an NRC or Agreement State licensee for use in research in accordance with an Investigational New Drug (IND) protocol accepted by FDA; or

(d) Prepared by the licensee for use in research in accordance with an Investigational New Drug (IND) protocol accepted by FDA.

[67 FR 20370, Apr. 24, 2002, as amended at 68 FR 19324, Apr. 21, 2003; 69 FR 55738, Sep. 16, 2004; 71 FR 15009, Mar. 27, 2006; 72 FR 55932 Oct. 1, 2007]

Appendix 2

§ 35.390 Training for use of unsealed byproduct material for which a written directive is required.

Except as provided in § 35.57, the licensee shall require an authorized user of unsealed byproduct material for the uses authorized under § 35.300 to be a physician who-

(a) Is certified by a medical specialty board whose certification process has been recognized by the Commission or an Agreement State and who meets the requirements in paragraphs (b)(1)(ii)(G) and (b)(2) of this section. (Specialty boards whose certification processes have been recognized by the Commission or an Agreement State will be posted on the NRC's Web page.) To be recognized, a specialty board shall require all candidates for certification to:

(1) Successfully complete residency training in a radiation therapy or nuclear medicine training program or a program in a related medical specialty. These residency training programs must include 700 hours of training and experience as described in paragraphs (b)(1)(i) through (b)(1)(ii)(E) of this section. Eligible training programs must be approved by the Residency Review Committee of the Accreditation Council for Graduate Medical Education, the Royal College of Physicians and Surgeons of Canada, or the Committee on Post-Graduate Training of the American Osteopathic Association; and

(2) Pass an examination, administered by diplomates of the specialty board, which tests knowledge and competence in radiation safety, radionuclide handling, quality assurance, and clinical use of unsealed byproduct material for which a written directive is required; or

(b)(1) Has completed 700 hours of training and experience, including a minimum of 200 hours of classroom and laboratory training, in basic radionuclide handling techniques applicable to the medical use of unsealed byproduct material requiring a written directive. The training and experience must include-

(i) Classroom and laboratory training in the following areas-

(A) Radiation physics and instrumentation;

(B) Radiation protection;

(C) Mathematics pertaining to the use and measurement of radioactivity;

(D) Chemistry of byproduct material for medical use; and

(E) Radiation biology; and

(ii) Work experience, under the supervision of an authorized user who meets the requirements in §§ 35.57, 35.390, or equivalent Agreement State requirements. A supervising authorized user, who meets the requirements in § 35.390(b), must also have experience in administering dosages in the same dosage category or categories (*i.e.*, § 35.390(b)(1)(ii)(G)) as the individual requesting authorized user status. The work experience must involve-

(A) Ordering, receiving, and unpacking radioactive materials safely and performing the related radiation surveys;

(B) Performing quality control procedures on instruments used to determine the activity of dosages, and performing checks for proper operation of survey meters;

(C) Calculating, measuring, and safely preparing patient or human research subject dosages;

(D) Using administrative controls to prevent a medical event involving the use of unsealed byproduct material;

(E) Using procedures to contain spilled byproduct material safely and using proper decontamination procedures;

(F) [Reserved]

(G) Administering dosages of radioactive drugs to patients or human research subjects involving a minimum of three cases in each of the following categories for which the individual is requesting authorized user status-

(*1*) Oral administration of less than or equal to 1.22 gigabecquerels (33 millicuries) of sodium iodide I-131, for which a written directive is required;

(*2*) Oral administration of greater than 1.22 gigabecquerels (33 millicuries) of sodium iodide I-131[2];

(*3*) Parenteral administration of any beta emitter, or a photon- emitting radionuclide with a photon energy less than 150 keV, for which a written directive is required; and/or

(*4*) Parenteral administration of any other radionuclide, for which a written directive is required; and

(2) Has obtained written attestation that the individual has satisfactorily completed the requirements in paragraphs (a)(1) and (b)(1)(ii)(G) or (b)(1) of this section, and has achieved a level of competency sufficient to function independently as an authorized user for the medical uses authorized under § 35.300. The written attestation must be signed by a preceptor authorized user who meets the requirements in §§ 35.57, 35.390, or equivalent Agreement State requirements. The preceptor authorized user, who meets the requirements in § 35.390(b) must have experience in administering dosages in the same dosage category or categories (*i.e.*, § 35.390(b)(1)(ii)(G)) as the individual requesting authorized user status.

[67 FR 20370, Apr. 24, 2002, as amended at 68 FR 19325, Apr. 21, 2003; 68 FR 75389, Dec. 31, 2003; 69 FR 55738, Sep. 16, 2004; 70 FR 16364, Mar. 30, 2005; 71 FR 15009, Mar. 27, 2006; 74 FR 33905, Jul. 14, 2009]

[2] Experience with at least 3 cases in Category (G)(*2*) also satisfies the requirement in Category (G)(*1*)

Appendix 3

§ 35.396 Training for the parenteral administration of unsealed byproduct material requiring a written directive.

Except as provided in § 35.57, the licensee shall require an authorized user for the parenteral administration requiring a written directive, to be a physician who-

(a) Is an authorized user under § 35.390 for uses listed in §§ 35.390(b)(1)(ii)(G)(3) or 35.390(b)(1)(ii)(G)(4), or equivalent Agreement State requirements; or

(b) Is an authorized user under §§ 35.490, 35.690, or equivalent Agreement State requirements and who meets the requirements in paragraph (d) of this section; or

(c) Is certified by a medical specialty board whose certification process has been recognized by the Commission or an Agreement State under §§ 35.490 or 35.690, and who meets the requirements in paragraph (d) of this section.

(d)(1) Has successfully completed 80 hours of classroom and laboratory training, applicable to parenteral administrations, for which a written directive is required, of any beta emitter, or any photon-emitting radionuclide with a photon energy less than 150 keV, and/or parenteral administration of any other radionuclide for which a written directive is required. The training must include—

(i) Radiation physics and instrumentation;

(ii) Radiation protection;

(iii) Mathematics pertaining to the use and measurement of radioactivity;

(iv) Chemistry of byproduct material for medical use; and

(v) Radiation biology; and

(2) Has work experience, under the supervision of an authorized user who meets the requirements in §§ 35.57, 35.390, 35.396, or equivalent Agreement State requirements, in the parenteral administration, for which a written directive is required, of any beta emitter, or any photon-emitting radionuclide with a photon energy less than 150 keV, and/or parenteral administration of any other radionuclide for which a written directive is required. A supervising authorized user who meets the requirements in § 35.390 must have experience in administering dosages as specified in §§ 35.390(b)(1)(ii)(G)(3) and/or 35.390(b)(1)(ii)(G)(4). The work experience must involve—

(i) Ordering, receiving, and unpacking radioactive materials safely, and performing the related radiation surveys;

(ii) Performing quality control procedures on instruments used to determine the activity of dosages, and performing checks for proper operation of survey meters;

(iii) Calculating, measuring, and safely preparing patient or human research subject dosages;

(iv) Using administrative controls to prevent a medical event involving the use of unsealed byproduct material;

(v) Using procedures to contain spilled byproduct material safely, and using proper decontamination procedures; and

(vi) Administering dosages to patients or human research subjects, that include at least 3 cases involving the parenteral administration, for which a written directive is required, of any beta emitter, or any photon-emitting radionuclide with a photon energy less than 150 keV and/or at least 3 cases involving the parenteral administration of any other radionuclide, for which a written directive is required; and

(3) Has obtained written attestation that the individual has satisfactorily completed the requirements in paragraph (b) or (c) of this section, and has achieved a level of competency sufficient to function independently as an authorized user for the parenteral administration of unsealed byproduct material requiring a written directive. The written attestation must be signed by a preceptor authorized user who meets the requirements in §§ 35.57, 35.390, 35.396, or equivalent Agreement State requirements. A preceptor authorized user, who meets the requirements in § 35.390, must have experience in administering dosages as specified in §§ 35.390(b)(1)(ii)(G)(3) and/or 35.390(b)(1)(ii)(G)(*4*).

[70 FR 16365, Mar. 30, 2005; 71 FR 15010. Mar. 27, 2006; 74 FR 33906, Jul. 14, 2009]

Appendix 4

§ 35.1000 Other medical uses of byproduct material or radiation from byproduct material.

A licensee may use byproduct material or a radiation source approved for medical use which is not specifically addressed in subparts D through H of this part if--

(a) The applicant or licensee has submitted the information required by § 35.12(b) through (d); and

(b) The applicant or licensee has received written approval from the Commission in a license or license amendment and uses the material in accordance with the regulations and specific conditions the Commission considers necessary for the medical use of the material.

Radium-223 Dichloride:
Bayer Responses to NRC Questions

November 8, 2012

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1. Introduction

On September 19, 2012, Bayer received 9 questions from the United States Nuclear Regulatory Commission (U.S. NRC). Bayer responses to the questions are provided below in a question and response format.

2. NRC Questions and Bayer Responses

2.1 NRC Question 1

1. Please provide data to support the use of ion chamber dose calibrators for activity measurements of radium-223 dichloride. In addition, please provide the standard dose calibrator procedure that will be supplied to clients that includes guidance on:
    a. Determination of the energy setting that will be used for dose calibrator measurements.
    b. Geometrical testing for plastic syringes used for radium-223 dichloride.
    c. Description of NIST traceable radium-223 calibration standard provided to clients for measurement (e.g., liquid radium-223 in syringe).

Bayer Response:

The accurate measurement of radium-223 activity is assured by calibration of dose calibrators using a NIST-traceable reference standard which is provided to the end user. Licensees possess different dose calibrators from various manufacturers, therefore the calibration factor (i.e., dial setting) for radium-223 may differ from instrument to instrument and even for the same instrument installed at different clinical sites. Consequently, each center must determine the radium-223 dial setting on their own dose calibrator(s).

For determination of the radium-223 dial setting, the licensees will receive radium-223 dichloride solution. The activity of radium-223 will be provided along with instructions for determining an accurate dial setting.

In order to obtain data regarding the accuracy of activity measurements of dose calibrators commonly available in nuclear medicine facilities in the United States, various activities of radium-223 were measured at two Nuclear Diagnostics Products (NDP) facilities located in NJ (Cherry Hill and Rockaway). Both radiopharmacies have state of the art equipment and cleanrooms and are fully compliant with New Jersey Department of Environmental Protection and New Jersey Board of Pharmacy regulations and requirements. All testing was performed under the immediate supervision of the pharmacy Radiation Safety Officers by highly qualified nuclear pharmacists and nuclear pharmacy technicians.

Each NDP facility received 4 vials containing NIST-traceable radium-223 activities. These reference sources were used by the facilities to determine the appropriate dial setting to be used for accurate activity measurements. The Cherry Hill facility used a Capintec CRC-25R and the Rockaway facility used a Capintec CRC-15R dose calibrator for this study; these dose calibrators are calibrated and routinely quality controlled in accordance with the manufacturer's instructions. The reference source was placed in the dose calibrator and the

dial setting adjusted until the activity reading matched that of the supplied reference source. The dial setting on both instruments at both NDP facilities was determined to be 264. This dial setting was used for all subsequent activity measurements.

A typical unit dosage of radium-223 dichloride will be supplied to the end user medical licensee by a radiopharmacy in a syringe containing the required patient specific activity, e.g., 3.5 MBq (0.095mCi) for a 70 kg patient at time of administration. In order to simulate supplied unit dosages and measure activity as decay occurs over a period of time, two syringes were prepared, a 10 cc and 5 cc syringe, at each NDP facility. Each syringe contained approximately 2 MBq (0.054mCi) of radium-223 dichloride solution in a volume of 3.5 cc. Both syringes were counted weekly at each facility to determine the accuracy of the dose calibrator at each activity level of radium-223. Therefore, the accuracy of the dose calibrator could be ascertained both pre-administration and post-administration when the activity remaining in the syringe, i.e., the residual activity, is expected to be 1% of the administered activity (an activity of 35 kBq (0.00095mCi) for a typical 3.5 MBq (0.095mCi) administration to a 70 kg patient).

The dose calibrator results are provided in Table 1 for the Cherry Hill facility and in Table 2 for the Rockaway facility. At each timepoint, the measured activity represents the average of 3 activity measurements.

Table 1: Dose Calibrator measurements of radium-223 activity in syringes using a Capintec CRC-25R (performed at Cherry Hill)

Elapsed Time (days)	Expected Activity (E)		Measured Activity (M)		% Deviation*	
	10 cc	5 cc	10 cc	5 cc	10 cc	5 cc
0	2.14 MBq	2.08 MBq	2.14 MBq	2.08 MBq	0%	0%
7	1.40 MBq	1.36 MBq	1.39 MBq	1.35 MBq	-0.6%	-0.4%
14	0.91 MBq	0.89 MBq	0.90 MBq	0.89 MBq	-1.5%	0.2%
21	0.60 MBq	0.58 MBq	0.60 MBq	0.59 MBq	0.2%	1.6%
28	0.39 MBq	0.38 MBq	0.39 MBq	0.38 MBq	-0.8%	1.3%
35	0.26 MBq	0.25 MBq	0.26 MBq	0.25 MBq	0%	1.7%
42	0.17 MBq	0.16 MBq	0.17 MBq	0.16 MBq	0%	0.6%
49	0.11 MBq	0.11 MBq	0.11 MBq	0.11 MBq	0.9%	0.3%
56	0.071 MBq	0.069 MBq	0.072 MBq	0.070 MBq	1.3%	1.3%
63	0.046 MBq	0.045 MBq	0.043 MBq	0.043 MBq	-6.5%	-4.4%
70	0.030 MBq	0.030 MBq	0.030 MBq	0.030 MBq	-1.3%	1.7%

* % deviation is equal to 100 x (M-E)/E

Table 2: Dose Calibrator measurements of radium-223 activity in syringes using a Capintec CRC-15R (performed at Rockaway)

Elapsed Time (days)	Expected Activity (E)		Measured Activity (M)		% Deviation*	
	10 cc	5 cc	10 cc	5 cc	10 cc	5 cc
0	1.76 MBq	1.84 MBq	1.76 MBq	1.84 MBq	0%	0%
7	1.15 MBq	1.20 MBq	1.14 MBq	1.21 MBq	-0.7%	0.5%
14	0.75 MBq	0.79 MBq	0.75 MBq	0.79 MBq	-0.5%	-0.1%
21	0.49 MBq	0.52 MBq	0.49 MBq	0.51 MBq	-1.2%	-1.2%
28	0.32 MBq	0.34 MBq	0.32 MBq	0.33 MBq	-0.6%	-1.2%
35	0.21 MBq	0.22 MBq	0.21 MBq	0.22 MBq	0.5%	0.9%
42	0.14 MBq	0.14 MBq	0.14 MBq	0.14 MBq	0.7%	0.7%
49	0.090 MBq	0.094 MBq	0.086 MBq	0.089 MBq	-3.9%	-4.9%
56	0.057 MBq	0.061 MBq	0.052 MBq	0.057 MBq	-8.8%	-6.6%

* % deviation is equal to 100 x (M-E)/E

In summary, the data presented in Table 1 and Table 2 indicate that standard dose calibrators that have been appropriately calibrated for radium-223 can accurately measure radium-223 activities down to 30 kBq. All measured activity values are within ± 10% of their expected values. Therefore, dose calibrator measurements of the unit dose activity prior to its administration and the residual activity following its administration can be accurately made.

A similar series of dose calibrator measurements of radium-223 were also made by Algeta ASA (Algeta) using a Capintec CRC-15R. This dial setting of the instrument was determined using a NIST-traceable radium-223 reference standard; a dial setting of 263 was obtained and used for all subsequent activity measurements. Prior to each set of measurements, daily tests were performed on the instrument using long-lived reference sources according to Algeta's QC procedures. The data are given in Table 3; all measured activity values are within ± 10% of their expected values. At each timepoint, the measured activity represents the average of 3 activity measurements. These data indicate, as above, that standard dose calibrators can accurately measure radium-223 activities down to 35 kBq, corresponding to the residual activity expected after a typical activity administration of a unit dose of radium-223 dichloride.

Table 3: Dose Calibrator measurements of radium-223 activity in a vial using a Capintec CRC-15R (performed by Algeta)

Elapsed Time (days)	Expected Activity (E)	Measured Activity (M)	% Deviation*
0	6.53 MBq	6.55 MBq	0.19%
4	5.13 MBq	5.13 MBq	0.12%
14	2.80 MBq	2.82 MBq	0.73%
21	1.83 MBq	1.70 MBq	-7.06%
49	0.33 MBq	0.35 MBq	3.00%
50	0.32 MBq	0.32 MBq	1.51%
52	0.28 MBq	0.28 MBq	0.15%
56	0.22 MBq	0.22 MBq	1.62%
58	0.19 MBq	0.20 MBq	1.67%
60	0.17 MBq	0.17 MBq	0.43%
63	0.14 MBq	0.15 MBq	2.33%
66	0.12 MBq	0.12 MBq	-2.09%
70	0.094 MBq	0.096 MBq	2.39%
73	0.078 MBq	0.078 MBq	-0.64%
77	0.061 MBq	0.059 MBq	-3.81%
80	0.051 MBq	0.055 MBq	8.21%
84	0.040 MBq	0.042 MBq	3.85%
86	0.036 MBq	0.033 MBq	-6.21%

* % deviation is equal to 100 x (M-E)/E

1a) Determination of the energy setting that will be used for dose calibrator measurements

Determination of dial setting of the dose calibrator by the licensee is important for obtaining accurate measurements of radium-223 dichloride radioactivity. The National Institute of Standards and Technology (NIST) and the manufacturer, the Institute for Energy Technology (IFE), have established a program to supply radium-223 reference standards that are traceable to NIST. Currently, while no manufacturer recommended dose calibrator settings exist for radium-223, identifying the appropriate dial setting is straightforward. To achieve acceptable levels of accuracy, appropriate calibration factors or dial settings must be employed.

The end user medical licensee will not require a primary NIST standard activity source as they will receive a unit dosage from a radiopharmacy which will serve as a secondary reference standard. Each licensee will then determine their own calibrated dial setting. For best accuracy, it is recommended that a single calibrated dial setting be an individually determined value. Specifically, it is recommended that (3):

1. Each radiopharmacy must establish a radium-223 dial setting based on a NIST-traceable source. Any subsequently prepared unit dosage can serve as a secondary reference standard.

and

2. Each licensee determines its own radium-223 dial setting based on a unit dosage of radium-223 activity received from the radiopharmacy. This dial setting should be recorded and used to make all subsequent dose calibrator radium-223 activity measurements.

1b) Geometric testing for glass vials and plastic syringes used for radium-223 dichloride

The licensee will not need to perform any geometric testing. NIST has performed activity measurements in a variety of dose calibrators for radium-223 in various dose vials and syringes containing a range of volumes and activities.(1) The dose calibrator measurement accuracies for radium-223 were shown to be within +/-5% for all geometries. Further, only a single dial setting was found to be necessary for accurate radium-223 activity measurements regardless of geometry.

1c) Description of NIST traceable radium-223 calibration standard provided to clients for measurement

As stated above, the licensees will be supplied unit dosages in a syringe from a commercial radiopharmacy; these dosages will serve as a secondary reference standard. The end user will use these unit dosages to determine the dial setting for radium-223 on their own instruments.

2.2 NRC Question 2

2. Please provide data on the efficiency and sensitivity of instruments commonly used in U.S. nuclear medicine departments for area surveys, wipe testing, and measurement of waste held for decay-in-storage prior to disposal to the normal trash. For instance, Geiger-Mueller (GM) detectors with a pancake probe such as a Ludlum 44-9 or equivalent are traditionally used for area surveys and sodium-iodide well counters are traditionally used for analysis of contamination wipes. In addition, please take into consideration that typical survey instruments in a medical setting are calibrated using cesium-137.

Bayer Response:

In order to obtain accurate data regarding the response of radiation detection/measurement equipment generally available in nuclear medicine facilities in the United States, various activities of radium-223 were measured at Nuclear Diagnostics Products (NDP).

Two types of radiation detection equipment were employed. Commonly available survey meters were used in order to determine the detectability of radium-223 during a typical survey for external radiation levels, such as during routine area surveys, checking incoming packages, testing after spills or other radiation incidents and measurement of

waste held for decay-in-storage prior to disposal. Well counters connected to multichannel analyzers (MCA) and single channel analyzers (SCA) were used to determine radium-223 detectability during typical removable contamination surveys that may be performed to assess wipe survey levels of removable radioactive contamination.

I. Survey Meter Response

In order to obtain data regarding the suitability of readily available instrumentation for the routine survey of external radiation levels and for measurements after decay-in-storage samples with radium-223 were prepared and measured at commercial radiopharmacies located in New Jersey.

i) Samples in syringes were prepared to demonstrate the suitability of typical pancake detectors for monitoring of waste bags held for decay in storage. Further, these measurements represent values due mostly to the photon emissions from radium-223 and its progeny as the emitted alphas and betas are attenuated by the syringes. These measurements therefore result in conservative exposure and count rate values and thus serve as worst case values. These studies demonstrate the suitability of pure gamma probes for the detection of radium-223 as the presence of low levels of contamination can be easily detected, even when only photon emissions are measured.

ii) To demonstrate the detectability of radium-223 in the event of a contamination incident such as a spillage, samples with low activities were prepared on sponges. The samples prepared on sponges reflect more realistic exposure and count rate values that would be obtained during routine contamination monitoring because these values include contributions of alpha, beta and gamma radiations from the decay of radium-223 and its progeny.

A detailed description of the investigations and results are presented below.

Various volumes corresponding to a variety of activities of radium-223 (based on dose calibrator measurements using NDP's calibrated dial setting of 264 as described in the response to question 1 were prepared in a number of different sizes of commonly used syringes (see Table 4); the activity in four of these syringes was transferred onto small 1 inch diameter sponges (see Table 5). All measurements of exposure rates (mR/h) and count rates (cpm) from the various syringes and sponges were made with Ludlum Model 14C rate meters connected to Model 44-9 GM Pancake probes. These pancake probes are capable of detecting alpha, beta, and gamma emissions. All measurements were obtained at a distance of 2 cm to simulate a distance commonly used in practice. Each NDP facility utilized 2 different Ludlum GM survey meters, for a total of 4 different meters to assess exposure and count rate reproducibility and variability. Exposure rates (mR/h) and count rates (cpm) for the various syringe configurations were first obtained. Efficiencies were determined from the count rate data based on the measured activity on the sponges. It must be noted that these GM probes are calibrated using Cs-137 (gamma energy of 0.662 MeV); the Ludlum 44-9 energy response curve provided by the manufacturer indicates an approximately 25% lower response when measuring radium-223 since the average photon energy for radium-223 in equilibrium with progeny is

estimated at 0.4 MeV. Thus, for quantitative measurements, rather than just detectability, an energy response correction would be necessary. In our case, since the response of the Ludlum 44-9 is lower for radium-223 than Cs-137, all measurements represent conservative values.

The results are given in Table 4 as a function of decreasing radium-223 activity contained in the syringes for the two NDP sites (values in bold were obtained at the Rockaway facility, the unbolded values were obtained at the Cherry Hill facility). The key points to be made are:

1. The minimum activity that would be present in one drop of radium-223 solution, a volume corresponding to 0.05 ml, from a dose vial before expiry (+14 days from reference date) is approximately 21 kBq. Two syringes containing radium-223 activities in the 25-30 kBq range were prepared. The survey meters, all placed at a distance of 2 cm from the activity, indicated exposure rates of at least 20-25 mR/h and count rates that exceeded 50K cpm. A third syringe contained 50 kBq, corresponding to the activity that would be present in one drop from a dose vial at the reference date. As expected, the exposure rate and count rate were higher (50 mR/h and 120K cpm). Based on these data, one drop of radium-223 spilled on a counter can be detected with a typical pancake detector.

2. Much lower radium-223 activities were also prepared (see last 4 syringes) and these were measurable as well.

Note the survey meter background exposure and count rate readings were on the order of 0.05 mR/h and 10-20 cpm, respectively, indicating that all radium-223 activity levels resulted in values that were distinguishable from background readings.

Table 4: Survey meter measurements of radium-223 activity in syringes*

Syringe/Volume	Activity	Ludlum mR/h		Ludlum cpm	
		1 bkg	2 bkg	1 bkg	2 bkg
1 cc syringe + 0.05 cc	50 kBq (1.35 µCi)	50 / 0.03	----	120,000 / 16	---
0.3 cc syringe + 0.25 cc	28.4 kBq (0.77 µCi)	20 / 0.03	---	60,000 / 0	---
0.3cc syringe + 0.25 cc	**26.75 kBq (0.72 µCi)**	**20 / 0.05**	**25 / 0.05**	**50,000 / 16**	**80,000 / 16**
3 cc syringe + 1 cc	5.98 kBq (0.16 µCi)	2.5 / 0.05	3.0 / 0.05	8,000 / 15	10,000 / 15
3 cc syringe + 1 cc	**5.63 kBq (0.15 µCi)**	**2.0 / 0.05**	**3.0 / 0.05**	**6,000 / 10**	**10,000 / 10**
0.3 cc syringe + 0.1 cc	0.598 kBq (0.016 µCi)	0.6 / 0.05	0.7 / 0.05	2,000 / 15	2,400 / 15
0.3 cc syringe + 0.1 cc	**0.563 kBq (0.015 µCi)**	**0.7 / 0.05**	**0.6 / 0.05**	**2,200 / 10**	**2,000 / 10**
0.3 cc syringe + 0.05 cc	0.299 kBq (0.0081 µCi)	0.3 / 0.05	0.4 / 0.05	1,000 / 15	1,150 / 15
0.3 cc syringe + 0.05 cc	**0.2815 kBq (0.0076 µCi)**	**0.4 / 0.05**	**0.4 / 0.05**	**1,100 / 10**	**1,100 / 10**

*The activity was prepared and surveyed in syringes. The measured exposure and count rate values represent conservative values and demonstrate that the presence of low levels of contamination can be easily detected, even when only photon emissions are considered.

For the last 4 syringes in Table 4, the activity was transferred onto small 1 inch diameter disk sponges and then exposure and count rate data were again obtained. This was to better simulate detection of an actual spill in that the alphas as well as the betas emitted by the radium-223 progeny, Pb-211 and Tl-207, would be more prominently detected due to lack of attenuation caused by the syringe.

The sponge data are given in Table 5(The values in bold were obtained at the Rockaway facility, the unbolded values were obtained at the Cherry Hill facility. Note that the sponge measurements were made 14 days later at Rockaway and within 1 hour at Cherry Hill). Efficiencies were determined from the count rate data based on the activity measured.

Table 5: Survey meter measurements of radium-223 dichloride activity in sponges

Sponge	Calculated Activity	Ludlum mR/h		Ludlum cpm		Efficiency (cpm/dpm)	
		1 bkg	2 bkg	1 bkg	2 bkg	1	2
0.1 cc	0. 598 kBq (35,880 dpm)	2.0 / 0.05	3.0 / 0.05	6,500 / 16	8,000 / 16	18%	22%
0.1 cc	**0.240 kBq (14,400 dpm)**	**0.75 / 0.05**	**0.79 / 0.05**	**2,650 / 16**	**2,900 / 16**	**18%**	**20%**
0.05 cc	0. 299 kBq (17,940 dpm)	1.6 / 0.05	1.8 / 0.05	5,300 / 16	6,500 / 16	29%	36%
0.05 cc	**0.120 kBq (7,200 dpm)**	**0.39 / 0.05**	**0.4 / 0.05**	**1,700 / 16**	**1,800 / 16**	**23%**	**25%**

As expected the exposure rates and count rates were higher upon counting the activity in the sponges compared to counting the activity in the syringes (compare 0.1 cc and 0.05 cc volumes from Cherry Hill). For example, for the 0.1 cc volume, the sponge exposure and count rates for Ludlum #1 at Cherry Hill were 2.0 mR/h and 6,500 cpm, respectively, compared to the syringe exposure and count rates of 0.6 mR/h and 2,000 cpm, respectively.

Based on the data in Table 5 the minimum detectable activities (MDAs) of the Ludlum survey meters for radium-223 were calculated by:

$$\text{MDA (dpm)} = \frac{4.65\sqrt{Bkg / 2t_c}}{E}$$

MDA = minimum detectable activity in disintegrations/minute (dpm)
Bkg = background count rate in counts/minute
tc = meter time constant in minutes (4 sec = 0.0667 min for fast response and 22 sec = 0.3667 min for slow response)
E = detector efficiency

The MDA results are presented below:

MDA (Cherry Hill):
Ludlum 1: 283 dpm = 4.7 Bq (0.1 cc) and 176 dpm = 2.9 Bq (0.05 cc)
Ludlum 2: 231 dpm = 3.9 Bq (0.1 cc) and 141 dpm = 2.4 Bq (0.05 cc)

MDA (Rockaway):
Ludlum 1: 283 dpm = 4.7 Bq (0.1 cc) and 221 dpm = 3.7 Bq (0.05 cc)
Ludlum 2: 255 dpm = 4.2 Bq (0.1 cc) and 204 dpm = 3.4 Bq (0.05 cc)

The MDA in all cases was estimated to be less than 5 Bq for all 4 survey meters studied.

Radium-223 dichloride is detectable using standard and readily available instrumentation. Good counting efficiencies are obtained and low activities are easily determined.

II. Well Counter Measurements

The syringes prepared above were placed in well counters attached to multichannel analyzers (MCAs) and single channel analyzers (SCAs) and counted for either 30 seconds (Cherry Hill) or 1 minute (Rockaway). Each facility had two Ludlum Model 243 wells, one connected to a MCA (PCAP in Cherry Hill and SPECTECH UCS30 in Rockaway) and the other connected to a SCA (Ludlum Model 2200 at both facilities). Radium-223 emits a number of photons that can be detected: including x-rays at 81 and 84 keV and gammas at 154, 269 and 271 keV. For the single channel analyzer a large energy window set from 75 – 300 keV was used. The results are given in Table 6.

Table 6: Well counter measurements of radium-223 activity

Syringe/Volume	Calculated Activity dpm	MCA Net cpm	SCA Net cpm	Efficiency MCA (Net cpm/dpm)	Efficiency SCA (Net cpm/dpm)
3 cc syringe + 1 cc*	358,800	281,458	200,442	78%	56%
3 cc syringe + 1 cc*	**337,800**	**268,034**	**237,530**	**79%**	**70%**
0.3 cc syringe + 0.1 cc	**33,780**	**23,518**	**21,803**	**70%**	**65%**
0.3 cc syringe + 0.1 cc	35,880	29,394	18,749	82%	52%
0.3 cc syringe + 0.05 cc	17,940	16,728	11,410	93%	64%
0.3 cc syringe + 0.05 cc	**16,890**	**13,538**	**13,457**	**80%**	**80%**

*3 cc syringe + 1 cc volume did not fit into MCA with needle (needle replaced with red cap for better counting geometry, i.e., activity sat further down in well)

The variation in counting efficiency is mostly due to geometry differences. The variation between MCA and SCA results from differences in the energy window settings.

As expected, the radium-223 detection efficiencies of the well counters attached to MCAs or SCAs were higher than that determined for the survey meters due to the much improved counting geometry.

