IN7900247

B.A.R.C.-964

B.A.R.C.-964

भारत सरकार
GOVERNMENT OF INDIA
परमाणु ऊर्जा आयोग
ATOMIC ENERGY COMMISSION

SI UNITS IN RADIATION PROTECTION

by

V. K. Jain and S. D. Soman
Health Physics Division

भाभा परमाणु अनुसंधान केन्द्र
BHABHA ATOMIC RESEARCH CENTRE
बंबई, भारत
BOMBAY, INDIA
1978

B. A. R. C. -964

GOVERNMENT OF INDIA
ATOMIC ENERGY COMMISSION

B. A. R. C. -964

SI UNITS IN RADIATION PROTECTION

by

V. K. Jain and S. D. Soman
Health Physics Division

BHABHA ATOMIC RESEARCH CENTRE
BOMBAY, INDIA
1978

INIS Subject Category: C53; D15

DESCRIPTORS

RADIATION PROTECTION

RADIATION DOSES

DOSE EQUIVALENTS

ICRU

RADIATION DOSE UNITS

KERMA

RADIOACTIVITY

MEASURING METHODS

PREFACE

International System of Units abbreviated as SI Units have been adopted by most of the countries of the world. Following this development, the implementation of SI units has become mandatory with a transistion period of about ten years. Some of the journals have already adopted the SI units and any material sent for publication to them must use only these.

International Commission on Radiation Units and Measurement (ICRU) published letters in several journals including 'Physics in Medicine and Biology, Health Physics, British Journal of Radiology, etc. outlining the latest recommendations on SI units to elicit the reactions of scientists in the general field of Radiological Sciences.

Reactions to the letters were numerous as can be seen in the correspondence columns of these journals for the last few years and ranged from great misgivings and apprehension to support and appreciation. SI units have also been the subject of editorial comments in several journals. On the basis of a survey of this literature, it may be said that there was general agreement on the long term advantage of SI units inspite of some practical difficulties in their use particular in the initial stages.

This report presents a review of SI units in radiological sciences with a view to familiarize the users with the new units in terms of the old. A time table for the gradual changeover to the SI units is also outlined.

CONTENTS

INTERNATIONAL SYSTEM OF UNITS

1. Historical Background

In 1875 seventeen countries signed the treaty of the metre ('Convention du Metre') in order to secure the international uniformity and perfection of the metric system. The participating countries also created the General Conference on Weights and Measures (CGPM) an assembly for intergovernmental decision making. The CGPM adopts definitions of units and their names, makes recommendations etc. The International Committee on Weights and Measures (CIPM) is responsible, for their implementation. It is only in 1960 after decades of deliberations that the CGPM adopted the International System of Units (SI from French 'Le Systeme International d'Unites'). Plans are now well advanced for the introduction of a unified, international system of units for common use in science, technology, commerce and daily life all over the world(1-3).

Independently of the CGPM, ICRU, since its inception in 1925, has been engaged in the development of internationally acceptable recommendations regarding quantities, units and measurement of ionising radiation and radioactivity. The ICRU thus came up with its definitions of the quantities 'activity', 'exposure', 'absorbed dose' and 'dose equivalent' with the corresponding <u>special units</u> 'curie' (1 Ci), 'roentgen' (1R) 'rad' and 'rem'. These quantities and units are understood and used throughout the world by workers in the fields of radiology, nuclear medicine, radiation research and radiation protection. The ICRU in its report issued in July 1971,(ICRU 19),(4) recommended SI units. Realising that special units do exist in other fields, for example herts for temporal frequency, the commission continued to recognize the existing special units. The special radiological units can all be exactly expressed in the SI units (sec. 2). But the conversion involves numerical factors which prevents their adoption as SI units.(There are strict rules regarding the use of numerical factors with the SI units). The ICRU published letters(5-7) in several journals to elicit opinion. On the basis of the replies received the ICRU considered that the introduction of the SI was favoured though with some reluctance. Further a large majority of those who favoured the adoption of the SI units, thought that some appropriate names must be selected for their every day use. The ICRU discussed these problems and became convinced that the introduction of the International System of Units into Radiological Sciences will be greatly facilitated by the use of new special names for certain SI derived units. Accordingly at its meeting at Seattle in July 1974, ICRU prepared proposals to be considered by the CIPM. At its 15th General Conference, the CIPM discussed the proposals sent by ICRU and passed two resolutions:

Resolution H 1:

Adopts the following name of SI unit for Activity:

The Becquerel*, symbol Bq equal to the second to the power minus one.

