Conversion Factors in Radiation Protection

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February 2007

As operations of the Large Hadron Collider commence and plans for the International Linear Collider progress, it will become more common to encounter documents that express quantities of importance for radiation protection in Système Internationale (SI) units of measure that are used by nearly everyone outside of the United States. Thus, it may be useful to have ready access to the conversion factors between the standard units used in the USA that are, loosely, based on the centimeter-gram-second (cgs) system to the SI ones that are based on a meter-kilogram-second (mks) system. Providing these is the intent of this short note and along the way standard definitions of the quantities of interest are given. The medical physics and radiation protection professions use other specialized units related to these that are not covered here.

The Situation

At present, regulatory agencies in the USA including the Department of Energy, the Nuclear Regulatory Commission, and the Environmental Protection Agency expressly require the use of the cgs units in practical personnel protection. Specifically, warning signs, dosimetry reports to individuals, "legal" reports to agencies, etc. are required to be in cgs units. Technical reports such as environmental assessments can, and do, use both. Professional journals now all require SI units to be used nearly exclusively.

All the major computer codes used to design shielding, etc. at large accelerators present their output in SI units. Specifically this is the case for MARS, MCNP, LAHET, FLUKA, and EGS. Even where cgs units are needed to quantify the results for practical purposes, the practice is to perform the calculations in SI units and make whatever conversions that are needed as the last step of the work.

Absorbed Dose

Absorbed dose is the amount of energy per unit mass deposited in a material medium. Absorbed dose is a purely physical quantity that can, in principle, be measured in any medium and is thus used in radiation damage work as well as in personnel or environmental protection. Absorbed dose is usually denoted by *D*.

The cgs unit of absorbed dose is the rad. One rad = 100 ergs gram^{-1}. One mrad = 1×10^{-3} rad.

The SI unit of absorbed dose is the Gray (Gy). One Gy = 1 Joule kilogram^{-1}. Thus 1 Gy = 100 rads and 1 mGy = 100 mrads. Also, 1 mrad = 10 microGy (μGy).

In "loose" jargon, one commonly hears the unit "1 R" associated with a "dose" of 1 rad. The "R" refers to the Roentgen, a unit of so-called "exposure" that is a defined only for radiation due to photons and not for other types of radiation. One R is the flux of photons required to liberate one cgs unit of charge (one e.s.u.) cm^{-3} of air at standard temperature and pressures (STP). (One may need to recall that in the cgs system, the charge of the electron is 4.8×10^{-10} e.s.u.) By coincidence, in air 1 R amounts to 87.6 ergs g^{-1}. Also, tissue placed in a 1 R field of photons will receive an absorbed dose of about 95 ergs g^{-1}, approximately one rad. Most US gamma-ray survey instruments read out in mR h^{-1}, etc. being calibrated in photon radiation fields. In SI units, 1 R = 2.58 x 10^{-4} Coulombs $kilogram^{-1}$ and so the conversion of these units to SI ones is not very convenient. Where SI units are used exclusively, gamma ray survey meters read out in Gy $hour^{-1}$, or submultiples such as μGy h^{-1}, etc. The use of the exposure concept is in decline worldwide.

Dose Equivalent

Dose equivalent is the quantity that takes into account the fact that some particle types have biological effects that are enhanced over others. Dose Equivalent is usually denoted by H. This is done by applying a dimensionless "quality factor" Q to absorbed dose. The value of Q is approximately reflective of the enhanced biological harm due to a given radiation relative to photons. (200 keV photons are the specified reference standard.) For example, in the present system of radiation protection, photons always have a $Q = 1$ as do muons and electrons of all but the lowest energies. Charged particles, especially at lower energies can have values of Q as high as 20 and neutrons can have Q as large as 10. The spectra of neutrons found outside of shielding at high energy accelerators have quality factors ranging from 3-10. The term dose equivalent is applied only to radiation dose received by people and can be viewed as a construct used for radiation protection purposes to weight radiation from different sources according to the level of hazard to people as determined from radiobiology. Dose equivalent is not directly measurable. Rather, it is determined by inference from details of the radiation field and its interaction with tissue. The values of Q specified by regulatory agencies are correlated with ionization stopping power in tissue (dE/dx) and can be averaged over the individual components of a given radiation field.

The cgs unit of dose equivalent is the rem. For a given value of Q, the value of dose equivalent in rem is the absorbed dose in rads multiplied by this factor. Thus $H = QD$. Thus, if one has $D = 1$ rad of absorbed dose and a radiation field where $Q = 5$, then the dose equivalent $H = 5$ rem.

The SI unit of dose equivalent is the Sievert (Sv). Since Q is dimensionless, it is independent of the system of units and $H = QD$ still applies. Thus if $Q = 5$ and $D = 1$ Gy, the dose equivalent is 5 Sv. Also, 1 mSv = 0.1 rad = 100 mrem and 1 mrad = 10 microSv (μSv).

Activity

Activity is the number of decays sec^{-1} of a given radionuclide.

The cgs unit of activity is the Curie (Ci). One Ci = 3.7 x 10^{10} decays sec^{-1}. The "odd" value comes from the fact that the pioneers in the discovery of radioactivity assigned 1 Ci to the activity of one gram of ^{226}Ra as a workable laboratory standard, since it could be weighed. (The modern value of the specific activity of ^{226}Ra is 0.988 Ci g^{-1}; the early "standard" was very well-measured indeed!)

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The SI unit of activity is the Becquerel (Bq). One Bq = 1 decay sec^{-1} = 27.027 pCi. Since 1 Bq an extremely small unit, in documents such as publications one sees the multiples kBq (1 kBq = 1 x 10^3 Bq = 27.027 nCi), MBq (1 MBq = 1 x 10^6 Bq = 27.027 µCi), GBq (1 Gbq = 1 x 10^9 Bq = 27.027 mCi) and TBq (1 TBq = 1 x 10^{12} Bq = 27.027 Ci). Since the Curie is such a large unit (1 Ci = 37 GBq), the submultiples mCi (1 mCi = 1 x 10^{-3} Ci = 37 MBq), µCi (1 µCi = 1 x 10^{-6} Ci = 37 kBq), nCi (1 nCi = 1 x 10^{-9} Ci = 37 Bq), and pCi (1 pCi = 1 x 10^{-12} Ci = 0.037 Ci) are commonly encountered.

One needs to take special care with the units associated with the term specific activity. In publications, etc., one sees this term used for both activity per unit volume and activity per unit mass. One also encounters SI and cgs units, etc. all mixed up such as Ci $meter^3$ and Bq $gram^{-1}$, apparently in all possible combinations.