Based on the data in Table 6, the MDAs of the well counters connected to MCAs or SCAs for radium-223 were calculated by:

$$\text{MDA (dpm)} = \frac{3 + 4.65\sqrt{Bkg \times t}}{t \times E}$$

MDA = minimum detectable activity in disintegrations/minute (dpm)
Bkg = background count rate in counts/minute
t = counting time in minutes for sample and background counts
E = detector efficiency

The MDA results are presented below:

MDA (Cherry Hill):
MCA: 168 dpm = 2.8 Bq (1.0 cc), 158 dpm = 2.6 Bq (0.1 cc), and 135 dpm = 2.3 Bq (0.05 cc)
SCA: 128 dpm = 2.1 Bq (1.0 cc), 133 dpm = 2.2 Bq (0.1 cc), and 109 dpm = 1.8 Bq (0.05 cc)

MDA (Rockaway):
MCA: 138 dpm = 2.3 Bq (1.0 cc), 156 dpm = 2.6 Bq (0.1 cc), and 171 dpm = 2.8 Bq (0.05 cc)
SCA: 112 dpm = 1.9 Bq (1.0 cc), 114 dpm = 1.9 Bq (0.1 cc), and 92 dpm = 1.5 Bq (0.05 cc)

The MDA in all cases was estimated to be less than 3 Bq for all well counter/MCA/SCA combinations studied.

2.3 NRC Question 3

3. Please provide data to support that there are no long lived contaminants in radium-223 dichloride.

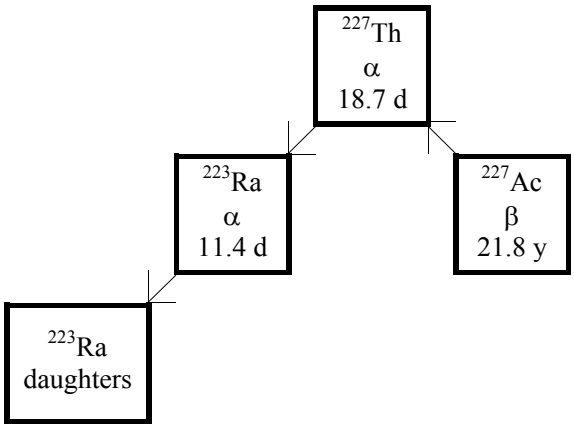
Bayer Response:

Quality control procedures are designed to exclude the presence of long lived contaminants in radium-223 dichloride. Potential long lived contaminants originating from the original production of the Ac-227 source material are rigorously analyzed in each Ac-227 generator as part of the raw material release procedures to exclude the possibility for long lived radionuclide impurities in the Ac-227 generators.

Based on the production method for radium-223 dichloride from Ac-227 generators, the most likely potential long lived contaminants are from the immediate parent radionuclides, Ac-227 ($t_{1/2}$ = 22 y) and Th-227 ($t_{1/2}$ = 18.7 d) (Figure 1). Tests for Ac-227 and Th-227, are performed on each individual batch of radium-223 dichloride produced as part of the overall batch testing.

To date, approximately 300 batches have been tested for residual Th-227 and Ac-227; no result above the limit of detection has been obtained.

Figure 1: Actinium-227 decay chain



2.4 NRC Question 4

4. Please provide data to support that radium-223 dichloride is not volatile or easily respirable due to the low inhalation Annual Limit on Intake (ALI) stated in Title 10 Code of Federal Regulations (CFR) Part 20.

Bayer Response:

Radium-223 dichloride is not volatile or easily respirable given the relatively low inhalation ALI of 0.7 μCi for radium-223 pursuant to 10 CFR Part 20.

The immediate daughter radionuclide of radium-223 is radon-219. Radon-219 has a half-life of 3.96 seconds which prevents significant migration of the gas from the source of radium-223 (i.e., the diffusion time for radon-219 to come out of solution is much longer than its physical half-life).

The total volume of gas produced per MBq of radium-223 is estimated to be 2.3E-16 liters/MBq for radon-219 based on the ideal gas law equation and the solubility of radon in water is 200 mL per liter (a value higher than that of oxygen). (6) The following calculations can be performed regarding the possibility of any Rn-219 becoming airborne:

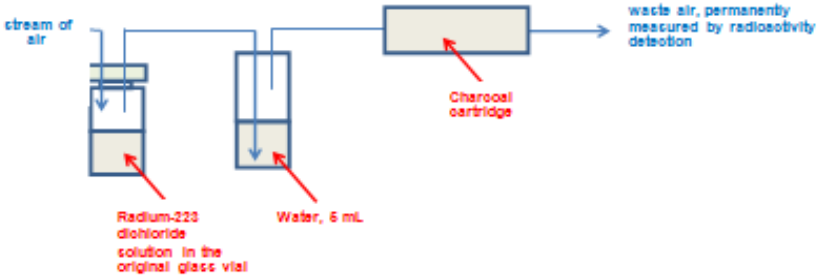
In a typical vial, there will be 6 MBq of radium-223 dichloride in a 6 ml aqueous solution at reference date. Based on the above, the volume of radon-219 gas produced will be equal to 1.4×10^{-12} ml and the solubility of this gas in 6 ml water is equal to 1.33 ml. This represents a factor of 10^{12}, i.e., a trillion times less radon-219 gas produced than is

soluble within the 6 ml volume contained in the vial, indicating that the likelihood of radon-219 gas escaping the solution is negligible.

In addition to these theoretically-based calculations, activity measurements of radium-223 in liquid scintillation cocktails have been performed by NIST (2). No loss of activity due to the release of radon-219 gas from the solution was observed during the measurements. Therefore, a significant release of radon-219 from the liquid phase was excluded.

Furthermore, Bayer Pharma AG (Wuppertal, Germany) investigated the likelihood of radon-219 volatility out of a radium-223 dichloride solution by using the following apparatus.

Figure 2: Diagram of Apparatus to Measure Radon-219 Volatility



The radium-223 vial contained a total radioactivity of 2.4 MBq in a 6 ml aqueous solution, resulting in an activity concentration of 402 kBq/ml. This headspace of the vial was continuously purged by a stream of fresh air for three hours. The air was passed through a water filled flask and subsequently through a charcoal cartridge. After three hours, no radioactivity above background was detected by gamma spectroscopy in either the water of the flask or in the charcoal. This measurement result is in agreement with the theoretical calculations and measurements made in liquid scintillation cocktails as given above, all indicating that no significant amounts of radon-219 are likely to be released from a radium-223 dichloride solution. Thus, radium-223 dichloride is not easily respirable given the relatively low inhalation ALI of 0.7 μCi for radium-223 pursuant to 10 CFR Part 20.

2.5 NRC Question 5

5. Please provide data to support that patients administered radium-223 dichloride are releasable in accordance with 10 CFR 35.75.

Bayer Response:

Pursuant to 10 CFR 35.75(a), based on the specific patient-specific dose calculations detailed below, radium-223 dichloride patients are immediately releasable.

Pursuant to 10 CFR 35.75(a), licensees may authorize the release from its control of any individual who has been administered unsealed byproduct material if the Total Effective Dose Equivalent (TEDE) to any other individual from exposure to the released individual is not likely to exceed 5 mSv (0.5 rem).

Pursuant to 10 CFR 35.75(b), if the TEDE is not likely to exceed 1 mSv (0.1 rem), instructions are not required to be provided to the released individual.

For radium-223 dichloride, based on NRC methodology given in NUREG-1556, Vol. 9, Appendix U, the external exposure to others, i.e., the deep-dose equivalent (DDE(∞)), is estimated to be 0.7 mrem for a typical patient administration of 3.5 MBq (i.e., 50 kBq/kg to 70 kg patient). This dose is < 1 mrem, 100-fold less than dose limit requiring instructions. The actual calculation is shown below:

DDE(∞) = 0.02 μSv/MBq h x 3.5 MBq x 1.44 x 24 h/day x 11.4 d x 0.25
= 7 μSv = 0.7 mrem

Due to attenuation in the patient's body mass, the likely external exposure to others due to photon emissions outside the patient's body would be even less than that estimated above which used the radium-223 exposure rate constant at 1 m of 0.02 μSv/MBq h for an unshielded source (4).

For internal exposure, it is generally assumed that activity intake by ingestion or inhalation by others is on the order of one-millionth of the administered activity. Using the ingestion dose conversion factor (DCF) for radium-223 given in EPA Federal Guidance Report No. 11 (5), this would correspond to an internal dose committed effective dose equivalent (CEDE) of 0.0626 mrem for radium-223. Using NRC-acceptable methodology given in NUREG-1556, Vol. 9, Appendix U, which assumes an intake higher by a factor of 10 for conservatism (i.e., an intake factor for I-131 equal to 10^{-5}), the CEDE due to ingestion of radium-223 would equal 0.626 mrem. As noted in the response to Question 4, the likelihood of any activity intake due to inhalation is extremely unlikely.

Given that the TEDE is equal to DDE (∞) + CEDE, the TEDE to any other individual from exposure to a released individual who has been administered radium-223 dichloride is less than 1.5 mrem.

Based on these patient-specific dose calculations, radium-223 dichloride patients are immediately releasable.

2.6 NRC Question 6

6. Please provide information on the expected activity radium-223 dichloride that is:
   a. Shipped from the manufacturer in Norway. (What is the activity on day 1?)
   b. Distributed to U.S. customers. (What is the activity upon arrival at the end user facility?)

Bayer Response:

6a) When the vial is shipped from the manufacturer in Norway, there is 14 MBq of radium-223 in the vial.

6b) The US customer (end user licensee) will receive a unit dosage that is patient specific (50 kBq/kg). For example, for an average 70 kg patient, the activity in the unit dosage would be 3.5 MBq radium-223 dichloride.

2.7 NRC Question 7

7. Please describe the procedure for adjusting the standard dosage provided by the manufacturer to obtain the dosage to be administered to the patient, which includes:
   a. A description of when and where the dosage will be transferred from the vial to the syringe.
   b. A description of the typical personnel safety measures suggested when preparing dosages.
   c. A step-by-step procedure for administering dosage to a patient.

Bayer Response:

7a) In the commercial setting, it is planned that unit dosages will be prepared in syringes by a commercial radiopharmacy for distribution to end users.

The volume to be administered to a given patient will be calculated using the:

- Patient's body weight (kg)
- Dosage level (50 kBq (0.00135 mCi)) per unit body weight (kg).

- Radioactivity concentration of the product (1000 kBq/mL; 0.027 mCi/mL) at reference date
- Decay correction (DK) factor to correct for physical decay of radium-223. A table of DK factors is provided with the product

The total volume to be administered to a patient is calculated as follows:

$$\text{Volume to be administered (mL)} = \frac{\text{Body weight (kg)} \times \text{dose (50 kBq /kg body weight)}}{\text{DK factor} \times \text{1000 kBq/mL}}$$

Using aseptic technique, the calculated volume of radium-223 dichloride solution to be administered is withdrawn from the vial into the syringe by a commercial radiopharmacy. It is currently planned that the unit dosage will be prepared approximately 24 hours prior to injection for shipment to the end user. Further adjustments of the syringe volume are not required by the end user.

7b) The radiopharmacy and end users should use standard radiation safety measures for the handling of the radium-223 dichloride drug product. All licensees should adhere to all relevant radiation safety regulations as promulgated by the regulatory authorities administering their site Radioactive Materials License.

7c) The administration of radium-223 dichloride to a patient is comprised of the following steps:

1. Secure an intravenous access line or cannula.
2. Flush the intravenous access line or cannula with 0.9% Sodium Chloride for Injection, USP in order to ensure that the intravenous access line is uninterrupted.
3. Inject radium-223 dichloride via the intravenous access line or cannula.
4. Flush the intravenous access line or cannula with 0.9% Sodium Chloride for Injection, USP.

The equipment used in connection with the administration of radium-223 dichloride is to be treated as radioactive waste and should be disposed in accordance with the institution's standard operating procedures.

2.8 NRC Question 8

8. Please describe the additional training necessary for an Authorized User and individuals working under the supervision of an Authorized User to safely handle and administer radium-223 dichloride.

Bayer Response:

No additional training is required for an Authorized User and individuals working under the supervision of an Authorized User to safely handle and administer radium-223 dichloride. Radium-223 dichloride specific informational material will be provided (e.g. dose administration instructions, dose calibrator procedure).

2.9 NRC Question 9

9. Please describe how medical use licensees determine doses (sievert), not dosages (becquerels), to the target and to other organs/tissues.

Bayer Response:

For treatment purposes, medical use licensees will not determine radium-223 dichloride doses to any organ or tissue.

2.10 References

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Applied Radiation and Isotopes 68 (2010) 1367–1370

Contents lists available at ScienceDirect

Applied Radiation and Isotopes

journal homepage: www.elsevier.com/locate/apradiso

Development of secondary standards for ^{223}Ra

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ARTICLE INFO

Keywords:
Dose calibrator
Secondary standardization
Ionization chamber
^{223}Ra

ABSTRACT

Ra-223 is a bone-seeking alpha emitter currently being evaluated as a radiopharmaceutical. Concurrent with the primary standardization, NIST established that calibration factors currently used for radionuclide calibrators in the clinical setting give readings 5.7–8.7% higher than the NIST calibrated activity. This work describes the determination of calibration factors specific to dose vials and syringes. Using the calibration factors derived with standard ampoules to measure syringe activities can give readings up to 3.6% too high.

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1. Introduction

The National Institute of Standards and Technology (NIST) recently developed a radioactivity measurement standard for a ^{223}Ra solution. A calibration factor for the NIST "4π"γ ionization chamber (IC) (Calhoun, 1987) was established based on activity measurements (Cessna and Zimmerman, 2009) via the CIEMAT/NIST ^{3}H-standard efficiency tracing method (Coursey et al., 1986; Zimmerman and Collé, 1997) of liquid scintillation (LS) counting. Radium-223 is being evaluated as a radiopharmaceutical for the treatment of skeletal metastases. As an alkaline earth metal, Ra exhibits intrinsic bone-seeking behavior, so that ligation (immunoconjugation or, for example, phosphonation) is not required for efficient, targeted delivery. Furthermore, while most commercial formulations currently available for this treatment are β-emitters, ^{223}Ra decays in a chain that results in the emission of a total of four alphas and two betas per decay of the parent. Alpha emitters are considered attractive for the treatment of metastases due to intrinsically high linear energy transfer and short path length; thus, high specificity and high efficacy are predicted. In particular, the rapid emission of α-particles from the first three nuclides in the ^{223}Ra decay chain has been touted as ensuring strong, targeted cytotoxicity (Brechbiel, 2007; Howell et al., 1997; Imam, 2001; Macklis et al., 1988; McDevitt et al., 1998; Vaidyanathan and Zalutsky, 1996).

In order to conduct clinical trials in the United States, high standards of accuracy in activity measurements must be met. In clinical applications, activity measurements are most often achieved with commercially available radionuclide calibrators which incorporate a reentrant IC, and are commonly referred to as "dose calibrators". To achieve acceptable levels of accuracy, appropriate calibration factors, or "dial settings" (DS), must be employed. Currently, no manufacturer recommended settings exist for ^{223}Ra. In our recent standardization, we found that the DS's adopted in previous trials gave average readings 5.7%–8.7% higher than the NIST calibrated activity. These measurements were performed in the 5 mL NIST ampoule geometry, which is the standard geometry for all DS's published by Capintec for their radionuclide calibrators.[1]

Because the characteristics (wall thickness, chemical composition, etc.) of the sample affect attenuation, accurate measurements require geometry-specific DS's (Calhoun et al., 1987; Zimmerman and Cessna, 2000; Zimmerman et al., 2001). Given the relatively low energy photons (<150 keV) and bremsstrahlung characteristic of the ^{223}Ra decay, attenuation effects might be expected to be relatively large. As part of the Nuclear Medicine Standards Program at NIST, we report here empirically determined DS's for several clinically relevant source geometries (dose vials and syringes) for a set of representative commercial radionuclide calibrators.[2]

2. Materials and methods

A total of four experiments, each using a separate shipment of ^{223}Ra solution, were performed. The solutions that were shipped to NIST were designated by Algeta, ASA (Oslo, Norway) as the

[1] Certain commercial equipment, instruments, or materials are identified in this paper to foster understanding. Such identification does not imply recommendation by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

[2] CRC-12, S/N: 12561 (electrometer and chamber); CRC 15-R, S/N: 155544 (electrometer and chamber); CRC 35-R, S/N: 350267 (electrometer and chamber); AtomLab 100, S/N: 1805001 (electrometer), 1757081 (chamber); Keithley 6514A, S/N: 0732150 (electrometer); Vinten 671, S/N: 3-2 (chamber).

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0969-8043/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.apradiso.2009.11.005

"Drug Substance" in their production process and had nominal activity concentrations of 2.5–3.0 MBq g^{-1} at the time of receipt. The composition of the "Drug Substance" consisted of a ^{223}Ra solution in a proprietary buffer solution. In order to maintain a stable composition throughout the studies, the same carrier/buffer solution was used for all dilutions. Over the course of the experiments, the mean solution density was measured as 1.008 g mL^{-1}, with a 0.10% relative standard deviation of the mean.

In four separate experiments, the received solution was brought to a desired volume of master solution by the addition of buffer. An automatic dispenser was then used to dispense this master solution into a NIST 5 mL ampoule and several dose vials and/or syringes containing a range of volumes. Prior to filling, the bottom of each syringe was sealed with epoxy to prevent spillage. No needles were affixed to the ends of the syringes. In total, 15 20 mL crimp-sealed dose vials (FIOLAX, MGlas AG, Münnerstadt, Germany) containing 0.5, 2, or 6 mL of solution; 12 2 mL syringes (BD Plastipak, Becton Dickinson S.A., S. Agustin del Guadalix, Madrid, Spain, REF 300186) containing 0.5, 1, or 2 mL of solution; 3 5 mL syringes (BD Plastipak, Luer-Lok, BD, Franklin Lakes, NJ, USA, REF 300911) containing 2 mL of solution; and 15 20 mL syringes (BD Plastipak, Luer-Lok, BD Drogheda, Ireland, REF 301189) containing 1, 5, 10, 15, or 20 mL of solution were prepared and measured. Dispensed sources contained 0.8–13.8 MBq at the time of measurement.

The massic activity of each master solution was determined by measuring the appropriate ampoule in the NIST "4π"γ IC, using the previously derived calibration factor relative to the appropriate radium (^{226}Ra) reference sources (RRS). The determined activity for each ampoule had an expanded uncertainty of 1.1%; the largest component was the standard uncertainty on the calibration factor (0.53%), followed by the uncertainty due to the positioning of the RRS (0.1%), the uncertainty due to the measurement repeatability (0.07%), the uncertainty on the ratio between the RRS's (0.027%), and the standard uncertainty on the half-life over the measurement interval (0.003%).

Ampoule, dose vial, and syringe sources were measured in each of the NIST-maintained Capintec (CRC-12, CRC-15R, and CRC-35R) and AtomLab-100 radionuclide calibrators. For each measurement sequence, readings were taken at 10 DS's (230–280 in the Capintec chambers, 16.0–18.0 in the AtomLab-100 chamber). For the dose vials and ampoules, the sources were placed at the bottom of the standard dippers. For the 2 and 5 mL syringes, measurements were made in two configurations: hanging from the syringe holder of the standard dippers and resting at the bottom of the standard dippers. No needles were used in this study. Addition of a needle to the syringe would not affect the configuration in the hanging geometry, and would make it impossible to place the syringes at the bottom of the standard dippers. The 20 mL syringes were too wide to hang from the syringe holder of the standard dippers and too tall to rest at the bottom of the standard dippers and were therefore mounted in the hanging position of a syringe holder customized (with a wider bore "hole" for hanging syringes) for use with a 35 mL syringe in a previous study (Zimmerman and Cessna, 1999).

Since the activity of the sources was known, it was possible to select a DS range for each radionuclide calibrator that included the correct setting. This initial range selection utilized the "dialing-in method" described in Zimmerman and Cessna (2000). The range of 10 DS's selected for each chamber was centered on the correct setting for the ampoule. Subsequent determinations used the "calibration curve method" described in Zimmerman and Cessna (1999, 2000). Activity data were decay corrected to a common reference time assigned for each experiment, and the ratio A_{obs}/A_{NIST} (A_{obs}=observed activity; A_{NIST}=calibrated activity) was plotted against the DS. The curves were fit to $y^{-1}=a+bx$, and the NIST-determined DS was assigned when $A_{obs}/A_{NIST}=1$.

In addition to the determination of DS's for the above radionuclide calibrators, calibration factors in terms of pA MBq^{-1} were determined for the NIST-maintained Vinten 671/Keithley 6517A radionuclide calibrator. Ampoules, dose vials, and syringes were all measured resting at the bottom of the standard dipper. This dipper has a well that accommodates a NIST 5 mL ampoule, but is too narrow for a 20 mL dose vial. Therefore, in some experiments, a piece of paper (cut to fit) was placed at the bottom of the dipper to prevent dose vials from falling over, and both dose vials and ampoules were placed at the center of the dipper on the piece of paper. Placement of ampoules in the well or on the piece of paper made no difference in the derived calibration factors to within the precision of the radionuclide calibrators. Syringes could not be placed in the central well, and so rested at the corner of the dipper.

High purity germanium detector gamma ray spectrometry indicated no radionuclidic impurities. Over the region 40 keV $\leq E \leq$ 2100 keV, the limits of detection expressed as massic photonic emission rates were within 30–300 $\gamma\,s^{-1}\,g^{-1}$.

Table 1
NIST-determined dial settings for the different sample geometries in the NIST-maintained Capintec and AtomLab radionuclide calibrators.

	Dial setting	U (k=2)	Δ (%)
CRC-12			
5 mL ampoule	265	4	0.3
20 mL dose vial—average	261	4	−0.8
2 mL syringe—average	271	5	2.0
5 mL syringe—2.0 mL	273	5	2.5
20 mL syringe—5.0 mL	277	5	3.6
20 mL syringe—10.0 mL	274	4	2.9
20 mL syringe—15.0 mL	273	4	2.2
20 mL syringe—20.0 mL	269	4	1.5
CRC-15R			
5 mL ampoule	264	5	0.2
20 mL dose vial—average	265	4	0.2
2 mL syringe—average	265	5	0.5
5 mL syringe—2.0 mL	268	4	1.4
20 mL syringe—5.0 mL	267	5	1.0
20 mL syringe—10.0 mL	269	4	1.6
20 mL syringe—15.0 mL	266	4	0.6
20 mL syringe—20.0 mL	263	4	$6.9\cdot10^{-2}$
CRC-35R			
5 mL ampoule	267	5	$-1.4\cdot10^{-3}$
20 mL dose vial—average	267	4	$-5.5\cdot10^{-2}$
2 mL syringe—average	267	5	$-6.9\cdot10^{-2}$
5 mL syringe—2.0 mL	269	4	0.65
20 mL syringe—5.0 mL	272	4	1.5
20 mL syringe—10.0 mL	270	4	0.95
20 mL syringe—15.0 mL	268	4	$-8.8\cdot10^{-2}$
20 mL syringe—20.0 mL	264	4	−0.74
Atomlab-100			
5 mL ampoule	16.9	0.2	−0.09
20 mL dose vial—average	16.9	0.2	0.24
2 mL syringe—average	16.9	0.2	−0.20
5 mL syringe—2.0 mL	16.8	0.2	0.80
20 mL syringe—5.0 mL	16.8	0.2	0.69
20 mL syringe—10.0 mL	16.8	0.2	0.39
20 mL syringe—15.0 mL	17.0	0.2	−0.80
20 mL syringe—20.0 mL	17.2	0.2	−1.5

Reliance solely on dial settings determined as optimal for the NIST 5 mL ampoule geometry can result in activity measurements that disagree with the NIST-determined activities by as much as 3.6%. U values are calculated by propagating the expanded uncertainty in the activity through the respective fitting equations. The percent discrepancy arising from measuring each source with the ampoule DS is given as Δ. See text for details.

Table 2
Calibration factors for the Vinten 671/Keithley 6514A radionuclide calibrator.

	Calibration factor ($pA\,MBq^{-1}$)	U (k=2) ($pA\,MBq^{-1}$)	Δ (%)
5 mL ampoule	3.50	0.04	$9.4 \cdot 10^{-4}$
20 mL dose vial—average	3.51	0.06	−0.05
2 mL syringe—average	3.65	0.10	3.4
5 mL syringe—2.0 mL	3.63	0.04	3.6
20 mL syringe—5.0 mL	3.59	0.08	3.4
20 mL syringe—10.0 mL	3.55	0.04	1.3
20 mL syringe—15.0 mL	3.50	0.04	−0.15
20 mL syringe—20.0 mL	3.45	0.04	−1.6

No 0.5 mL samples in 2 mL syringes were measured with the Vinten 671/Keithley 6514A radionuclide calibrator. The percent discrepancy arising from calculating the activity of each source with the ampoule calibration factor is given as Δ.

3. Results and discussion

Uncertainty analyses were performed in accord with NIST policy (ISO, 1995; Taylor and Kuyatt, 1994). The combined standard uncertainty on the DS was determined from the combined standard uncertainty on the activity ($<0.8\%$), the measurement repeatability (standard deviation of DS's derived with different sources of the same geometry, $<0.5\%$), the uncertainty on the half-life ($<5 \cdot 10^{-5}\%$), and the average standard uncertainty on the curve fit ($<0.4\%$). The dominant contribution to the DS uncertainty was always the combined standard uncertainty on the activity. The low activities of the sources with the smallest volumes gave rise to the largest uncertainties, as both the standard deviation of the derived DS's and the average standard uncertainty on the curve fit are larger for sources with lower activity; of these two uncertainty factors, the standard deviation of the derived DS's was consistently dominant. The expanded uncertainty on the measured activity due to the DS uncertainty is in most cases similar to the expanded uncertainty on the activity (1.1%, k=2). Even for the lowest activities measured, the expanded uncertainty on the measured activity due to the DS uncertainty is still below 1.7%.

The NIST-determined calibration factors and their uncertainties are given in Tables 1 and 2. Since 5 mL of solution in the NIST 5 mL ampoule is the standard geometry for manufacturer-recommended DS's from Capintec, Tables 1 and 2 also include the discrepancy resulting from measuring each source with the ampoule calibration factors. The percent discrepancy arising from measuring each source with the ampoule DS is determined and an average of these discrepancies is reported for each specific geometry as Δ. The small Δ reported for measuring the 5 mL ampoule at the DS for the 5 mL ampoule can be attributed primarily to the effect of rounding the recommended DS to the nearest whole number (or 10th for the AtomLab).

The NIST-determined DS's for the ampoule and the dose vial geometries for the Capintec and AtomLab systems agreed to within the expanded uncertainty on the DS's ($\pm 1.5\%$). A 1.5% change in DS gives a 0.5% difference in measured activity in the Capintec chambers. In the AtomLab chambers, a 0.6% change in DS gives a 0.5% difference in measured activity. For the dose vial geometry, DS's determined for volumes from 0.5 to 6 mL agree to within their expanded uncertainties and so only the average DS for dose vials is reported for each chamber.

NIST-determined DS's for the syringe geometries differ from the settings for the NIST 5 mL ampoule by as much as 4.3%. Use of the ampoule DS to measure samples in the syringe geometry yields activity values that disagree with the NIST-determined activities by as much as 3.6%. For the 2 mL syringes, variations in the NIST-determined DS's over the 0.5–2 mL volume range fall within the expanded uncertainty on the DS's. For the 2 and 5 mL syringes, the difference in the activities derived using the optimum DS's in the "hanging" geometry and the "bottom" geometry is less than the expanded uncertainty on the activity (note that since affixing a needle to the end of a syringe would access a height intermediate between the hanging geometry and the bottom geometry, DS's appropriate to measurements made with a needle are necessarily encompassed in the same range). The DS values are typically smaller for the Capintec chambers for the hanging geometry; they are larger for the AtomLab chamber. This indicates better detection efficiency in the bottom geometry than in the hanging geometry.

For the 20 mL syringes, significant variation (up to 2.9%) occurs in the NIST-determined DS's over the 5–20 mL volume range. This is due to the decreased geometric efficiency as the liquid level of the radioactive solution approaches the mouth of the IC.

It should be noted that the results of measurements reported herein should be considered valid only for the specific solution composition and containers described, and for the actual NIST-maintained chambers. Users of the reported dial settings should verify their validity on their own systems.

4. Conclusions

NIST has completed the secondary standardization of a solution of ^{223}Ra having a composition specific to a particular drug product submitted in four shipments by the manufacturer. NIST determined calibration factors for each of five NIST-maintained radionuclide calibrators in several clinically relevant geometries. Samples in syringes produce higher ionization currents than samples with the same activity in ampoules or dose vials; measuring at the NIST-determined DS's for the ampoule (instead of the appropriate syringe settings) gives an activity reading that is up to 3.6% too high. Volume effects were insignificant to within the expanded uncertainty for the 20 mL dose vial and 2 mL syringe geometries, but led to discrepancies from the NIST-determined activities as large as 2.9% over the 5–20 mL volume range in the 20 mL syringe geometry.

Acknowledgments

We thank M. Hammond, L. Pibida, and L. King for performing impurity measurements. A portion of this study was funded by Algeta, ASA.

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Discussion:

Q (Mike Woods): Obviously a very clear explanation, can I just ask you to say a little more about the volume effect? I was wondering about the CRC-15R, 5 ml, the fact that it has turned over and come back down, is that just an uncertainty effect or is there some real effect going on there?

A (Denis Bergeron): Difficult to say, that seems to be the only case where it actually does turn over like that and as you noted it is within the uncertainty bars. So, whether that is a real effect to begin with is tough to say. There is no reason in terms of just geometric efficiency why that would happen. If there is some combination of the geometric effect and the chamber sweet spot that could possibly explain it.

Applied Radiation and Isotopes 68 (2010) 1523–1528

Contents lists available at ScienceDirect

Applied Radiation and Isotopes

journal homepage: www.elsevier.com/locate/apradiso

Standardization of radium-223 by liquid scintillation counting

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ARTICLE INFO

Keywords:
Liquid scintillation counting
^{223}Ra
CIEMAT/NIST method

ABSTRACT

Liquid scintillation (LS) counting was undertaken as part of the primary standardization of ^{223}Ra. Radium-223 decays with a half life of 11.43 d through a chain of shorter-lived daughter radionuclides, resulting in five alpha decays and three beta decays. The CIEMAT/NIST method of tritium efficiency tracing was employed, with the beta efficiencies being calculated using the program CN2004, developed by the Physikalisch-Technische Bundesanstalt (PTB). The total calculated LS efficiency, considering all daughter radionuclides, was approximately 598%. Separate experiments were performed to rule out loss of the 3.96 s ^{219}Ra daughter from the cocktail and possible counting loss of the 1.78 ms ^{215}Po daughter due to LS counter dead-time. No loss was observed in either experiment. In the final experiment an expanded uncertainty (k=2) of 0.55% was achieved. Results were in excellent agreement with confirmatory measurements performed by $2\pi\alpha$ proportional counting. However, results are not in agreement with methods based on gamma ray measurements.

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1. Introduction

Radium-223 decays with a half-life of 11.43 ± 0.05 days (ENSDF, 2006) through a series of daughter radionuclides to stable ^{207}Pb. This series is depicted in Fig. 1. The resulting 5 alpha decays and three beta branches are the reason there is interest in this radionuclide as a radiopharmaceutical. Radium-223 has undergone Phase II clinical trials in Europe to assess the anti-tumor efficacy and the effect on skeletal metastases in late-stage, hormone refractory prostate cancer (Nilsson et al., 2007). Radium-223 is also of interest in environmental measurements where it is used in conjunction with shorter lived ^{224}Ra ($t_{1/2}$=3.66 d) to trace submarine groundwater discharge (Santos et al., 2009) or understand transport processes in marine sediment (Hancock et al., 2000).

The aim of this study was to develop the methods to accurately assay the activity of a solution by absolute methods. That primary standard is then used to develop a secondary method used to routinely assay samples submitted for calibration. The primary methods employed were $4\pi\alpha\beta$ liquid scintillation (LS) counting and $2\pi\alpha$ proportional counting (PC).