Resolution H 2:

Adopts the following name of SI unit for ionizing radiations.

The Gray+, symbol Gy equal to the joule per kilogram.

Explanatory Note:

The 'gray' is the unit of absorbed dose. The gray can also be used with other physical quantities expressed in joules

---

*Antoni Henri Becquerel (1852-1908) discovered radioactivity in 1896 and was given the Nobel Prize in Physics in 1903 together with Marie and Pierre Curie.

+Louis Harold Gray (1905-1965) made one of the most fundamental contributions to radiation dosimetry the principle now known as the Bragg-Gray Principle.

per kg provided these quantities belong to the field of ionising radiation.

The ICRU now recommends that the special units (rad, rem and Ci) be gradually abandoned over a period of ten years and replaced by the SI units, the Gy and the Bq.

2. Principles of SI Units$^{(1,8,9)}$

The SI is founded on the principle that there should be one and only one SI unit for each physical quantity. Thus the quantity energy whatever its source, mechanical, thermal, electrical or radiation has the SI unit Joule and its symbol is J.

The SI is based on seven well defined units, which are called base units:

Quantity	Unit	Symbol
Length	Meter	m
Mass	Kilogram	kg
Time	Second	s
Electric current	Ampere	A
Temperature	Degree Kelvin	°K
Luminous intensity	Candela	Cd
Substance	mole	mol

There are two other classes of SI units viz. derived units and supplementary units. The SI system is coherent in the sense that no conversion factors are needed for the formation of derived units. The latter can be formed by combining base units according to the algebraic relations linking the corresponding quantities. There are several derived units with special names such as the newton (N) for force, the pascal (Pa) for pressure, the volt (V) for potential difference, the siemens (S) for condutance, etc.

The third class of SI units, the supplementary units, contains only two purely geometrical units: the radian (rad) for the plain angle and the steradian (sr) for the solid angle.

Certain other units like the time units, the minutes (min), the hour (h) and the day (d) and five other units are in such widespread use that CIPM has recognised that they must be retained for general use with the SI.

Decimal multiples and sub multiples of SI units are formed with the use of SI prefixes only. The CGPM has adopted a series of 16 names and symbols of prefixes in the range 10^{-18} to 10^{18}. These are given in Table I.

3. SI Units in Radiation Protection(1,8,9)

3.1. The change over:

The basic units used in radiation protection work are, the curie the roentgen, the rad and the rem. These can be converted exactly into SI units.

1 curie = 1 Ci = 3.7×10^{10} s^{-1} (exactly)

1 roentgen = 1 R = 2.58×10^{-4} C/kg (coulomb per kilogram)

1 rad = 1 rad = 0.01 J kg^{-1} (exactly) (joule per kilogram)

1 rem = 1 rem = 0.01 J kg^{-1} (exactly).

However, as pointed out earlier, the strict SI rules on numerical factors prevent their adoption as SI units. There are also practical difficulties posed by the use of SI units besides the general hardship caused by the very fact of change over from an established to a new system. Some of the practical problems can be overcome as we shall see below, by giving new names to the units. Hence the units of activity absorbed dose and dose equivalent have been given the new names Becquerel (Bq), Gray(Gy) and Sievert (Sv) respectively. Table II lists the SI units and their new names along with their symbols for the radiological quantities and their present equivalents.

