HP SURVEY INSTRUMENT CALIBRATION AND SELECTION

PRINCIPLES OF RADIATION
DETECTION AND QUANTIFICATION
CHAPTER 1

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TECHNICAL MANAGEMENT SERVICES

Canadian Nuclear Laboratories

Laboratoires Nucléaires Canadiens

CHAPTER 1 – BASICS

A. DEFINITIONS AND UNITS

GLOSSARY from 10CFR20, 10CFR835, the DOE RadCon Standard, and Other Stated References

abnormal situation: Unplanned event or condition that adversely affects, potentially affects, or indicates degradation in the safety, security, environmental, or health protection performance or operation of a facility.

accountable sealed radioactive source: A sealed radioactive source having a half-life equal to or greater than 30 days and an isotopic activity equal to or greater than the corresponding value provided in Appendix 4A of 10CFR835.

activation: Process of producing a radioactive material by bombardment with neutrons, protons, or other nuclear particles.

airborne radioactivity: Radioactive material dispersed in the air in the form of dusts, fumes, particulates, mists, vapors, or gases.

airborne radioactivity area: Any area, accessible to individuals, where:

A. the concentration of airborne radioactivity, above natural background, exceeds or is likely to exceed the derived air concentration (DAC) values listed in Appendix A or Appendix C of 10CFR835; or
B. an individual present in the area without respiratory protection could receive an intake exceeding 12 DAC-hours in a week.

annual limit on intake (ALI): The derived limit for the amount of radioactive material taken into the body of an adult worker by inhalation or ingestion in a year. ALI is the smaller value of intake of a given radionuclide in a year by the reference man (ICRP Publication 23) that would result in a committed effective dose equivalent of 5 rems (0.05 sievert) or a committed dose equivalent of 50 rems (0.5 sievert) to any individual organ or tissue.

As Low As is Reasonably Achievable (ALARA): The approach to radiation protection to manage and control exposures (both individual and collective) to the work force and to the general public to as low as is reasonable, taking into account social, technical, economic, practical, and public policy considerations. ALARA is not a dose limit but a process that has the objective of attaining doses as far below the applicable controlling limits as is reasonably achievable.

assessment: Evaluation or appraisal of a process, program, or activity to estimate its acceptability.

background radiation: Radiation from:

A. Naturally occurring radioactive materials which have not been technologically enhanced;
B. Cosmic sources;
C. Global fallout as it exists in the environment (such as from the testing of nuclear explosive devices);
D. Radon (radon and thoron collectively) and their progeny in concentrations or levels existing in buildings or the environment which have not been elevated as a result of current or prior activities; and
E. Consumer products containing nominal amounts of radioactive material or producing nominal amounts of radiation.

becquerel (Bq): The International System (SI) unit for activity of radioactive material. One becquerel is that quantity of radioactive material in which one atom is transformed per second or undergoes one disintegration per second.

bioassay: The determination of the kinds, quantities, or concentrations, and, in some cases, locations of radioactive material in the human body, whether by direct measurement or by analysis and evaluation of radioactive materials excreted or removed from the human body.

calibration: The process of adjusting or determining either:

A. The response or reading of an instrument relative to a standard (e.g., primary, secondary, or tertiary) or to a series of conventionally true values; or
B. The strength of a radiation source relative to a standard (e.g., primary, secondary, or tertiary) or conventionally true value.

containment device: Barrier, such as a glovebag, glovebox, or tent, for inhibiting the release of radioactive material from a specific location.

contamination area: Any area, accessible to individuals, where removable surface contamination levels exceed or are likely to exceed the removable surface contamination values specified in Appendix D of 10CFR835, but do not exceed 100 times those values.

continuing training: Training scheduled over a specified time, such as over a two-year period, for the purpose of maintaining and improving technical knowledge and skills.

continuous air monitor (CAM): Instrument that continuously samples and measures the levels of airborne radioactive materials on a "real-time" basis and has alarm capabilities at preset levels. Also referred to as a real-time air monitor.

controlled area: Any area to which access is managed to protect individuals from exposure to radiation and/or radioactive material..

critical mass: The smallest mass of fissionable material that will support a self-sustaining chain reaction under specified conditions.

declared pregnant worker: A woman who has voluntarily declared to her employer, in writing, her pregnancy for the purpose of being subject to the occupational exposure limits to the embryo/fetus. This declaration may be revoked, in writing, at any time by the declared pregnant worker.

decontamination: Process of removing radioactive contamination from personnel, equipment, or areas.

derived air concentration (DAC): For the radionuclides listed in Appendix A of 10CFR835, the airborne concentration that equals the ALI divided by the volume of air breathed by an average worker for a working year of 2000 hours (assuming a breathing volume of 2400m^3). For radionuclides listed in Appendix C of 10CFR835, the air immersion DACs were calculated for a continuous, non-shielded exposure via immersion in a semi-infinite atmospheric cloud. The values are based upon the derived airborne concentration found in Table 1 of the U. S. Environmental Protection Agency's Federal Guidance Report No. 11, *Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion*, published September 1988.

derived air concentration-hour (DAC-hour): The product of the concentration of radioactive material in air (expressed as a fraction or multiple of the DAC for each radionuclide) and the time of exposure to that radionuclide, in hours.

disintegration per minute (dpm): The rate of emission by radioactive material as determined by correcting the counts per minute observed by an appropriate detector for background, efficiency, and geometric factors associated with the instrumentation. 1 Bq is equal to 60 dpm.

DOELAP: Department of Energy Laboratory Accreditation Program for personnel dosimetry and bioassay programs.

dose: A general term for absorbed dose, dose equivalent, effective dose equivalent, committed dose equivalent, committed effective dose equivalent, or total effective dose equivalent. Various technical terms, such as dose equivalent, effective dose equivalent, and collective dose, are used to describe the amount of radiation an exposed individual receives. These terms are used to describe the differing interactions of radiation with tissue as well as to assist in the management of personnel exposure to radiation.

Some types of radiation, such as neutron and alpha, deposit their energy more densely in affected tissue than gamma radiation, thereby causing more damage to tissue. The term **dose equivalent**, measured in units of rem, is used to take into account this difference in tissue damage. Therefore 1 rem from gamma radiation causes damage **equivalent** to 1 rem from alpha radiation. However, it takes one-twentieth as much energy from alpha radiation, as compared with gamma radiation, to produce this 1 rem **dose equivalent**.

Definitions for dose terms necessary for various exposure calculations and recordkeeping purposes include the following:

absorbed dose (D): Energy absorbed by matter from ionizing radiation per unit mass of irradiated material at the place of interest in that material. The absorbed dose is expressed in units of rad (or gray) (1 rad = 0.01 gray).

collective dose: The sum of the total effective dose equivalent values for all individuals in a specified population. Collective dose is expressed in units of person-rem (or person-sievert).

committed dose equivalent ($H_{T,50}$): The dose equivalent calculated to be received by a tissue or organ over a 50- year period after the intake of a radionuclide into the body. It does not include contributions from radiation sources external to the body. Committed dose equivalent is expressed in units of rem (or sievert).

committed effective dose equivalent ($H_{E,50}$): The sum of the committed dose equivalents to various tissues in the body ($H_{T,50}$), each multiplied by the appropriate weighting factor (W_T) - that is $H_{E,50}=\Sigma W_T H_{T,50}$. Committed effective dose equivalent is expressed in units of rem (or sievert).

cumulative total effective dose equivalent: The sum of all total effective dose equivalent values recorded for an individual, where available, for each year occupational exposure was received, beginning January 1, 1989.

deep dose equivalent: The dose equivalent derived from external radiation at a depth of 1 cm in tissue.

dose equivalent (H): The product of the absorbed dose (D) (in rad or gray) in tissue, a quality factor (Q), and other modifying factors (N). Dose equivalent is expressed in units of rem (or sievert) (1 rem = 0.01 sievert).

effective dose equivalent (H_E): The summation of the products of the dose equivalent received by specified tissues of the body (H_T) and the appropriate weighting factors (W_T) - that is ($H_E = \Sigma W_T H_T$). It includes the dose from radiation sources internal and/or external to the body. For purposes of demonstrating compliance with the regulatory dose limits, deep dose equivalent to the whole body may be used as effective dose equivalent for external exposures. The effective dose equivalent is expressed in units of rem (or sievert).

external dose or exposure: That portion of the dose equivalent received from radiation sources outside the body (e.g., "external sources").

extremity: Hands and arms below the elbow or feet and legs below the knee.

internal dose or exposure: That portion of the dose equivalent received from radioactive material taken into the body (e.g., "internal sources").

lens of the eye dose equivalent: The external exposure of the lens of the eye and is taken as the dose equivalent at a tissue depth of 0.3 cm.

quality factor: The modifying factor used to calculate the dose equivalent from the absorbed dose; the absorbed dose (expressed in rad or gray) is multiplied by the appropriate quality factor (Q). Quality factors are provided in 10CFR835.

shallow dose equivalent: The dose equivalent deriving from external radiation at a depth of 0.007 cm in tissue.

total effective dose equivalent (TEDE): The sum of the effective dose equivalent (for external exposures) and the committed effective dose equivalent (for internal exposures).