These measurements were performed as part of a larger exercise to standardize ^{223}Ra. Experiments 1 and 3–5 (E1, E3, E4, and E5) are in some part discussed here. Comparison of results between experiments was achieved by measurement of a 5 mL ampoule versus a radium (^{226}Ra) reference source on the NIST secondary "4π"-γ ionization chamber. Full details of the overall exercise and the confirmatory measurements by $2\pi\alpha$ proportional counting can be found in Zimmerman et al. (in prep.). In addition, the development of secondary standards is presented in these proceedings by Bergeron et al. (these proceedings).

2. Material and methods

2.1. General

The solutions for all experiments were supplied by Algeta ASA[1] (Oslo, Norway). The proprietary composition was specific to the use as a radiopharmaceutical and could be considered to be ^{223}Ra in a saline solution and a citrate buffer. Additional inactive solution of the same composition was also supplied and was used for all dilutions and carrier additions to LS cocktails. From the received solutions, a 5 mL solution sample in a NIST 5 mL flame-sealed ampoule and a dilution by a factor of nominally 200, were gravimetrically prepared. Liquid scintillation sources were prepared from the dilution of the master. All solutions were determined to be free of gamma-ray-emitting impurities and estimates of activity were made by HPGe spectroscopy measurements of dilution ampoules. The ampoules prepared from the

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0969-8043/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.apradiso.2009.11.068

[1] Certain commercial equipment, instruments, or materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

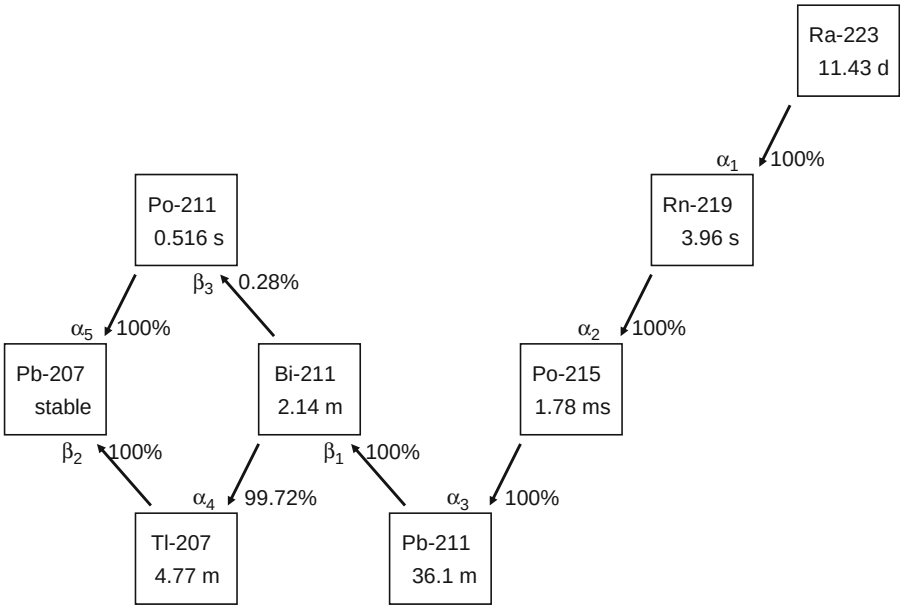

Fig. 1. The decay of ^{223}Ra and daughter radionuclides to stable ^{207}Pb.

Table 1
Composition of liquid scintillation cocktails used in the experiments.

Experiment & composition number	Scintillator	Scintillator volume (mL)	Aqueous component	Aliquot size (mL)	Aqueous fraction, % (vol)	Stable
E1-1	HF	10	0.02 mL H_2O	~0.05	0.8	N
E1-2	OF	10	0.02 mL H_2O	~0.05	0.8	N
E1-3	HSIII	10	0.02 mL H_2O	~0.05	0.8	Y
E1-4	RS	10	0.02 mL H_2O	~0.05	0.8	N
E3-1	HSIII	3,10,22	–	~0.04	1.3,0.4,0.2	Y
E3-2	PCS	3,10,22	–	~0.04	1.3,0.4,0.2	N,Y,Y
E3-3	HSIII	10	1 mL carrier	~0.05	11	Y
E3-4	PCS	10	1 mL carrier	~0.05	11	N
E4-1	UGAB	15	1 mL carrier	~0.05	8	N
E4-2	UGAB	15	1 mL 6 mol L^{-1} HNO_3	~0.05	8	Y
E4-3	HSIII	15	1 mL carrier	~0.05	8	Y
E4-4	HSIII	15	1 mL 6 mol L^{-1} HNO_3	~0.05	8	Y
E5	HSIII	10	0.5 mL carrier	~0.07	6	Y

See text for explanation of scintillator codes and discussion of carrier solution.

high activity solutions were measured on the NIST "4π"-γ IC against a radium (^{226}Ra) reference source. By assigning activity values to this ampoule based on individual measurement methods and determining a *K*-value from each measurement, results were compared across methods and between experiments.

The cocktail compositions of the various LS series are summarized in Table 1, where HF refers to HionicFluor (Packard Biosciences, Inc., Groningen, Netherlands), OF refers to OptiFluor (Packard Biosciences, Inc., Groningen, Netherlands), HSIII refers to Optiphase HiSafe III (Perkin Elmer Life Sciences, Norwalk, CT, USA), RS refers to Ready Safe (Beckman-Coulter, Inc., Fullerton, CA, USA), PCS refers to PCS (GE Healthcare, Buchinghamshire, England), and UGAB refers to Ultima Gold A/B (Packard Biosciences, Inc., Groningen, Netherlands).

All liquid scintillation samples were prepared in standard 22 mL low potassium glass LS vials with foil-lined caps (Wheaton model #986542, Millville, New Jersey, USA). Quenching was varied in all cocktails of E1, E4, and E5 by the addition of between 40 and 240 μL of a 1 to 10 dilution, by volume, of nitromethane in alcohol. No quench agent was added to E3 cocktails used for examining possible ^{219}Rn loss nor to those used in the NIST triple-to-double coincidence ratio (TDCR) LS system. For each composition at least two background samples of identical chemical composition were prepared at the two extremes of the quench range.

2.2. Experiment 1

Experiment 1 was considered preliminary, to find a suitable cocktail composition that resulted in stable cocktails. Cocktails were prepared as noted above. The vials were sequentially counted 5 min each for 10 cycles on the Packard 2500TR LS spectrometer, removed, re-agitated, and counted in the same fashion on the Beckman LS6500 spectrometer counter. Count rates were of the order of 2500 s^{-1}. Results were assessed for the stability of the counting rates.

Preliminary measurements revealed a discrepancy of 5–10% between the LS estimated activities, the Ge measured activities, and those stated by the supplier (also Ge based). Therefore, experiments were designed to look for possible losses of that magnitude.

2.3. Experiment 3

Because the decay chain includes a ^{219}Rn daughter an experiment was designed to look for possible losses into the air space above the cocktail into the LS vial. Being the second member of the decay chain, the loss of radon would have a non-negligible effect on the efficiency if the following daughter radionuclides did not return to the cocktail. Loss of ^{219}Rn was not expected because of the short, 3.98 s half-life. This was confirmed experimentally by preparing three liquid scintillation vials for each of two scintillants in experiment 3. The volume of cocktail was varied from 3 to 22 ml. The change in the volume of the air gap in the top of the vial is presumed to allow more radon to leave the solution in the vial with the smallest volume of scintillator. A background vial was made at each volume. The vials were kept in the dark immediately after being made, to begin dark adapting, and placed in the counter within 30 min of preparation. Vials were sequentially counted in the Packard LS spectrometer 15 min per vial for 4 cycles and, following a weekend power outage, 10 cycles.

In order to investigate the possible loss of counts of the 1.78 ms ^{215}Po daughter due to the coincidence resolving time and the deadtime of the LS counters, one of the cocktails (composition E3-3) was counted in the NIST TDCR (Zimmerman et al., 2003, 2004) using deadtime settings of 24 and 80 ms. No efficiency variation techniques (i.e., gray filters, defocusing, etc.) were applied. Four repeated measurements were taken at each deadtime setting with the source remaining in the sample chamber throughout the experiment. The theoretical magnitude of the effect on the count rate was calculated by integrating the portion of the distribution of time intervals between the decay of ^{219}Rn and the decay of ^{215}Po that would fall within the deadtime setting of the TDCR. The deadtime of the Packard spectrometer is unknown, but predicted to be on the order of 12 μs. The results of the experiment were intended to verify the calculations. From this point forward count rates for all experiments were kept at levels previously determined to have little effect on LS counter deadtime, nominally 1000 cps.

Finally, another two series of samples were prepared to confirm the stability of cocktails prepared with HSIII and to check the stability of those prepared with PCS. These sources were sequentially counted for 10 cycles of 15 min each on the Packard LS spectrometer. The samples were removed from the counter, re-agitated, and counted for 10 cycles of 20 min per sample on the Beckman LS spectrometer.

2.4. Experiments 4 and 5

In E4 and E5 the CIEMAT/NIST ^{3}H-standard efficiency tracing method (Coursey et al., 1986; Zimmerman and Collé, 1997) of LS counting was used as the primary measurement of the activity concentrations of the dilutions. Briefly, this method involves imposing a chemical quench agent to vary the efficiency of a set of tritium LS cocktails compositionally matched to a set of ^{223}Ra LS cocktails. A calculational model is used to translate the change in tritium efficiency to a change in efficiency for the beta branches in the decay of ^{223}Ra and its daughters. LS alpha efficiencies are taken as 100%. In most cases, decay and atomic data provided with CN2004 were used for the calculations. The decay data are in agreement with those listed in ENSDF (2006).

In Experiment 4, LS sources were prepared in two types of scintillant: UGAB and HSIII. Ten ^{223}Ra sources and four background sources were prepared for each scintillant. The cocktails contained 15 mL of scintillant, nominally 44 mg aliquots of active solution and between 2 and 14 drops of a 1 to 10 dilution (by volume) of nitromethane in alcohol, as a quenching agent. Five samples for each scintillant also contained nominally 1 mL of inactive carrier solution, with the remaining five for each scintillant containing nominally 1 mL of 6 mol L^{-1} nitric acid. After discussions of preliminary results, the addition of nitric acid was used at the suggestion of PTB, as it had been used successfully in the measurement of ^{227}Ac, a parent of ^{223}Ra (Kossert, 2007). Background sources were prepared in a similar manner, substituting carrier for the active component. Samples were sequentially counted 10 min each for 10 cycles on the Packard spectrometer.

Counting sources for Experiment 5 were prepared in a similar manner, using HSIII as the scintillant. Five ^{223}Ra sources and two background sources were prepared. The cocktails contained 10 mL of scintillant, nominally 71 mg aliquots of active solution, nominally 500 μL inactive carrier solution, nominally 100 μL distilled water, and between 2 and 14 drops of diluted nitromethane, as a quenching agent. A set of five sources with similar composition was prepared using a dilution of a NIST tritium standard reference material 4927F (NIST, 2000) and inactive carrier. Samples were sequentially counted 15 min each for 10 cycles on a Packard spectrometer. Samples were then removed from the counter, agitated and sequentially counted 20 min each for 10 cycles on a Wallac Guardian 1414 LS spectrometer, modified to disable the anticoincidence shield.

The efficiency tracing code CN2004 (Günther, 2004) was utilized in the analysis of the beta branch efficiency tracing. The transitions considered in activity determinations are listed in Table 2, where Nr Pro is the program code for the degree of forbiddenness. A *kB* value of 0.012 g MeV^{-1} cm^{-2} was used in the calculation. Given the high beta energy and number of alpha particles, the choice of *kB* does not have a large impact on the

Table 2
Listing of principal radiations considered in activity determinations conducted in this study.

E_α (keV)	I_α	Nuclide	Nr Pro
5433.6(5)	0.0222(20)	^{223}Ra	
5501.6(10)	0.0100(15)	^{223}Ra	
5539.80(90)	0.090(2)	^{223}Ra	
5606.73(30)	0.252(5)	^{223}Ra	
5716.23(29)	0.516(13)	^{223}Ra	
5747.0(4)	0.090(20)	^{223}Ra	
5871.3(10)	0.010(2)	^{223}Ra	
6278.2(7)	0.1623(14)	^{211}Bi	
6425.0(10)	0.075(6)	^{219}Rn	
6552.6(10)	0.129(6)	^{219}Rn	
6622.9(6)	0.8377(14)	^{211}Bi	
6819.1(3)	0.794(10)	^{219}Rn	
7386.2(8)	1	^{215}Po	
E_β (keV)	**I_β**	**Nuclide**	
18.564(3)	1	^{3}H	0
534	0.00268(9)	^{207}Tl	1
535(6)	0.0632(10)	^{211}Pb	0
574(5)	1	^{211}Bi	0
962(6)	0.0154(8)	^{211}Pb	1
1367(6)	0.9130(12)	^{211}Pb	0
1436(6)	0.99732(9)	^{207}Tl	0
E_γ (keV)	**I_γ**	**Nuclide**	
328.10(12)	0.0000140(14)	^{207}Tl	
404.853(10)	0.0378(5)	^{211}Pb	
427.088(10)	0.0176(4)	^{211}Pb	
569.62(12)	0.0000159(20)	^{207}Tl	
832.01(3)	0.0352(5)	^{211}Pb	
897.77(12)	0.00260(9)	^{207}Tl	

Data were obtained from ENSDF (2006). Uncertainties are given as standard (k=1) uncertainties. Absolute intensities are given as fractional values per decay of the respective radionuclide. Nr Pro is the CN2004 code for the degree of forbiddenness.

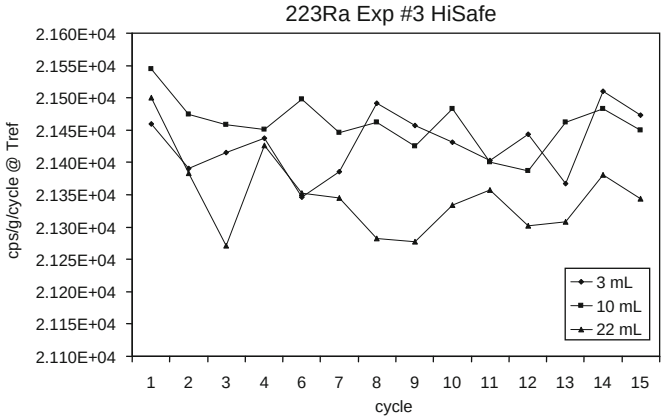

Fig. 2. Decay corrected count rates as a function of measurement time for LS vials containing 3, 10 and 22 mL of LS cocktail.

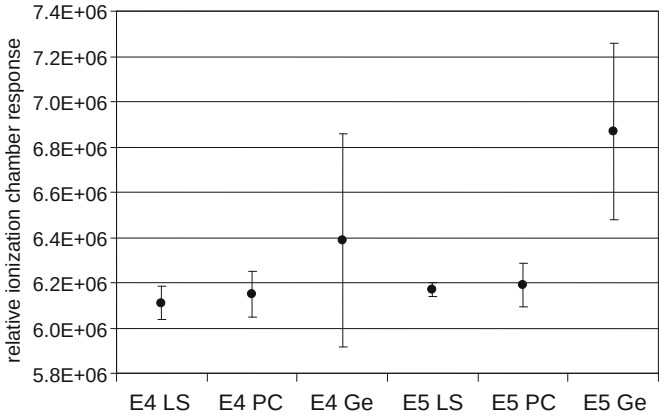

Fig. 3. Results of activity determinations by the CIEMAT/NIST method of ^{3}H efficiency tracing liquid scintillation counting (LS), $2\pi\alpha$ proportional counting (PC), and germanium spectroscopy (Ge) expressed relative to measurements of a radium (^{226}Ra) reference source on the NIST 4π–γ secondary ionization chamber. Uncertainty bars represent expanded uncertainties, k=2.

results. Over a range of 0.005–0.012 g MeV^{-1} cm^{-2} the resulting calculated efficiency changes by 0.01%. Due to the relationship of half-lives in the decay chain, equilibrium factors were calculated using Mathematica. Tritium samples from E5 were used in the tracing of both E4 and E5. The effect due to the difference in cocktail volume and the degree of quenching was calculated by comparing the tracing results for the two volumes and the difference was added as a component of uncertainty in E4. The average calculated ^{223}Ra LS efficiency was 599% in E5, for both LS spectrometers, covering a range of 598.7–599.0%, corresponding to a ^{3}H LS efficiency of 28.1–34.3% and a figure of merit range of 2.1–1.7. In E4 the average ^{223}Ra LS efficiency was 596%, covering a range of 594.2–597.2%, corresponding to a ^{3}H LS efficiency of 19.8–38.8% and a figure of merit range of 2.95–1.50.

Additionally in E4 and E5 $2\pi\alpha$ proportional measurements were made on sources prepared from the same solutions used to prepare the LS samples. Details of these measurements are presented elsewhere.

3. Results and discussion

Those compositions that resulted in stable cocktails are noted in Table 1. Cocktails were considered unstable if the efficiency-traced activity showed a discernable trend and changed by more than 0.5% over 10 cycles. The measurements from unstable cocktails were not included in the activity determinations.

3.1. Experiment 3

Fig. 2 shows decay-corrected massic count rates for the three E3-1 sources as a function of time. If there were a loss of radon to the air space above the vial a lower count rate should be observed in the vial with the lowest volume of scintillant. Instead, a lower count rate was observed in the vial containing 22 mL of scintillant. This was considered to be a loss of light collection in this sample due to the fact that the meniscus was not visible to the phototubes, being in the neck of the vial rather than the body. It has previously been shown that a larger fraction of the light produced in the cocktail exits the vial at the meniscus (Durán Ramiro and García-Toraño, 2005).

Assuming a deadtime of 50 μs, the calculated counting loss of a radionuclide having a 1.78 ms half-life is 1.93%. From the TDCR experimental data, a difference in the average counting rates in the logical sum of doubles counting channel of 1.4% was observed between the two deadtime settings, which is consistent with the calculated value. Because of this, combined with the fact that the magnitude of the suspected effect was 5–10%, it was concluded that losses due to the Po-215 half-life and instrument resolving time were not the cause of the observed discrepancy. Given the consistency of the data and calculation, the theoretical loss was calculated for a deadtime value of 12 μs.

The theoretical loss is 0.47% of the ^{215}Po. As a fraction of the overall uncertainty, the effect is 0.47/599=0.08%. Because the deadtime was estimated, no correction was made to the activity and the effect was included as a component of the uncertainty.

3.2. Experiments 4 and 5

Results of activity determinations can be found in Fig. 3. Uncertainty bars represent expanded, k=2, uncertainties on the individual determinations. It can be seen that there is good agreement between the LS and PC activity determinations, being less than 0.2% in both experiments. While the gamma-ray spectrometry based activity determinations cannot be said to disagree in both cases, the uncertainties overlap in one instance, there remains a difference of nominally 4% and 12% in experiments E4 and E5, respectively. Further experiments are planned to investigate these possible differences and measure gamma probabilities based on the LS and PC data.

The associated evaluated components of uncertainty on the LS measurements can be found in Table 3. The uncertainty analysis methodology and nomenclature used for the reported uncertainties are based on uniform NIST guidelines and are compatible with those adopted by the principal international metrology standardization bodies (Taylor and Kuyatt, 1996; ISO Guide, 1995). The combined standard uncertainty is the quadratic combination of the standard deviations (or standard deviations of the mean where appropriate), or approximations thereof, for the component uncertainties. For discussion of uncertainties on PC and gamma-ray spectrometry measurements see Zimmerman et al. (in prep).

Using two different techniques for assaying the solutions—LS counting, which detects all radiations emitted in the ^{223}Ra decay chain with differing degrees of efficiency, and proportional counting, which was performed in a manner to detect alpha particles only—agreement to better than 0.2% was achieved for the two methods with both master solutions. Moreover, this was achieved with an expanded uncertainty (k=2) of the order of only 1.1%. These results give us confidence in the LS results and in the determination that no large effects are being observed from either

Table 3
Components of uncertainty in E4 and E5 activity determinations.

Component, u_i	Comment	Evaluation type	%, E4A1	%, E5A1
LS Measurement precision E4	Standard deviation for n=15 determinations (equivalent to standard deviation of the mean) as obtained with 3 different cocktail compositions (5 sources each composition) measured 10 times (150 determinations in all). Passes normality test at 95% and 99%. The typical internal relative standard deviation of the mean (n=10 cycles) for each determination ranged from 0.02% to 0.09%.	A	0.08	–
LS Measurement precision E5	Standard deviation for n=10 determinations (equivalent to standard deviation of the mean) as obtained with 5 sources measured 10 times in 2 different LS counters (150 determinations in all). Passes normality test at 95% and 99%. The typical internal relative standard deviation of the mean (n=10 cycles) for each determination ranged from 0.02% to 0.05%.	A	–	0.16
Counting losses	Estimated counting loss of 1.78 ms decay of ^{218}Po due to an assumed 12 μs counter deadtime	B	0.08	0.08
Gravimetric determinations for LS cocktails	Estimated standard uncertainty on the determination of ^{223}Ra mass for a single cocktail	B	0.05	0.05
Dilution factor	Estimated standard uncertainty on the gravimetric determination of the dilution factor	B	0.18	0.07
^{223}Ra decay corrections	For a standard uncertainty of decay corrections over: E4-16 hours, and E5-5 days	B	0.002	0.01
^{223}Ra efficiency calculations	Step size in CN2004 calculations	B	0.02	0.02
Cocktail volume	Estimated uncertainty due to difference in cocktail volume between ^{3}H and ^{223}Ra	B	0.45	–
Livetime	Estimated uncertainty in the correction to the LS counting interval	B	0.05	0.05
Background	Estimated uncertainty due to an average 5% uncertainty in background determination	B	0.003	0.001
Activity of ^{3}H standard	Estimated uncertainty due to 0.72% (k=2) uncertainty in ^{3}H standard activity	B	0.001	0.001
Branching ratios	Estimated uncertainty due to uncertainty in branching ratios	B	0.18	0.18
Combined ($u_c = \sqrt{\sum u_i^2}$)			0.54	0.27
Expanded (U_c=$u_c k$; k=2)			1.07	0.55

loss of ^{219}Rn from solution or loss of counts from the ^{215}Po decay due to counter deadtime. Loss of radon has been avoided in the solid PC sources and count rates were very low in the PC system so it would not suffer from the same potential type of losses due to counter deadtime as the LS system.

4. Conclusions

Liquid scintillation (LS) counting was undertaken as part of the primary standardization of the alpha-emitting medical radionuclide ^{223}Ra. Radium-223 decays with a half life of 11.43 d though a chain of shorter-lived daughter radionuclides, resulting in the emission of five alpha particles and three high energy beta emissions. The CIEMAT/NIST method of tritium efficiency tracing was employed, with the beta efficiencies being calculated using the program CN2004, developed by the Physikalisch-Technische Bundesanstalt (PTB). The total calculated LS efficiency, considering all daughter radionuclides, was approximately 599%. Cocktails were prepared using the commercial liquid scintillants Hionic-Fluor, Opti-Fluor, Opti-Phase HiSafe III, Ready Safe, and Ultima Gold AB, with an additional aqueous fraction of either a carrier solution or, for some cocktails, 6 mol L^{-1} nitric acid. Not all compositions resulted in stable cocktails. Only HSIII consistently resulted in stable cocktails, while UGAB resulted in stable cocktails with the addition of nitric acid, but not with the addition of the identical amount of carrier solution. Separate experiments were performed to rule out loss of the 3.96 s ^{219}Ra daughter from the cocktail and possible counting loss of the 1.78 ms ^{215}Po daughter due to LS counter dead-time. No loss was observed in either experiment. In the final experiment an expanded uncertainty (k=2) of 0.5% was achieved. Results were in excellent agreement with confirmatory measurements performed by $2\pi\alpha$ proportional counting.

Acknowledgements

The authors acknowledge the support of Michelle Hammond for impurity measurements, Ryan Fitzgerald for equilibrium calculations and Ron Collé for discussions of many aspects, but particularly uncertainty evaluation and testing for radon loss. This work was partially funded by Algeta, ASA (Oslo, Norway).

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Accurate Dose Calibrator Activity Measurement of ^{90}Y-Ibritumomab Tiuxetan

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This investigation examined the accuracy of dose calibrator activity measurement of the β-emitting radiopharmaceutical ^{90}Y-ibritumomab tiuxetan. **Methods:** Five different facilities independently measured ^{90}Y in a 10-mL syringe geometry with 30 dose calibrator models from 3 different manufacturers. The activities ranged from 81.4 MBq (2.2 mCi) to 1,406 MBq (38 mCi) over the volume range of 3–9 mL. **Results:** The mean dial settings for ^{90}Y measurement were 375, 51 × 10, and 897 × 100 for Atomlab, CRC, and Mark V dose calibrators, respectively. The maximum volume dependence was 0.28%/mL. **Conclusion:** This study demonstrated that when measuring all volumes of ^{90}Y-ibritumomab tiuxetan activity prescriptions, only a single dial setting for a given manufacturer's dose calibrator is required for accurate measurements. Volume corrections are not necessary. For best accuracy, an individually determined dial value should be used.

Key Words: ^{90}Y measurement; dose calibrator; ibritumomab tiuxetan

J Nucl Med 2004; 45:450–454

The U.S. Food and Drug Administration has approved for commercial use the radioimmunotherapeutic agent ^{90}Y-ibritumomab tiuxetan (^{90}Y-Zevalin; IDEC Pharmaceuticals Corp.) for the treatment of non-Hodgkin's lymphoma (*1*). This radiopharmaceutical is generally prepared at a commercial radiopharmacy and then supplied to medical facilities as a unit dosage in a 10-mL syringe with volumes ranging from 3 to 9 mL, dependent on the prescribed activity for an individual patient.

All Nuclear Regulatory Commission and Agreement State licensees must determine and record the activity of unsealed by-product material before medical use. Except in certain Agreement States, this activity determination does not require the use of a dose calibrator, pursuant to 10 CFR part 35.63 (*2*), provided unit dosages are obtained from an appropriately licensed manufacturer or preparer. However, because the package insert for ^{90}Y-ibritumomab tiuxetan (*1*) states that patient dosages should be measured immediately before administration, licensees may prefer to directly measure activity with a dose calibrator.

Commercial reentrant ionization chambers (dose calibrators) are the de facto standard instrument to measure radioactivity in nuclear medicine. The dose calibrator measurement of β-emitting radionuclides depends on the bremsstrahlung radiation produced from the β-interaction with the source matrix, its container, and the calibrator chamber wall. The use of different volumes or containers may result in measurement errors, as is the case for low-energy photon emitters.

The purpose of this study was to involve the National Institute of Standards and Technology (NIST), dose calibrator manufacturers, and a commercial radiopharmacy in a common effort to investigate the applicability of a single calibrator dial setting for a particular manufacturer's dose calibrator model and determine the significance of volume corrections for accurate measurement of the β-emitting radiopharmaceutical ^{90}Y-ibritumomab tiuxetan in a syringe geometry.

MATERIALS AND METHODS

Dose calibrator measurements of ^{90}Y were performed independently at 5 different sites: Capintec, Inc., NIST, Cardinal Health Nuclear Pharmacy Services, Cardinal Health Radiation Management Services (Nuclear Associates), and Sun Nuclear Corp. (sites 1, 2, 3, 4, and 5, respectively). Thirty dose calibrators of the pressurized argon well reentrant design were used, including CRC (Capintec), Mark V (Cardinal Health Radiation Management Services), and Atomlab (Sun Nuclear; distributed by Biodex Medical Systems Inc.). Table 1 summarizes the various dose calibrators and procedures used at each site.

The ^{90}Y was delivered to site 3 by MDS Nordion in a 2-mL closed-septum vial containing a ^{90}Y-chloride solution with a product data sheet that indicated the NIST-traceable activity concentration, volume, and total activity. The radioactive solution was transferred from the vial to a 10-mL syringe (Becton Dickinson & Co.). Dose calibrator measurements for ^{90}Y after transfer to the syringe were based on vial measurements and an activity difference method. This procedure specifies measurement of the activity

Received Jun. 2, 2003; revision accepted Oct. 9, 2003.
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TABLE 1
Dose Calibrators Used and ^{90}Y Activity Measurement Procedures at Each Site

Site	Calibrator	^{90}Y Activity measurement	Procedure
1	5 CRC-15R	^{90}Y in saline*	Calibrated dial setting determination: Start activity and volume of 1,406 MBq (38 mCi) in 3 mL Volume dependence: Start activity and volume of 81.4 MBq (2.2 mCi) in 3 mL Sequential addition of 1 mL saline up to 9 mL
2	CRC-12, CRC-15R, 35R, and Atomlab 100	^{90}Y in saline	A. Start activity and volume of 1,184 MBq (32 mCi) in 8 mL B. Dilute with YCl_3/HCl carrier to give enough volume for preparation of syringes and liquid scintillation master C. Accurately (to within 0.1%) dispense large volume master into syringes whose needles had been previously sealed to prevent leaks—total of 14 syringes prepared over the volume range, with several repeated preparations at 3, 5, 7, and 9 mL to study syringe variability and repeatability D. Prepare nominally 200-fold dilution of large volume master for liquid scintillation measurements E. Determine activity concentration of diluted solution and master by liquid scintillation counting using 2 different, independent techniques
		^{90}Y ibritumomab tiuxetan in formulation buffer	Same procedure as for ^{90}Y in saline, but large volume master is prepared with formulation buffer instead of carrier; smaller number of syringes are prepared (3, 5 [×2], 7 mL); liquid scintillation cocktails are prepared using both formulation buffer and carrier solution to study composition/stability effects
3	3 CRC-15R	^{90}Y ibritumomab tiuxetan in formulation buffer	Start activity and volume of 1,184 MBq (32 mCi) in 9 mL Sequential withdrawal of 1 mL of solution volume down to 3 mL Sequential addition of 1 mL ibritumomab tiuxetan in formulation buffer up to 9 mL
4	3 Mark V	^{90}Y in saline	Start activity and volume of 509 MBq (13.8 mCi) in 3 mL Sequential addition of 1 mL saline up to 9 mL
5	15 Atomlab†	^{90}Y in saline‡	Start activity and volume of 481 MBq (13.0 mCi) in 3 mL Sequential addition of 1 mL saline up to 9 mL

*Activity for calibrated dial setting determination and volume dependence study are different because of use of different syringes.

†Ten new and 5 repaired units as old as 11 y; all 4 models of this type of dose calibrator use the same chamber assembly, so there is no need to distinguish between models.

‡During initial volume test, on the 8 mL step, a backfill into the saline vial resulted in source material loss, but initial calibration for activity measurement was unaffected. Volume test was repeated, with a start activity of 92.5 MBq (2.5 mCi) in 3 mL. Repeated results are reported; no backfill was detected.

in the vial, both before and after removal of source material, but with the volume in the vial restored to its initial value with saline before remeasurement. The difference between these 2 vial measurements is the activity drawn into the syringe, which is still NIST traceable. Site 3 established traceability for the ^{90}Y vial measurements through prior proficiency testing in a measurement assurance program with NIST. Calibrated dial settings for ^{90}Y measurement for each calibrator were determined by adjusting the dial settings to read the correct activity; the standard uncertainty on the activity value in the present study was based primarily on the standard uncertainty on the activity provided by Nordion, which was ±5%. Sites 4 and 5 received a calibrated activity in a syringe from site 3; site 1 received a calibrated activity in an MDS Nordion vial and performed a nontraceable volumetric transfer of activity into the syringe.