3.2. Radiological Quantities and their Units:

3.2.1.a) Exposure

No new name was sought by the ICRU for roentgen (R) the special unit of exposure. The SI unit of exposure is the coulomb per kilogram ($C\ kg^{-1}$). Since exposure by definition is the charge produced per unit mass, the SI unit expresses the physical quantity measured. The SI unit of exposure means that amount of X or gamma radiation which produces in 1 kilogram of air ions of either sign having absolute value of the total charge equal to 1 coulomb. The unit is therefore large:

$$1\ C\ kg^{-1} \approx 3876\ R$$

conversely $1\ R = 2.58 \times 10^{-4}\ C\ kg^{-1}$ (exactly)

(1 e su = $(3 \times 10^{9})^{-1}$ coulomb of charge in 0.001293 g of air).

The SI unit is about 4000 times of roentgen. For exposure therefore roentgen SI unit equivalence is approximately as follows:

$$kR \longrightarrow C.kg^{-1}$$
$$R \longrightarrow mC.kg^{-1}$$
$$mR \longrightarrow \mu C.kg^{-1}$$
$$\mu R \longrightarrow nC.kg^{-1}$$

Fig.1 gives the nomogram showing roentgen SI unit equivalence over a wide range.

3.2.1.b) Exposure rate

The SI unit of exposure rate is Ampere per kilogram ($A.kg^{-1}$). Since

$$1\ C = 1\ A\ s$$
$$1\ C\ kg^{-1}\ s^{-1} = 1\ A\ kg^{-1}$$

This amounts to saying that the exposure rate is 1 A/kg when the exposure per second is 1C/kg. Again as in the case of exposure the unit is too large and same rough equivalence as for exposure holds. Some of the commonly encountered exposure rate figures and their SI equivalents are as follows:

$$2.5 \text{ mR h}^{-1} = 0.18 \text{ n A kg}^{-1}$$

$$= 0.18 \text{ n C kg}^{-1} \text{ s}^{-1}$$

$$= 0.645 \text{ μC kg}^{-1} \text{ h}^{-1}$$

$$10 \text{ R} = 2.58 \text{ mA kg}^{-1}$$

$$= 2.58 \text{ mC kg}^{-1} \text{ s}^{-1}$$

It is clear from the above equivalence that a complete reorientation of thinking and experience in this field will have to be brought about while using the SI units. There are further difficulties in the use of SI units for exposure rate. The unit nA/kg does not contain the time factor explicitly and therefore does not provide the feeling of a rate unit, This is overcome by the use of the relation

$$1 \text{ nA}\cdot\text{kg}^{-1} = 1 \text{ nC kg}^{-1} \text{ s}^{-1}.$$

However the unit nanocoulomb per kilogram per sec is too long and unwieldy at least for oral communication. Coulomb per kilogram can perhaps be abbreviated to CPK and short forms like nano Cpk per sec ($\text{nC kg}^{-1} \text{ s}^{-1}$) or micro Cpk per hour ($\text{μC kg}^{-1} \text{ h}^{-1}$), etc. used. In fig.1 nomograms showing the equivalence of exposure rates in special and SI units are given.

It is seen above that the present exposure and exposure rate when converted to SI units give inconvenient fractional numbers. Since no great sanctity except that of years of usage are attached to these numbers may be at a future date, the limit will be set in terms of convenient SI units. Let us recall that

$$100 \text{ mR} = 25.8 \text{ μC kg}^{-1}$$

$$\text{and } 2.5 \text{ mR h}^{-1} = 0.645 \text{ μC kg}^{-1} \text{ h}^{-1}$$

just a factor of about 4 is involved in both. In Table III are shown some conversions of exposure and exposure rate into SI units.

3-2.2 a) Activity

The activity A of a radionuclide is

$$A = dN/dt$$

The SI unit of activity for a radioactive nuclide is the reciprocal second (s^{-1}).