weighting factor (W_T): The fraction of the overall health risk, resulting from uniform, whole body irradiation, attributable to specific tissue (T). The dose equivalent to the affected tissue (H_T) is multiplied by the appropriate weighting factor to obtain the effective dose equivalent contribution from that tissue..

whole body: For the purposes of external exposure, head, trunk (including male gonads), arms above and including the elbow, or legs above and including the knee.

embryo/fetus: Developing human organism from conception until birth. Same as unborn child.

engineering controls: A special form of physical design feature in which components and systems, such as piping, containments, ventilation, filtration, or shielding, are used to reduce airborne radioactivity, radiation levels, and the spread of contamination.

entrance or access point: Any location through which an individual could gain access to areas controlled for the purposes of radiation protection. This includes entry or exit portals of sufficient size to permit human entry, irrespective of their intended use.

facility: For the purpose of this Standard, a facility includes systems, buildings, utilities, and related activities whose use is directed to a common purpose at a single location. Examples include: accelerators, storage areas, test loops, nuclear reactors, radioactive waste disposal systems and burial grounds, testing laboratories, research laboratories, and accommodations for analytical examinations of components. Also includes: pipelines, ponds, impoundments, landfills and the like, and motor vehicles, rolling stock, and aircraft.

filter integrity test: Test performed on High-Efficiency Particulate Air (HEPA) filters to identify any damage to the filter or leakage around the filter.

fixed contamination: Radioactive material that has been deposited onto a surface and cannot be readily removed by non-destructive means, such as casual contact, wiping, brushing, or laundering. Fixed contamination does not include radioactive material that is present in a matrix, such as soil or cement, or radioactive material that has been induced in a material through activation processes.

frisk or frisking: Process of surveying personnel for contamination. Frisking can be performed with hand-held survey instruments or automated monitoring devices.

gray (Gy): SI unit of absorbed dose. One gray is equal to an absorbed dose of 1 joule per kilogram (100 rads).

high-efficiency particulate air (HEPA) filter: Throwaway extended pleated medium dry-type filter with 1) a rigid casing enclosing the full depth of the pleats, 2) a minimum particle removal efficiency of 99.97 percent for thermally generated monodisperse di-octyl phthalate smoke particles with a diameter of 0.3 micrometer, and 3) a maximum pressure drop of 1.0 inch w.g. when clean and operated at its rated airflow capacity.

high contamination area: Any area, accessible to individuals, where removable surface contamination levels exceed or are likely to exceed 100 times the removable surface contamination values specified in 10CFR835.

high radiation area: Any area, accessible to individuals, in which radiation levels could result in an individual receiving a deep dose equivalent in excess of 0.1 rem (0.001 Sv) in 1 hour at 30 centimeters from the radiation source or from any surface that the radiation penetrates.

hot particle: Fuel, activated corrosion product, or other particles of small size that have a high specific activity as a result of nuclear fission or neutron activation. When in direct contact with the skin, hot particles are capable of producing a shallow dose equivalent of 100 millirem or more in one hour to a localized area.

hot spot: Localized source of radiation or radioactive material normally within facility piping or equipment. The radiation levels of hot spots exceed the general area radiation level by more than a factor of 5 and are greater than 100 millirem (1 mSv) per hour on contact.

irradiator: Sealed radioactive material used to irradiate other materials that has the potential to create a radiation level exceeding 500 rad (5 grays) in 1 hour at 1 meter. Although not addressed in this Standard, acceptable radiological controls for irradiator use are specified in Title 10CFR20.

low-level waste: Waste that contains radioactive material and is not classified as high-level waste, transuranic waste, spent nuclear fuel, or byproduct material as defined in Section 11e(2) of the Atomic Energy Act, as amended. Test specimens of fissionable material irradiated only for research and development and not for production of power or plutonium may be classified as low-level waste provided the concentration of transuranic activity is less than 100 nCi/g.

mixed waste: Waste containing both radioactive and hazardous components as defined by the Atomic Energy Act and the Resource Conservation and Recovery Act, respectively.

monitoring: The measurement of radiation levels, airborne radioactivity concentrations, radioactive contamination levels, quantities of radioactive material, or individual doses and the use of the results of these measurements to evaluate radiological hazards or potential and actual doses resulting from exposures to ionizing radiation.

occupational dose: An individual's ionizing radiation dose (external and internal) as a result of that individual's work assignment. Occupational dose does not include doses received as a medical patient or doses resulting from background radiation or participation as a patient in medical research programs.

personal protective equipment: Equipment such as respirators, face shields, and safety glasses used to protect workers from excessive exposure to radioactive or hazardous materials.

personnel dosimeters: Devices designed to be worn by a single individual for the assessment of dose equivalent such as film badges, thermoluminescent dosimeters (TLDs), and pocket ionization chambers.

personnel monitoring: Systematic and periodic estimate of radiation dose received by individuals during working hours. Also, the monitoring of individuals, their excretions, skin, or any part of their clothing to determine the amount of radioactivity present.

planned special exposure: Preplanned, infrequent exposure to radiation, separate from and in addition to the annual dose limits.

protective clothing: Clothing provided to personnel to minimize the potential for skin and personal and company- issued clothing contamination. Also referred to as "anti-contamination clothing," "anti-Cs," and "PCs."

rad: Unit of absorbed dose. One rad is equal to an absorbed dose of 100 ergs per gram or 0.01 joules per kilogram (0.01 gray).

radiation or ionizing radiation: Alpha particles, beta particles, gamma rays, X-rays, neutrons, high-speed electrons, high-speed protons, and other particles capable of producing ions. Radiation, as used in this Standard, does not include non-ionizing radiation, such as radio- or micro-waves, or visible, infrared, or ultraviolet light.

radiation area: Any area, accessible to individuals, in which radiation levels could result in an individual receiving a deep dose equivalent in excess of 0.005 rem (0.05 mSv) in one hour at 30 centimeters from the radiation source or from any surface that the radiation penetrates.

radioactive material: Any material that spontaneously emits ionizing radiation (e.g., X- or gamma rays, alpha or beta particles, neutrons). The term “radioactive material” also includes materials onto which radioactive material is deposited or into which it is incorporated. For purposes of practicality, both 10CFR835 and this Standard establish certain threshold levels below which specified actions, such as posting, labeling, or individual monitoring, are not required. These threshold levels are usually expressed in terms of total activity or concentration, contamination levels, individual doses, or exposure rates.

radioactive material area: Any area within a controlled area, accessible to individuals, in which items or containers of radioactive material exist and the total activity of radioactive material exceeds the applicable values provided in appendix 4A of this Standard.

radioactive waste: Solid, liquid, or gaseous material that contains radionuclides regulated under the Atomic Energy Act, as amended, and is of negligible economic value considering the cost of recovery.

radioactivity: A natural and spontaneous process by which the unstable atoms of an element emit or radiate excess energy and/or particles from their nuclei and, thus change (or decay) to atoms of a different element or to a lower energy state of the same element.

radiography: Examination of the structure of materials by non-destructive methods, using a radioactive source or a radiation generating device.

radiological area: Any area(s) within a controlled area (but not including the controlled area) defined as a "radiation area," "high radiation area," "very high radiation area," "contamination area," "high contamination area," or "airborne radioactivity area".

radiological buffer area (RBA): An intermediate area established to prevent the spread of radioactive contamination and to protect personnel from radiation exposure.

radiological control hold point: Cautionary step in a technical work document requiring the radiological control organization to perform some action or verification. The radiological control hold point requirements should be satisfactorily completed before the work is continued.

radiological work permit (RWP): Permit that identifies radiological conditions, establishes worker protection and monitoring requirements, and contains specific approvals for radiological work activities. The radiological work permit serves as an administrative process for planning and controlling radiological work and informing the worker of the radiological conditions.

radiological worker A general employee whose job assignment involves operation of radiation producing devices or working with radioactive materials, or who is likely to be routinely occupationally exposed above 0.1 rem (0.001 sievert) per year total effective dose equivalent [see 835.2(a)].

real-time air monitoring: Measurement of the concentrations or quantities of airborne radioactive materials on a continuous basis. Also see "continuous air monitor."

release to uncontrolled areas: Release of material from administrative control after confirming that the residual radioactive material meets the guidelines in DOE 5400.5.

rem: Unit of dose equivalent. Dose equivalent in rem is numerically equal to the absorbed dose in rad multiplied by a quality factor, distribution factor and any other necessary modifying factor (1 rem = 0.01 sievert).

removable contamination: Radioactive material that can be removed from surfaces by non-destructive means, such as casual contact, wiping, brushing, or washing.

respiratory protective device: An apparatus, such as a respirator, worn by an individual for the purpose of reducing the individual's intake of airborne radioactive materials [see 835.2(a)].

sealed radioactive source: A radioactive source manufactured, obtained, or retained for the purpose of utilizing the emitted radiation. The sealed radioactive source consists of a known or estimated quantity of radioactive material contained within a sealed capsule, sealed between layer(s) of non-radioactive material, or firmly fixed to a non- radioactive surface by electroplating or other means intended to prevent leakage or escape of the radioactive material. Sealed radioactive sources do not include reactor fuel elements, nuclear explosive devices, and radioisotope thermoelectric generators.