Activity measurements were made either at a start volume of 9 mL and after sequential 1-mL volume withdrawals to a final volume of 3 mL or at a start volume of 3 mL and after sequential 1-mL volume additions to a final volume of 9 mL. The latter procedure was different in that only the volume was varied; the activity remained constant.

The correction factor for each volume was obtained by comparing the measured activity with the calculated activity for each volume. The volume correction factor is given by:

$$\text{Correction factor} = \frac{\text{calculated } ^{90}\text{Y activity}}{\text{measured } ^{90}\text{Y activity}},$$

where the calculated ^{90}Y activity for each volume is a constant either for the 3-mL start volume or for the 9-mL start volume; it is the original calibrated activity multiplied by the respective volume divided by 9.

The measurements performed by site 2 used a different approach involving a direct determination of the solution activity by liquid scintillation counting (*3*–*5*) and determination of calibration settings for a set of syringes, each independently prepared with different volumes covering the 3- to 9-mL range. The amount of ^{90}Y solution added to each of the syringes was carefully controlled using an automated dispenser (Hamilton Co.) having an accuracy of 0.1%. In addition to the measurements made with ^{90}Y-ibritumomab tiuxetan, the same procedure was repeated by site 2 for syringes containing ^{90}Y in a carrier solution containing additional YCl_3 and 1 mol·L^{-1} HCl to ascertain what effect the different source matrix may have on dose calibrator measurement because of differences in self-absorption or bremsstrahlung production.

The calibrated dial settings were also converted to response values for the ion chamber of the dose calibrator to compare the different manufacturers' values. The relationship between chamber response, C_R, normalized to ^{60}Co and dial setting, DS, can be expressed as $C_R = 5.0/DS$ for Atomlab; $C_R = \{(DS/1,083) + 0.0855\}/M$ for CRC, where M is the display multiplier of 10; and $C_R = \{120/(1,009 - DS)\}/M$ for Mark V, where M is the display multiplier of 100.

RESULTS

The calibrated dial settings for ^{90}Y measurement for each dose calibrator at each site are given in Table 2. For the Atomlab, the mean calibrated dial setting measured at site 5 was 375, with a range of 363–394 for 15 calibrators. Of the 15 calibrators, 10 were new and their dial settings exhibited a narrower range: 372–378. The mean calibrated dial setting at site 2 for 1 Atomlab was 393, with a range of 387–399.

For the 5 new CRC calibrators, the mean calibrated dial setting measured by site 1 was 50 × 10, with a range of 47 × 10 to 53 × 10. The mean calibrated dial setting at site 2 for 3 CRCs was 55.7 × 10, with a range of 54 × 10 to 58 × 10. The mean calibrated dial setting at site 3 for 3 CRCs was 47.3 × 10, with a range of 47 × 10 to 48 × 10. There was no overlap in the ranges between sites 1 and 2 or between sites 3 and 2. For the Mark V calibrators, the mean calibrated dial setting measured was 897 × 100, with a range of 896 × 100 to 897 × 100; no other sites studied these calibrators.

Based on the calibrated dial settings, the Atomlab chamber response value at site 2 was 0.01272 and the mean value at site 5 was 0.01333, a factor of 4.8% higher. The mean CRC response was 0.01369 at site 2 and 0.01317 at site 1, a factor of 3.8% lower. The mean CRC response at site 3 was 0.01292, a factor of 5.6% lower than the site 2 value. The mean Mark V response at site 4 was 0.01071.

For the measurements at site 2, the expanded ($k = 2$) uncertainty on the calibrated dial settings based on the liquid scintillation activity calibration was determined to be 1.6% and was calculated from the quadratic combination of the average SD and the mean deviate estimate calculated from range statistics (*6*). Similar uncertainty analysis was not performed at the other sites.

Volume correction factors determined by each site, normalized to 6 mL, are shown in Figures 1–4. The equation and correlation coefficient (r) for each line, resulting from linear regression analysis, are given in each figure. The largest volume dependence was determined to be 0.28%/mL. Using this maximum observed volume variation and the applicable volume range of 6 mL, the volume effect for all dose calibrators included in this study should be limited to 1.7%.

A comparison of ^{90}Y measurements made with ibritumomab tiuxetan and the NIST standard solution in the identical measurement geometry indicated no difference in results to within the expanded measurement uncertainty of 1.6%. Moreover, variability in measurement results for both solutions due to variability in syringe manufacture was found to be less than 0.26% (SD), inclusive of 0.1% vari-

TABLE 2
Calibrated Dial Setting for Each Dose Calibrator at Each Site

Site	Calibrator	Setting
1	5 CRC	48, 47, 50, 52, 53
2	3 CRC	58 ± 2*, 55 ± 2*, 54 ± 2*
	Atomlab	393 ± 6*
3	3 CRC	47, 48, 47
4	3 Mark V	897, 897, 896
5	10 New Atomlab	375, 375, 374, 375, 378, 372, 374, 376, 375, 373
	5 older units after recalibration	394, 373, 363, 368, 371
Summary	Atomlab	mean calibrated dial setting = 375; range = 363–394
	CRC	mean calibrated dial setting = 51; range = 47–60
	Mark V	mean calibrated dial setting = 897; range = 896–897

*Uncertainties on the dial settings are expanded uncertainties determined from the combined standard uncertainty on the ^{90}Y activity calibration. The uncertainties at the other sites were not evaluated; thus, only ranges of values are given.

For the CRC dose calibrators, all dial settings are ×10; that is, the instrument readout must be multiplied by a factor of 10 to obtain the correct activity value. For the Mark V dose calibrators, all dial settings are ×100.

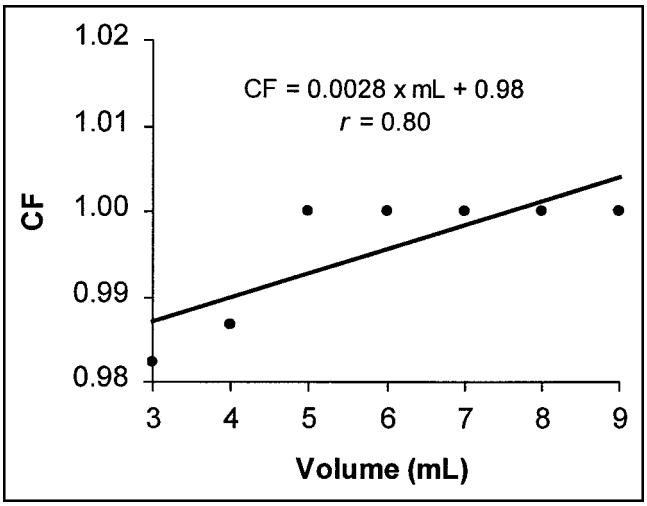

FIGURE 1. Correction factor (CF) as function of volume normalized to 6 mL, determined by site 1 based on measurements obtained on 1 CRC dose calibrator. Volume dependence is 0.28%/mL.

ability due to uncertainty in filling volume, at a volume of 5 mL for 8 syringes.

DISCUSSION

Proper dose calibrator measurement of pure β-emitting radionuclides is important for the safe and accurate dosing of various radionuclide therapies in nuclear medicine. According to NUREG-1556, volume 13 (*7*), and Nuclear Regulatory Commission Information Notice 2002-19 (*8*), accurate measurement of pure β-emitters is a potential problem. This study was performed to explore the pitfalls and examine the possible solutions when using dose calibrators for accurate measurement of ^{90}Y-ibritumomab tiuxetan.

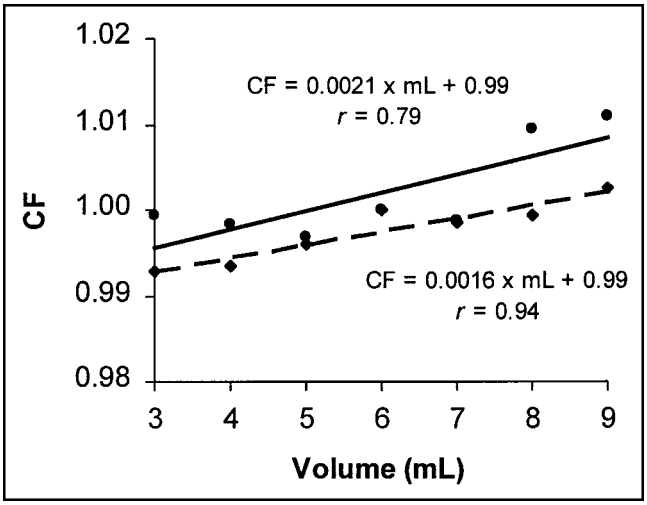

FIGURE 2. Correction factor (CF) as function of volume normalized to 6 mL, determined by site 2 based on measurements obtained on 3 CRC (●) and 1 Atomlab (♦) dose calibrators. Volume dependence is 0.21%/mL and 0.16%/mL, respectively.

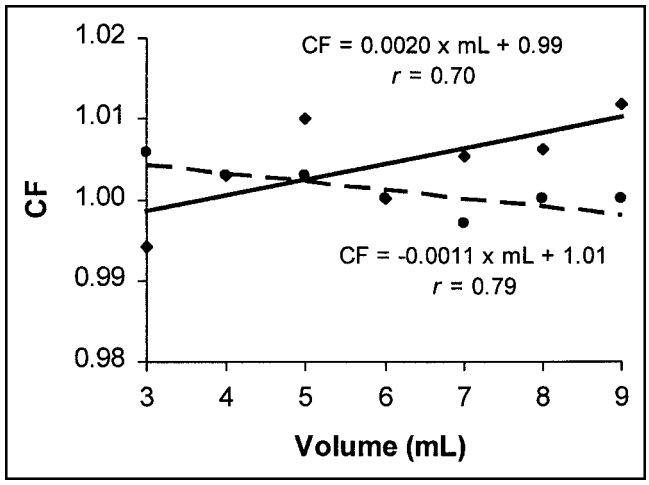

FIGURE 3. Correction factor (CF) as function of volume normalized to 6 mL, determined by site 3 based on average of measurements obtained on 3 CRC dose calibrators. Bold line (♦) represents results for sequential 1-mL volume withdrawal from 9 to 3 mL, and dashed line (●) represents results for sequential 1-mL volume addition from 3 to 9 mL. Volume dependence is 0.20%/mL and 0.11%/mL, respectively.

This study indicated that use of a single calibrated dial setting for a given manufacturer's dose calibrator resulted in accurate measurements of ^{90}Y in a syringe geometry regardless of volume in a 3- to 9-mL range. Although different model dose calibrators have very different dial settings, their chamber response values are very similar. The ^{90}Y measurement variation based on the calibrator response values for the range of observed dial settings was determined to be within ±5%, which is the level of the standard

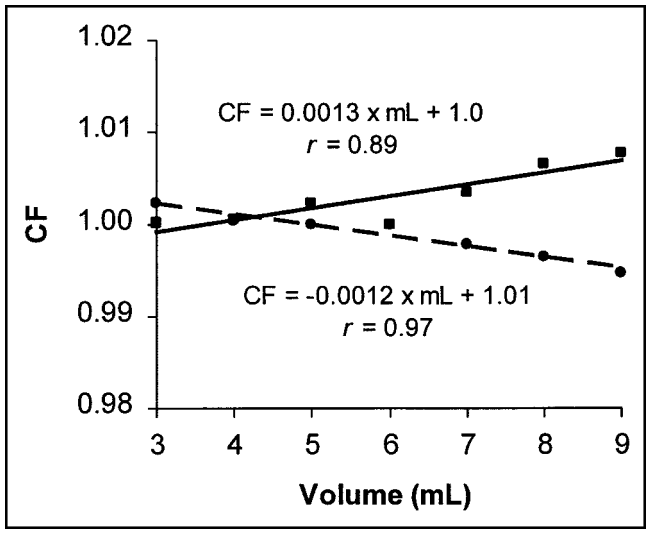

FIGURE 4. Correction factor (CF) as function of volume normalized to 6 mL, determined by sites 4 (●) and 5 (■) based on average of measurements obtained on 3 Mark V and 15 Atomlab dose calibrators, respectively. Volume dependence is 0.12%/mL and 0.13%/mL, respectively.

uncertainty on the activity value as provided by the supplier, MDS Nordion. This uncertainty was propagated to the activity values provided to all participants in the study by the commercial radiopharmacy, with the exception of NIST, which performed its own independent activity calibration, and site 1, which used nominal techniques.

For best accuracy, it is recommended that the single calibrated dial setting be an individually determined value, using the reported range for the appropriate manufacturer's dose calibrator as a guide. (The limited range of reported Mark V values does not allow users to check their calibrated dial setting for reasonableness in this manner.) Specifically, we recommend, first, that each radiopharmacy establish a ^{90}Y-calibrated dial setting based on NIST-supplied or NIST-traceable activity sources so that each activity source supplied to a medical facility can be used as a secondary reference standard and, second, that each medical facility determine its own calibrated dial setting based on the initial ^{90}Y activity received from a commercial radiopharmacy or, alternatively, based on measurement of a NIST-traceable activity source in the same syringe geometry.

Using this approach, volume correction factors should not be necessary when measuring the activity of ^{90}Y-ibritumomab tiuxetan at any volume in the range of 3–9 mL using the same type of syringe used in this study.

The type of syringe holder (e.g., T-handle or hook style dipper) used and inconsistent use of the protective well liner may cause further measurement variations. It is recommended that facilities always have the well liner installed during dose calibrator measurement of ^{90}Y and not interchange syringe holders once they have established their calibrated ^{90}Y dial setting.

CONCLUSION

This study demonstrated that, for accurate measurements, no adjustment is necessary for a dose calibrator dial setting when measuring different volumes of ^{90}Y-ibritumomab tiuxetan activity prescriptions. Medical facilities need only establish their own calibrated dial setting for ^{90}Y using their first prescription measurement based on the stated activity of the radiopharmacy.

ACKNOWLEDGMENT

This study was supported by IDEC Pharmaceuticals Corp.

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Paper

EXPOSURE RATE CONSTANTS AND LEAD SHIELDING VALUES FOR OVER 1,100 RADIONUCLIDES

David S. Smith and Michael G. Stabin*

Abstract—**The authors have assembled a compilation of exposure rate constants, *f*-factors, and lead shielding thicknesses for more than 1,100 radionuclides described in ICRP Publication 107. Physical data were taken from well established reference sources for mass-energy absorption coefficients in air, attenuation coefficients, and buildup factors in lead and other variables. The data agreed favorably for the most part with those of other investigators; thus this compilation provides an up-to-date and sizeable database of these data, which are of interest to many for routine calculations. Emissions were also segregated by emitting nuclide, and decay product emissions were emitted from the calculated coefficients, thus for the first time providing for the calculation of exposure rates from arbitrary mixtures of nuclides in arbitrary equilibrium states.**

Health Phys. 102(3):271–291; 2012

Key words: gamma radiation, radiation protection, radionuclide, shielding

INTRODUCTION

EXPOSURE RATE constants and lead shielding thicknesses are needed by many for routine calculations in radiation safety, medical uses of radionuclides, and other applications. A number of compilations have been found to be useful, including the Radiological Health Handbook (USDHEW 1970), which included exposure rate constants from Jaeger et al. (1968), an article by Unger and Trubey (1982), and others. The goal of this work was to provide an updated and comprehensive list of such values, using data from the recent ICRP Publication 107 (ICRP 2009). Comparisons of the calculated values with those of other investigators are also provided. This compilation uses newly released decay data for many radionuclides and traditional definitions of exposure rate constants, which can be related to absorbed dose or equivalent dose via well known relationships. Nuclide-specific *f*-factors for conversion between exposure rate in air and dose rate to tissue are also presented.

METHODS

The exposure rate constant Γ relates the activity of a point isotropic radiation source to the exposure rate in air at a given distance:

$$\dot{X} = \Gamma_\delta \frac{A}{d^2}, \quad (1)$$

where A is the source activity, d is distance to the source, and δ is a minimum cutoff energy, which determines the minimum energy photon that can contribute to the exposure. In this work, δ = 15 keV is used. In terms of the decay spectrum of a nuclide, the exposure rate constant can be written as

$$\Gamma_\delta = \frac{1}{4\pi}\sum_i \left(\frac{\mu_{en}}{\rho}\right)_i Y_i E_i, \quad (2)$$

where $(\mu_{en}/\rho)_i$ is the mass-energy absorption coefficient in air for photons of energy E_i emitted by the nuclide with yield Y_i. This equation will have units of exposure rate per unit activity at distance d when appropriate unit conversions and assumptions (e.g., about the amount of energy needed to produce an ion pair in air) are applied, as in this example from Stabin (2007) for ^{60}Co (considering just the two principal photons for demonstration purposes):

$$\Gamma = \left[\left(1.17\frac{MeV}{\gamma}\right)\left(1.0\frac{\gamma}{dis}\right)(0.0035\,m^{-1}) + \left(1.33\frac{MeV}{\gamma}\right)\left(1.0\frac{\gamma}{dis}\right)(0.0034\,m^{-1})\right] \times \frac{1}{4\pi}\frac{10^6\,eV}{MeV}\frac{i.p.}{34\,eV}\frac{1.6\times10^{-19}\,C}{i.p.}\frac{m^3}{1.293\,kg}\frac{10^6\,dis}{s-MBq} = 2.5\times10^{-12}\frac{(C/kg)m^2}{MBq\,s} \quad (3)$$

$$2.5\times10^{-12}\frac{(C/kg)m^2}{MBq\,s}\frac{37\,MBq}{mCi}\frac{3{,}600\,s}{h}\frac{R}{2.58\times10^{-4}\,C/kg}\frac{10^4\,cm^2}{m^2} = 12.9\frac{R\,cm^2}{mCi\,h}. \quad (4)$$

The nuclear decay data from ICRP Publication 107 were taken in electronic form and used to find the yield Y_i and

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The authors declare no conflict of interest.

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(*Manuscript accepted* 29 *August* 2011)
0017-9078/12/0

DOI: 10.1097/HP.0b013e318235153a

energy E_i of all photon emissions of each nuclide. The authors included only gamma rays, x-rays, annihilation photons, and prompt and delayed photons of spontaneous fission given in ICRP 107 with energies of at least 15 keV and yields of at least 10^{-4}. Bremsstrahlung was neglected. All mass-energy absorption coefficients were obtained by log-log interpolation of Hubbell and Seltzer (1996).

Additionally, for nuclides that have no photon emissions themselves but are in secular equilibrium with photon-emitting products (e.g., ^{137}Cs/^{137m}Ba), the decay schemes have been combined in selected cases with this being noted. In general the authors did NOT combine emissions for parent/progeny situations. This segregation of the emissions by the actual emitting nuclide allows more accurate determination of the exposure due to a complex mixture of nuclides. If the decay equilibrium of a mixture is known, the resulting exposure rate can be found by simple linear combination of the appropriate nuclides from Table 1 below. However, the lead shielding thicknesses cannot be combined easily for mixtures of nuclides.

The shielding requirements were calculated by energy-dependent attenuation of the exposure rates calculated here through varying thickness of pure lead. The broad-beam transmission, $T(E,x)$, for photons of energy E through lead thickness x was modeled as exponential attenuation modified by an energy- and depth-dependent buildup factor:

$$T(E,x) = B(E,x)\ \exp[-\mu(E)x]. \quad (5)$$

Two recent works have calculated in detail the buildup curves for monoenergetic photons in lead (Shimizu et al. 2004; Kharrati et al. 2007), albeit in different energy ranges. Shimizu et al. (2004) present data for energies from 30 keV to 15 MeV; Kharrati et al. (2007) include data for 15 to 150 keV. (The lower limit of 15 keV for the buildup factors is the reason for the 15 keV lower cutoff on photon emissions in this effort.) Since the energy coverage overlaps between 30 and 150 keV between these two works, transmission values in the overlap region were averaged:

$$B(E,x) = \begin{cases} B_K(E,x) & : \ 15\,\text{keV} \le E < 30\,\text{keV} \\ \dfrac{B_K(E,x) + B_S(E,x)}{2} & : \ 30\,\text{keV} \le E \le 150\,\text{keV}, \\ B_S(E,x) & : \quad E > 150\,\text{keV} \end{cases} \quad (6)$$

where the subscript K denotes data taken from Kharrati et al. and S denotes Shimizu et al. For the Shimizu et al. (2004) data, the buildup factors were taken directly from Table 4. For the Kharrati et al. (2007) data, the empirical fit given in their eqn (6) was used:

$$B_K(E_i,x) = \left\{ [1 + \beta(E)/\alpha(E)]e^{\alpha(E)\gamma(E)x} - \beta(E)/\alpha(E) \right\}^{-1/\gamma(E)}, \quad (7)$$

where x is depth in units of 0.1 mm. The coefficients α, β, and γ were taken from the columns for dose from Table I of Kharrati et al.

Finally, the nuclide-specific f-factors (cGy/R) in Table 1 were calculated as spectrally averaged tissue-to-air stopping power ratios. The tissue model was based on the ICRU-44 soft tissue model, and the mass-energy absorption coefficients for it were obtained from Hubbell and Seltzer (1996).

RESULTS

A listing of the results for all nuclides is given in Table 1. The complete list in electronic form will be made available from the web site maintained by the RAdiation Dose Assessment Resource (RADAR) Task Group of the Society of Nuclear Medicine (www.doseinfo-radar.com).

DISCUSSION

Tables 2–4 show comparisons of the values in this report to those reported in the original Radiological Health Handbook (RHH; U.S. DHEW 1970), Unger and Trubey (1982), and Tschurlovits et al. (1992) for selected radionuclides. In converting the current values for comparison to dose rate, as in Tables 3 and 4, the calculated nuclide-specific f-factors in Table 1 were applied. Table 2 shows a comparison between these results and those of the RHH. The authors find good agreement except for ^{125}I, for which the value is listed as "~0.7," but the nature of this difference is unknown due to the approximate nature of the RHH value provided and the age of the publication.

A comparison between the exposure rate constants calculated here and values of equivalent dose constants given in Unger and Trubey (1982) is given in Table 3. The current values are systematically lower than those of Unger and Trubey. This is likely due to differences in methodology. Unger and Trubey included emissions down to 10 keV and used a fitted function of dose rate per unit flux density to obtain their constants instead of using absorption coefficients directly. Contributions from emissions in the 10–15 keV range were neglected, as in practice these emissions almost never contribute to dose due to the rapid attenuation of photons at these energies and the frequent presence of encapsulating materials.

Table 4 shows comparisons of the current values to those of Tschurlovits et al. (1992). Agreement is quite good in many cases, but the current values are notably lower in several cases (^{133}Ba, ^{67}Ga, ^{166}Ho, ^{123}I, ^{125}I, ^{111}In, ^{99m}Tc, ^{201}Tl, and ^{65}Zn). As agreement is very good for most cases, and agreement with the RHH is good for all nuclides except for ^{125}I, some error in calculation or reporting in the Tschurlovits et al. work for these particular nuclides is suspected.

Finally, comparison of shielding values shows good agreement for many commonly used nuclides, but it is hard to make an extensive comparison because such data

Table 1. Exposure rate constants, *f*-factors, and lead shielding data developed in this work for all photon-emitting nuclides in the ICRP 107 nuclear decay data set.

	Exposure rate constant			Lead attenuation thicknesses (mm Pb)				
Nuclide	C m^2 / kg MBq s	R cm^2 / mCi h	*f*-factor (cGy/R)	HVL	QVL	TVL	CVL	MVL
Ac-223	2.33×10^{-14}	0.12	0.956	0.639	2.3	5.86	16.9	28.8
Ac-224	3.57×10^{-13}	1.84	0.955	0.168	0.631	1.42	3.71	6.09
Ac-225	2.45×10^{-14}	0.126	0.952	0.0698	0.459	1.21	9.26	22.1
Ac-226	2.04×10^{-13}	1.05	0.957	0.284	0.932	1.92	4.95	13.2
Ac-227	1.23×10^{-14}	0.0635	0.921	0.00676	0.0135	0.0225	0.048	0.0982
Ac-228	1.03×10^{-12}	5.31	0.958	7.86	18.6	32.7	69.4	109
Ac-230	5.97×10^{-13}	3.08	0.957	11.1	25.3	44.1	91.1	138
Ac-231	5.23×10^{-13}	2.7	0.960	0.894	2.36	4.6	11.1	18.5
Ac-232	1.18×10^{-12}	6.11	0.959	14.1	29.1	48.7	97.7	145
Ac-233	5.58×10^{-13}	2.88	0.965	5.19	9.93	15.9	30.5	44.7
Ag-100m	2.95×10^{-12}	15.3	0.965	8.41	17.6	32.7	78.5	125
Ag-101	1.76×10^{-12}	9.1	0.962	5.48	12.2	23.3	62.7	108
Ag-102m	1.90×10^{-12}	9.83	0.962	11.8	26.6	47.8	101	152
Ag-102	3.55×10^{-12}	18.3	0.963	8.89	19.1	35.4	82.6	131
Ag-103	1.09×10^{-12}	5.65	0.953	3.91	11.4	24.4	63.4	104
Ag-104	3.07×10^{-12}	15.8	0.959	8.38	17.7	31	69.2	111
Ag-104m	1.94×10^{-12}	10	0.961	7.05	15.2	30.6	81.6	133
Ag-105	8.48×10^{-13}	4.38	0.947	1.19	4.37	10.8	36	66.3
Ag-105m	1.75×10^{-15}	0.00904	0.942	0.178	2.3	5.71	26.9	56.5
Ag-106	8.79×10^{-13}	4.54	0.958	4.12	8.69	14.5	28.8	44.6
Ag-106m	3.21×10^{-12}	16.6	0.958	7.66	17	30.8	69	109
Ag-108	2.68×10^{-14}	0.138	0.949	3.6	9.34	16.7	35.2	54.1
Ag-108m	2.02×10^{-12}	10.4	0.956	5.08	11.1	19.2	39.7	60.2
Ag-109m	1.25×10^{-13}	0.644	0.924	0.0111	0.022	0.0372	0.205	1.15
Ag-110	3.39×10^{-14}	0.175	0.963	7.11	13.6	21.8	41.7	61.8
Ag-110m	2.91×10^{-12}	15	0.965	10.3	20	33	69.2	109
Ag-111	2.91×10^{-14}	0.15	0.964	1.93	3.89	6.49	13.1	20.2
Ag-111m	7.00×10^{-14}	0.361	0.923	0.0118	0.0241	0.0459	7.63	27
Ag-112	6.95×10^{-13}	3.59	0.965	10.8	22.2	39.4	87.4	135
Ag-113m	2.56×10^{-13}	1.32	0.960	2.56	6.05	12.3	32.2	53.1
Ag-113	7.83×10^{-14}	0.404	0.964	3.04	7.56	18.5	50.7	85.2
Ag-114	2.62×10^{-13}	1.35	0.965	9.27	19.7	37	86.3	136
Ag-115	4.71×10^{-13}	2.43	0.964	10.6	25.5	45.4	95	144
Ag-116	2.00×10^{-12}	10.3	0.964	13.3	28.2	49	101	153
Ag-117	1.20×10^{-12}	6.18	0.962	14.9	31.8	53.1	105	155
Ag-99	2.43×10^{-12}	12.6	0.964	7.22	16.3	31.4	76.9	125
Al-26	2.60×10^{-12}	13.4	0.965	11.9	26.6	47	96.3	144
Al-28	1.62×10^{-12}	8.37	0.876	19.8	35.9	56.4	105	152
Al-29	1.34×10^{-12}	6.93	0.965	16.6	30.5	48.2	91.2	135
Am-237	5.57×10^{-13}	2.87	0.955	0.508	2.52	7.01	28.5	55.6
Am-238	1.09×10^{-12}	5.65	0.956	7.29	17.8	31.6	67.4	106
Am-239	4.91×10^{-13}	2.53	0.951	0.0306	0.334	1.09	4.53	8.47
Am-240	1.30×10^{-12}	6.73	0.954	7.89	18.6	31.6	62.7	92.9
Am-241	1.45×10^{-13}	0.749	0.932	0.00974	0.0235	0.106	0.528	0.948
Am-242	9.22×10^{-14}	0.476	0.937	0.01	0.0227	0.1	0.779	1.55
Am-242m	7.60×10^{-14}	0.392	0.921	0.00758	0.0151	0.0252	0.0532	0.249
Am-243	1.16×10^{-13}	0.597	0.944	0.0234	0.193	0.49	1.24	2.01
Am-244	1.12×10^{-12}	5.78	0.950	5.24	13.8	24.3	49.9	75.4
Am-244m	5.09×10^{-14}	0.263	0.930	0.0174	3.57	18.3	52.5	85.1
Am-245	5.28×10^{-14}	0.273	0.953	0.138	0.683	1.85	5.14	8.53
Am-246	1.17×10^{-12}	6.02	0.949	2.21	9.09	18.4	40.9	63.1
Am-246m	1.09×10^{-12}	5.6	0.959	11	21.8	35.6	69.8	104
Am-247	1.98×10^{-13}	1.02	0.955	0.267	1.08	2.71	7.01	11.3
Ar-41	1.27×10^{-12}	6.58	0.965	16.1	29.6	46.6	86.8	126
Ar-43	1.47×10^{-12}	7.6	0.965	15	28.9	47.2	94.9	144
Ar-44	1.80×10^{-12}	9.29	0.965	16.8	32.9	53	101	148
As-68	3.78×10^{-12}	19.5	0.965	9.93	20.9	37.2	82.5	129
As-69	1.24×10^{-12}	6.42	0.965	5.28	10.5	18.1	51.2	98.7
As-70	4.35×10^{-12}	22.5	0.965	10.5	21.8	37.9	81.2	126
As-71	6.07×10^{-13}	3.13	0.965	3.76	9.27	17.5	46.3	81.3
As-72	1.92×10^{-12}	9.9	0.965	7.11	14.2	24.7	58.1	102
As-73	7.80×10^{-15}	0.0403	0.876	0.101	0.196	0.319	0.631	0.944
As-74	8.38×10^{-13}	4.33	0.965	5.87	11.2	18	35.4	54
As-76	4.46×10^{-13}	2.3	0.965	7.37	14.7	26.1	64.6	108
As-77	8.75×10^{-15}	0.0452	0.964	1.64	3.94	9.24	23.6	37.6

(Continued on next page)