Compared to the existing unit viz. 1 curie = $3.7x10^{10} s^{-1}$ this is too small (Table II) and will require multiples for any meaningful deployment. However, as per the strict SI rules multiples cannot be formed in the usual straight forward manner. For example 10^6 s^{-1} ($\approx$ 27 uCi) cannot be written Ms^{-1} because this would mean $(Ms)^{-1}$ or 1/Ms = 10^{-6} s^{-1}. The recommended symbol for 10^6 s^{-1} is 1 μ s^{-1} or 1 per microsecond, for 10^9 s^{-1} it is 1 ns^{-1} i.e. 1 per nanosecond and so on.

Similarly in expressing the rate of change of activity with time, per second will come twice causing confusion. Thus a rate of change of 27 μCi sec^{-1} = 1 μ $s^{-1} s^{-1}$ = 1 μ s^{-2}.

The use of mathematical notations like 10^6, 10^9 etc to avoid the use of prefixes is inappropriate for communicating with non-scientific people and also cumbersome. Some of these difficulties are avoided by giving the unit a new name as has been done i.e. becquerel (Bq) unit s^{-1}. It may be remembered that another name for the same unit is Hertz (Hz) but the two cannot be used interchangeably.

$$1 \ Bq = 1 \ s^{-1}$$

$$\text{and} \ 1 \ Ci = 3.7 \times 10^{10} \ s^{-1} = 3.7x10^{-10} Bq$$

$$= 37 GBq$$

Table IV gives the conversions of curie to Becqueral and vice a versa.

Now activity $A = N\lambda$
where N is the number of atoms, λ is the decay constant
for $N = 1$, $A = \lambda = \ln 2/T_{\frac{1}{2}}$
Thus the activity of one atom of ^{60}Co, $T_{\frac{1}{2}} = 5.24$ years, $\lambda = 4$ n Bq
that of 208 Tl, $T_{\frac{1}{2}} = 3.1$ min, $\lambda = 3.7$ m Bq
On the other hand the quantity of activity one comes across in nuclear technology and radiation therapy is in the range of thousands of curie to milli curie. Thus 10,000 Ci ^{60}Co = 0.37 P Bq, and 100 mCi ^{131}I = 3.7 G Bq.
Thus it is clear that a transition from curie and milli curie to SI units will require not merely getting used to Becquerel but to the prefixes; mCi is still GBq.

An interesting suggestion for the SI unit of activity has been put forward by Day$^{(10)}$. He uses mol per sec as the macroscopic unit of activity and comes up with some useful numbers:

$$\begin{aligned}
\text{Since} \quad 1 \text{ mol} &= 6.023 \times 10^{23} \\
1 \text{ mol s}^{-1} &= 6.023 \times 10^{23}\ \text{s}^{-1} = 6.023 \times 10^{23}\ \text{Bq} \\
\text{and} \quad 1 \text{ Ci} &= \frac{3.7 \times 10^{10}}{6.023 \times 10^{23}} = 0.0614\ \text{p mol s}^{-1} \\
5000 \text{ Ci} &= 307\ \text{p mol s}^{-1} \\
1 \text{ mCi h} &= 10^{-3} \times 3600 \times 0.0614\ \text{p mol} \\
&= 0.221\ \text{p mol} \\
\text{and } 1 \text{ Ci year} &= 3.156 \times 10^{7}\ (\text{sec/year}) \times 0.0614\ \text{p mol} \\
&= 1.94\ \mu\text{ mol}
\end{aligned}$$

Since there is familiarity with the unit mol, expressing activity in mole s^{-1} gives an idea of the amount of substance involved. The mean life τ of a radioactive atom is given by $T_{\frac{1}{2}} \times 1.443$.

For ^{60}Co $\tau = 5.24 \times 1.443 = 7.56$ y

A 5000 Ci ^{60}Co source which gives 38000 Ci year is
38000 x 1.94 = 74 m mol
or 60 x 74 x 10^{-3} g = 4.44 g
In other words a 5000 Ci ^{60}Co (only) source is just 4.44 g.

3.2.2.b) Activity concentration

Concentration of activity takes three forms viz.