sievert (Sv): SI unit of any of the quantities expressed as dose equivalent. The dose equivalent in sieverts is equal to the absorbed dose in grays multiplied by the quality factor (1 Sv = 100 rems).

soil contamination area: An area in which soil contamination is present at levels that are not releasable in accordance with DOE's environmental protection standards.

source leak test: A test to determine if a sealed radioactive source is leaking radioactive material.

standard radiological warning trefoil: Symbol designed and proportioned as illustrated in ANSI N2.1.

step-off pad: Transition area between contaminated and non-contaminated areas that is used to allow exit of personnel and removal of equipment.

sticky pad: Step-off pad provided with a tacky surface to reduce the potential for inadvertently tracking contamination out of a contaminated area.

survey: An evaluation of the radiological conditions and potential hazards incident to the production, use, transfer, release, disposal, or presence of radioactive material or other sources of radiation. When appropriate, such an evaluation includes a physical survey of the location of radioactive material and measurements or calculations of levels of radiation, or concentrations or quantities of radioactive material present].

thermoluminescent dosimeter (TLD): Radiation monitoring device used to record the exposure of personnel or areas to certain types of radiation.

transuranic waste: Without regard to source or form, waste that is contaminated with alpha-emitting transuranic radionuclides having half-lives greater than 20 years and concentrations greater than 100 nCi/g at the time of assay.

unusual occurrence: Non-emergency occurrence that has significant impact or potential for impact on safety, environment, health, security, or operations. Examples of the types of occurrences that are to be categorized as unusual occurrences are contained in DOE Order 232.1, *Occurrence Reporting and Processing of Operations Information*.

very high radiation area: Any area, accessible to individuals, in which radiation levels could result in an individual receiving an absorbed dose in excess of 500 rads (5 grays) in one hour at 1 meter from a radiation source or from any surface that the radiation penetrates.

whole body dose: The sum of the effective dose equivalent for external exposures and the committed effective dose equivalent for internal exposures. Also referred to as total effective dose equivalent.

Appendix 4A

Values for Establishing Sealed Radioactive Source Accountability and Radioactive Material Posting and Labeling Requirements

Nuclide	Activity (uCi)	Nuclide	Activity (uCi)	Nuclide	Activity (uCi)
Ac-227	1.5E+00	Cl-36	4.6E+05	Ge-68	5.7E+02
Ag-105	2.1E+06	Cm-241	6.8E+04	H-3	1.6E+08
Ag-108m	1.8E+01	Cm-242	5.8E+02	Hf-172	3.1E+04
Ag-110m	2.2E+01	Cm-243	3.3E+01	Hf-175	1.8E+06
Al-26	1.6E+01	Cm-244	4.0E+01	Hf-178m	4.1E+03
Am-241	2.3E+01	Cm-245	2.2E+01	Hf-181	3.5E+02
Am-242m	2.4E+01	Cm-246	2.2E+01	Hf-182	3.0E+03
Am-243	2.3E+01	Cm-247	2.4E+01	Hg-194	3.5E+04
As-73	5.4E+02	Cm-248	6.0E+00	Hg-203	4.9E+02
Au-195	4.8E+02	Cm-250	1.1E+00	Ho-166m	2.2E+01
Ba-133	5.2E+01	Co-56	4.0E+01	I-125	3.5E+02

Be-10	2.8E+04	Co-57	2.3E+02	I-129	1.8E+02
Be-7	3.2E+03	Co-58	1.4E+02	In-114m	7.8E+02
Bi-207	1.7E+01	Co-60	1.8E+01	Ir-192	1.4E+02
Bi-208	1.5E+01	Cs-134	2.7E+01	Ir-192m	2.6E+04
Bi-210m	1.3E+03	Cs-135	2.2E+06	Ir-194m	2.7E+01
Bk-247	1.7E+01	Cs-137	6.0E+01	K-40	2.8E+02
Bk-249	7.2E+03	Dy-159	4.1E+06	La-137	1.1E+05
C-14	4.8E+06	Es-254	6.3E+01	Lu-173	4.4E+05
Ca-41	7.4E+06	Es-255	4.6E+04	Lu-174	2.5E+05
Ca-45	1.5E+06	Eu-148	7.0E+05	Lu-174m	3.9E+05
Cd-109	1.6E+02	Eu-149	5.3E+06	Lu-177m	5.8E+01
Cd-113m	6.5E+03	Eu-152	3.1E+01	Md-258	6.0E+02
Cd-115m	1.0E+04	Eu-154	3.1E+01	Mn-53	2.0E+07
Ce-139	2.4E+02	Eu-155	3.7E+02	Mn-54	6.5E+01
Ce-141	2.4E+03	Fe-55	3.7E+06	Mo-93	7.7E+01
Ce-144	1.5E+03	Fe-59	2.0E+02	Na-22	1.9E+01
Cf-248	2.0E+02	Fe-60	1.3E+04	Nb-91	7.0E+01
Cf-249	1.7E+01	Fm-257	4.3E+02	Nb-91m	3.6E+02

Cf-250	3.8E+01	Gd-146	2.6E+05	Nb-92	1.8E+01
Cf-251	1.7E+01	Gd-148	3.0E+01	Nb-93m	4.4E+02
Cf-252	6.4E+01	Gd-151	1.1E+06	Nb-94	2.3E+01
Cf-254	3.4E+01	Gd-153	2.1E+02	Nb-95	3.4E+02
Ni-59	7.5E+06	Re-184	2.6E+02	Tc-97m	3.6E+02
Np-235	1.2E+02	Re-184m	1.5E+02	Tc-98	2.5E+01
Np-236	2.2E+01	Re-186m	2.8E+05	Tc-99	6.8E+061
Np-237	1.9E+01	Rh-101	2.5E+05	Te-121m	1.9E+02
Os-185	1.4E+02	Rh-102	8.3E+04	Te-123m	2.8E+02
Os-194	1.5E+04	Rh-102m	2.1E+05	Te-125m	4.4E+02
Pa-231	7.8E+00	Ru-103	4.4E+02	Te-127m	8.0E+02
Pb-202	1.0E+05	Ru-106	2.1E+04	Te-129m	2.3E+039
Pb-205	9.1E+01	S-35	4.0E+06	Th-228	2.9E+01
Pb-210	9.2E+01	Sb-124	9.1E+01	Th-229	4.7E+00
Pd-107	7.8E+05	Sb-125	6.8E+01	Th-230	3.1E+01
Pm-143	1.3E+02	Sc-46	6.2E+01	Th-232	6.1E+00
Pm-144	2.9E+01	Se-75	6.4E+01	T-44	1.6E+02
Pm-145	2.6E+02	Se-79	1.0E+06	Tl-204	2.2E+04

Pm-146	4.5E+01	Si-32	9.9E+03	Tm-170	8.4E+03
Pm-147	2.5E+05	Sm-145	9.1E+05	Tm-171	2.8E+04
Pm-148m	1.1E+02	Sm-146	1.2E+02	U-232	1.5E+01
Po-209	6.3E+03	Sm-151	2.5E+05	U-233	7.4E+01
Po-210	1.1E+03	Sn-113	3.1E+02	U-234	7.5E+01
Pt-193	4.4E+07	Sn-119m	3.3E+02	U-235	6.7E+01
Pu-236	6.9E+01	Sn-121m	8.7E+05	U-236	8.0E+01
Pu-237	3.3E+02	Sn-123	1.3E+04	U-238	8.4E+01
Pu-238	2.5E+01	Sn-126	1.8E+02	V-49	2.9E+07
Pu-239	2.3E+01	Sr-85	1.2E+02	W-181	1.1E+03
Pu-240	2.3E+01	Sr-89	2.4E+05	W-185	3.9E+06
Pu-241	1.2E+03	Sr-90	7.7E+03	W-188	6.4E+04
Pu-242	2.4E+01	Ta-179	1.5E+06	Y-88	3.4E+01
Pu-244	2.5E+01	Ta-182	7.3E+01	Y-91	5.0E+04
Ra-226	1.2E+03	Tb-157	2.5E+03	Yb-169	5.5E+02
Ra-228	2.1E+03	Tb-158	3.9E+04	Zn-65	1.1E+02
Rb-83	9.2E+01	Tb-160	1.2E+02	Zr-88	1.2E+02
Rb-84	2.0E+02	Tc-95m	1.3E+02	Zr-93	3.1E+04

Re-183	5.4E+02	Tc-97	8.1E+01	Zr-95	2.0E+02

Notes:

1. The value for any alpha emitting nuclide not listed above and for mixtures of unknown alpha emitters is 10 µCi [10CFR835, Appendix E].
2. The value for any non-alpha emitting nuclide and for mixtures of these nuclides of unknown composition is 100 µCi [10CFR835, Appendix E].
3. When the radioactive material consists of a mixture of known quantities of listed nuclides, determine the value by summing the fractions of the quantity of each radionuclide divided by the accountability value for that nuclide. If the sum of the fractions exceeds unity (1), the value has been exceeded [10CFR835, Appendix E].