Table 1. *(Continued)*

Nuclide	Exposure rate constant		*f*-factor (cGy/R)	Lead attenuation thicknesses (mm Pb)				
	C m^2 / kg MBq s	R cm^2 / mCi h		HVL	QVL	TVL	CVL	MVL
As-78	1.32×10^{-12}	6.83	0.965	11.2	22.7	39.2	84.5	131
As-79	3.67×10^{-14}	0.19	0.965	5.44	12	22.3	49.9	77.3
At-204	2.56×10^{-12}	13.2	0.963	5.72	11.6	19.5	41.1	64.7
At-205	1.21×10^{-12}	6.24	0.960	7.72	16.6	29.9	70.3	115
At-206	2.67×10^{-12}	13.8	0.963	6.54	13.9	24.9	59.5	102
At-207	2.06×10^{-12}	10.6	0.961	9.81	20.9	36.7	81.2	128
At-208	3.18×10^{-12}	16.4	0.962	8.88	18.2	31.5	71.4	117
At-209	2.46×10^{-12}	12.7	0.961	7.67	15.9	27	57.8	93.6
At-210	2.95×10^{-12}	15.2	0.962	13.8	27.8	45.2	87.3	129
At-211	4.15×10^{-14}	0.214	0.951	0.175	0.461	0.96	16.1	37.1
At-215	1.83×10^{-16}	0.000946	0.876	3.22	6.19	9.97	19.3	28.4
At-216	2.57×10^{-15}	0.0133	0.953	0.338	0.849	2.12	6.9	12
At-217	2.43×10^{-16}	0.00126	0.962	1.75	4.17	10.4	28	45
At-220	4.85×10^{-13}	2.5	0.964	1.95	4.62	10.2	28.3	47.6
Au-186	1.58×10^{-12}	8.15	0.962	5.69	13.2	25.8	66.8	112
Au-187	1.05×10^{-12}	5.44	0.956	10.8	24.3	42.7	89.1	135
Au-190	2.18×10^{-12}	11.3	0.960	12	28.5	50	103	155
Au-191	6.36×10^{-13}	3.28	0.956	3.17	8.07	15.8	39.3	68.7
Au-192	1.83×10^{-12}	9.43	0.959	12.2	28.2	48.8	99.3	149
Au-193	1.69×10^{-13}	0.871	0.950	0.505	1.54	4.29	17	35.9
Au-193m	2.03×10^{-13}	1.05	0.960	1.02	2.04	3.37	6.68	9.99
Au-194	1.03×10^{-12}	5.31	0.958	8.23	22.4	41.4	88.4	135
Au-195	7.93×10^{-14}	0.409	0.947	0.19	0.375	0.623	1.3	1.95
Au-195m	2.07×10^{-13}	1.07	0.960	1.06	2.12	3.5	6.95	10.4
Au-196	5.11×10^{-13}	2.64	0.957	2.04	4.31	7.28	15.3	28
Au-196m	2.34×10^{-13}	1.21	0.955	0.447	0.927	1.73	5.35	10.4
Au-198	4.46×10^{-13}	2.3	0.965	3.35	6.47	10.5	21.2	35.9
Au-198m	5.25×10^{-13}	2.71	0.959	0.634	1.36	2.53	7.23	13.3
Au-199	9.13×10^{-14}	0.471	0.959	0.483	0.9	1.47	3.18	5.22
Au-200	2.80×10^{-13}	1.45	0.965	9.66	22.8	39.5	79.6	118
Au-200m	2.15×10^{-12}	11.1	0.964	4.32	9.96	18.1	40.1	63.3
Au-201	3.77×10^{-14}	0.195	0.960	4.74	9.87	16.6	33.8	51.7
Au-202	1.80×10^{-13}	0.93	0.965	8.73	19.4	34.6	72.8	111
Ba-124	7.09×10^{-13}	3.66	0.947	4.11	11	22.2	56.6	93.2
Ba-126	7.13×10^{-13}	3.68	0.946	4.45	13.5	26.8	61.5	96.9
Ba-127	8.49×10^{-13}	4.38	0.953	4.7	10.2	18.8	56.7	105
Ba-128	1.68×10^{-13}	0.868	0.929	0.0436	0.24	1.83	5.99	10.6
Ba-129	4.38×10^{-13}	2.26	0.943	3	8.82	18.5	60.1	107
Ba-129m	1.75×10^{-12}	9.06	0.954	7.26	17.6	32.6	72.4	113
Ba-131	6.38×10^{-13}	3.29	0.946	1.8	5.78	11.8	30	56.2
Ba-131m	1.28×10^{-13}	0.659	0.942	0.0644	0.202	0.465	1.16	1.82
Ba-133	5.89×10^{-13}	3.04	0.943	0.819	2.84	5.65	12.7	19.9
Ba-133m	1.37×10^{-13}	0.707	0.932	0.0693	0.849	2.5	6.49	10.4
Ba-135m	1.28×10^{-13}	0.663	0.931	0.0605	0.637	2.15	5.85	9.51
Ba-137m	6.64×10^{-13}	3.43	0.962	7.19	13.7	21.8	41.5	60.7
Ba-139	4.91×10^{-14}	0.254	0.957	0.496	1.04	2.44	46.1	88.9
Ba-140	2.21×10^{-13}	1.14	0.953	3.46	8.01	13.9	28.6	43
Ba-141	9.67×10^{-13}	4.99	0.963	5.72	15.7	31.6	74.4	118
Ba-142	1.11×10^{-12}	5.75	0.959	9.43	20.8	35.1	70.3	105
Be-7	5.54×10^{-14}	0.286	0.876	4.35	8.33	13.4	25.6	37.7
Bi-197	1.76×10^{-12}	9.07	0.961	10.4	21.5	36.4	75.6	116
Bi-200	2.60×10^{-12}	13.4	0.962	6.06	14	26.4	59.1	90.9
Bi-201	1.73×10^{-12}	8.92	0.960	12.8	25.5	42.2	85.5	130
Bi-202	2.90×10^{-12}	15	0.962	8.41	17.9	31.3	67.9	109
Bi-203	2.35×10^{-12}	12.1	0.961	13.5	26.8	44.5	90.4	137
Bi-204	3.02×10^{-12}	15.6	0.962	9.99	20.8	35.1	73.1	114
Bi-205	1.66×10^{-12}	8.58	0.960	13.1	26.6	44.7	91.2	137
Bi-206	3.41×10^{-12}	17.6	0.962	9.35	19.5	33.7	73.6	117
Bi-207	1.61×10^{-12}	8.33	0.961	9.28	19.1	32.9	69.7	108
Bi-208	2.15×10^{-12}	11.1	0.959	21.4	39.5	62.5	117	170
Bi-210m	2.77×10^{-13}	1.43	0.963	1.56	3.23	6.09	21.7	40.8
Bi-211	5.13×10^{-14}	0.265	0.962	2.19	4.35	7.12	14	20.7
Bi-212	1.08×10^{-13}	0.556	0.961	10.3	20.6	34.8	76.2	120
Bi-213	1.41×10^{-13}	0.728	0.963	3.75	7.42	12.4	29.4	59.6
Bi-214	1.45×10^{-12}	7.48	0.965	13.4	26.9	45.1	91.8	138
Bi-215	2.69×10^{-13}	1.39	0.962	3.62	10.6	24.3	60.6	97.7
Bi-216	8.20×10^{-13}	4.23	0.965	4.88	9.48	15.4	30.4	45.3
Bk-245	3.88×10^{-13}	2	0.953	0.0927	0.515	1.58	6.33	13.8

Table 1. *(Continued)*

Nuclide	Exposure rate constant		*f*-factor (cGy/R)	Lead attenuation thicknesses (mm Pb)				
	C m^2 / kg MBq s	R cm^2 / mCi h		HVL	QVL	TVL	CVL	MVL
Bk-246	1.10×10^{-12}	5.66	0.953	6.47	16.1	27.9	57.5	87.8
Bk-247	1.88×10^{-13}	0.969	0.956	0.377	1.15	2.51	6.08	9.62
Bk-248m	1.40×10^{-13}	0.723	0.944	0.0219	0.585	6.17	22.2	37.4
Bk-250	1.04×10^{-12}	5.39	0.957	10.8	21.8	35.3	67.6	98.9
Bk-251	3.46×10^{-13}	1.78	0.944	0.0117	0.0382	0.334	1.25	2.39
Br-72	3.09×10^{-12}	15.9	0.965	8.73	18.4	33.2	75.6	121
Br-73	1.57×10^{-12}	8.12	0.963	5.29	10.7	18.3	42.5	73.9
Br-74	4.10×10^{-12}	21.2	0.964	12.2	27.2	49	104	159
Br-74m	4.01×10^{-12}	20.7	0.965	10.1	21.7	40.3	92.6	145
Br-75	1.31×10^{-12}	6.77	0.965	3.9	8.4	14.8	34.2	63.4
Br-76	2.70×10^{-12}	14	0.965	10.3	22.8	42.6	94.8	146
Br-76m	5.76×10^{-14}	0.297	0.930	0.0917	0.214	2.84	22.4	43.9
Br-77	3.41×10^{-13}	1.76	0.965	3.61	8.64	15.8	36.4	61.1
Br-77m	1.29×10^{-14}	0.0665	0.876	0.248	0.442	0.697	1.48	1.74
Br-78	1.15×10^{-12}	5.93	0.965	5.09	9.73	15.6	30.5	47.5
Br-80	8.36×10^{-14}	0.431	0.965	6.28	12	19.4	38.4	60
Br-80m	4.97×10^{-14}	0.257	0.923	0.0386	0.0741	0.121	0.239	0.364
Br-82m	2.94×10^{-15}	0.0152	0.949	8.72	17.4	28.7	59.4	95.3
Br-82	2.80×10^{-12}	14.4	0.965	9.56	18.8	31.7	67.9	107
Br-83	7.61×10^{-15}	0.0393	0.965	5.26	10	16	30.7	45.1
Br-84m	2.82×10^{-12}	14.5	0.965	11.5	24.1	40.8	83	125
Br-84	1.56×10^{-12}	8.07	0.964	16.6	31.8	52.1	105	157
Br-85	6.87×10^{-14}	0.355	0.965	11.4	21.9	35.5	72.8	114
C-10	1.92×10^{-12}	9.94	0.965	6.08	11.8	19.4	39.5	60.7
C-11	1.13×10^{-12}	5.86	0.876	4.95	9.46	15.1	28.9	42.5
Ca-47	1.05×10^{-12}	5.43	0.965	15.1	28.5	45.2	85.5	124
Ca-49	2.41×10^{-12}	12.4	0.961	22.4	40.9	64.5	121	176
Cd-101	2.64×10^{-12}	13.6	0.959	8.8	20.6	38.7	86	133
Cd-102	1.13×10^{-12}	5.84	0.951	3.94	10	20.3	55.8	94.3
Cd-103	2.23×10^{-12}	11.5	0.954	10.7	25	44.7	94.1	143
Cd-104	5.94×10^{-13}	3.07	0.937	0.0395	3.8	12.8	33.9	54.6
Cd-105	1.47×10^{-12}	7.57	0.952	8.77	21.6	40.4	88.7	136
Cd-107	3.94×10^{-13}	2.03	0.922	0.0112	0.0222	0.038	2	23.5
Cd-109	3.66×10^{-13}	1.89	0.922	0.0109	0.0213	0.0353	0.0805	0.74
Cd-111m	4.16×10^{-13}	2.15	0.954	0.455	1.29	2.46	5.43	8.38
Cd-113m	2.11×10^{-16}	0.00109	0.936	0.0227	0.419	1.86	5.41	8.9
Cd-115	2.24×10^{-13}	1.16	0.961	4.52	9.14	15	29.2	43.2
Cd-115m	3.40×10^{-14}	0.175	0.965	12.5	23.8	38.2	74.2	111
Cd-117	1.10×10^{-12}	5.68	0.963	11.2	24.9	42.2	84.9	127
Cd-117m	1.96×10^{-12}	10.1	0.965	15.3	29.8	48.8	97	145
Cd-119	1.57×10^{-12}	8.1	0.964	14.1	29.5	49	97.2	145
Cd-119m	2.22×10^{-12}	11.5	0.964	15	29.3	47.9	95.2	143
Ce-130	6.31×10^{-13}	3.26	0.945	2.51	9.57	22	55.9	90.8
Ce-131	1.79×10^{-12}	9.25	0.957	6.35	14.6	28.8	71	115
Ce-132	3.69×10^{-13}	1.91	0.947	0.407	1.21	3.04	14.7	30.2
Ce-133	7.21×10^{-13}	3.72	0.944	2.51	7.16	13	27.3	41.2
Ce-133m	1.89×10^{-12}	9.78	0.951	7.86	18.8	35.5	80.1	125
Ce-134	1.12×10^{-13}	0.579	0.923	0.0316	0.0609	0.102	0.322	3.71
Ce-135	9.83×10^{-13}	5.08	0.951	3.72	9.97	19.3	45.7	76.8
Ce-137	1.25×10^{-13}	0.645	0.923	0.0366	0.0775	0.361	13.3	31.6
Ce-137m	1.14×10^{-13}	0.59	0.930	0.0697	0.615	2.6	23.2	49.6
Ce-139	2.46×10^{-13}	1.27	0.943	0.141	0.532	1.05	2.3	3.53
Ce-141	8.78×10^{-14}	0.453	0.953	0.249	0.577	0.981	1.96	2.93
Ce-143	3.58×10^{-13}	1.85	0.944	1.78	5.16	12.9	36.4	61.6
Ce-144	2.61×10^{-14}	0.135	0.945	0.123	0.372	0.709	1.53	2.36
Ce-145	9.57×10^{-13}	4.94	0.946	6.22	14.3	25.2	54.5	86.9
Cf-244	2.66×10^{-14}	0.137	0.921	0.00779	0.0155	0.0259	0.0527	0.0818
Cf-246	1.83×10^{-14}	0.0947	0.921	0.0078	0.0156	0.026	0.0536	0.094
Cf-247	5.74×10^{-13}	2.96	0.938	0.00948	0.0224	0.16	1.8	11
Cf-248	2.20×10^{-14}	0.114	0.921	0.00781	0.0156	0.026	0.0539	0.101
Cf-249	4.15×10^{-13}	2.14	0.959	2.02	4.61	7.97	16.4	25.1
Cf-250	2.50×10^{-14}	0.129	0.929	0.0205	4.94	20.8	67.4	116
Cf-251	2.36×10^{-13}	1.22	0.951	0.0425	0.366	0.965	3.44	6.99
Cf-252	4.48×10^{-13}	2.31	0.960	11.5	25.5	44.7	94.9	146
Cf-253	1.01×10^{-13}	0.522	0.921	0.00761	0.0154	0.0261	0.0582	0.147
Cf-254	1.59×10^{-11}	82.3	0.963	12.3	26.4	45.7	96	147

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Table 1. *(Continued)*

Nuclide	Exposure rate constant		*f*-factor (cGy/R)	Lead attenuation thicknesses (mm Pb)				
	C m^2 / kg MBq s	R cm^2 / mCi h		HVL	QVL	TVL	CVL	MVL
Cl-34	1.14×10^{-12}	5.87	0.876	4.95	9.46	15.1	28.9	42.5
Cl-34m	1.94×10^{-12}	10	0.965	12.3	27.9	49.5	103	155
Cl-36	1.58×10^{-16}	0.000816	0.876	4.95	9.46	15.1	28.9	42.5
Cl-38	1.28×10^{-12}	6.6	0.965	20.4	37.1	58.2	109	158
Cl-39	1.43×10^{-12}	7.37	0.965	14.8	29.1	46.9	89.3	131
Cl-40	3.42×10^{-12}	17.7	0.964	19.6	36.4	57.7	110	163
Cm-238	1.69×10^{-13}	0.87	0.951	0.0252	0.179	0.452	1.15	1.78
Cm-239	3.74×10^{-13}	1.93	0.956	0.191	0.585	1.18	2.88	5.32
Cm-240	3.48×10^{-14}	0.179	0.921	0.00732	0.0146	0.0242	0.0489	0.0776
Cm-241	7.61×10^{-13}	3.93	0.953	1.18	4.9	10.1	22.7	35.9
Cm-242	3.12×10^{-14}	0.161	0.921	0.00732	0.0146	0.0242	0.0488	0.077
Cm-243	2.64×10^{-13}	1.36	0.951	0.042	0.527	1.69	5.37	9.3
Cm-244	2.67×10^{-14}	0.138	0.921	0.00732	0.0146	0.0241	0.0487	0.076
Cm-245	2.39×10^{-13}	1.23	0.950	0.0219	0.182	0.507	1.55	2.79
Cm-246	2.28×10^{-14}	0.118	0.922	0.00833	0.0176	0.0376	30.9	73.6
Cm-247	3.50×10^{-13}	1.81	0.964	2.95	5.85	9.58	18.8	27.9
Cm-248	1.26×10^{-12}	6.51	0.962	12	26	45.3	95.6	146
Cm-249	2.26×10^{-14}	0.117	0.961	5.14	10.9	18.3	36.4	54.3
Cm-250	1.26×10^{-11}	65	0.963	12.3	26.5	45.8	96.1	147
Cm-251	1.54×10^{-13}	0.797	0.956	3.01	8.16	15.2	36.2	63.3
Co-54m	4.07×10^{-12}	21	0.965	9.46	20.9	37.2	77.8	117
Co-55	2.12×10^{-12}	11	0.965	8.06	16.8	29.9	66.4	105
Co-56	3.46×10^{-12}	17.9	0.965	14.5	28.2	46.7	95.5	146
Co-57	1.09×10^{-13}	0.563	0.961	0.298	0.533	0.85	2.39	24
Co-58	1.05×10^{-12}	5.44	0.965	8.85	17	27.5	53.7	80.3
Co-58m	1.23×10^{-16}	0.000636	0.876	0.0161	0.0299	0.0473	0.09	0.133
Co-60	2.50×10^{-12}	12.9	0.965	15.6	28.8	45.3	84.7	123
Co-60m	4.59×10^{-15}	0.0237	0.942	8.27	23.2	40.7	82.1	122
Co-61	1.02×10^{-13}	0.525	0.946	0.69	8.35	21	50.2	78
Co-62	1.54×10^{-12}	7.94	0.965	16.3	30.2	48	93.2	140
Co-62m	2.63×10^{-12}	13.6	0.965	15.9	29.4	46.7	89.9	135
Cr-48	4.50×10^{-13}	2.32	0.963	1.26	3.05	5.47	12.6	23.6
Cr-49	1.15×10^{-12}	5.95	0.962	4.39	8.92	14.6	28.6	43.1
Cr-51	3.44×10^{-14}	0.178	0.876	1.92	3.74	6.07	11.8	17.5
Cr-55	5.38×10^{-16}	0.00278	0.876	18.3	33.4	52.5	97.5	141
Cr-56	1.97×10^{-13}	1.02	0.943	0.0331	0.17	0.576	1.58	2.58
Cs-121	1.31×10^{-12}	6.76	0.962	4.78	9.75	16.6	40.3	77.6
Cs-121m	1.33×10^{-12}	6.86	0.961	4.27	9.34	16.6	42	78.4
Cs-123	1.25×10^{-12}	6.47	0.957	4.85	10.2	17.7	43.8	79.9
Cs-124	1.28×10^{-12}	6.59	0.964	5.06	10.1	17.3	47.6	95.1
Cs-125	8.92×10^{-13}	4.61	0.953	4.79	10.2	18.2	52	99.8
Cs-126	1.29×10^{-12}	6.64	0.963	4.87	9.72	16.7	43.9	88
Cs-127	5.84×10^{-13}	3.01	0.945	2.24	5.93	11.3	33.4	70.7
Cs-128	1.02×10^{-12}	5.24	0.960	4.7	9.34	15.6	35.7	74.9
Cs-129	4.61×10^{-13}	2.38	0.937	0.915	3.69	7.62	19	35.3
Cs-130m	1.87×10^{-13}	0.963	0.932	0.0369	0.0905	0.391	5.13	20.5
Cs-130	6.15×10^{-13}	3.18	0.952	4.3	9.06	15.3	34.9	74.7
Cs-131	1.31×10^{-13}	0.679	0.921	0.0262	0.0481	0.0765	0.15	0.226
Cs-132	8.90×10^{-13}	4.6	0.947	5.9	12.6	21.1	42.5	66.6
Cs-134	1.70×10^{-12}	8.76	0.965	8.04	15.4	25.1	50.9	79.5
Cs-134m	6.55×10^{-14}	0.338	0.933	0.0392	0.0941	0.345	1.11	1.88
Cs-135m	1.73×10^{-12}	8.91	0.965	9.82	18.5	29.2	55	80.2
Cs-136	2.25×10^{-12}	11.6	0.963	10.1	20.5	33.8	66.7	99.9
Cs-137†	6.64×10^{-13}	3.43	0.962	7.19	13.7	21.8	41.5	60.7
Cs-138m	4.72×10^{-13}	2.44	0.946	7.32	20.6	39	82.8	125
Cs-138	2.27×10^{-12}	11.7	0.965	14.9	29.5	48.3	95.2	142
Cs-139	2.79×10^{-13}	1.44	0.965	17	32.2	51.8	101	150
Cs-140	1.64×10^{-12}	8.45	0.965	14.6	29.7	50.1	102	153
Cu-57	1.26×10^{-12}	6.48	0.965	5.4	10.5	17.6	43.1	82.5
Cu-59	1.57×10^{-12}	8.1	0.965	6.08	12.3	22.3	58.2	98.4
Cu-60	3.83×10^{-12}	19.8	0.965	12.1	25.8	44.6	92.2	140
Cu-61	9.06×10^{-13}	4.68	0.965	5.2	10.3	17.4	40.7	74.7
Cu-62	1.12×10^{-12}	5.78	0.965	4.98	9.52	15.3	29.7	46.3
Cu-64	2.04×10^{-13}	1.05	0.965	5.11	9.81	16	34.5	68.3
Cu-66	1.02×10^{-13}	0.525	0.965	12.9	24.1	37.9	71	103
Cu-67	1.11×10^{-13}	0.574	0.962	0.544	1.06	1.76	4.16	10.1
Cu-69	5.53×10^{-13}	2.86	0.965	11.4	22	35.8	70.8	107
Dy-148	8.17×10^{-13}	4.22	0.950	6.08	12.3	20.3	42.1	70.5

Table 1. *(Continued)*

Nuclide	Exposure rate constant		*f*-factor (cGy/R)	Lead attenuation thicknesses (mm Pb)				
	C m^2 / kg MBq s	R cm^2 / mCi h		HVL	QVL	TVL	CVL	MVL
Dy-149	1.67×10^{-12}	8.63	0.951	11.1	23.6	40.6	85.4	131
Dy-150	3.27×10^{-13}	1.69	0.949	2.48	5.38	9.06	18.1	27
Dy-151	1.45×10^{-12}	7.5	0.953	8.84	20	35.7	77.4	120
Dy-152	3.32×10^{-13}	1.71	0.949	0.792	1.83	3.16	6.46	9.73
Dy-153	9.68×10^{-13}	5	0.945	5.36	15.6	31.3	72.4	114
Dy-155	7.25×10^{-13}	3.74	0.949	5	15.8	31	69.9	110
Dy-157	4.09×10^{-13}	2.11	0.948	1.41	3.31	5.78	12.2	20.8
Dy-159	8.58×10^{-14}	0.443	0.929	0.066	0.128	0.213	0.439	0.697
Dy-165m	2.23×10^{-14}	0.115	0.941	0.672	4.21	9.78	23.7	37.4
Dy-165	3.06×10^{-14}	0.158	0.944	2.25	7.65	16.3	40.4	68.1
Dy-166	6.09×10^{-14}	0.315	0.936	0.105	0.255	0.823	8.9	18.3
Dy-167	5.86×10^{-13}	3.03	0.959	3.46	8.6	16.2	37.7	65.3
Dy-168	4.40×10^{-13}	2.27	0.955	3.02	7.43	13.4	29.1	46
Er-154	1.77×10^{-13}	0.914	0.930	0.0479	0.199	4.16	18.6	32.3
Er-156	1.25×10^{-13}	0.647	0.930	0.0653	0.156	0.452	6.69	14.7
Er-159	1.03×10^{-12}	5.31	0.952	7.57	16.8	31	74.1	120
Er-161	1.07×10^{-12}	5.52	0.950	9.12	19.1	31.9	65.7	102
Er-163	6.52×10^{-14}	0.336	0.931	0.0795	0.157	0.266	3.78	38.2
Er-165	6.19×10^{-14}	0.319	0.931	0.0776	0.151	0.25	0.508	0.788
Er-167m	1.02×10^{-13}	0.526	0.955	0.651	1.33	2.2	4.39	6.57
Er-171	4.03×10^{-13}	2.08	0.956	1.42	3.28	5.99	21.6	48
Er-172	5.80×10^{-13}	3	0.952	4.14	8.95	15.5	32.9	50.3
Er-173	8.75×10^{-13}	4.52	0.957	5.25	15.2	27	55.2	82.5
Es-249	7.26×10^{-13}	3.75	0.951	0.474	4.01	11.6	40.3	71.1
Es-250	2.54×10^{-12}	13.1	0.944	0.259	5.16	16.4	43.3	69
Es-250m	8.56×10^{-13}	4.42	0.949	3.5	14.5	29.2	65.3	102
Es-251	4.86×10^{-13}	2.51	0.941	0.0101	0.0253	0.209	0.998	1.89
Es-253	1.33×10^{-14}	0.0686	0.922	0.0073	0.0148	0.0258	1.61	10.4
Es-254	4.42×10^{-13}	2.28	0.921	0.00709	0.0143	0.0242	0.0608	2.87
Es-254m	6.68×10^{-13}	3.45	0.951	4.74	11.6	20	40.7	62.1
Es-256	6.45×10^{-14}	0.333	0.921	0.00813	0.0164	0.0278	0.0598	0.101
Eu-142	1.30×10^{-12}	6.71	0.964	5.85	11.6	20.4	58.6	107
Eu-142m	3.70×10^{-12}	19.1	0.964	7.95	16	27.3	59	93.3
Eu-143	1.20×10^{-12}	6.21	0.961	6.59	13.7	26.6	71.7	119
Eu-144	1.18×10^{-12}	6.11	0.963	5.84	11.6	21.1	63	110
Eu-145	1.33×10^{-12}	6.89	0.950	11.4	23.3	39.4	83.9	130
Eu-146	2.54×10^{-12}	13.1	0.957	9.31	18.8	32.6	74.3	120
Eu-147	5.50×10^{-13}	2.84	0.944	4.85	14.1	26.5	58.6	92
Eu-148	2.44×10^{-12}	12.6	0.958	7.14	14.6	25.9	62.1	104
Eu-149	1.21×10^{-13}	0.626	0.930	0.0844	0.546	3.08	12.7	26.2
Eu-150	1.73×10^{-12}	8.92	0.957	4.68	10.6	20.7	53.9	91.7
Eu-150m	5.73×10^{-14}	0.296	0.947	3.41	8.44	19.3	58.4	101
Eu-152	1.25×10^{-12}	6.44	0.952	9.52	21.5	36.7	75.1	114
Eu-152m	3.26×10^{-13}	1.68	0.949	9.31	19.4	32	63.4	95.7
Eu-152n	8.52×10^{-14}	0.44	0.948	0.133	0.294	0.537	1.2	1.2
Eu-154	1.30×10^{-12}	6.69	0.959	11.2	22.5	37.1	74.3	112
Eu-154m	1.02×10^{-13}	0.524	0.940	0.0809	0.214	0.439	1.08	1.61
Eu-155	6.80×10^{-14}	0.351	0.947	0.162	0.396	0.764	1.75	2.87
Eu-156	1.20×10^{-12}	6.21	0.961	14.6	28.4	46.5	93.1	140
Eu-157	3.49×10^{-13}	1.8	0.944	2.53	6.34	12.1	30.3	52.5
Eu-158	1.33×10^{-12}	6.87	0.959	12.4	23.9	38.9	78.5	121
Eu-159	3.69×10^{-13}	1.9	0.940	3.77	12.5	24.5	57.9	95
F-17	1.14×10^{-12}	5.86	0.965	4.96	9.46	15.1	29	42.5
F-18	1.10×10^{-12}	5.68	0.876	4.95	9.46	15.1	28.9	42.5
Fe-52	7.97×10^{-13}	4.12	0.965	3.5	8.1	13.9	28.8	48.9
Fe-53	1.30×10^{-12}	6.72	0.965	4.67	9.09	15	32.6	72.1
Fe-53m	3.09×10^{-12}	16	0.965	13	25	40.9	82.4	125
Fe-59	1.20×10^{-12}	6.2	0.965	14.7	27.3	43.1	80.9	118
Fe-61	1.39×10^{-12}	7.18	0.965	13.7	26.7	43.1	84.4	127
Fe-62	5.63×10^{-13}	2.91	0.876	4.88	9.33	14.9	28.6	41.9
Fm-251	3.97×10^{-13}	2.05	0.946	0.0213	0.388	4.78	32.7	63.3
Fm-252	3.63×10^{-14}	0.187	0.921	0.00744	0.0149	0.0251	0.0535	0.103
Fm-253	4.37×10^{-13}	2.25	0.935	0.00947	0.0216	0.104	1.44	5.43
Fm-254	4.22×10^{-14}	0.218	0.924	0.00998	0.0243	4.87	47.6	95
Fm-255	3.85×10^{-13}	1.99	0.921	0.00718	0.0144	0.0243	0.0551	0.45
Fm-256	1.18×10^{-11}	60.9	0.963	12.2	26.2	45.5	95.6	146