(i) Surface concentration (disintegrations per sec per unit area) μ Ci/cm^2 which in SI unit will be Bq/m^2

Examples: 20 dps/cm^2 (0.54 pCi/cm^2) = 2 k Bq/m^2
or 5000 dps/cm^2 (13.5 μCi/cm^2) 0.5 M Bq/m^2

(ii) Volume concentration (Activity conc. in air and water)

Example Ci/cc ⟶ Bq/m^3

1 μCi/cc = 37 G Bq/m^3
or 1 μCi/l = 37 M Bq/m^3
and 1 mCi/cc = 37 T Bq/m^3
or 1 mCi/l = 37 G Bq/m^3

(iii) Specific activity (disintegration per sec per unit mass)

Ci/g ⟶ Bq/kg

Example;

Specific activity of ^{137}Cs

98.5 Ci/g = 3645 T Bq/kg
= 3.645 P Bq/kg

^{60}Co 1.14 x 10^3 Ci/g = 421.8 P Bq/kg

^{226}Ra 0.98 Ci/g = 36.3 T Bq/kg

^{235}U 2.15 x 10^{-6} Ci/g = 79.55 M Bq/kg

In Table IV activity and activity concentration conversions from special to SI units and vice versa are given. In Fig.2 the conversions are shown on nomograms.

3.2.3. Absorbed Dose and Absorbed Dose Rate

The special unit of absorbed dose is the rad and the SI unit is joule per kilogram.

$$1 \text{ rad} = 10^{-2} \text{ J kg}^{-1}$$

The special unit of absorbed dose rate is rad per unit time and the SI unit watt per kilogram.

$$\begin{aligned} \text{rad} \cdot \text{sec}^{-1} &= 10^{-2} \text{ W kg}^{-1} \\ &= 10^{-2} \text{ J kg}^{-1} \text{ s}^{-1} \end{aligned}$$

As with exposure rate, the unit for absorbed dose rate does not include time explicitly. In all radiological work dose rate with time explicit is of utmost importance. The unit joule per kilogram per second which contains time explicitly is cumbersome and too long in view of the importance and frequent use of the quantity. This will certainly find a multiplicity of local unsatisfactory forms unless given special name. Hence the Gray (Gy).

$$\begin{aligned} 1 \text{ Gy} &= 100 \text{ rad} = 1 \text{ J kg}^{-1} \\ \text{and } 1 \text{ Gy s}^{-1} &= 100 \text{ rad s}^{-1} = 1 \text{ W kg}^{-1} \\ &= 1 \text{ J kg}^{-1} \text{ s}^{-1} \end{aligned}$$

The net effect of the switch over from rad to gray is that the unit of absorbed dose has become 100 times larger i.e.

$$1 \text{ rad} = 0.01 \text{ Gy}$$

Fig.3 gives the nomogram showing relationship of special unit to SI unit and vice versa.

Absorbed Dose Index D_1

Absorbed dose index D_1 at a point defined as the maximum absorbed dose within a 30 cm diameter sphere centred at this point and consisting of material equivalent to soft tissue with a density of 1 kg m^{-3}. The special unit of D_1, rad, in the SI unit is J kg^{-1} with the name gray (Gy). Unit of collective dose which is man-rad in special unit is in SI man-Gy.

3.2.4. Kerma

Kerma is the sum of the initial kinetic energies of all the charged particles liberated by indirectly ionizing particles. Kerma is equal to the absorbed dose under conditions of charged particle equilibrium (CPE) at the point of interest and with bremsstrahlung losses being negligible. Usually kerma is slightly less than the absorbed dose(11). The special unit of kerma is also rad and the SI unit, Gray.

The special name Gray (Gy) has been given to the absorbed dose. However, according to CGPM, Gray may also be used for other physical quantities having the units J kg^{-1}, provided they belong to the field of ionizing radiation. Opinion on whether Gray applies to kerma or not differs. In two reports emanating from DDR one argues in favour(12) and the other against(13).

From the definition of Kerma and the possibility of using it in place of absorbed dose at least in radiation protection (ICRU 19) it appears that kerma with the SI unit J kg^{-1} can have the name Gray. In finer work where one differentiates between Kerma and absorbed dose, Gray will cause the same sort of confusion as does rad.