B. CONSTANTS AND CONVERSION FACTORS

SI and US "Traditional" Units

Activity			Dose Equivalent		
1 TBq	=	27 Ci	1 Sv	=	100 rem
1 GBq	=	27 mCi	1 mSv	=	100 mrem
1 MBq	=	27 µCi	1 mSv	=	0.10 rem
1 kBq	=	27 nCi	1 µSv	=	100 µrem
1 Bq	=	27 pCi	1 µSv	=	0.10 mrem
1 Bq	=	1 dps	1 nSv	=	0.10 µrem
1 Bq	=	60 dpm			
1 kCi	=	37 TBq	1 krem	=	10 Sv
1 Ci	=	37 GBq	1 rem	=	10 mSv
1 mCi	=	37 MBq	1 mrem	=	10 µSv
1 µCi	=	37 kBq	1 mrem	=	0.01 mSv

1 nCi	=	37 Bq
1 nCi	=	37 dps
1 nCi	=	2220 dpm
1 pCi	=	0.037 Bq
1 pCi	=	2.22 dpm

1 μrem	=	0.01 μSv
1 μrem	=	10 nSv

Absorbed Dose

1 kGy	=	100 krad
1 Gy	=	100 rad
1 mGy	=	100 mrad
1 μGy	=	100 μrad
1 krad	=	10 Gy
1 rad	=	10 mGy
1 mrad	=	10 μGy
1 μrad	=	10 nGy

Dose Rate

1 Sv/h	=	100 rem/h
1 mSv/h	=	100 mrem/h
1 mSv/h	=	0.10 rem/h
1 μSv/h	=	100 μrem/h
1 μSv/h	=	0.1 mrem/h
1 krem/h	=	10 Sv/h
1 rem/h	=	10 mSv/h
1 mrem/h	=	10 μSv/h
1 mrem/h	=	0.01 mSv/h

1 μrem/h = 0.01 μSv/h

CONVERSION OF UNITS

Length

1 angstrom (Å)	=	1E-8 cm	1 cm	=	1E8 Å
1 inch	=	2.54 cm	1 cm	=	0.3937 in
1 meter	=	3.2808 feet	1 foot	=	0.3048 m
1 kilometer	=	0.6214 miles	1 mile	=	1.609 km
1 mile	=	5,280 feet	1 foot	=	1.894E-4 mi
1 micron (μm)	=	1E-6 meters	1 m	=	1E6 μm
1 mil	=	1E-3 inches	1 inch	=	1E3 mil
1 thousandth of an inch (0.001")	=	2.54E-2 mm	1 mm	=	0.03937 in
1 yard	=	0.9144 meters	1 m	=	1.0936 yard

Area

1 acre	=	43,560 ft^2	1 ft^2	=	2.296E-5 acre
1 barn	=	1E-24 cm^2	1 cm^2	=	1E24 barn
1 cm^2	=	0.1550 in^2	1 in^2	=	6.452 cm^2
1 m^2	=	10.764 ft^2	1 ft^2	=	0.0929 m^2
1 m^2	=	3.861E-7 $mile^2$	1 $mile^2$	=	2.59E6 m^2
1 $mile^2$	=	640 acres	1 acre	=	1.5625E-3 mi^2

Volume

1 cm^3 (cc)	=	3.5315E-5 ft^3	1 ft^3	=	28,316 cm^3
1 cm^3	=	1E-6 m^3	1 m^3	=	1E6 cm^3
1 cm^3	=	0.03381 ounces	1 ounce	=	29.58 cm^3
1 ft^3	=	28.316 liters	1 liter	=	0.035315 ft^3
1 ft^3	=	7.481 gallons	1 gal	=	0.1337 ft^3
1 liter	=	1.057 quarts	1 quart	=	0.946 liter
1 liter	=	0.2642 gallons	1 gal	=	3.785 liter
1 liter	=	61.0237 in^3	1 in^3	=	0.016387 liter
1 m^3	=	35.315 ft^3	1 ft^3	=	0.028316 m^3
1 m^3	=	1,000 liters	1 liter	=	1E-3 m^3
1 milliliter (ml)	=	1 cm^3	1 cm^3	=	1 ml

Mass

1 gram	=	0.03527 ounces	1 ounce	=	28.35 g
1 kilogram	=	2.2046 pounds	1 lbs	=	0.4536 kg
1 pound	=	16 ounces	1 ounce	=	0.0625 lb
1 pound	=	453.59 grams	1 gram	=	2.2046E-3 lb

Density

1 gram / cm^3 = 62.428 lbs / ft^3 1 lb/ft^3 = 0.016018 g/cm^3

1 gram / cm^3 = 8.345 lbs / gal 1 lb/gal = 0.1198 g/cm^3

Concentration

1 Bq / M^3 = 60 DPM / M^3 1 DPM/M^3 = 0.0167 Bq/M^3

1 Bq / M^3 = 0.027027pCi/L 1 pCi / L = 37 Bq / M^3

1 pCi / L = 1E-9 µCi / cc 1 µCi / cc = 1E9 pCi / L

1 µCi / cc = 2.22E12 DPM/M^3

1 DPM / M^3 = 4.5045E-13 µCi/cc

1 µCi / cc = 3.7E10 Bq / M^3

1 Bq / M^3 = 2.7027E-11 µCi/cc

1 pCi / ft^3 = 3.5315E-11 µCi / cc

1 µCi / cc = 2.8316E10 pCi / ft^3

Pressure

1 atmosphere = 1.01325 bars	1 bar = 0.9869 atm
1 atmosphere = 101.325 kPa	1 kPa = 0.009869 atm
1 atmosphere = 14.696 lbs / in^2	1 lbs/in^2 = 0.06805 atm
1 atmosphere = 760 mm Hg	1 mm Hg = 0.001316 atm
1 atmosphere = 29.9213 “Hg	1 “Hg = 0.033421 atm
1 atmosphere = 33.8995 feet H_2O	1 ft H_2O = 0.0295 atm
1 bar = 1E6 dynes / cm^2	1 dyne/cm^2 = 1E-6 bar
1 dyne/cm^2 = 0.1 Pascals	1 Pascal = 10 dyne/cm^2
1 Torr = 1 mm Hg	1 mm Hg = 1 Torr
1 dyne/cm^2 = 1.0197E-3 g/cm^2	
1 g/cm^2 = 980.68dyne/cm^2	

Radiological

1 rad	=	100 ergs / g
1 erg / g	=	0.01 rad
1 rad	=	6.242E13 eV / g
1 eV / g	=	1.602E-13 roentgen
1 roentgen	=	87.7 ergs / g of air
1 erg / g of air	=	0.0114 roentgen
1 roentgen	=	1.61E12 ion pairs/g of air
1 ion pair / g of air	=	6.21E-13 roentgen
1 roentgen	=	5.47E13 eV / g of air
1 eV / g of air	=	1.828E-14 roentgen
1 roentgen	=	0.98 rads (in soft tissue)
1 rad (in soft tissue)	=	1.02 roentgen
1 rem	=	100 ergs / g in tissue
1 erg /g in tissue	=	0.01 rem
1 sievert (Sv)	=	100 rem

1 rem	=	0.01 Sv
1 sievert	=	1 J / kg
1 curie (Ci)	=	3.7E10 dps
1 dps	=	2.7027E-11 Ci
1 curie	=	2.22E12 dpm
1 dpm	=	4.5045E-13 Ci
1 μCi / m^2	=	222 dpm / cm^2
1 dpm / cm^2	=	0.0045 μCi / m^2
1 megaCi / sq mile	=	0.386 Ci / m^2
1 Ci / m^2	=	2.59 megaCi/sq mile
1 dpm / m^3	=	4.5E-13 μCi / cm^3
1 μCi / cm^3	=	2.22E12 dpm / m^3
1 becquerel (Bq)	=	2.7027E-11 Ci
1 Ci	=	3.7E10 Bq
1 becquerel	=	1 dps
1 dps	=	1 Bq

1 BTU	=	1.28E-8 g U^{235} fissioned
1 g U^{235} fissioned	=	7.81E7 BTU
1 BTU	=	3.29E13 fissions
1 fission	=	3.04E-14 BTU
1 g U^{235} fissioned	=	1 megawatt-days
1 MW-days	=	1 g U^{235} fissioned
1 g U^{235} fissioned	=	1.8E-2 kilotons TNT
1 kilotons TNT	=	55.6 g U^{235} fissioned
1 fission	=	8.9058E-18 kW-hours
1 kW-hrs	=	1.123E17 fissions
1 fission	=	3.204E-4 ergs
1 erg	=	3.121E3 fissions
1 fission	=	6.9E-21 Megatons TNT
1 Megatons TNT	=	1.45E20 fissions
1 gray	=	100 rads
1 rad	=	0.01 gray

1 joule (J)	=	6.24E18 eV
1 eV	=	1.602E-19 joule
1 ampere	=	2.998E9 electrostatic units/sec
3.336E-10 amp	=	1 electrostatic unit/sec
1 ampere	=	6.242E18 electronic charges/sec
1.602E-19 amp	=	1 electronic charge/sec
1 coulomb	=	6.242E18 electronic charges
1 electronic charge	=	1.602E-19 coulomb

CONSTANTS

Avogadro's number (N_0)	6.02252E23
electron charge (e)	4.80298E-10 esu
e electron rest mass (m)	9.1091E-28 g
acceleration of gravity (g)	32.1725 ft / sec^2
@ sea level & 45^0 latitude	980.621 cm / sec^2
Planck's constant (h)	6.625E-27 erg-sec
velocity of light (c)	2.9979E10 cm / sec
	186,280 miles / sec
ideal gas volume (V_0) (STP)	22,414 cm3 / mole
neutron mass	1.67482E-24 g
proton mass	1.67252E-24 g
ratio of proton to electron mass	1836.13
natural base of logarithms (e)	2.71828
pi	3.14159

1C	6.2418E18 esus
1A	1 C/sec
1 barn (b)	1E-24 cm^2
charge (e-1)	1.6E-19 C
W for air	33.8 eV / ion pair
Universal gas constant (R)	8.32E7 ergs/^{0}C gram mol

A gram-molecular weight of any gas contains Avogadro's number, N_0 (6.02252E23) atoms and occupies a volume of 22,414 cm^3 at STP.