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Table 1. *(Continued)*

	Exposure rate constant			Lead attenuation thicknesses (mm Pb)				
Nuclide	C m^2 / kg MBq s	R cm^2 / mCi h	*f*-factor (cGy/R)	HVL	QVL	TVL	CVL	MVL
Fm-257	4.87×10^{-13}	2.51	0.943	0.0141	0.119	1.06	32.8	81.9
Fr-212	1.17×10^{-12}	6.06	0.961	10.4	23.3	39.4	78.4	116
Fr-219	3.83×10^{-15}	0.0198	0.963	2.67	5.7	10.1	22.7	36.2
Fr-220	1.39×10^{-14}	0.0719	0.951	0.1	0.404	0.889	3.84	11.2
Fr-221	3.06×10^{-14}	0.158	0.962	0.769	1.52	2.57	6.14	14.1
Fr-222	2.92×10^{-13}	1.51	0.956	0.356	1.54	7.97	45.8	82.7
Fr-223	1.53×10^{-13}	0.788	0.937	0.0172	0.158	1.13	20.2	45.4
Fr-224	6.12×10^{-13}	3.16	0.960	7.55	20.4	37.1	79.5	122
Fr-227	5.55×10^{-13}	2.86	0.956	2.78	8.37	16.9	46.1	84.7
Ga-64	3.23×10^{-12}	16.7	0.965	10.9	23.8	43	94.6	147
Ga-65	1.26×10^{-12}	6.53	0.963	4.95	10.1	17.1	39.9	75.6
Ga-66	2.24×10^{-12}	11.6	0.965	12.8	27.7	48.7	103	156
Ga-67	1.55×10^{-13}	0.803	0.961	0.861	2.23	4.8	13.9	34
Ga-68	1.05×10^{-12}	5.43	0.965	5.12	9.84	16	33.8	61.7
Ga-70	7.52×10^{-15}	0.0388	0.965	11.9	23.1	37.1	70.2	102
Ga-72	2.60×10^{-12}	13.4	0.965	14	27.4	46	96.2	147
Ga-73	3.75×10^{-13}	1.94	0.962	2.14	4.54	9.6	35.5	64
Ga-74	2.93×10^{-12}	15.1	0.965	14.3	29.4	50.1	102	153
Gd-142	1.13×10^{-12}	5.83	0.958	6.14	13.3	25.8	68.3	113
Gd-143m	2.27×10^{-12}	11.7	0.958	6.54	15.1	29.2	71.6	116
Gd-144	9.43×10^{-13}	4.87	0.955	7.13	15.9	33	85.1	137
Gd-145m	7.58×10^{-13}	3.91	0.960	7.34	14.4	23.4	45.2	66.5
Gd-145	2.27×10^{-12}	11.7	0.956	14.8	30.5	51.1	101	151
Gd-146	3.36×10^{-13}	1.73	0.941	0.128	0.328	0.692	1.79	6.12
Gd-147	1.53×10^{-12}	7.92	0.954	5.89	14.8	27.5	61	96.9
Gd-149	6.16×10^{-13}	3.18	0.948	2.23	6.84	16	41.3	67.1
Gd-151	1.24×10^{-13}	0.639	0.932	0.0839	0.257	1.09	4.54	9.27
Gd-153	1.64×10^{-13}	0.847	0.936	0.0783	0.172	0.349	1.01	1.58
Gd-159	6.62×10^{-14}	0.342	0.942	1.38	3.73	6.79	14.6	23.5
Gd-162	4.65×10^{-13}	2.4	0.963	3.37	6.58	10.7	20.9	31
Ge-66	7.50×10^{-13}	3.87	0.958	3.62	8.2	15.3	42.5	82
Ge-67	1.52×10^{-12}	7.84	0.965	5.37	11.4	21.1	59.5	106
Ge-69	9.98×10^{-13}	5.15	0.965	9.4	19.4	33.4	70.1	108
Ge-75	3.71×10^{-14}	0.192	0.965	1.27	2.49	4.29	12.8	28
Ge-77	1.13×10^{-12}	5.82	0.965	4.92	13.2	26.9	66.5	109
Ge-78	2.96×10^{-13}	1.53	0.965	1.37	2.64	4.27	8.35	12.4
Hf-167	6.84×10^{-13}	3.53	0.957	3.2	7.02	12.4	26.2	39.8
Hf-169	7.19×10^{-13}	3.71	0.954	3.99	8.22	13.6	26.8	39.8
Hf-170	4.83×10^{-13}	2.49	0.950	2.58	7.91	15.1	32.9	50.9
Hf-172	1.83×10^{-13}	0.943	0.938	0.0552	0.178	0.368	0.977	1.75
Hf-173	4.15×10^{-13}	2.14	0.952	0.639	2.35	6.03	32.9	64.7
Hf-175	3.94×10^{-13}	2.04	0.950	1.62	3.73	6.43	13.2	20.1
Hf-177m	2.44×10^{-12}	12.6	0.959	1.5	3.5	7.12	21.7	39.4
Hf-178m	2.43×10^{-12}	12.5	0.961	2.78	6.57	12.1	26.7	41.7
Hf-179m	9.92×10^{-13}	5.12	0.957	1.79	4.52	8.53	19	29.7
Hf-180m	1.07×10^{-12}	5.54	0.959	2.08	4.81	8.84	19.7	31.1
Hf-181	5.78×10^{-13}	2.98	0.960	3.22	7.13	12.2	24.7	37
Hf-182	2.53×10^{-13}	1.3	0.961	1.13	2.29	3.8	7.55	11.3
Hf-182m	9.85×10^{-13}	5.08	0.956	3.59	9.28	18.9	46.5	74.7
Hf-183	8.36×10^{-13}	4.32	0.957	7.31	15.2	25.9	54.1	86.9
Hf-184	2.50×10^{-13}	1.29	0.954	0.817	2.44	5.13	11.8	18.3
Hg-190	1.91×10^{-13}	0.985	0.954	0.323	0.644	1.16	9.36	27.9
Hg-191m	1.54×10^{-12}	7.97	0.960	5.96	15.4	30.6	72.9	116
Hg-192	2.79×10^{-13}	1.44	0.954	0.722	1.84	3.52	8.05	13.9
Hg-193	8.43×10^{-13}	4.35	0.956	8.92	21.1	37.4	80.3	125
Hg-193m	1.06×10^{-12}	5.46	0.958	7.99	18.8	34.5	76	118
Hg-195	2.04×10^{-13}	1.05	0.950	4.25	13	24.8	55.4	87.6
Hg-195m	2.10×10^{-13}	1.08	0.955	1.66	4.69	11.9	37.4	71.4
Hg-197	6.76×10^{-14}	0.349	0.947	0.216	0.431	0.727	1.59	2.88
Hg-197m	8.94×10^{-14}	0.461	0.955	0.359	0.746	1.6	5.57	9.65
Hg-199m	1.79×10^{-13}	0.926	0.956	0.602	1.5	4.32	12.2	20
Hg-203	2.52×10^{-13}	1.3	0.963	1.32	2.6	4.25	8.35	12.4
Hg-205	5.04×10^{-15}	0.026	0.961	0.719	1.37	2.25	4.81	11.1
Hg-206	1.30×10^{-13}	0.672	0.961	1.96	4.11	7.72	24.5	43.7
Hg-207	2.58×10^{-12}	13.3	0.964	14	28.6	47.3	93.9	140
Ho-150	2.07×10^{-12}	10.7	0.964	6.8	13.4	22.5	47	72.5
Ho-153	1.13×10^{-12}	5.84	0.957	4.61	10.7	20.5	52.9	89.3
Ho-153m	1.18×10^{-12}	6.08	0.957	4.22	9.43	17	41.6	73.8

Table 1. *(Continued)*

Nuclide	Exposure rate constant		*f*-factor (cGy/R)	Lead attenuation thicknesses (mm Pb)				
	C m^2 / kg MBq s	R cm^2 / mCi h		HVL	QVL	TVL	CVL	MVL
Ho-154m	2.68×10^{-12}	13.8	0.962	4.68	10	18.9	49.8	85.3
Ho-154	2.02×10^{-12}	10.4	0.962	5.78	12.9	25.2	64.8	108
Ho-155	6.74×10^{-13}	3.48	0.949	4.22	11.1	24	68.5	116
Ho-156	2.16×10^{-12}	11.2	0.958	7.79	18.8	35.7	81.8	129
Ho-157	6.69×10^{-13}	3.45	0.946	2.6	8.13	19.3	53.1	89.8
Ho-159	4.49×10^{-13}	2.32	0.945	0.604	3.04	11.4	40.6	69.9
Ho-160	1.84×10^{-12}	9.52	0.954	8.79	17.7	29.3	58.5	88.3
Ho-161	1.62×10^{-13}	0.837	0.929	0.0335	0.0841	0.187	0.675	6.71
Ho-162	2.00×10^{-13}	1.03	0.936	3.18	12.3	28.1	69.7	110
Ho-162m	6.07×10^{-13}	3.14	0.946	7.25	19.9	35.2	72.3	109
Ho-164	4.88×10^{-14}	0.252	0.931	0.0764	0.151	0.257	0.631	1.25
Ho-164m	7.87×10^{-14}	0.406	0.930	0.0701	0.141	0.24	0.514	0.825
Ho-166	3.10×10^{-14}	0.16	0.942	5.68	20.6	39.3	83.4	126
Ho-166m	1.75×10^{-12}	9.05	0.961	6.42	14.2	24.3	49.8	76.6
Ho-167	4.02×10^{-13}	2.08	0.959	1.99	4.13	7.03	15.1	26.2
Ho-168	9.38×10^{-13}	4.84	0.961	9.16	17.8	29.1	59.1	95.2
Ho-168m	1.03×10^{-14}	0.0531	0.931	0.0777	0.152	0.25	0.51	0.792
Ho-170	1.80×10^{-12}	9.28	0.959	9.45	19.8	32.8	64.5	96.3
I-118m	4.09×10^{-12}	21.1	0.964	7.31	14.8	25.7	59.2	96.5
I-118	2.19×10^{-12}	11.3	0.964	6.6	13.2	23.7	61.6	106
I-119	1.08×10^{-12}	5.56	0.958	3.1	7.76	14.6	37.3	74
I-120	2.65×10^{-12}	13.7	0.962	9.31	20.9	40.3	92.3	144
I-120m	3.75×10^{-12}	19.4	0.963	7.74	16	29.6	73.8	121
I-121	5.69×10^{-13}	2.94	0.948	1	3.73	10.5	32.3	64.8
I-122	1.09×10^{-12}	5.65	0.962	5.01	9.86	16.3	36.2	76.2
I-123	3.46×10^{-13}	1.78	0.942	0.0667	0.442	1.12	11.1	27.1
I-124	1.28×10^{-12}	6.59	0.953	7.2	15.9	30.5	76.5	124
I-125	3.38×10^{-13}	1.75	0.921	0.0211	0.039	0.0623	0.124	0.193
I-126	5.57×10^{-13}	2.88	0.950	3.98	9.57	17.5	39	62.7
I-128	8.53×10^{-14}	0.44	0.953	3.24	7.07	12.2	28.2	53.9
I-129	1.34×10^{-13}	0.692	0.922	0.0269	0.0499	0.0805	0.166	0.272
I-130m	1.48×10^{-13}	0.766	0.943	3.87	9.47	17.5	49.4	95.3
I-130	2.34×10^{-12}	12.1	0.965	7.01	13.7	22.8	47.8	77.4
I-131	4.26×10^{-13}	2.2	0.963	2.74	5.59	9.93	25.9	45.3
I-132	2.42×10^{-12}	12.5	0.965	8.93	17.4	28.9	62.3	102
I-132m	4.42×10^{-13}	2.28	0.949	4.94	11.9	20.6	42.3	64
I-133	6.71×10^{-13}	3.47	0.965	6.05	11.9	20.3	48.5	84.1
I-134m	4.48×10^{-13}	2.31	0.943	0.595	2.16	4.99	30.6	58
I-134	2.73×10^{-12}	14.1	0.965	10.6	20.6	33.8	69.5	109
I-135	1.56×10^{-12}	8.04	0.965	14.9	28.6	46.1	89.4	133
In-103	2.81×10^{-12}	14.5	0.964	8.32	18.4	35	83.3	134
In-105	2.09×10^{-12}	10.8	0.961	6.82	15.3	29.7	75.3	124
In-106	3.88×10^{-12}	20	0.964	7.92	16	27.3	59	93.8
In-106m	2.84×10^{-12}	14.7	0.964	8.84	19.1	37.1	89	140
In-107	1.68×10^{-12}	8.67	0.957	7.46	18.9	37.5	86.8	136
In-108	4.25×10^{-12}	22	0.961	9.44	19.8	34.1	73.1	115
In-108m	2.69×10^{-12}	13.9	0.960	10.4	23.8	44.3	98.1	151
In-109	8.95×10^{-13}	4.62	0.949	2.6	10.7	24.8	64.8	107
In-109m	6.83×10^{-13}	3.53	0.963	6.99	13.4	21.3	40.6	59.4
In-110	3.55×10^{-12}	18.3	0.958	8.58	17.3	28.7	58.4	90.4
In-110m	1.76×10^{-12}	9.08	0.961	6.55	13.4	24.2	67.1	119
In-111	6.70×10^{-13}	3.46	0.951	0.257	0.95	1.96	4.82	7.77
In-111m	5.49×10^{-13}	2.83	0.961	4.99	9.84	15.9	30.8	45.3
In-112	3.74×10^{-13}	1.93	0.950	3.46	8.34	14.6	31.7	56.4
In-112m	1.97×10^{-13}	1.02	0.929	0.018	0.0371	0.114	1.29	2.4
In-113m	3.59×10^{-13}	1.85	0.953	1.98	4.8	8.36	17.1	25.6
In-114	3.40×10^{-15}	0.0175	0.937	5.86	18.3	35.2	76.1	115
In-114m	1.89×10^{-13}	0.977	0.937	0.0473	1.6	8.81	29.7	50.5
In-115m	2.74×10^{-13}	1.42	0.946	0.74	2.69	5.29	11.6	18
In-116m	2.45×10^{-12}	12.6	0.965	14.6	28.1	45.3	88	131
In-117	7.76×10^{-13}	4.01	0.962	3.87	9.02	15.4	31	46.1
In-117m	1.54×10^{-13}	0.793	0.948	0.334	1.57	3.82	9.61	16.2
In-118m	2.85×10^{-12}	14.7	0.965	12.9	24.7	40	78.1	117
In-118	7.82×10^{-14}	0.404	0.965	14.6	27.6	44	83.9	123
In-119	8.85×10^{-13}	4.57	0.959	8.31	16.3	26.1	50.1	73.7
In-119m	9.16×10^{-14}	0.473	0.942	6.12	18.6	34.1	71.3	108

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Table 1. *(Continued)*

	Exposure rate constant			Lead attenuation thicknesses (mm Pb)				
Nuclide	C m^2 / kg MBq s	R cm^2 / mCi h	*f*-factor (cGy/R)	HVL	QVL	TVL	CVL	MVL
In-121	9.85×10^{-13}	5.09	0.965	10.8	20.5	32.7	62	90.4
In-121m	1.62×10^{-13}	0.839	0.930	0.0375	2.35	18.1	60.1	106
Ir-180	1.73×10^{-12}	8.92	0.962	5.32	11.7	20.9	47.4	76.8
Ir-182	1.50×10^{-12}	7.77	0.961	5.3	12.4	23.7	58.5	96.9
Ir-183	1.18×10^{-12}	6.11	0.955	8.93	21.9	40.2	87.7	135
Ir-184	2.01×10^{-12}	10.4	0.960	7.64	18.5	34.5	77.6	123
Ir-185	8.29×10^{-13}	4.28	0.952	10.7	26	45.6	93.4	140
Ir-186	1.69×10^{-12}	8.73	0.959	7	17.6	34.1	80.1	128
Ir-186m	1.26×10^{-12}	6.52	0.958	9.83	21	37	82.9	131
Ir-187	3.52×10^{-13}	1.82	0.950	4.85	12.7	24	53.9	83.8
Ir-188	1.95×10^{-12}	10.1	0.958	14.9	30.7	51.2	102	151
Ir-189	8.02×10^{-14}	0.414	0.945	0.243	0.569	1.42	4.45	7.76
Ir-190	1.61×10^{-12}	8.3	0.960	4.26	9.43	16.7	38	65.3
Ir-190n	6.04×10^{-14}	0.312	0.943	0.166	0.345	0.609	1.68	3.67
Ir-191m	7.04×10^{-14}	0.364	0.950	0.227	0.438	0.715	1.44	2.19
Ir-192	8.91×10^{-13}	4.6	0.964	2.67	5.68	10.5	25.3	42.1
Ir-192m	2.45×10^{-17}	0.000127	0.876	0.117	0.228	0.374	0.739	1.11
Ir-192n	5.90×10^{-16}	0.00305	0.946	0.221	0.447	0.776	1.75	2.8
Ir-193m	3.03×10^{-16}	0.00156	0.944	0.172	0.341	0.565	1.15	1.79
Ir-194	9.55×10^{-14}	0.493	0.964	3.7	9.28	22.5	60.3	99.5
Ir-194m	2.57×10^{-12}	13.3	0.965	4.47	9.38	16.3	35.2	56.1
Ir-195	5.73×10^{-14}	0.296	0.948	0.211	0.43	0.775	2.33	4.55
Ir-195m	4.05×10^{-13}	2.09	0.958	2.69	6.45	12.6	31.7	52.4
Ir-196	2.49×10^{-13}	1.28	0.964	5.49	13	25.3	60	98.6
Ir-196m	2.71×10^{-12}	14	0.964	4.43	9.09	15.9	36.8	65.3
K-38	2.99×10^{-12}	15.5	0.965	12.1	27.7	49.6	103	153
K-40	1.51×10^{-13}	0.779	0.965	17.6	32.3	50.8	94.7	137
K-42	2.65×10^{-13}	1.37	0.965	18.2	33.3	52.3	97.4	141
K-43	1.06×10^{-12}	5.48	0.965	4.62	9.62	16.8	36.5	58.8
K-44	2.17×10^{-12}	11.2	0.965	17.2	32.4	52	102	152
K-45	1.68×10^{-12}	8.68	0.965	16.8	32.9	53.1	102	150
K-46	2.48×10^{-12}	12.8	0.964	18.7	34.5	54.7	105	157
Kr-74	1.15×10^{-12}	5.94	0.963	3.95	8.5	14.5	29.9	48.1
Kr-75	1.39×10^{-12}	7.15	0.964	4.72	9.9	17.3	45.4	87
Kr-76	4.61×10^{-13}	2.38	0.960	2.15	4.79	9.34	27.8	54.6
Kr-77	1.12×10^{-12}	5.78	0.964	3.99	8.59	14.5	30	52.1
Kr-79	2.71×10^{-13}	1.4	0.965	3.9	8.8	16.2	40.3	72.4
Kr-81	8.71×10^{-16}	0.0045	0.876	1.35	2.58	4.18	8.15	12.1
Kr-81m	1.28×10^{-13}	0.658	0.876	0.675	1.22	1.93	3.68	5.43
Kr-83m	8.00×10^{-17}	0.000413	0.876	0.0271	0.0515	0.0833	0.163	0.244
Kr-85	2.48×10^{-15}	0.0128	0.876	5	9.54	15.3	29.2	42.8
Kr-85m	1.53×10^{-13}	0.79	0.964	0.626	1.27	2.81	8.17	13.5
Kr-87	7.38×10^{-13}	3.81	0.965	10.9	26.7	48.1	101	154
Kr-88	1.74×10^{-12}	8.97	0.964	18.1	34.8	56.1	108	159
Kr-89	1.79×10^{-12}	9.25	0.965	13.8	28.4	48.2	99.1	150
La-128	3.03×10^{-12}	15.7	0.964	6.55	14.5	27.5	66.7	109
La-129	1.06×10^{-12}	5.48	0.957	3.91	8.74	15.7	41.1	81.1
La-130	2.39×10^{-12}	12.3	0.962	6.44	14.2	27.5	70.1	117
La-131	8.11×10^{-13}	4.19	0.950	2.95	7.35	14	40.3	83
La-132	2.08×10^{-12}	10.7	0.959	7.72	17.3	34.7	84.6	135
La-132m	7.77×10^{-13}	4.01	0.953	4.42	10.9	20.6	49.1	79.5
La-133	2.57×10^{-13}	1.33	0.933	1.32	5.88	13.1	34.9	64.6
La-134	8.25×10^{-13}	4.26	0.958	4.84	9.64	16	36.7	77.9
La-135	1.30×10^{-13}	0.672	0.923	0.0329	0.0685	0.19	15.6	36.7
La-136	5.09×10^{-13}	2.63	0.948	4.08	8.9	15.2	33.5	62.1
La-137	1.15×10^{-13}	0.593	0.922	0.0283	0.054	0.0881	0.177	0.272
La-138	1.27×10^{-12}	6.55	0.953	14.2	27.7	45.1	87.8	129
La-140	2.26×10^{-12}	11.7	0.965	13.7	28.1	46.8	93.2	138
La-141	2.51×10^{-14}	0.13	0.965	17	31.2	49.3	92.4	135
La-142	2.12×10^{-12}	10.9	0.964	16.5	32.6	53.8	107	158
La-143	2.53×10^{-13}	1.31	0.965	14.2	28.2	47	95.4	144
Lu-165	1.16×10^{-12}	5.98	0.953	6.43	16	32.5	78.3	124
Lu-167	1.69×10^{-12}	8.74	0.952	11.6	26.3	45.5	93.2	140
Lu-169	1.34×10^{-12}	6.91	0.951	11.8	24.8	41.5	83.4	126
Lu-170	2.36×10^{-12}	12.2	0.954	16.8	32.3	52.2	102	152
Lu-171m	3.56×10^{-16}	0.00184	0.940	0.137	0.28	0.487	1.08	1.73
Lu-171	7.80×10^{-13}	4.03	0.945	5.87	13.7	23.3	46.9	70.8
Lu-172	2.04×10^{-12}	10.5	0.955	10.5	21.6	35.9	72.1	110

Table 1. *(Continued)*

	Exposure rate constant			Lead attenuation thicknesses (mm Pb)				
Nuclide	C m^2 / kg MBq s	R cm^2 / mCi h	*f*-factor (cGy/R)	HVL	QVL	TVL	CVL	MVL
Lu-173	2.15×10^{-13}	1.11	0.941	0.262	1.09	3.2	16.4	34.8
Lu-174	1.30×10^{-13}	0.673	0.937	2.81	15.4	32.7	72.5	110
Lu-174m	7.66×10^{-14}	0.395	0.936	0.128	0.289	1.18	33	65.4
Lu-176	5.05×10^{-13}	2.61	0.960	1.16	2.54	4.58	9.97	15.4
Lu-176m	1.41×10^{-14}	0.073	0.946	0.145	0.294	0.527	1.16	1.16
Lu-177	3.52×10^{-14}	0.181	0.957	0.542	1.19	2.11	4.7	8.46
Lu-177m	1.06×10^{-12}	5.47	0.957	1.15	2.88	5.93	14.7	23.9
Lu-178	1.23×10^{-13}	0.635	0.955	14.5	28.6	46.1	87.8	128
Lu-178m	1.12×10^{-12}	5.8	0.959	1.82	4.24	7.79	17.3	27.1
Lu-179	3.00×10^{-14}	0.155	0.962	0.907	1.82	3.5	27.7	57.1
Lu-180	1.54×10^{-12}	7.95	0.962	11	23.9	40.3	80.1	119
Lu-181	6.24×10^{-13}	3.22	0.957	5.09	11.8	20.7	43.8	67.5
Mg-27	9.48×10^{-13}	4.89	0.965	11	20.5	32.6	61.8	90.8
Mg-28	1.48×10^{-12}	7.64	0.951	11.3	24.2	40.7	81	120
Mn-50m	4.80×10^{-12}	24.8	0.965	10.5	21.5	36.9	77.4	119
Mn-51	1.11×10^{-12}	5.73	0.965	4.97	9.5	15.2	29.4	44.8
Mn-52	3.56×10^{-12}	18.4	0.965	11.9	23.4	38.8	79	119
Mn-52m	2.47×10^{-12}	12.8	0.965	9.6	21.3	38.9	82.6	125
Mn-54	8.97×10^{-13}	4.63	0.876	10.1	19	29.9	56.3	81.9
Mn-56	1.65×10^{-12}	8.54	0.965	14.1	27	44.7	92.7	141
Mn-57	9.87×10^{-14}	0.51	0.963	5.83	14.4	27.2	66	110
Mn-58m	2.40×10^{-12}	12.4	0.965	13	25.3	41.7	84.7	129
Mo-101	1.50×10^{-12}	7.74	0.964	11.4	24	41.2	86.1	131
Mo-102	2.07×10^{-14}	0.107	0.962	0.582	1.25	2.27	6.1	12.7
Mo-89	1.34×10^{-12}	6.92	0.965	5.65	11.2	19.4	52.5	97.9
Mo-90	1.40×10^{-12}	7.23	0.952	0.879	4.73	13.8	48.9	88.6
Mo-91m	1.48×10^{-12}	7.65	0.964	8.42	18	33.1	75.7	118
Mo-91	1.11×10^{-12}	5.72	0.965	4.88	9.49	15.4	32	65.1
Mo-93	3.99×10^{-13}	2.06	0.921	0.00673	0.0134	0.0221	0.0439	0.0622
Mo-93m	2.46×10^{-12}	12.7	0.962	11	23.9	41.2	85.2	128
Mo-99	1.78×10^{-13}	0.917	0.959	5.83	13.7	23.4	46.8	69.5
N-13	1.13×10^{-12}	5.86	0.876	4.95	9.46	15.1	28.9	42.5
N-16	2.76×10^{-12}	14.2	0.949	21.7	39	61.5	117	171
Na-22	2.29×10^{-12}	11.8	0.965	9.2	19.9	35.7	75.8	114
Na-24	3.53×10^{-12}	18.2	0.964	19.9	36.8	58.1	111	162
Nb-87	1.62×10^{-12}	8.39	0.960	2.47	6.92	12.7	26.6	40.2
Nb-88m	4.34×10^{-12}	22.4	0.965	8.65	18.5	33	72.3	114
Nb-88	4.77×10^{-12}	24.6	0.962	7.54	16.6	29.7	63.9	98.1
Nb-89	1.48×10^{-12}	7.65	0.962	7.01	15.7	32.8	84.7	137
Nb-89m	1.54×10^{-12}	7.93	0.963	4.71	9.42	15.5	32.2	55.9
Nb-90	4.25×10^{-12}	21.9	0.960	12.7	28.1	48.4	99.2	149
Nb-91	4.37×10^{-13}	2.26	0.921	0.00657	0.0131	0.0218	0.0482	9.59
Nb-91m	3.63×10^{-13}	1.87	0.923	0.00779	0.0165	0.0383	37.1	75.3
Nb-92	2.03×10^{-12}	10.5	0.955	5.91	14.4	25.6	54.6	83.4
Nb-92m	1.45×10^{-12}	7.48	0.948	6.03	16.7	29.4	60	90.6
Nb-93m	7.12×10^{-14}	0.368	0.921	0.00673	0.0134	0.0221	0.0439	0.0622
Nb-94m	2.74×10^{-13}	1.42	0.921	0.00696	0.014	0.0241	8.39	37.8
Nb-94	1.68×10^{-12}	8.69	0.965	9.36	17.6	28.1	54	79.8
Nb-95	8.31×10^{-13}	4.29	0.965	9.03	17	26.8	50.6	73.6
Nb-95m	3.32×10^{-13}	1.71	0.938	0.0101	0.0295	0.929	3.76	7.43
Nb-96	2.63×10^{-12}	13.6	0.965	9.31	18.5	30.9	63.5	97.4
Nb-97	7.31×10^{-13}	3.77	0.965	7.38	14	22.3	43.1	65.9
Nb-98m	2.92×10^{-12}	15.1	0.965	11	21.6	36.1	77.3	122
Nb-99	3.89×10^{-13}	2.01	0.952	0.0222	0.218	0.565	1.42	2.24
Nb-99m	7.15×10^{-13}	3.69	0.960	14.2	30.4	51.6	104	156
Nd-134	6.42×10^{-13}	3.32	0.951	2	6.45	13.8	38	68.3
Nd-135	1.44×10^{-12}	7.43	0.955	3.92	8.84	15.9	42.9	85.5
Nd-136	3.98×10^{-13}	2.05	0.938	1.02	6.28	14.8	40.9	73
Nd-137	1.32×10^{-12}	6.83	0.950	6.54	15	28.7	70.8	116
Nd-138	1.16×10^{-13}	0.597	0.926	0.0468	0.104	0.697	6.69	13.5
Nd-139	5.34×10^{-13}	2.76	0.947	4.73	10.6	19.8	52.2	90
Nd-139m	1.75×10^{-12}	9.06	0.951	8.79	18.5	31.4	66.7	107
Nd-140	9.77×10^{-14}	0.504	0.923	0.0374	0.0719	0.118	0.239	0.369
Nd-141	1.48×10^{-13}	0.765	0.927	0.0934	3.78	13.7	49.2	86.8
Nd-141m	7.60×10^{-13}	3.92	0.963	8.76	16.6	26.2	49.6	72.3
Nd-147	1.80×10^{-13}	0.931	0.943	1.48	5.77	11.9	27.3	43

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Table 1. *(Continued)*

	Exposure rate constant			Lead attenuation thicknesses (mm Pb)				
Nuclide	C m^2 / kg MBq s	R cm^2 / mCi h	*f*-factor (cGy/R)	HVL	QVL	TVL	CVL	MVL
Nd-149	4.11×10^{-13}	2.12	0.956	1.7	4.93	11.6	31.4	54.6
Nd-151	8.86×10^{-13}	4.57	0.959	7.92	18.9	33.4	71.1	110
Nd-152	2.13×10^{-13}	1.1	0.957	1.04	2.52	4.98	18.6	35.5
Ne-19	1.14×10^{-12}	5.86	0.965	4.95	9.46	15.1	28.9	42.5
Ne-24	5.99×10^{-13}	3.09	0.965	4.69	9.19	15.4	35.6	61.7
Ni-56	1.81×10^{-12}	9.35	0.965	7.46	16.3	28.3	62.1	101
Ni-57	1.92×10^{-12}	9.93	0.965	12.5	26.4	44.7	89.3	133
Ni-65	5.49×10^{-13}	2.83	0.965	15.7	29.7	47.3	90	132
Np-232	1.50×10^{-12}	7.75	0.957	4.63	13.5	25.3	54.2	83.8
Np-233	1.94×10^{-13}	1	0.951	0.023	0.197	0.554	6.25	20.2
Np-234	1.24×10^{-12}	6.4	0.955	11.9	26.6	45.1	89.7	133
Np-235	1.04×10^{-13}	0.538	0.922	0.007	0.0139	0.0233	0.051	0.44
Np-236	5.72×10^{-13}	2.95	0.944	0.0119	0.0389	0.356	1.42	3.06
Np-236m	1.22×10^{-13}	0.628	0.949	0.0188	0.177	0.703	18.4	38
Np-237	2.32×10^{-13}	1.2	0.932	0.0091	0.0206	0.0552	0.983	2.31
Np-238	7.12×10^{-13}	3.67	0.954	9.96	20.9	34.3	66.4	97.5
Np-239	3.32×10^{-13}	1.72	0.952	0.0674	0.552	1.77	6.01	10.9
Np-240	1.39×10^{-12}	7.19	0.954	5.14	13.7	25.4	55.7	86.2
Np-240m	4.30×10^{-13}	2.22	0.953	4.95	12.2	23	58.6	100
Np-241	7.92×10^{-14}	0.409	0.951	0.0318	0.307	1.06	17.6	42.3
Np-242	2.78×10^{-13}	1.44	0.960	12.6	25.4	42.7	88.2	134
Np-242m	1.26×10^{-12}	6.49	0.952	5.4	14.8	26.3	54.3	81.8
O-14	3.07×10^{-12}	15.9	0.965	12.4	28.3	50.5	104	156
O-15	1.14×10^{-12}	5.86	0.876	4.95	9.46	15.1	28.9	42.5
O-19	9.22×10^{-13}	4.76	0.965	11.9	26.5	44.2	86.3	127
Os-180	1.80×10^{-13}	0.929	0.942	0.321	3.31	10.8	31.6	52.3
Os-181	1.41×10^{-12}	7.29	0.956	9.03	20.6	36	77.5	122
Os-182	4.66×10^{-13}	2.4	0.954	2.46	6.78	12.5	26.5	40.1
Os-183	6.69×10^{-13}	3.46	0.953	2.55	6.36	13.8	46.6	83
Os-183m	1.04×10^{-12}	5.35	0.955	12.4	24.1	38.7	73.7	108
Os-185	7.55×10^{-13}	3.9	0.955	6.89	13.7	22.4	44.5	67.7
Os-190m	1.74×10^{-12}	8.97	0.964	4.11	8.87	15.4	32.3	49.4
Os-191	7.82×10^{-14}	0.404	0.950	0.227	0.438	0.715	1.44	2.19
Os-191m	6.03×10^{-15}	0.0311	0.943	0.162	0.32	0.531	1.09	1.69
Os-193	7.05×10^{-14}	0.364	0.955	2	5.45	10.5	24.1	38.9
Os-194	5.24×10^{-15}	0.027	0.927	0.0582	0.112	0.184	0.382	0.706
Os-196	8.54×10^{-14}	0.441	0.956	1.91	5.17	10.4	26.1	43.2
P-30	1.14×10^{-12}	5.87	0.965	4.96	9.47	15.2	29.2	44
Pa-227	1.03×10^{-13}	0.533	0.940	0.00952	0.0237	0.174	0.836	1.45
Pa-228	1.73×10^{-12}	8.94	0.955	5.73	16	30.4	68.9	111
Pa-229	1.85×10^{-13}	0.953	0.948	0.0143	0.0662	0.321	1.03	1.34
Pa-230	9.04×10^{-13}	4.67	0.954	5	14.3	26.6	56.9	86.2
Pa-231	2.41×10^{-13}	1.24	0.931	0.00972	0.0247	0.761	6.21	11.8
Pa-232	1.15×10^{-12}	5.96	0.957	7.05	16.4	28.5	58.3	87.4
Pa-233	3.83×10^{-13}	1.98	0.953	0.304	1.86	4.31	10.6	17.6
Pa-234	1.83×10^{-12}	9.44	0.956	6.33	16	28.8	62.5	100
Pa-234m	1.58×10^{-14}	0.0816	0.958	9.33	19.9	33.3	67.1	103
Pa-236	1.01×10^{-12}	5.24	0.958	9.68	21.8	39.2	86.6	134
Pa-237	6.63×10^{-13}	3.42	0.965	8.53	16.8	27.6	54.9	82.3
Pb-194	1.10×10^{-12}	5.66	0.958	8.39	20.2	36.8	80.3	124
Pb-195m	1.77×10^{-12}	9.16	0.961	5.39	12.2	23	53.9	88.9
Pb-196	5.19×10^{-13}	2.68	0.957	2.37	6.61	13.8	36.4	63.7
Pb-197	1.53×10^{-12}	7.91	0.960	9.92	22.7	40.1	85.6	132
Pb-197m	1.25×10^{-12}	6.43	0.960	4.87	11.7	23.3	57.5	96.2
Pb-198	4.58×10^{-13}	2.36	0.957	1.87	4.95	11.5	35.9	61.8
Pb-199	1.05×10^{-12}	5.4	0.959	8.66	21.4	38.8	83.3	128
Pb-200	2.01×10^{-13}	1.04	0.954	0.49	1.21	3.33	14.7	28.8
Pb-201	7.98×10^{-13}	4.12	0.959	4.26	11.2	23.9	57.1	91.5
Pb-201m	4.00×10^{-13}	2.07	0.960	6.35	12.5	20.1	38.7	56.8
Pb-202m	2.14×10^{-12}	11.1	0.964	7.85	16.3	27.8	56.9	85.8
Pb-203	3.24×10^{-13}	1.68	0.957	1.08	2.45	4.4	11.6	28.2
Pb-204m	2.20×10^{-12}	11.4	0.965	8.89	18.3	30.3	59.1	86.9
Pb-210	1.79×10^{-14}	0.0923	0.926	0.00875	0.0211	0.073	0.288	0.504
Pb-211	6.97×10^{-14}	0.36	0.964	6.25	13.5	23.8	50.4	76.9
Pb-212	1.53×10^{-13}	0.792	0.958	0.756	1.64	2.88	6.37	11.1
Pb-214	2.78×10^{-13}	1.43	0.961	1.88	4.09	7.48	23.1	47.6
Pd-100	5.94×10^{-13}	3.07	0.935	0.0106	0.0251	0.164	1.08	2.04
Pd-101	8.49×10^{-13}	4.38	0.935	0.0336	3.71	12.6	44.1	81.8