Temperature

^0C = $(^0F - 32)(5/9)$

^0F = $^0C \times 1.8 + 32$

K (Kelvin) = $^0C + 273.15$

^0R (Rankine) = $^0F + 459.58$

Absolute zero is 0 Kelvin, 0 ^0R, -273.15 ^0C, -459.67 ^0F

MULTIPLES AND SUBMULTIPLES

1E18 Exa E	1E2 hecto h	1E-6 micro u
1E15 Peta P	1E1 deka da	1E-9 nano n
1E12 tera T	1E0 1 1	1E-12 pico p
1E9 giga G	1E-1 deci d	1E-15 femto f
1E6 mega M	1E-2 centi c	1E-18 atto a
1E3 kilo k	1E-3 milli m	

COUNTING STATISTICS AND UNCERTAINTY

COUNTING STATISTICS

Minimum Detectable Activity (MDA)

$[k^2 + 2k\sqrt{(R_B \times t_S \times (1+t_S/t_B))}] / t_S \times Eff$

Minimum Detectable Count Rate (MDCR = LLD = L_D)

$[k^2 + 2k\sqrt{(R_B \times t_S \times (1+t_S/t_B))}] / t_S$

$L_C = k\sqrt{(R_B \times t_S + R_B \times t_B)}$

k = 1.645 (95% Confidence Level for a two-tailed distribution)

t_S = sample count time

t_B = background count time

R_B = background count rate

Eff = efficiency of the detector (expressed as a decimal)

R_S = sample count rate

LLD is Lower Limit of Detection

L_D is the Decision Level

L_C is the Critical Level and generally expressed as counts (or signal level) above background

K	0.674	1	1.645	1.96	2.58	3.00
% C.L.	50	68.3	90	95	99	99.7

If R_B is in DPM it must be converted to CPM before using the above equations.

A ‘k’ of 1.645 is used as the 95% confidence level for a two-tailed distribution.

Gaussian statistics should be used for > 30 counts and Poisson statistics for < 30 counts. The typical formulas such as those above are an attempt to blend the two statistical models.

MDA when background and sample count times are one minute and k is 1.645. $(3 + 4.65 \sqrt{R_B \times t_B}) / Eff$

MDA when background count time is ten minutes and sample count time is one minute and k is 1.645.
$(3 + 3.45 \sqrt{R_B \times t_B}) / Eff$

POISSON STATISTICS

For Poisson distributions the following logic applies.

Pn is the probability of getting count "n"

Pn = $\mu^n e^{-\mu} / n!$

n = the hypothetical count

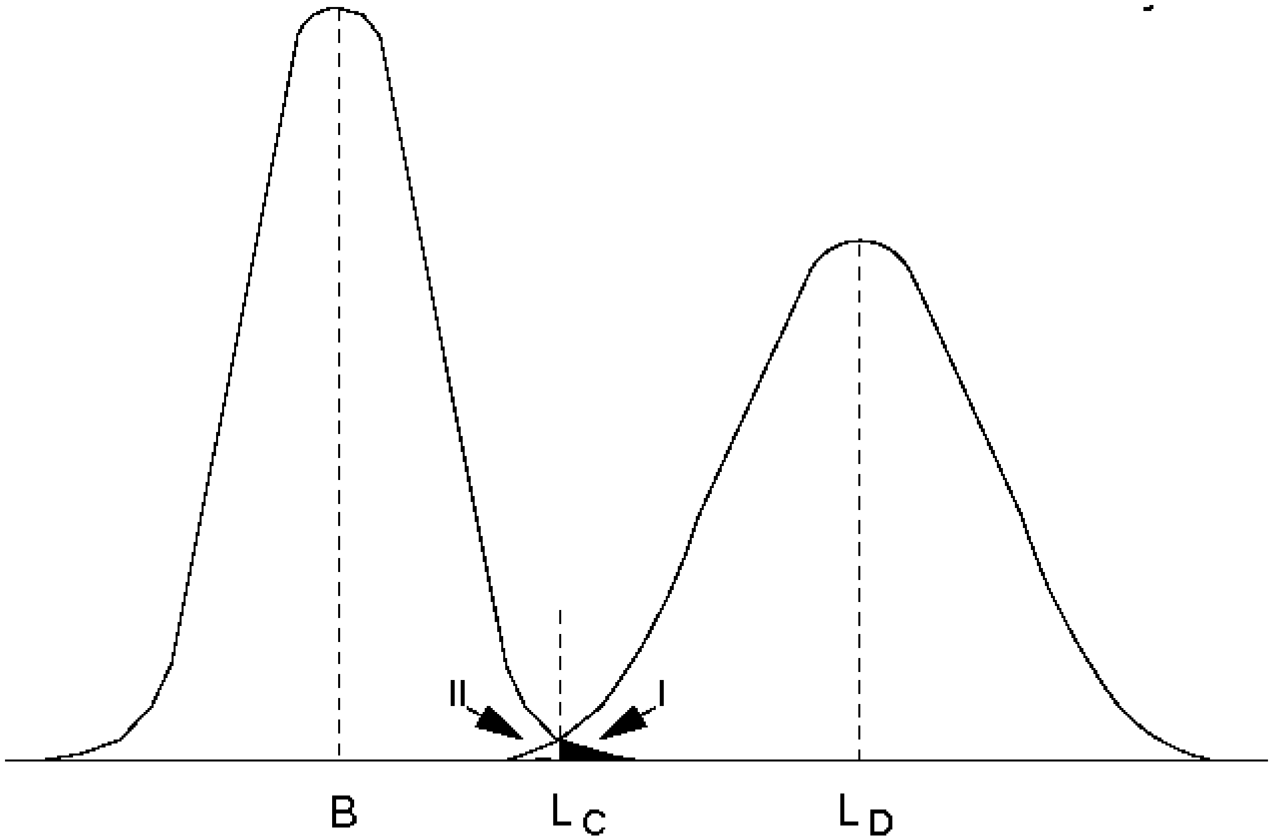
μ = true mean counts

If the true mean, μ, is 3, then there is a 5% probability that we will get a zero count and a 95% probability that we will get greater than zero counts. There is a 65% probability that we will get 3 or more counts.

I = Probability of Type I error

II = Probability of Type II error

B = Bkg L_C = Critical level L_D = Decision level


II
I
B
L_C
L_D

The MDA can be improved by;

- Increasing the background count time
- Decreasing the background count rate
- Increasing the sample count time
- Increasing the detector efficiency
- Applying the appropriate confidence level
- Applying analysis algorithms to the collected counts

Uncertainty Calculations in Radioactive Sources

Objectives

- To understand the origin of the components that result in the uncertainty value associated with a calibrated source's activity and/or output value.
- To understand the magnitude of these components and thus their relative contributions to the overall uncertainty value(s).
  - a source can have more than one calibrated characteristic and thus more than one uncertainty value associated with it
- To understand how to numerically combine these components' values to calculate an overall uncertainty value.

- The meaning of uncertainty
- Measurement components leading to uncertainty
- Which components apply to which source types
- Which components apply to which instruments
- Which components apply to which calibration methods
- Example calculation
- Final thoughts
- References

WHAT DOES UNCERTAINTY MEAN ?

- No radioactivity measurement is without uncertainty
- An uncertainty value is only an estimate
- An uncertainty value is of little worth without an indication of the likelihood the correct value falls within the activity/output range indicated by the uncertainty value (e.g., 10 ± 1 means a range of 9 -11)
  - a confidence level must be stated with an uncertainty value, typically 95% or greater

RADIOACTIVE SOURCES – THE BEGINNING

- A national metrology institute (NMI) such as NIST must produce a source activity measurement with a properly determined uncertainty value using a primary measurement technique (e.g., 4π Beta-γ) to produce a primary standard.
- An entity traceable to the NMI such as Eckert & Ziegler Isotope Products (EZIP) uses the primary measurement result to calibrate an instrument EZIP will use to make future measurements or a source it has manufactured (direct and comparator measurements, respectively) to produce a secondary standard.
- The secondary standard's uncertainty value can't be less than the uncertainty value of the primary standard but it can theoretically be statistically insignificantly larger than the primary standard's uncertainty value, albeit highly unlikely.

- Both primary and secondary standards can be used to calibrate instrumentation in the laboratory or field.

- Some of the components that go into a source's activity uncertainty value are
  - radioactive decay
  - activity decay correction
  - background and "signal-to-noise" ratio
  - instrument stability
  - source configuration, including variation
  - source position relative to the detector, when applicable
  - duration of count, when applicable
  - weighing of active matrix (e.g., powder or solution)
    - NIST-traceable balance(s) necessary

MAGNITUDE OF UNCERTAINTY VALUES

- Historical data
  - typical difference from known values
- Repeatability measurements
  - multiple source measurements using consecutive counts
- Reproducibility measurements
  - multiple source measurements over a longer period of time
    - typically involves multiple days or longer
    - involves placing and replacing the source (reproducing count geometry)
- Intercomparisons with one or more national metrology institutes
  - requirement to be formally traceable to NIST, etc.

- Known instrument limitations
  - readability of output
  - technical specifications
  - geometric configuration
- Equipment and accessory variation
  - source holder placement
    - counting stands for gamma ray spectrometers
  - component movement
    - drawer on gas flow proportional counter
- Location effects on instrumentation/equipment
  - analytical balance in a on a bench top

TRACEABILITY TO AN NMI (National Metrology Institute)

- Clearly declared uncertainty values required for intercomparison tests with an NMI such as NIST
  - ANSI N42.22:1995 has six categories for source traceability
    - alpha particle sources for total alpha activity
    - alpha particle sources used for high-resolution alpha spectrometry
    - beta particle emission sources with E_{avg} < 100 keV
    - beta particle emission sources with E_{avg} > 100 keV
    - gamma-ray emission sources with energies < 250 keV
    - gamma-ray emission sources with energies >250 keV
  - each intercomparison test requires an uncertainty value specific to the test
    - uncertainty value specified for each test is the minimum uncertainty value allowed for sources supplied by the source provider

Radioactive Decay

- Poisson distribution
  - standard deviation = $(events)^{½}$
    - 4 times the events leads to doubling the precision (i.e., “halving” the uncertainty)
  - precision improvement reaches a “point of diminishing returns”
    - source calibration is often a balance between throughput and precision
  - counting statistics for a standard source ideally does not significantly statistically increase the uncertainty value for a production source calibration
    - standard sources typically should not have activity levels at the lower limits of an instrument’s capabilities

Decay Corrections

- Factors
  - uncertainty value for half-life
    - strictly dependent on nuclear data parameter measurements
  - amount of correction
    - typically not a large contributor to the overall uncertainty value
  - large relative half life value uncertainty combined with significant decay correction leads to statistically significant increase in total uncertainty value

Background and Noise

- Signal-to-Noise ratio influences multiple aspects
  - source strength
    - source activity should be sufficiently high relative to the background level
  - source-to-detector distance
    - typically photon measurements only
    - larger source-to-detector distances reduce uncertainty in terms of source placement reproducibility but decrease counting statistics which increases relative uncertainty values unless longer count times are used
  - count duration
    - greater benefit for short duration measurements but short duration counts have larger relative uncertainty values in terms of count rate but not a major factor in most cases

Source Configurations

- Point sources
  - placement of active material (i.e., reproducibility of placement within holder)
  - density of support matrix
- Planar sources
  - shape (i.e., round vs. square vs. rectangular)
  - backing material
- Large volume sources
  - applies almost exclusively to gamma emitting sources
  - matrix density affects low-energy measurements most
  - container material increasingly important with higher Z
- Matching standard source configuration to unknown source configuration reduces total uncertainty value

Instruments Used For Measurements

- Photon measurements
  - gamma rays
    - ionization chambers
    - germanium detectors (e.g., HPGe)
    - NaI(Tl) detectors
  - x-rays
    - Si(Li) detectors

- Particle measurements
  - gas flow proportional counter
    - alpha and beta particle emission sources
  - liquid scintillation counter
    - alpha and beta contained activity sources
  - surface barrier detector
    - alpha particle emission sources only, energy and activity value

Source Position

- Source dimensions vs. detector dimensions
  - solid angle subtended
  - edge effects
  - depth of activity relative to source surface
- Often a significant contributor to contained activity value uncertainty for environment samples due to small source-to-detector distance
  - Marinelli beakers
  - filter papers

Stability of Instrument

- Temperature
  - NaI(Tl) typically most affected instrument
  - thermal equilibrium is important for all instruments

- Barometric pressure
  - ionization chambers most affected instrument

- Humidity
  - particle emission source measurements most affected

- Power supply
  - voltage bias stability important for plateaus

Weighing

- Absolute weighing
  - not typically used because active matrix must be contained in some object if for no other reason than to transfer the activity to final container
- Weighing by difference
  - relative difference in container mass vs. active matrix mass
    - weighing a pipette tip full and then empty typically leads to less uncertainty than weighing solution in pipette by adding solution directly to container
    - typical pipette tip is < 1g but some containers are >50g

Particle Counting

- Branching Ratio
  - strictly dependent on nuclear data parameter measurements
  - detector efficiency for detecting emitted particle
- Source efficiency for emitting particles from source surface
  - typically an experimentally determined value
- Contained activity value and surface emission rate value are typically linearly correlated for alpha sources but independent for beta sources
  - surface emission rate for solid alpha sources used to determine contained activity
  - activity gravimetrically deposited for beta sources while surface emission rate is measured directly

Photon Counting

- Detector efficiency
  - direct, energy point for energy point calibration of detector
  - curve fitting for a set of efficiency points
    - often one of the biggest components of uncertainty in photon measurement
- Branching ratio
  - strictly dependent on nuclear data parameter measurements
    - use of different nuclear data parameter sets without proper correction can lead to additional uncertainty, which is unnecessary
- Use of comparator method eliminates some uncertainty components (e.g., detector efficiency and branching ratio) but is costly and time consuming

– matching standard needed for each source configuration and radionuclide

Uncertainty Propagation

- Total uncertainty value only increases
- Formal definition

$(\sigma_u)^2 = (\delta_u/\delta_x)^2(\sigma_x)^2 + (\delta_u/\delta_y)^2(\sigma_y)^2 + (\delta_u/\delta_z)^2(\sigma_z)^2 + \ldots$

- Addition/subtraction

$(A \pm a) +/- (B \pm b) = A +/- B \pm (a^2 + b^2)^{1/2}$

- Multiplication/division

$(A \pm a) * (B \pm b) = A*B \pm A*B*[(a/A)^2 + (b/B)^2]^{1/2}$ $(A \pm a) / (B \pm b) = A/B \pm A/B*[(a/A)^2 + (b/B)^2]^{1/2}$

- Exponentiation

$e^{\lambda A} = e^{\lambda A}\lambda\sigma_A$ (used when half life precisely known)

Combined Statistical Uncertainty and Relative Expanded Uncertainty

- The result of the propagation of uncertainty is the combined statistical uncertainty (CSU)
  - combined statistical uncertainty is given at 1σ
- The relative expanded uncertainty (REU), the final uncertainty value provided with source, is the product of the combined statistical uncertainty (CSU) times the coverage factor, k:

REU = k * CSU

Gamma Spectrometry Example

$$A_u = \{C_u F_u I P_u e^{-[\ln(2)]t/T}\}/\{EBD_u\}$$

where

A_u = activity of unknown

C_u = counts of unknown

F_u = fit of peak for unknown

I = instrument stability

P_u = position of unknown

t = time of decay (days)

T = half life for nuclide (days)

E = gamma ray detector efficiency

B = branching ratio

D_u = duration of unknown count

Distributions

- Normal (i.e., Gaussian)
  - variation probability from the true value follows the “bell curve”
- Rectangular
  - variation probability from the true value is equally likely regardless of variation magnitude
  - typically for measurement results at the limit of readability

mass determination is an example

- Triangular
  - special case of rectangular distribution
    - mass determination by weighing difference is an example

Qty	Definition	Value	% Unc (k=1)	Standard Uncertainty	Distribution	Sensitivity	Uncertainty Contribution
C_u	unknown counts	1214076	0.193	2343.167	Normal	0.0174	40.79318
E	detector efficiency	0.04133	1.0	0.00041	Normal	511404.9079	211.36365
t	decay (d)	321	-	0.1	Rectangular	1.71468	0.17147
T	half life (d)	4933	-	11	Normal	0.19326	2.12584
B	branching ratio	0.2657	-	0.0011	Normal	79549.73595	87.50471
D_u	unknown count duration	5000	0.01	0.5	Rectangular	2.44062	1.22031
F_u	unknown peak fit	1	1.0	0.010	Triangular	8628.8848	86.28885
I	instrument stability	1	0.1	0.001	Rectangular	12203.0859	12.20309
P_u	unknown position	1	0.1	0.001	Rectangular	12203.0859	12.20309
A_u	unknown activity	21136.36	-	-	-	-	496.97
						REU (k=2)	**2.35%**

- Most of the time, the majority of a measurement uncertainty value is the result of only a few components.
- It is better to overestimate an uncertainty value than to underestimate it but one should make the best estimate possible given the objective evidence available.
- There is no substitute for experience when there is not enough data and estimations must be made.