Table 1. *(Continued)*

	Exposure rate constant			Lead attenuation thicknesses (mm Pb)				
Nuclide	C m^2 / kg MBq s	R cm^2 / mCi h	*f*-factor (cGy/R)	HVL	QVL	TVL	CVL	MVL
Pd-103	2.73×10^{-13}	1.41	0.921	0.00811	0.0161	0.0267	0.054	0.0865
Pd-109m	2.03×10^{-13}	1.05	0.950	0.143	0.683	1.39	3.11	4.81
Pd-109	1.26×10^{-13}	0.649	0.924	0.0112	0.0222	0.0378	0.362	9.3
Pd-111	5.09×10^{-14}	0.263	0.959	8.13	18.2	33.1	74.5	116
Pd-112	1.39×10^{-13}	0.718	0.876	0.00716	0.0142	0.0235	0.0466	0.0697
Pd-114	2.95×10^{-14}	0.152	0.960	0.689	1.73	3.56	10	17.1
Pd-96	1.74×10^{-12}	8.98	0.957	5.98	13.8	25.1	57.8	94.3
Pd-97	2.49×10^{-12}	12.9	0.962	8.16	19.3	37.2	85.8	135
Pd-98	7.55×10^{-13}	3.9	0.945	0.517	6.35	16.3	42.9	72.7
Pd-99	1.49×10^{-12}	7.69	0.958	5.42	13.6	27.9	73.5	121
Pm-136	2.98×10^{-12}	15.4	0.964	5.86	12.2	21.3	47.1	74.8
Pm-137m	1.98×10^{-12}	10.2	0.958	4.57	10.5	19.9	52.3	89.7
Pm-139	1.05×10^{-12}	5.4	0.960	5.11	10.3	18	50.9	97.3
Pm-140m	3.28×10^{-12}	16.9	0.963	7.7	16.1	28	60.1	94.1
Pm-140	1.16×10^{-12}	6.01	0.964	5.33	10.4	17.5	42.2	80.9
Pm-141	8.18×10^{-13}	4.22	0.955	5.87	12.4	23.3	64.4	109
Pm-142	9.55×10^{-13}	4.93	0.961	5.15	10.1	17	44.4	90.6
Pm-143	4.03×10^{-13}	2.08	0.938	5.69	13.5	23	45.9	68
Pm-144	1.78×10^{-12}	9.2	0.955	6.34	12.6	20.6	40.5	60.2
Pm-145	9.23×10^{-14}	0.476	0.925	0.0418	0.0813	0.136	0.321	0.85
Pm-146	8.64×10^{-13}	4.46	0.953	5.52	11.7	20.2	42.5	64.6
Pm-148	5.83×10^{-13}	3.01	0.965	12.1	24.5	41.4	84.2	126
Pm-148m	2.18×10^{-12}	11.3	0.964	6.68	13.3	22.3	47.3	75
Pm-149	1.28×10^{-14}	0.0659	0.962	1.96	4.31	10.3	36.4	62.5
Pm-150	1.49×10^{-12}	7.68	0.965	10.5	23.4	40.1	82.9	127
Pm-151	3.68×10^{-13}	1.9	0.955	2.3	6.18	13.7	36.4	60
Pm-152m	1.56×10^{-12}	8.07	0.960	8.38	21	37	77.6	119
Pm-152	2.96×10^{-13}	1.53	0.957	10.3	21.6	36.7	78.1	123
Pm-153	1.02×10^{-13}	0.527	0.946	0.176	0.589	1.93	18	39.3
Pm-154	1.71×10^{-12}	8.82	0.958	15.7	30.3	49.4	98	147
Pm-154m	1.81×10^{-12}	9.34	0.958	11.3	24.9	42.7	87.1	131
Po-203	1.69×10^{-12}	8.73	0.960	10.6	21.9	36.7	75.9	118
Po-204	1.26×10^{-12}	6.49	0.957	6.35	15.9	28.1	58.6	89
Po-205	1.64×10^{-12}	8.49	0.960	10.9	21.9	36.2	74.7	117
Po-206	1.30×10^{-12}	6.69	0.959	6.42	15.4	27.7	59.3	91
Po-207	1.36×10^{-12}	7.01	0.960	9.86	20.1	33.3	66.9	102
Po-209	6.44×10^{-15}	0.0332	0.960	5.83	15.8	27.8	56.4	83.9
Po-211	8.81×10^{-15}	0.0455	0.965	8.61	16.7	27.5	55	82.5
Po-212m	6.75×10^{-14}	0.349	0.964	17.4	35.1	57.8	113	166
Po-214	8.95×10^{-17}	0.000462	0.876	9.67	18.2	28.6	53.9	78.4
Po-215	1.95×10^{-16}	0.00101	0.876	3.7	7.1	11.4	22	32.4
Pr-134	3.40×10^{-12}	17.5	0.963	6.12	13.3	24.8	61.7	106
Pr-134m	2.41×10^{-12}	12.4	0.963	7.09	15.7	32.1	80.9	130
Pr-135	1.02×10^{-12}	5.26	0.952	4.13	9.45	17.6	51.8	98.5
Pr-136	2.27×10^{-12}	11.7	0.961	7.31	15.4	29.7	76.7	126
Pr-137	4.57×10^{-13}	2.36	0.945	4.3	9.85	18.2	51.4	95.3
Pr-138	9.22×10^{-13}	4.76	0.961	4.93	9.65	15.8	33.6	65.9
Pr-138m	2.70×10^{-12}	14	0.958	8.24	17.8	30.4	62.5	95.6
Pr-139	2.10×10^{-13}	1.08	0.931	1.28	6.37	14.2	47.5	91.8
Pr-140	6.43×10^{-13}	3.32	0.954	4.47	9.07	15	31	58
Pr-142	5.48×10^{-14}	0.283	0.965	18.6	33.8	53.2	98.9	143
Pr-144	2.72×10^{-14}	0.14	0.965	14.2	28.5	48.5	99.7	150
Pr-144m	4.00×10^{-14}	0.206	0.924	0.0405	0.0809	0.151	23.2	67.1
Pr-145	1.93×10^{-14}	0.0994	0.953	9.14	18.3	30.3	61.2	92.6
Pr-146	1.00×10^{-12}	5.18	0.965	11	24.4	42.9	90	137
Pr-147	5.86×10^{-13}	3.02	0.943	4.51	12.8	26.3	65.6	107
Pr-148	9.94×10^{-13}	5.13	0.964	9.44	22.4	39.8	85.3	132
Pr-148m	1.01×10^{-12}	5.21	0.964	4.29	10.1	20.4	54.1	94.8
Pt-184	7.61×10^{-13}	3.93	0.954	2.01	6.74	14.2	33.7	54.2
Pt-186	7.40×10^{-13}	3.82	0.955	5.82	12.6	21	41.6	61.6
Pt-187	6.49×10^{-13}	3.35	0.953	4.19	11.7	23.2	55.1	89.3
Pt-188	2.09×10^{-13}	1.08	0.951	0.617	1.78	4.94	14.8	25.1
Pt-189	5.11×10^{-13}	2.64	0.952	4.06	11.1	21.5	53.5	92.8
Pt-191	3.12×10^{-13}	1.61	0.950	1.56	5.2	10.6	25.2	40.3
Pt-193m	1.04×10^{-14}	0.0535	0.945	0.188	0.373	0.62	1.27	1.99
Pt-195m	7.24×10^{-14}	0.374	0.947	0.186	0.375	0.63	1.35	2.18

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Table 1. *(Continued)*

	Exposure rate constant			Lead attenuation thicknesses (mm Pb)				
Nuclide	C m^2 / kg MBq s	R cm^2 / mCi h	*f*-factor (cGy/R)	HVL	QVL	TVL	CVL	MVL
Pt-197	2.23×10^{-14}	0.115	0.952	0.355	0.732	1.32	3.28	5.95
Pt-197m	8.36×10^{-14}	0.432	0.949	0.754	2.55	5.19	11.8	18.3
Pt-199	2.17×10^{-13}	1.12	0.963	4.43	9.65	16.9	38.1	63.5
Pt-200	5.85×10^{-14}	0.302	0.951	0.413	1.04	2.53	9.26	18.8
Pu-232	1.38×10^{-13}	0.712	0.951	0.0213	0.151	0.415	1.12	1.63
Pu-234	1.63×10^{-13}	0.84	0.950	0.0185	0.126	0.391	1.09	1.63
Pu-235	2.36×10^{-13}	1.22	0.948	0.0178	0.136	0.506	18.6	46
Pu-236	4.04×10^{-14}	0.209	0.921	0.00694	0.0138	0.0229	0.0465	0.0788
Pu-237	1.73×10^{-13}	0.891	0.945	0.0126	0.0419	0.278	0.95	1.61
Pu-238	3.71×10^{-14}	0.192	0.921	0.00693	0.0138	0.0228	0.0459	0.0683
Pu-239	1.53×10^{-14}	0.079	0.921	0.00694	0.0138	0.0229	0.0466	0.082
Pu-240	3.50×10^{-14}	0.181	0.921	0.00693	0.0138	0.0228	0.046	0.0683
Pu-242	3.00×10^{-14}	0.155	0.921	0.00693	0.0138	0.0228	0.046	0.0683
Pu-243	5.66×10^{-14}	0.292	0.946	0.0181	0.23	0.804	6.26	14.4
Pu-244	4.27×10^{-14}	0.22	0.935	0.0526	8.67	26.7	75.4	125
Pu-245	4.68×10^{-13}	2.42	0.960	4.05	10.7	21.4	49.9	78.9
Pu-246	2.64×10^{-13}	1.36	0.947	0.0637	0.42	1.17	3.51	5.99
Ra-219	1.84×10^{-13}	0.95	0.962	1.76	3.77	6.75	20.8	43.5
Ra-220	5.18×10^{-15}	0.0267	0.965	4.12	7.89	12.7	24.4	35.8
Ra-221	4.76×10^{-14}	0.246	0.956	0.211	0.584	1.14	6.38	17.8
Ra-222	9.86×10^{-15}	0.0509	0.965	1.94	3.8	6.18	12.1	17.9
Ra-223	1.49×10^{-13}	0.77	0.958	0.69	1.92	4.22	12.2	23.8
Ra-224	1.08×10^{-14}	0.0557	0.963	0.952	1.83	2.98	5.84	8.69
Ra-225	8.04×10^{-14}	0.415	0.924	0.0119	0.0347	0.0904	0.237	0.384
Ra-226	7.63×10^{-15}	0.0394	0.962	0.555	1.06	1.72	3.36	5
Ra-227	3.43×10^{-13}	1.77	0.944	0.0394	1.81	5.82	21.4	41.1
Ra-228	9.43×10^{-14}	0.487	0.921	0.00651	0.0129	0.0213	0.0425	0.0593
Ra-230	1.24×10^{-13}	0.638	0.952	0.362	2.19	6.73	18.9	31
Rb-77	1.67×10^{-12}	8.63	0.962	5.48	11.3	20.3	53.7	97.4
Rb-78m	3.28×10^{-12}	16.9	0.965	8.44	18.5	35.4	83.6	132
Rb-78	3.66×10^{-12}	18.9	0.965	11.2	26.2	48.4	104	158
Rb-79	1.57×10^{-12}	8.09	0.965	4.87	10	17.1	40.3	79
Rb-80	1.32×10^{-12}	6.82	0.965	5.21	9.99	16.1	31.8	50.3
Rb-81	5.55×10^{-13}	2.86	0.965	4.96	9.69	16.2	37.9	71.6
Rb-81m	2.86×10^{-14}	0.148	0.954	3.46	9.85	20.2	56.9	99.2
Rb-82	1.23×10^{-12}	6.33	0.965	5.3	10.2	16.8	35.5	61.5
Rb-82m	3.09×10^{-12}	16	0.965	9.24	18.4	31.3	67.6	107
Rb-83	5.38×10^{-13}	2.78	0.965	5.28	10.1	16.1	31.2	46.7
Rb-84	9.73×10^{-13}	5.02	0.965	8.47	16.8	27.9	56.7	87.1
Rb-84m	4.08×10^{-13}	2.11	0.965	1.76	4.12	8.58	20.3	31.8
Rb-86m	6.06×10^{-13}	3.13	0.876	5.68	10.8	17.2	32.8	48
Rb-86	9.60×10^{-14}	0.495	0.876	13.5	25	39.3	73.5	106
Rb-88	5.85×10^{-13}	3.02	0.965	17.5	33.1	53.2	103	152
Rb-89	2.15×10^{-12}	11.1	0.965	15.6	29.4	47.5	94.4	143
Rb-90	1.61×10^{-12}	8.3	0.962	17.9	34.2	56.1	112	167
Rb-90m	2.89×10^{-12}	14.9	0.964	16	30.8	50.9	104	157
Re-178	1.62×10^{-12}	8.38	0.958	9.56	22.7	42.3	94.5	147
Re-179	1.12×10^{-12}	5.78	0.957	5.64	15	32.3	78.4	124
Re-180	1.27×10^{-12}	6.56	0.956	9.47	19.1	31.4	62.8	97.1
Re-181	8.63×10^{-13}	4.46	0.954	4.26	10.7	22.6	56.2	92.2
Re-182	1.83×10^{-12}	9.43	0.955	7.5	20.9	37.1	75.7	113
Re-182m	1.23×10^{-12}	6.36	0.952	12.2	25	41.1	80.6	120
Re-183	1.64×10^{-13}	0.847	0.945	0.248	0.592	1.34	5.27	10.8
Re-184	9.51×10^{-13}	4.91	0.954	9.13	18.3	29.7	57.3	84.5
Re-184m	4.00×10^{-13}	2.06	0.953	3.7	12.1	24.3	54.4	84.3
Re-186	1.99×10^{-14}	0.103	0.952	0.268	0.53	0.918	9.97	32.9
Re-186m	1.93×10^{-14}	0.0997	0.937	0.103	0.219	0.386	0.844	1.43
Re-188	6.11×10^{-14}	0.316	0.960	2.54	9.98	21.7	56.6	96.9
Re-188m	6.95×10^{-14}	0.359	0.945	0.171	0.332	0.552	1.19	1.75
Re-189	5.70×10^{-14}	0.294	0.960	1	2.27	5.5	20.2	35.6
Re-190	1.44×10^{-12}	7.45	0.964	4.98	11.3	20.7	49.2	84.3
Re-190m	1.00×10^{-12}	5.17	0.961	4.51	10.2	18.6	45.3	79.6
Rh-100m	3.95×10^{-13}	2.04	0.925	0.0106	0.0244	1.14	34.2	80.6
Rh-100	2.92×10^{-12}	15.1	0.956	10.9	25.1	44.8	94.6	144
Rh-101	6.22×10^{-13}	3.21	0.949	0.0331	0.502	1.42	5.54	11.5
Rh-101m	6.06×10^{-13}	3.13	0.945	0.125	1.86	4.39	12.6	26.3
Rh-102	7.43×10^{-13}	3.83	0.951	3.11	8.05	15.1	40	75.2
Rh-102m	2.63×10^{-12}	13.6	0.957	6.27	13.9	24.8	55	87

Table 1. *(Continued)*

	Exposure rate constant			Lead attenuation thicknesses (mm Pb)				
Nuclide	C m^2 / kg MBq s	R cm^2 / mCi h	*f*-factor (cGy/R)	HVL	QVL	TVL	CVL	MVL
Rh-103m	2.91×10^{-14}	0.15	0.921	0.00813	0.0162	0.0269	0.0549	0.0929
Rh-104	1.46×10^{-14}	0.0755	0.960	5.21	10.7	18.1	40.5	74.2
Rh-104m	3.01×10^{-13}	1.56	0.927	0.00995	0.0221	0.0581	0.436	7.83
Rh-105	8.51×10^{-14}	0.44	0.964	1.83	3.61	5.9	11.6	17.3
Rh-106	2.24×10^{-13}	1.15	0.965	6.29	12.3	21	49.8	87.7
Rh-106m	3.00×10^{-12}	15.5	0.965	8.97	18.7	32.8	71.6	112
Rh-107	3.45×10^{-13}	1.78	0.964	2.03	4.14	7.34	20.9	41.8
Rh-108	3.52×10^{-13}	1.82	0.965	4.55	9	15.2	33.3	55.2
Rh-109	3.57×10^{-13}	1.84	0.960	1.54	3.53	6.43	16.6	41.4
Rh-94	3.82×10^{-12}	19.7	0.965	10.3	22.2	39.3	83.9	129
Rh-95	2.68×10^{-12}	13.8	0.963	9.54	20.6	36.9	81.7	129
Rh-95m	9.06×10^{-13}	4.68	0.962	7.45	15.7	31.5	86.9	143
Rh-96	4.25×10^{-12}	21.9	0.964	8.39	17	29.6	68.4	113
Rh-96m	1.43×10^{-12}	7.37	0.958	8.54	19	34.9	80.4	128
Rh-97	1.67×10^{-12}	8.6	0.960	5.42	11.9	23.4	64.8	112
Rh-97m	2.30×10^{-12}	11.9	0.956	10.8	26.1	46.6	97.8	148
Rh-98	1.99×10^{-12}	10.3	0.964	6.39	12.7	22.1	58.3	106
Rh-99	1.03×10^{-12}	5.31	0.945	1.01	5.13	12.3	39.3	78.6
Rh-99m	9.83×10^{-13}	5.08	0.950	2.43	7.65	18.9	55.2	93.1
Rn-207	1.07×10^{-12}	5.52	0.962	5.23	11.8	21.8	51.1	86.8
Rn-209	1.24×10^{-12}	6.42	0.961	6.98	16.2	31	74.8	123
Rn-210	6.60×10^{-14}	0.341	0.960	5.83	13.4	24.1	53.3	84.3
Rn-211	1.96×10^{-12}	10.1	0.962	9.92	20.5	35	73.3	112
Rn-212	3.70×10^{-16}	0.00191	0.876	7.72	14.5	23	43.6	63.7
Rn-218	8.36×10^{-16}	0.00432	0.876	6.62	12.5	19.9	37.8	55.3
Rn-219	6.33×10^{-14}	0.327	0.964	1.85	3.94	7.18	16.4	26.1
Rn-220	6.96×10^{-16}	0.00359	0.876	5.57	10.6	16.9	32.2	47.2
Rn-222	4.31×10^{-16}	0.00223	0.876	4.94	9.43	15.1	28.9	42.4
Rn-223	3.79×10^{-13}	1.96	0.960	5.83	13.2	23.9	56.2	93.2
Ru-103	5.56×10^{-13}	2.87	0.965	4.79	9.23	14.8	28.8	42.9
Ru-105	8.59×10^{-13}	4.44	0.961	5.85	12.7	21.9	45.6	71.1
Ru-107	3.64×10^{-13}	1.88	0.964	8.02	18.4	32.9	72	114
Ru-108	8.58×10^{-14}	0.443	0.956	0.257	0.656	1.15	2.34	3.54
Ru-92	2.80×10^{-12}	14.4	0.954	2.7	9.85	24	68.5	115
Ru-94	9.00×10^{-13}	4.65	0.947	1.59	5.99	15.5	44.1	71.8
Ru-95	1.59×10^{-12}	8.2	0.955	5.14	14.4	29.2	69.3	111
Ru-97	5.95×10^{-13}	3.07	0.946	0.0233	0.689	1.93	7.6	22.8
S-37	2.24×10^{-12}	11.6	0.962	22.4	41	64.7	121	176
S-38	1.50×10^{-12}	7.76	0.965	20.7	37.5	58.9	110	158
Sb-111	1.67×10^{-12}	8.64	0.962	4.89	10.4	18.3	45.5	80
Sb-113	1.47×10^{-12}	7.59	0.961	4.73	9.66	16.6	42.2	82.8
Sb-114	2.80×10^{-12}	14.4	0.963	10.1	21.8	38.3	80.5	122
Sb-115	1.11×10^{-12}	5.74	0.955	4.1	8.73	14.8	33.8	70.8
Sb-116	2.38×10^{-12}	12.3	0.959	11	23.8	41.2	85.5	131
Sb-116m	3.46×10^{-12}	17.8	0.956	9.53	21	36.2	74.1	112
Sb-117	3.98×10^{-13}	2.05	0.943	0.0556	0.475	1.41	19.9	50.8
Sb-118	9.40×10^{-13}	4.85	0.960	4.78	9.6	16	36.6	71.7
Sb-118m	3.02×10^{-12}	15.6	0.950	9.82	22.4	37.8	74.8	111
Sb-119	2.64×10^{-13}	1.36	0.921	0.0165	0.0308	0.049	0.0955	0.144
Sb-120	6.14×10^{-13}	3.17	0.950	3.59	8.37	14.6	32.8	62.1
Sb-120m	2.77×10^{-12}	14.3	0.954	10.2	22.3	37.1	72.5	107
Sb-122m	2.50×10^{-13}	1.29	0.932	0.025	0.0552	0.178	0.746	1.42
Sb-122	4.97×10^{-13}	2.57	0.964	6.02	11.6	18.8	39.1	66.9
Sb-124	1.85×10^{-12}	9.57	0.965	11.7	24.1	42.2	89.5	136
Sb-124m	4.87×10^{-13}	2.51	0.965	6.21	11.9	19.2	37.9	58
Sb-125	5.87×10^{-13}	3.03	0.948	3.22	8.04	14.6	31.9	49.5
Sb-126	3.02×10^{-12}	15.6	0.965	7.09	14	23	46.3	71.7
Sb-126m	1.70×10^{-12}	8.79	0.965	6.35	12.6	21	42.4	65.3
Sb-127	7.68×10^{-13}	3.96	0.963	6.21	12.7	21.4	44.1	68.6
Sb-128	3.36×10^{-12}	17.4	0.965	7.51	15.1	25.1	51.8	82.8
Sb-128m	2.07×10^{-12}	10.7	0.965	7.27	15.1	25.1	50	76.6
Sb-129	1.51×10^{-12}	7.81	0.965	10.9	21.6	36.1	76.1	119
Sb-130m	2.87×10^{-12}	14.8	0.964	10.1	19.8	32.2	64.7	101
Sb-130	3.48×10^{-12}	18	0.964	8.41	17.8	30.3	64.4	104
Sb-131	2.08×10^{-12}	10.8	0.965	12.5	24.7	41	85.1	131
Sb-133	2.63×10^{-12}	13.6	0.965	15.1	29.1	47.4	94.3	142

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Table 1. *(Continued)*

	Exposure rate constant			Lead attenuation thicknesses (mm Pb)				
Nuclide	C m^2 / kg MBq s	R cm^2 / mCi h	*f*-factor (cGy/R)	HVL	QVL	TVL	CVL	MVL
Sc-42m	4.30×10^{-12}	22.2	0.965	10.1	22.5	40	83.1	125
Sc-43	1.09×10^{-12}	5.65	0.965	4.7	9.08	14.7	28.5	42.2
Sc-44	2.26×10^{-12}	11.7	0.965	8.49	18	32.1	68.8	105
Sc-44m	2.89×10^{-13}	1.49	0.965	1.63	3.44	8.43	45.4	80.3
Sc-46	2.09×10^{-12}	10.8	0.965	12.5	23.4	37	70.4	103
Sc-47	1.03×10^{-13}	0.534	0.876	0.492	0.86	1.33	2.47	3.61
Sc-48	3.43×10^{-12}	17.7	0.965	13.9	25.9	41	77.9	115
Sc-49	9.57×10^{-16}	0.00494	0.965	19.6	35.5	55.8	104	150
Sc-50	3.19×10^{-12}	16.5	0.965	13.7	27.2	44.8	88	131
Se-70	7.95×10^{-13}	4.11	0.958	3.86	8.07	13.7	29.8	58.7
Se-71	1.72×10^{-12}	8.88	0.965	6.26	13	23.8	59.7	101
Se-72	5.13×10^{-14}	0.265	0.876	0.068	0.131	0.214	0.423	0.633
Se-73	1.20×10^{-12}	6.2	0.960	3.71	7.65	13.1	28.3	49.1
Se-73m	2.88×10^{-13}	1.49	0.964	4.81	9.57	15.9	34.6	61.8
Se-75	3.93×10^{-13}	2.03	0.963	0.985	2.29	4.32	11.3	20.3
Se-77m	8.23×10^{-14}	0.425	0.876	0.502	0.881	1.36	2.54	3.71
Se-79m	7.96×10^{-15}	0.0411	0.876	0.23	0.406	0.672	1.4	1.4
Se-81	8.60×10^{-15}	0.0444	0.965	3.54	9.13	18.4	42.9	67.8
Se-81m	1.20×10^{-14}	0.0621	0.959	0.251	0.45	0.745	1.67	5.29
Se-83m	9.87×10^{-13}	5.1	0.965	12.4	24.9	41.6	85.9	132
Se-83	2.65×10^{-12}	13.7	0.965	9.64	21.8	39	85.2	132
Se-84	4.65×10^{-13}	2.4	0.965	3.3	6.36	10.3	20	29.7
Si-31	8.84×10^{-16}	0.00456	0.876	15.9	29.2	45.9	85.5	124
Sm-139	1.59×10^{-12}	8.18	0.961	5.07	11.1	20.7	57.5	104
Sm-140	6.43×10^{-13}	3.32	0.948	5.59	14	28.2	68.9	110
Sm-141	1.52×10^{-12}	7.82	0.959	6.16	13.5	27.7	72.5	118
Sm-141m	2.08×10^{-12}	10.7	0.958	7.36	16.8	31.2	72.2	116
Sm-142	1.69×10^{-13}	0.875	0.932	1.08	5.66	12.2	31.9	65.7
Sm-143	6.10×10^{-13}	3.15	0.953	4.79	9.8	16.7	41.8	81
Sm-143m	7.48×10^{-13}	3.86	0.962	8.71	16.5	26.1	49.4	72
Sm-145	1.62×10^{-13}	0.837	0.926	0.0475	0.0933	0.158	0.385	0.78
Sm-151	1.19×10^{-16}	0.000614	0.876	0.0093	0.0183	0.0298	0.0584	0.0868
Sm-153	9.32×10^{-14}	0.481	0.938	0.0876	0.204	0.432	1.67	17.6
Sm-155	1.05×10^{-13}	0.541	0.953	0.232	0.5	1.13	16.4	53.5
Sm-156	1.30×10^{-13}	0.673	0.953	0.477	1.11	2.07	5.23	9.21
Sm-157	4.37×10^{-13}	2.26	0.958	2.77	10.7	26	66.1	106
Sn-106	1.51×10^{-12}	7.81	0.953	4.29	11.4	23.1	57	92.6
Sn-108	9.78×10^{-13}	5.05	0.951	1.65	5.28	12	35.6	66.3
Sn-109	2.34×10^{-12}	12.1	0.953	12.4	26.5	44.8	91.2	138
Sn-110	5.24×10^{-13}	2.7	0.946	0.337	1.64	3.4	7.69	11.9
Sn-111	6.66×10^{-13}	3.44	0.947	4.43	11.2	23.5	68	115
Sn-113	2.34×10^{-13}	1.21	0.922	0.0153	0.0294	0.0494	1.4	4.68
Sn-113m	1.47×10^{-13}	0.759	0.921	0.017	0.0317	0.0506	0.102	0.336
Sn-117m	3.27×10^{-13}	1.69	0.945	0.0567	0.374	0.864	2.01	3.14
Sn-119m	1.74×10^{-13}	0.898	0.921	0.0159	0.0298	0.0475	0.0924	0.14
Sn-121m	4.25×10^{-14}	0.219	0.921	0.0197	0.0367	0.0592	0.124	0.213
Sn-123	7.06×10^{-15}	0.0364	0.965	13.6	25.2	39.6	74.1	107
Sn-123m	1.59×10^{-13}	0.823	0.959	0.385	0.767	1.25	2.47	4.9
Sn-125m	3.78×10^{-13}	1.95	0.964	2.21	4.43	7.72	36	79.6
Sn-125	3.41×10^{-13}	1.76	0.965	12.7	24.4	39.5	78.9	122
Sn-126	1.46×10^{-13}	0.753	0.940	0.0271	0.0937	0.494	1.62	2.77
Sn-127m	6.15×10^{-13}	3.18	0.965	5.8	11.7	22.2	63.6	107
Sn-127	1.93×10^{-12}	9.99	0.964	11.9	24	40	82.4	128
Sn-128	9.98×10^{-13}	5.15	0.940	1.6	6.12	12.4	28.8	46.6
Sn-129	1.07×10^{-12}	5.51	0.965	9.07	18	30.8	69.6	112
Sn-130	1.13×10^{-12}	5.81	0.954	4.15	11.8	21.7	46.2	70.3
Sn-130m	1.00×10^{-12}	5.16	0.953	8.74	19.7	34.4	74.6	117
Sr-79	1.32×10^{-12}	6.8	0.961	4.33	8.78	14.5	28.5	42.4
Sr-80	4.79×10^{-13}	2.47	0.965	4.98	10.1	16.7	33	49.2
Sr-81	1.51×10^{-12}	7.78	0.965	4.73	9.84	17	41	76
Sr-82	5.77×10^{-15}	0.0298	0.921	0.00633	0.0125	0.0207	0.0412	0.0617
Sr-83	8.79×10^{-13}	4.54	0.964	6.82	14.3	25.6	60.8	102
Sr-85	5.53×10^{-13}	2.86	0.965	4.93	9.47	15.2	29.1	42.8
Sr-85m	2.23×10^{-13}	1.15	0.964	0.875	1.67	2.73	5.41	8.43
Sr-87m	3.62×10^{-13}	1.87	0.964	2.81	5.53	8.99	17.5	25.9
Sr-91	7.48×10^{-13}	3.86	0.965	10.7	20.4	33.1	65.6	98.9
Sr-92	1.31×10^{-12}	6.77	0.965	16.3	30.4	48	90	130
Sr-93	2.30×10^{-12}	11.9	0.965	10.7	22	38.2	83.3	131