References

- NIST Technical Note 1297-1994 Edition, “Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results”

- Guide to Uncertainty Measurement (GUM)

  – GUM Workbench by Metrodata GmbH

- ILAC-G17:2002, “Introducing the Concept of Uncertainty of Measurement in Testing in Association with the Application of the Standard ISO/IEC 17025”

INSTRUMENT CALIBRATION UNCERTAINTY

- The calibration goal is to provide a calibration that will yield an "acceptably accurate" estimate of the desired quantity (i.e. exposure or dose rate) when used in the field
  - To determine that a calibration is "acceptably accurate" one must know the uncertainty in the measurement
  - General Calibration Process Uncertainty Parameters
  - Determine Source Exposure Rate Uncertainty
  - Determine Random and Systematic Uncertainty in Detector Measurements
  - Determine Total Uncertainty in Measurement Results

Accuracy and Precision

- **Accuracy:** a measure of how well a true quantity is estimated, measured value/true value

- **Precision:** a measure of reproducibility

Types of Uncertainty

- **Random**: Uncertainties in the random variations in the measurement process that quantifies the precision

- **Systematic**: Uncertainties that cannot be estimated by statistical methods

Random Uncertainties

$\delta_{Random} = t * \sigma_R$

Random uncertainties can be calculated using the following equation:

Where:

t = Student t value for particular degrees of freedom to yield a given probability that the true value X will be included in the confidence interval

σ_R= Standard Deviation in the value with random error

Value of Student t-factor

	Probability			
Degrees of Freedom, n-1	0.50	0.90	0.95	0.99
1	1.000	6.31	12.71	63.7
2	0.816	2.92	4.30	9.92
3	0.765	2.35	3.18	5.84
4	0.741	2.13	2.78	4.60
5	0.727	2.02	2.57	4.03
6	0.718	1.94	2.45	3.71
7	0.711	1.90	2.36	3.50
9	0.703	1.83	2.26	3.25
14	0.692	1.76	2.14	2.98
19	0.688	1.73	2.09	2.86
29	0.683	1.70	2.04	2.76
49	0.679	1.68	2.01	2.68
99	0.677	1.66	1.98	2.63
∞	0.674	1.64	1.96	2.58

NCRP 112

Systematic Uncertainties

- May result from a number of causes
  - Errors in reading instrument
  - Source to detector distance errors
  - Attenuator placement errors

- May be positive or negative

- May not be normally distributed

- You should try to eliminate them by investigating and correcting

Systematic Uncertainties

- Systematic uncertainties can be estimated by determining the apparent standard deviation, u

- The apparent standard deviation, u, can be estimated as 1/3 of the maximum systematic uncertainty

- For 95% confidence, $2u$ is the range of uncertainty around the mean

Determining Exposure Rate Calibration Uncertainty

Assumptions

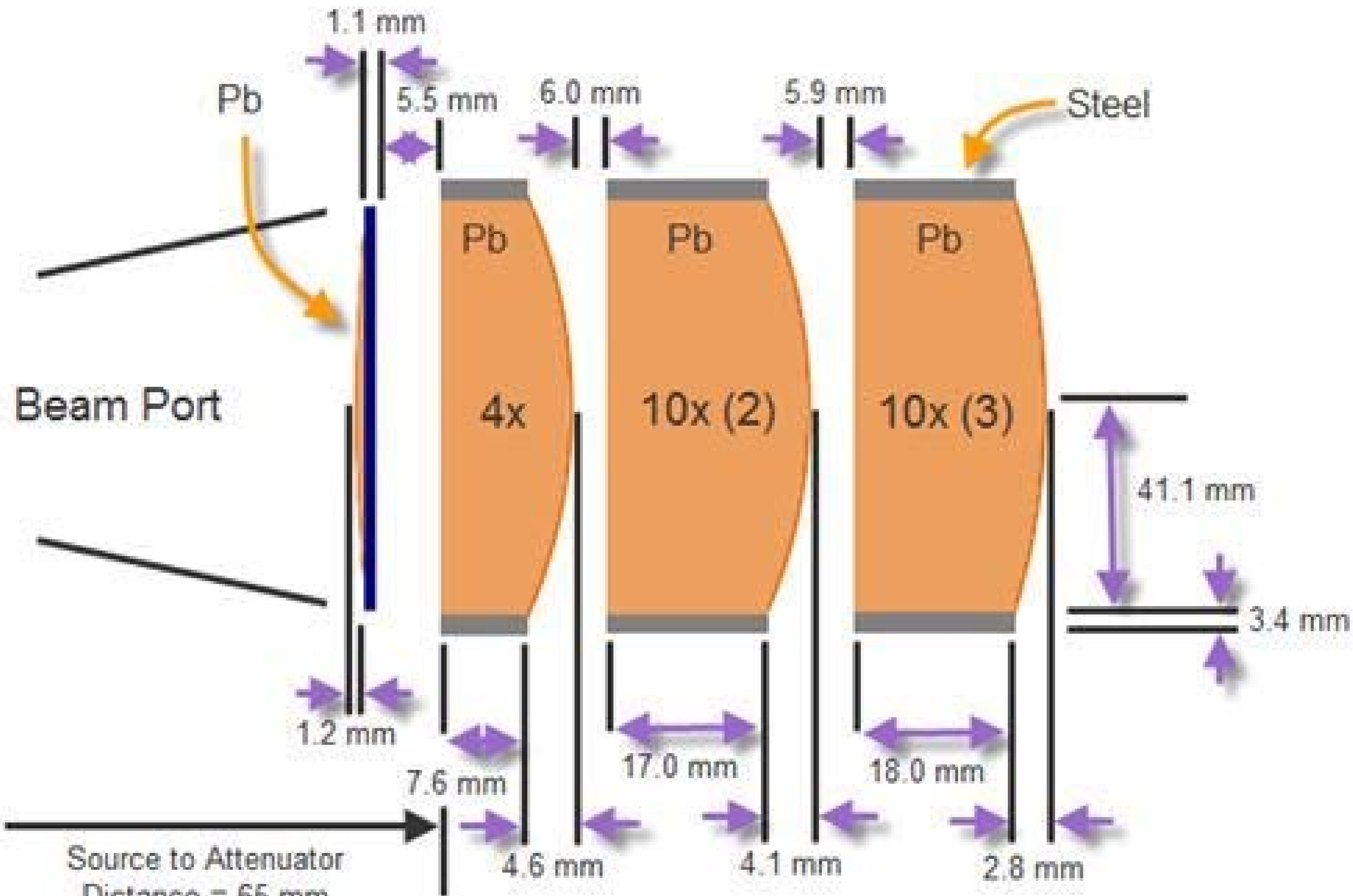
- Cs-137 Calibration Beam Source installed on track system
- 3 attenuator used in multiple combinations
- Multiple instruments calibrated

– Ion Chambers

– GM Detectors

– Scintillation Detectors

– Solid State Detectors


1.1 mm
Pb
5.5 mm
6.0 mm
5.9 mm
Steel
Pb
Pb
Pb
Beam Port
4x
10x (2)
10x (3)
41.1 mm
3.4 mm
1.2 mm
7.6 mm
17.0 mm
18.0 mm
Source to Attenuator
Distance = 65 mm
4.6 mm
4.1 mm
2.8 mm

Evaluate the “true” Exposure Rate and its Uncertainty

• Use a transfer standard instrument such as an Exradin Shonka – Wychoff ionization chamber (used with a calibrated electrometer system to measure current)

or Reuter Stokes HPIC for low dose rates

• Transfer Standards calibrated and traceable to NIST

Uncertainty Evaluation

- Review of measurement process identified both random and systematic errors associated with determination of true exposure rates

- Radom Error
  – Associated with the statistical results of the transfer instruments