Table 1. *(Continued)*

Nuclide	Exposure rate constant		*f*-factor (cGy/R)	Lead attenuation thicknesses (mm Pb)				
	C m^2 / kg MBq s	R cm^2 / mCi h		HVL	QVL	TVL	CVL	MVL
Sr-94	1.39×10^{-12}	7.16	0.965	16.8	31.1	49.2	92.5	134
Ta-170	1.16×10^{-12}	5.98	0.960	5.33	11.1	19.5	46.6	78.7
Ta-172	1.75×10^{-12}	9.04	0.958	8.76	20	35.7	76.5	118
Ta-173	6.06×10^{-13}	3.13	0.948	6.56	17	32.9	76.3	121
Ta-174	9.98×10^{-13}	5.15	0.956	6.54	16.7	33.4	79.3	127
Ta-175	1.12×10^{-12}	5.78	0.951	9.53	23.4	41.3	85.8	130
Ta-176	2.13×10^{-12}	11	0.955	15.3	30	48.9	95.9	143
Ta-177	7.72×10^{-14}	0.398	0.940	0.165	0.374	1.98	30.9	62.3
Ta-178	1.31×10^{-13}	0.678	0.941	2.03	12.5	29.6	71.6	112
Ta-178m	1.25×10^{-12}	6.44	0.956	1.7	4.06	7.53	16.9	26.6
Ta-179	2.98×10^{-14}	0.154	0.937	0.118	0.232	0.384	0.783	1.22
Ta-180	5.60×10^{-14}	0.289	0.939	0.125	0.245	0.408	0.871	1.32
Ta-182	1.31×10^{-12}	6.75	0.957	12.8	25.4	41.1	78.5	115
Ta-182m	2.67×10^{-13}	1.38	0.952	0.405	0.879	1.65	5.86	11.7
Ta-183	3.09×10^{-13}	1.6	0.952	0.663	1.78	3.68	9.67	16.5
Ta-184	1.68×10^{-12}	8.67	0.962	5.06	12.6	24.2	54.4	84.9
Ta-185	1.55×10^{-13}	0.801	0.954	0.56	1.35	4.45	28.4	58.2
Ta-186	1.52×10^{-12}	7.86	0.963	4.85	11.6	21	47.5	79.2
Tb-146	3.56×10^{-12}	18.4	0.963	12.5	26.4	45.1	91.7	138
Tb-147m	1.89×10^{-12}	9.75	0.956	13.5	27.9	46.6	92.3	137
Tb-147	2.26×10^{-12}	11.7	0.957	10.5	22	37.8	78.9	122
Tb-148m	3.42×10^{-12}	17.7	0.961	7.31	15	25.6	54.1	87.1
Tb-148	2.42×10^{-12}	12.5	0.961	9.21	19.4	35.2	82.4	132
Tb-149m	1.52×10^{-12}	7.84	0.956	7.71	15.4	25.6	52.5	83.5
Tb-149	1.41×10^{-12}	7.27	0.955	8.09	19.1	35.3	80.9	129
Tb-150m	2.80×10^{-12}	14.5	0.960	5.84	11.8	19.8	40.8	63
Tb-150	2.35×10^{-12}	12.2	0.957	11.2	24.3	43.8	95.8	147
Tb-151	1.11×10^{-12}	5.71	0.951	3.82	9.99	20.3	54.4	95
Tb-151m	1.03×10^{-13}	0.534	0.940	2.47	7.66	16.6	42.1	67.7
Tb-152m	8.60×10^{-13}	4.44	0.952	2.58	6.64	14.9	45.1	79.3
Tb-152	1.52×10^{-12}	7.84	0.955	7.95	19.8	38.3	87.3	137
Tb-153	3.91×10^{-13}	2.02	0.944	1.38	6.27	17.3	46.9	77.1
Tb-154	2.15×10^{-12}	11.1	0.952	15.3	30.7	50.8	101	152
Tb-155	2.26×10^{-13}	1.17	0.942	0.178	0.623	1.73	8.31	19
Tb-156	2.04×10^{-12}	10.5	0.954	8.96	20.7	36.8	77.5	118
Tb-156m	5.75×10^{-14}	0.297	0.876	0.0839	0.163	0.266	0.525	0.784
Tb-156n	5.98×10^{-15}	0.0309	0.933	0.0743	0.15	0.268	0.849	1.16
Tb-157	9.67×10^{-15}	0.0499	0.927	0.0598	0.116	0.191	0.388	0.6
Tb-158	8.83×10^{-13}	4.56	0.947	9.65	19.9	32.5	63.1	93
Tb-160	1.18×10^{-12}	6.09	0.960	10.5	21.6	35.5	69.8	104
Tb-161	1.11×10^{-13}	0.571	0.930	0.0283	0.0707	0.187	0.857	8.15
Tb-162	1.18×10^{-12}	6.1	0.962	6.88	16.2	27.6	55.3	83
Tb-163	8.72×10^{-13}	4.5	0.963	3.48	7.21	12.6	28	46
Tb-164	2.52×10^{-12}	13	0.962	9.26	19.8	34.9	77.6	123
Tb-165	8.32×10^{-13}	4.3	0.963	14.1	27.7	45.1	87.4	129
Tc-101	3.70×10^{-13}	1.91	0.964	2.02	4.19	7.71	23.2	43.8
Tc-102m	2.44×10^{-12}	12.6	0.965	11.4	24.6	43.4	91.7	140
Tc-102	8.48×10^{-14}	0.438	0.965	7.35	15.8	30.2	73.8	121
Tc-104	2.14×10^{-12}	11.1	0.965	11.3	26.2	46.2	96.8	147
Tc-105	8.86×10^{-13}	4.57	0.959	5.49	15.5	32	77.9	125
Tc-91	2.45×10^{-12}	12.6	0.964	9.7	22.2	42.1	93.7	144
Tc-91m	1.58×10^{-12}	8.13	0.965	5.45	10.7	18.4	49.7	92.2
Tc-92	4.03×10^{-12}	20.8	0.963	8.1	18.9	35.5	80.5	125
Tc-93	1.86×10^{-12}	9.63	0.951	11.6	26.2	44.4	87.8	130
Tc-93m	9.97×10^{-13}	5.15	0.955	8.47	24.5	47.2	102	155
Tc-94	3.20×10^{-12}	16.5	0.959	8.03	16.6	27.6	55	83.9
Tc-94m	2.15×10^{-12}	11.1	0.962	7.96	16.9	30.5	71.9	120
Tc-95	1.23×10^{-12}	6.35	0.948	4.62	13.2	23.5	48.8	74.3
Tc-95m	1.11×10^{-12}	5.71	0.951	2.23	9.3	19.6	45.6	71.9
Tc-96	3.06×10^{-12}	15.8	0.957	8.26	17.2	28.3	55.6	83.3
Tc-96m	2.19×10^{-13}	1.13	0.926	0.0114	0.0389	10.7	45.2	81.7
Tc-97	3.64×10^{-13}	1.88	0.921	0.00695	0.0138	0.0228	0.0453	0.0678
Tc-97m	2.51×10^{-13}	1.3	0.921	0.00725	0.0144	0.0239	0.0483	0.0797
Tc-98	1.55×10^{-12}	7.99	0.965	7.96	15	23.9	45.6	67
Tc-99m	1.54×10^{-13}	0.795	0.959	0.234	0.535	0.905	1.8	2.7
Te-113	2.30×10^{-12}	11.9	0.964	8.59	18.5	34.7	80.6	128

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Table 1. *(Continued)*

	Exposure rate constant			Lead attenuation thicknesses (mm Pb)				
Nuclide	C m^2 / kg MBq s	R cm^2 / mCi h	*f*-factor (cGy/R)	HVL	QVL	TVL	CVL	MVL
Te-114	1.51×10^{-12}	7.8	0.948	7.63	19.5	37.1	83.2	129
Te-115	2.39×10^{-12}	12.3	0.962	8.72	19.1	34.7	76.5	119
Te-115m	2.73×10^{-12}	14.1	0.961	9.99	21.5	38.1	83	129
Te-116	3.83×10^{-13}	1.98	0.931	0.0288	0.0761	3.15	26	53.3
Te-117	1.69×10^{-12}	8.73	0.954	9.09	20	36.5	84	133
Te-118	1.88×10^{-13}	0.971	0.921	0.019	0.0352	0.0559	0.109	0.165
Te-119	9.96×10^{-13}	5.14	0.947	5.72	13	23	55.4	99.1
Te-119m	1.69×10^{-12}	8.73	0.953	9.85	22.9	39	78.6	119
Te-121	8.14×10^{-13}	4.2	0.946	3.61	8.95	15.6	31.7	47.5
Te-121m	3.32×10^{-13}	1.71	0.948	0.415	1.39	3.6	38.5	73.3
Te-123	3.09×10^{-16}	0.00159	0.921	0.0188	0.0346	0.0548	0.106	0.159
Te-123m	2.40×10^{-13}	1.24	0.948	0.14	0.521	1	2.15	3.28
Te-125m	2.79×10^{-13}	1.44	0.921	0.0212	0.0392	0.0628	0.127	0.216
Te-127	5.55×10^{-15}	0.0287	0.961	2.94	5.99	9.9	19.6	29.2
Te-127m	8.67×10^{-14}	0.448	0.921	0.021	0.039	0.0623	0.131	1.39
Te-129	1.01×10^{-13}	0.523	0.939	1.67	5.98	12.7	38.5	71.8
Te-129m	9.62×10^{-14}	0.497	0.927	0.048	3.7	13.3	35.5	57.3
Te-131	4.57×10^{-13}	2.36	0.960	4.26	11.8	24	58.1	92.7
Te-131m	1.57×10^{-12}	8.1	0.960	9.21	19.2	32.5	68.3	108
Te-132	3.73×10^{-13}	1.93	0.944	0.262	1.04	2.08	4.66	7.21
Te-133	1.22×10^{-12}	6.29	0.964	8.46	20.8	38.1	83.9	131
Te-133m	1.97×10^{-12}	10.2	0.961	9.82	20.4	34.6	73.8	117
Te-134	9.94×10^{-13}	5.13	0.958	4.32	10.9	19.8	43.1	66.5
Th-223	1.57×10^{-13}	0.81	0.951	0.0218	0.219	0.636	3.11	8.92
Th-224	3.37×10^{-14}	0.174	0.958	0.338	0.998	2.27	10.6	20.1
Th-226	3.51×10^{-14}	0.181	0.944	0.0103	0.0308	0.409	2.62	5.43
Th-227	3.07×10^{-13}	1.58	0.947	0.0224	0.735	2.31	7.04	12.5
Th-228	3.71×10^{-14}	0.192	0.930	0.00706	0.0146	0.0276	1.08	3.03
Th-229	3.16×10^{-13}	1.63	0.945	0.0115	0.0463	0.429	1.92	3.97
Th-230	3.05×10^{-14}	0.157	0.923	0.00658	0.0132	0.0222	0.0691	0.968
Th-231	2.69×10^{-13}	1.39	0.927	0.00822	0.0173	0.0326	0.523	1.53
Th-232	2.78×10^{-14}	0.143	0.922	0.00654	0.013	0.0218	0.0513	0.51
Th-233	7.01×10^{-14}	0.362	0.945	0.247	3.89	11.4	32.5	55.8
Th-234	3.98×10^{-14}	0.206	0.941	0.0106	0.029	0.208	0.82	1.3
Th-235	6.01×10^{-14}	0.31	0.963	5.91	12.5	21.6	45.1	69.2
Th-236	5.63×10^{-14}	0.29	0.953	0.518	3.85	10.9	29.7	48.9
Ti-44	1.35×10^{-13}	0.698	0.948	0.222	0.443	0.742	1.53	2.35
Ti-45	9.68×10^{-13}	5	0.965	4.97	9.49	15.2	29.3	44.5
Ti-51	3.99×10^{-13}	2.06	0.965	2.53	5.28	11.4	40.8	69.8
Ti-52	2.25×10^{-13}	1.16	0.955	0.0579	0.297	0.595	1.33	2.11
Tl-190	1.41×10^{-12}	7.29	0.963	5.06	10.2	17.9	46.3	83.2
Tl-190m	2.67×10^{-12}	13.8	0.963	6.01	12.4	21.8	50.2	84.6
Tl-194	1.00×10^{-12}	5.17	0.961	4.71	9.58	16.5	38.9	68.5
Tl-194m	2.73×10^{-12}	14.1	0.962	5.95	12.4	21.4	48.6	86.3
Tl-195	1.19×10^{-12}	6.16	0.957	12.1	25.7	44	91.3	139
Tl-196	1.86×10^{-12}	9.59	0.961	9.55	22.8	42	90.5	138
Tl-197	4.69×10^{-13}	2.42	0.954	5.93	15.3	30.2	71.1	112
Tl-198	1.96×10^{-12}	10.1	0.960	11.2	25.5	44.7	92.7	140
Tl-198m	1.32×10^{-12}	6.84	0.961	4.52	9.8	17	36.3	58.7
Tl-199	2.59×10^{-13}	1.33	0.954	1.46	4.88	11.9	38.2	69.1
Tl-200	1.36×10^{-12}	7	0.960	7.56	18.9	34.7	74.6	114
Tl-201	8.72×10^{-14}	0.45	0.949	0.258	0.52	0.887	1.94	3.1
Tl-202	5.06×10^{-13}	2.61	0.957	3.14	6.59	11	21.8	32.9
Tl-204	1.14×10^{-15}	0.0059	0.948	0.215	0.428	0.714	1.47	2.3
Tl-206m	2.59×10^{-12}	13.4	0.964	5.62	13.3	24.5	55.3	86.7
Tl-206	4.47×10^{-17}	0.000231	0.949	0.233	0.459	0.755	1.5	2.26
Tl-207	2.48×10^{-15}	0.0128	0.876	11	20.6	32.4	60.8	88.3
Tl-208	2.94×10^{-12}	15.2	0.964	15.5	32.4	54.9	110	163
Tl-209	2.09×10^{-12}	10.8	0.963	11.9	26.8	46	92	136
Tl-210	2.74×10^{-12}	14.2	0.965	11.9	24.6	41.8	88	136
Tm-161	1.33×10^{-12}	6.88	0.946	8.35	22.5	41.9	89.6	136
Tm-162	1.87×10^{-12}	9.65	0.956	11.3	24.8	43.7	93.1	143
Tm-163	1.36×10^{-12}	7	0.948	10.5	24.1	41.6	84.5	127
Tm-164	8.24×10^{-13}	4.25	0.954	6.79	14.8	29.3	75.2	122
Tm-165	6.29×10^{-13}	3.24	0.948	2.81	8.65	19.8	52.4	87.9
Tm-166	1.96×10^{-12}	10.1	0.954	12.5	25.9	44	91.2	139
Tm-167	1.75×10^{-13}	0.903	0.942	0.32	1.04	2.23	12.1	26.8
Tm-168	1.35×10^{-12}	6.98	0.955	6.38	14.5	24.9	51.2	78.5

Table 1. *(Continued)*

Nuclide	Exposure rate constant		*f*-factor (cGy/R)	Lead attenuation thicknesses (mm Pb)				
	C m^2 / kg MBq s	R cm^2 / mCi h		HVL	QVL	TVL	CVL	MVL
Tm-170	4.34×10^{-15}	0.0224	0.943	0.157	0.354	0.7	1.72	2.77
Tm-171	7.81×10^{-16}	0.00403	0.936	0.107	0.212	0.357	0.765	1.24
Tm-172	4.64×10^{-13}	2.4	0.958	15.6	29.8	47.7	90.9	133
Tm-173	4.31×10^{-13}	2.23	0.962	3.13	6.1	9.9	19.4	28.8
Tm-174	1.88×10^{-12}	9.71	0.962	5.14	14.3	27.9	61	93.4
Tm-175	1.17×10^{-12}	6.02	0.962	7.47	15.8	27.9	61.6	97.6
Tm-176	1.92×10^{-12}	9.9	0.961	10.9	24.7	42.7	90	139
U-227	2.24×10^{-13}	1.16	0.953	0.0789	0.697	1.95	5.67	10.1
U-228	4.31×10^{-14}	0.222	0.933	0.00797	0.017	0.0413	1.57	4.32
U-230	4.85×10^{-14}	0.25	0.924	0.00693	0.014	0.0242	0.462	2.39
U-231	4.33×10^{-13}	2.23	0.939	0.0101	0.0241	0.126	0.869	1.82
U-232	4.53×10^{-14}	0.234	0.921	0.00672	0.0134	0.0223	0.0487	0.398
U-233	2.09×10^{-14}	0.108	0.921	0.00673	0.0134	0.0224	0.0488	0.235
U-234	4.11×10^{-14}	0.212	0.921	0.0067	0.0133	0.0221	0.0465	0.238
U-235	2.64×10^{-13}	1.36	0.957	0.208	0.692	1.35	3.13	5.36
U-236	3.72×10^{-14}	0.192	0.921	0.00669	0.0133	0.022	0.0453	0.119
U-237	3.21×10^{-13}	1.66	0.946	0.0234	0.246	0.816	3.51	8.27
U-238	2.99×10^{-14}	0.154	0.921	0.00669	0.0133	0.022	0.0451	0.101
U-239	9.12×10^{-14}	0.471	0.944	0.0439	0.36	1.82	28.2	54.7
U-240	8.71×10^{-14}	0.449	0.928	0.00787	0.0163	0.0306	0.577	1.99
U-242	5.27×10^{-14}	0.272	0.949	1.61	6.13	13	29.7	46
V-47	1.10×10^{-12}	5.7	0.965	4.99	9.53	15.3	30.1	50.3
V-48	3.00×10^{-12}	15.5	0.965	11.7	23.5	39	77.6	116
V-50	1.37×10^{-12}	7.05	0.965	17.1	32	50.8	96.2	140
V-52	1.40×10^{-12}	7.21	0.965	17.5	32	50.2	93.5	135
V-53	1.08×10^{-12}	5.57	0.965	12.9	24.1	38.1	71.9	105
W-177	9.68×10^{-13}	5	0.953	4.86	13.3	26.3	60.2	94.1
W-178	1.72×10^{-14}	0.0888	0.939	0.128	0.252	0.417	0.85	1.32
W-179	8.56×10^{-14}	0.442	0.936	0.0668	0.175	0.338	0.769	1.24
W-179m	5.92×10^{-14}	0.305	0.944	0.251	0.631	1.53	4.08	6.78
W-181	4.58×10^{-14}	0.236	0.939	0.128	0.252	0.417	0.853	1.33
W-185m	2.47×10^{-14}	0.127	0.950	0.27	0.565	1.02	2.35	3.79
W-185	4.47×10^{-17}	0.000231	0.948	0.206	0.398	0.655	1.35	2.11
W-187	4.89×10^{-13}	2.52	0.958	5.79	11.9	19.8	40.3	61.1
W-188	1.95×10^{-15}	0.0101	0.958	1.13	2.4	4.13	8.67	13.3
W-190	1.50×10^{-13}	0.776	0.949	0.276	0.572	0.999	2.12	3.25
Xe-120	6.94×10^{-13}	3.59	0.937	1.03	6.67	16.4	42.4	69.7
Xe-121	1.54×10^{-12}	7.96	0.955	7.68	18.6	37.7	89.7	141
Xe-122	2.09×10^{-13}	1.08	0.928	0.0352	0.116	2.39	10.1	18.3
Xe-123	7.88×10^{-13}	4.07	0.949	3.88	11.6	25.7	69.3	115
Xe-125	4.65×10^{-13}	2.4	0.941	0.23	1.3	4.41	32.6	65.7
Xe-127	4.42×10^{-13}	2.28	0.946	0.3	1.14	2.72	10	17.9
Xe-127m	2.38×10^{-13}	1.23	0.948	0.15	0.465	0.907	2.15	3.46
Xe-129m	2.42×10^{-13}	1.25	0.923	0.0283	0.0536	0.0938	1.27	3.22
Xe-131m	1.01×10^{-13}	0.521	0.923	0.0276	0.0516	0.0875	0.745	1.98
Xe-133	1.10×10^{-13}	0.568	0.935	0.0379	0.0982	0.4	1.35	2.29
Xe-133m	1.24×10^{-13}	0.639	0.928	0.0369	0.0924	0.92	3.63	6.31
Xe-135	2.67×10^{-13}	1.38	0.963	1.16	2.32	4.19	18.3	36.9
Xe-135m	4.92×10^{-13}	2.54	0.959	4.85	9.56	15.5	29.9	44
Xe-137	2.01×10^{-13}	1.04	0.965	5.1	10.4	20.5	65	113
Xe-138	1.06×10^{-12}	5.46	0.963	13.1	29.7	50.6	101	150
Y-81	1.31×10^{-12}	6.77	0.963	4.16	8.61	14.2	28	41.5
Y-83	1.51×10^{-12}	7.82	0.961	5.57	11.4	20.5	55.8	101
Y-83m	9.39×10^{-13}	4.85	0.965	3.7	7.93	13.5	27.1	40.6
Y-84m	4.22×10^{-12}	21.8	0.965	9.26	18.7	31.8	67.3	106
Y-85	1.21×10^{-12}	6.26	0.965	5.1	9.97	16.4	35.6	62
Y-85m	1.38×10^{-12}	7.13	0.964	7.59	16.8	33.1	81.5	130
Y-86	3.66×10^{-12}	18.9	0.965	11.1	22.9	39.3	83.2	129
Y-86m	2.26×10^{-13}	1.17	0.964	0.943	1.9	4.23	35.6	70.6
Y-87	5.47×10^{-13}	2.82	0.962	3.8	7.92	13.1	25.8	38.1
Y-87m	3.48×10^{-13}	1.8	0.964	2.69	5.32	8.7	17.3	26.3
Y-88	2.62×10^{-12}	13.5	0.963	15.8	30.3	49.3	97.5	145
Y-89m	9.57×10^{-13}	4.94	0.965	11.1	20.8	32.9	61.7	89.5
Y-90m	6.91×10^{-13}	3.57	0.965	2.54	6.42	11.6	24.1	36.5
Y-91	3.16×10^{-15}	0.0163	0.876	15.1	27.8	43.8	81.7	118
Y-91m	5.89×10^{-13}	3.04	0.965	5.63	10.7	17.1	32.7	47.9

(Continued on next page)

Table 1. *(Continued)*

Nuclide	Exposure rate constant		*f*-factor (cGy/R)	Lead attenuation thicknesses (mm Pb)				
	C m^2 / kg MBq s	R cm^2 / mCi h		HVL	QVL	TVL	CVL	MVL
Y-92	2.60×10^{-13}	1.34	0.965	11.7	22.8	37.4	75.2	115
Y-93	9.45×10^{-14}	0.488	0.965	10.2	24.7	43.4	91.3	139
Y-94	7.93×10^{-13}	4.09	0.965	12	22.9	37.2	75.8	119
Y-95	9.61×10^{-13}	4.96	0.964	18.4	34.7	55.7	109	161
Yb-162	2.74×10^{-13}	1.41	0.948	0.65	3.54	11.4	31.2	51.6
Yb-163	7.72×10^{-13}	3.99	0.951	7.34	16.6	31.3	73.9	118
Yb-164	7.25×10^{-14}	0.374	0.934	0.13	0.328	3.85	23.6	47.3
Yb-165	3.75×10^{-13}	1.93	0.942	3.65	12.2	26.1	64.2	103
Yb-166	1.15×10^{-13}	0.593	0.935	0.102	0.206	0.362	1.01	1.97
Yb-167	2.95×10^{-13}	1.53	0.944	0.194	0.468	1.32	30.5	68.4
Yb-169	3.75×10^{-13}	1.94	0.943	0.242	0.678	1.64	5.71	11
Yb-175	4.27×10^{-14}	0.22	0.957	2.03	4.57	8.04	16.9	25.8
Yb-177	1.99×10^{-13}	1.03	0.956	9.16	21.5	36.5	72.7	108
Yb-178	4.22×10^{-14}	0.218	0.962	2.61	5.14	8.42	16.7	25
Yb-179	1.08×10^{-12}	5.55	0.963	5.73	11.4	18.8	38.1	59.7
Zn-60	1.69×10^{-12}	8.73	0.963	5.26	10.4	17.1	34.6	53.4
Zn-61	1.62×10^{-12}	8.34	0.965	6.55	13.4	26.1	73.9	123
Zn-62	5.01×10^{-13}	2.59	0.956	4.9	9.97	16.4	32.7	49.7
Zn-63	1.21×10^{-12}	6.24	0.965	5.38	10.4	17.3	39.5	74.6
Zn-65	5.94×10^{-13}	3.07	0.965	13.5	25.4	40.2	75.5	110
Zn-69m	4.62×10^{-13}	2.38	0.965	3.7	7.1	11.4	22	32.4
Zn-71	3.40×10^{-13}	1.76	0.965	6.55	13.5	24.2	56.6	93.3
Zn-71m	1.71×10^{-12}	8.83	0.965	5.16	10.5	18.5	44.8	80.5
Zn-72	1.88×10^{-13}	0.97	0.959	0.243	0.589	1.04	2.26	3.78
Zr-85	1.61×10^{-12}	8.31	0.965	5.29	10.5	18.6	53	97.5
Zr-86	4.35×10^{-13}	2.25	0.953	0.55	1.71	3.7	19.5	37.6
Zr-87	1.03×10^{-12}	5.31	0.965	5.31	10.4	17.4	44	85.7
Zr-88	4.82×10^{-13}	2.49	0.961	2.47	5.28	8.86	17.6	26.3
Zr-89	1.28×10^{-12}	6.59	0.963	9.02	18.1	29.9	59.5	89.5
Zr-89m	7.10×10^{-13}	3.66	0.964	6.71	13.3	22.8	57.2	101
Zr-95	7.98×10^{-13}	4.12	0.965	8.62	16.2	25.7	48.5	70.7

† Data based on emissions of progeny Ba-137m.

simply do not exist for most nuclides, and decay product emissions have been omitted from what is reported here. Thus the shielding values should be used, as with the exposure rate constants, by combining the appropriate entries with regard to their proportion in a particular equilibrium situation. The notable discrepancies are easily explained by the improved treatment of bremsstrahlung in Shimizu et al. 2004. Photon buildup factors are extremely dependent on bremsstrahlung at shallow depths and high energies (e.g., Shimizu et al. 2004, Fig. 5). For example, if the current value of the HVL of ^{60}Co is compared, 15.6 mm Pb is found, while the commonly used value is 12.5 mm Pb. The majority of its emissions are at 1.17 and 1.33 MeV, which would be highly sensitive to a change in the treatment of bremsstrahlung. Low-energy emitters

Table 2. Comparison of selected exposure rate constants from this work and those from the 1970 Radiological Health Handbook.

	Exposure rate constant (R cm^2 / mCi h)		
	This work	Radiological Health Handbook	Ratio
Ba-133	3.0	2.4	1.27
C-11	5.86	5.9	0.993
Cs-137	3.43	3.3	1.04
Co-60	12.9	13.2	0.977
Ga-67	0.80	1.1	0.730
Ga-72	13.4	11.6	1.16
I-125	1.75	0.7	2.5
I-131	2.2	2.2	1.00
Ir-192	4.6	4.8	0.958
Zn-65	3.07	2.7	1.14

Table 3. Comparison of selected exposure rate constants from this work and dose constants from Unger and Trubey (1982).

	Exposure rate constant (mSv m^2 / MBq h)		
	This work	Unger and Trubey	Ratio
Al-26	3.52×10^{-4}	4.00×10^{-4}	0.880
Al-28	2.19×10^{-4}	2.36×10^{-4}	0.929
Ar-41	1.72×10^{-4}	1.88×10^{-4}	0.916
Au-195m	2.74×10^{-5}	4.13×10^{-5}	0.663
Ba-133	7.72×10^{-5}	1.23×10^{-4}	0.628
C-11	1.54×10^{-4}	1.91×10^{-4}	0.804
Cs-137	8.90×10^{-5}	1.02×10^{-4}	0.872
Co-60	3.38×10^{-4}	5.15×10^{-4}	0.657
F-18	1.49×10^{-4}	1.85×10^{-4}	0.805
Ga-67	2.08×10^{-5}	3.00×10^{-5}	0.694
Ga-72	3.51×10^{-4}	3.90×10^{-4}	0.901
Ho-166	4.08×10^{-6}	6.26×10^{-6}	0.651
I-123	4.54×10^{-5}	7.48×10^{-5}	0.607
I-125	4.54×10^{-5}	7.43×10^{-5}	0.584
I-131	5.65×10^{-5}	7.64×10^{-5}	0.739
In-111	8.88×10^{-5}	1.36×10^{-4}	0.653
Ir-192	1.19×10^{-4}	1.60×10^{-4}	0.746
N-13	1.53×10^{-4}	1.91×10^{-4}	0.801
O-15	1.54×10^{-4}	1.91×10^{-4}	0.805
Tc-99m	2.06×10^{-5}	3.32×10^{-5}	0.621
Tl-201	1.16×10^{-5}	2.37×10^{-5}	0.488
Zn-65	1.08×10^{-4}	8.92×10^{-5}	1.21

Table 4. Comparison of selected exposure rate constants from this work and dose constants from Tschurlovits et al. (1992).

	Exposure rate constant (mSv m^2 / MBq h)		
	This work	Tschurlovits et al.	Ratio
Al-26	3.52×10^{-4}	3.82×10^{-4}	0.921
Al-28	2.19×10^{-4}	2.00×10^{-4}	1.10
Ar-41	1.72×10^{-4}	1.57×10^{-4}	1.10
Ba-133	7.72×10^{-5}	2.74×10^{-4}	0.282
C-11	1.53×10^{-4}	1.39×10^{-4}	1.10
Cs-137	8.90×10^{-5}	8.87×10^{-5}	1.00
Co-60	3.38×10^{-4}	3.08×10^{-4}	1.10
F-18	1.49×10^{-4}	1.37×10^{-4}	1.09
Ga-67	2.08×10^{-5}	3.10×10^{-4}	0.067
Ho-166	4.07×10^{-6}	4.15×10^{-5}	0.098
I-123	4.54×10^{-5}	1.69×10^{-4}	0.269
I-125	4.34×10^{-5}	2.52×10^{-4}	0.172
I-131	5.65×10^{-5}	5.93×10^{-5}	0.953
In-111	8.88×10^{-5}	2.22×10^{-4}	0.400
Ir-192	1.19×10^{-4}	1.23×10^{-4}	0.971
N-13	1.53×10^{-4}	1.39×10^{-4}	1.10
O-15	1.54×10^{-4}	1.39×10^{-4}	1.10
Tc-99m	2.06×10^{-5}	3.60×10^{-5}	0.573
Tl-201	1.16×10^{-5}	1.05×10^{-4}	0.110
Zn-65	1.0×10^{-4}	1.98×10^{-4}	0.545

with no significant decay products are extremely close to commonly accepted values (0.021 mm Pb for ^{125}I and 0.026 mm Pb for ^{131}Cs).

CONCLUSION

The authors have calculated exposure rate constants, nuclide-specific *f*-factors, and lead shielding thicknesses for most of the more than 1,100 radionuclides described in ICRP Publication 107. This compilation adds to the literature on this important practical area of radiation protection, using up-to-date radionuclide decay and radiation attenuation data. Agreement with previous works in this area is generally good, with a few exceptions.

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