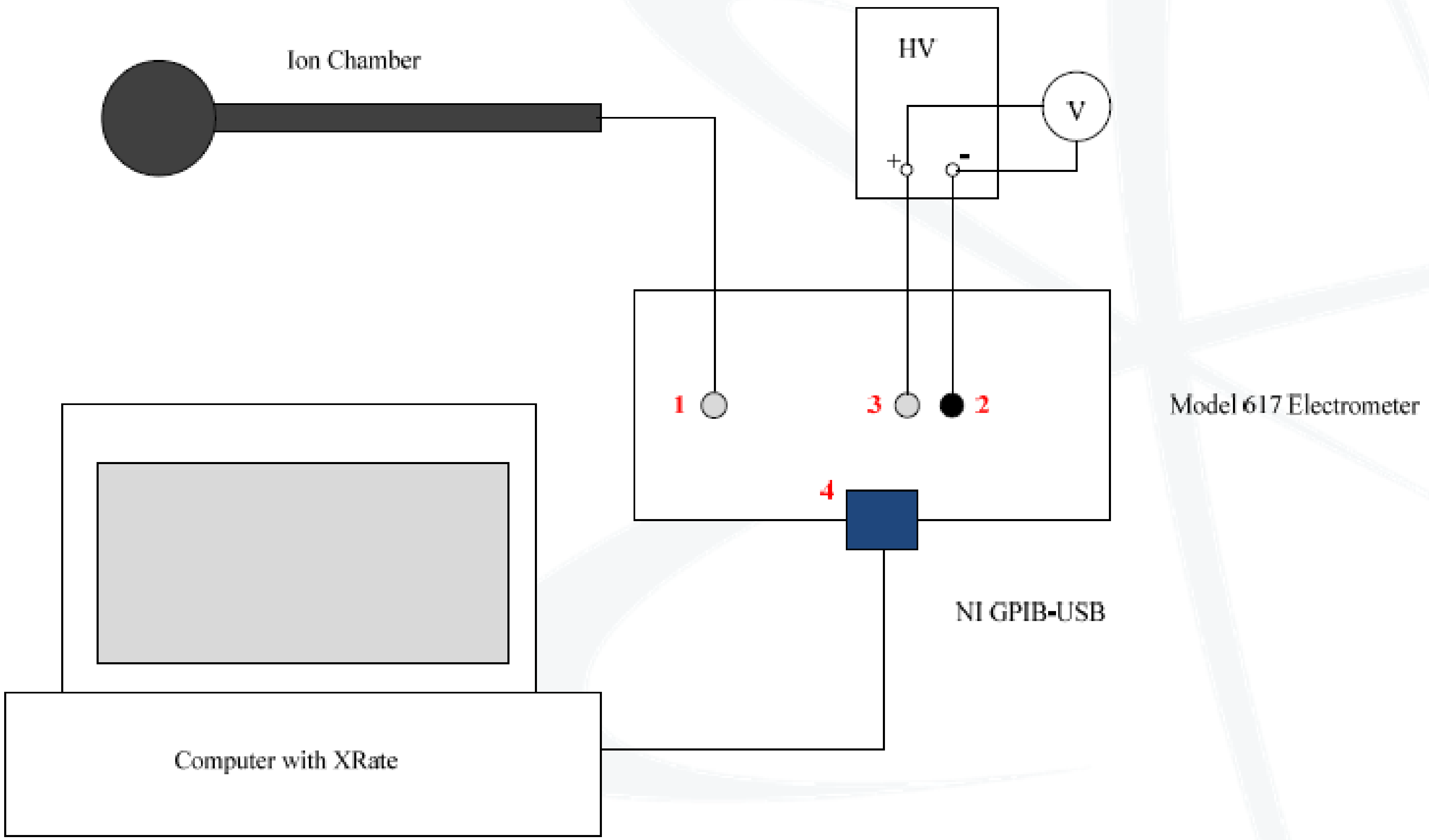
- Systematic Errors
  – Detector Placement (distance)
  – Ion Chamber Calibration
  – Electrometer Calibration
  – Temperature
  – Pressure
  – Exposure rate curve fit (residuals)

Evaluation of “true” Exposure Rate

- Background measurements recorded using a lead shield in front of the source (“Shadow Shield”)

- Unattenuated and attenuated measurements taken at source to center of detector at distances of 30, 50, 80, 100, 200, and 300 cm

- Six measurements taken at each location and averaged to yield exposure rate at each location


Ion Chamber
HV
V
+
-
1
3
2
Model 617 Electrometer
4
NI GPIB-USB
Computer with XRate

Exposure Rate Power Functions Table

Beam			
Source	Base	Exponent	Corr. Fit
Attenuator	*a*	*b*	r^2
1x	6.279100E+02	-2.004660E+00	9.999627E-01
4x	1.345762E+02	-1.973129E+00	9.999258E-01
10x2	6.621852E+01	-2.016499E+00	9.999716E-01
10x3	6.417209E+01	-1.999544E+00	9.999254E-01
40x2	2.215078E+01	-2.060330E+00	9.996309E-01
40x3	1.783889E+01	-2.008843E+00	9.993982E-01
100x	9.883114E+00	-2.059398E+00	9.986914E-01
400x	1.605974E+00	-1.938399E+00	9.994158E-01

$$X = a_* x^b$$

Overall Random Uncertainty

- Several measurements using various attenuators and distance are used to compute relative errors

- Maximum relative error used in overall random uncertainty calculation

$\delta_{Random} = t * \sigma_R$

$\delta_{Random} = 2.447 * 0.0082$

$\delta_{Random} = 2.0\%$

Systematic Uncertainties

δ distance max = maximum error associated with distance = 3.9%

δ distance = 2 sigma (95% confidence) error associated with
distance = 2(3.9%/3) = 2.6%

δ ion chamber = 2 sigma (95% confidence) error associated with
ion chamber calibration = 1.6%

δ Electrometer = 2 sigma (95% confidence) error associated
electrometer calibration = 0.20%

Systematic Uncertainties

δ temperature = 2 sigma (95% confidence) error associated with temperature monitoring device calibration (+/- 1.0 C) = 0.34%

δ pressure = 2 sigma (95% confidence) error associated with pressure monitoring device calibration = 1.0%

δ residuals max = maximum error associated with curve fit residuals = 4.4%

δ residuals = 2 sigma (95% confidence) error associated with curve fit residuals = 2(4.4%/3) = 2.9%

Overall Systematic Uncertainty

+/- Systematic =
$\sqrt{[(2.6)^2 + (1.6)^2 + (0.2)^2 + (0.34)^2 + (1.0)^2 + (2.9)^2]} = 4.3\%$

Overall Total Uncertainty in Exposure Rate

+/- Total = $\sqrt{[(2.0)^2 + (4.3)^2]} = 4.8\%$

Total Uncertainty in Instrument Calibration

- Requires knowledge of “true” beam exposure uncertainty and meter uncertainties
  - Meter distance placement
  - Meter reading
  - Pressure and temperature (for unsealed detectors only)

- Calibration uncertainty is a combination of exposure uncertainty and meter uncertainties

Meter Uncertainties

• Meter placement
– Can be estimated to be the same as the ion chamber distance uncertainty

• Meter reading
– Can be ascertained experimentally by taking a series of meter reading by different individuals and calculating the standard deviation
– Can be ascertained by assuming a maximum error in meter reading

• Pressure and Temperature
– Can be assumed to be the same uncertainties as used to calculate total exposure uncertainty

• Other uncertainties related to calibration specific calibration conditions

Meter Reading Uncertainties

	Distance	Measurer 1	Measurer 2	Measurer 3
1 R 44-9	16.6	16.4	16.5	16.7
1 R 44-6	16.6	16.4	17	16.5
1 R ND2000	16.6	17	16.5	17.2
1 R DMC-2000	16.6	16.8	16.6	16.9
200 mR 44-9	37.1	36.8	37.3	36.8
200 mR 44-6	37.1	37	37.2	37.1
200 mR ND2000	37.1	37.2	37	37.8
200 mR DMC-2000	37.1	36.8	37.1	37.3
40 mR 44-9	82.9	82.9	82.8	83
40 mR 44-6	82.9	82.1	82.2	82.7
40 mR ND2000	82.9	83	82.5	83
40 mR DMC-2000	82.9	82.8	82.7	83.1

Meter Reading Uncertainties

- The average error for all measurements is 0.75%

- The maximum error for an individual measurement (at the 16.6 cm distance) = 3.61%

- The standard deviation in meter reading can be estimated as $\sigma_{Meter} = (\sigma_{Meter\ Max})/3 = 3.61/3$

- The 95% probability in meter read uncertainty can be calculated as $2\sigma_{Meter} = 2.4\%$

Total Calibration Uncertainty

$$\sqrt{(\delta^2_{\text{total exposure}} + \delta^2_{\text{meter reading}} + \delta^2_{\text{temp}} + \delta^2_{\text{pressure}} + \delta^2_{\text{distance}})}$$

Total Calibration Uncertainty

$\delta_{total\ exposure}$ = 2 sigma uncertainty in exposure = 4.3 %

$\delta_{meter\ reading}$ = 2 sigma uncertainty in meter reading = 2.4%

δ_{temp} = 2 sigma uncertainty associated with temperature monitoring device = 0.34%

$\delta_{pressure}$ = 2 sigma uncertainty associated with pressure monitoring device = 1.0%

$\delta_{distance}$ = 2 sigma uncertainty associated with distance = 2.6%

Total Calibration Uncertainty

$$\sqrt{[(0.043)^2 + (0.024)^2 + (0.0034)^2 + (0.01)^2 + (0.026)^2]}$$

+/- 5.7%

CHAPTER 2 – RADIATION

A. SOURCES OF RADIATION xxx

B. RADIATION INTERACTIONS

CHAPTER 3 - GENERAL PROPERTIES OF RADIATION DETECTORS

Gas Filled Detectors

Ionization Chambers

Gas Proportional Detectors

Geiger-Muller Detectors

Scintillation Detectors

Photomultiplier Tubes and Photodiodes

Semiconductor Diode Detectors

Neutron Detectors

CHAPTER 4 - RADIATION BACKGROUND AND DETECTOR SHIELDING

CHAPTER 5 - INTERFERRING RADIATIONS

CHAPTER 6 - SPECIFIC RADIATION DETECTOR RESPONSES

CHAPTER 7 - REVIEW AND SUMMARY

A. ALMOST EVERY TYPE OF RADIATION DETECTOR RESPONDS TO ALMOST EVERY TYPE OF RADIATION

B. BACKGROUND INTERFERENCE

C. WEBSITES

D. REFERENCES