In Table V, conversion of rad to Gray over a wide range of values is given.

3.2.5.a) Dose Equivalent

The dose equivalent H at a point in tissue is given by

$$\underline{H} = \underline{D}\ Q\ N$$

where $\underline{D}$ is the absorbed dose, Q is the quality factor and N is the product of all other modifying factors, specified by ICRP. Since Q and N are dimensionless quantities $\underline{H}$ has the same unit as $\underline{D}$. Therefore, the unit of $\underline{H}$ is joule per kilogram.

However, for the dose equivalent the special unit is rem, different from the special unit of absorbed dose, rad. Thus dose equivalent has a separate special unit inspite of dimensionally being the same as absorbed dose. The use of the same SI unit J kg^{-1} for both will remove the distinction which is very important in radiation protection and radiobiology. The unit of dose equivalent has therefore been given by ICRP a special name Sievert (Sv):

$$1\ \mathrm{Sv} = 1\ \mathrm{J\ kg^{-1}} \quad (= 100\ \mathrm{rem})$$

$$H\ (\text{in Sv}) = Q.N.D.\ (\mathrm{Gy}).$$

or 1 Sv = 100 rem

or 1 rem = 10^{-2} Sv

or 5 rem = 50 m Sv

Thus the unit Sievert is 100 times larger.

Unit of collective dose: man-Sv.

3.2.5.b) Dose Equivalent Index H1

Dose equivalent index H1 at a point is defined as the maximum dose equivalent within a 30 cm diameter sphere centred at this point and consisting of material equivalent to soft tissue with a density of 1 10 kg m^{-3}. The special unit of dose equivalent index being rem, the SI unit is the J kg^{-1} with the special name, Sievert (Sv).

4. Problem of Adopting SI Units in Radiation Protection(14-16)

It is seen in the proceeding sections that the SI units in relation to the special units are either too large or too small. Further there are restrictions on the mode of use of SI units. The adoption of these units therefore poses three types of problems:

1. The foremost of these stems from that of changing over to a new system from an existing one and inherent lethargy and reluctance (conservatism) in doing so. Workers have become

well versed in the concepts, meaning and scope of the special radiation units. The change-over will be sort of thrust upon and so unpalatable with consequent slow and uneasy adoption.

2. The differences in the magnitude of the existing and the new units are so drastic that it will take some time to grasp their full import. From curie to becquerel is a great fall and essentially one will have to become conversant with the SI prefixes. From rem to sievert and rad to gray is perhaps not a very big change but from roentgen to coulomb per kilogram is. From roentgen rate to watt per kilogram is really a big change in concept. The adoption of SI units requires not merely magnitudinal adjustment but conceptual reorientation.

3. The various figures used routinely (in radiation protection dose limits, instrument readings, radiation source strengths, etc.) will have to be converted to the SI units and suitably adjusted/modified wherever necessary so as to be amenable to easy manipulation. Survey instruments reading exposure in roentgen, exposure rate in roentgen per unit time will require change to coulomb per kilogram and watt per kilogram respectively.

5. Plan for the Switch over to the SI Units

A transition period of ten years, beginning 1976, has been recommended for the gradual abandonment of the special radiation units and implementation of the SI units. During the transition period SI units can be used along with the special radiation units. After the expiry of the transition period only SI units are expected to be used. To ensure thorough assimilation and proper use of the new units, the introduction should be gradual and in phases.

Phase I :

The first phase of the programme should be one of educating the workers about the impending change and the concepts behind this. The programme should include, lectures, discussions and practice sessions. Charts and tables giving mutual conversion of the existing and the new units should be made available. Workers should be encouraged to think in terms of the SI units. Since many journals have already gone SI, people at the senior level shall be exposed to the new units through the literature too. Any reports published in addition to the research papers, can have both the SI units and the special radiation units. However, the routine work should continue to be executed in the existing units. It is felt that a period of three years of extensive discussion, education and exposure to literature should provide the necessary feel for the new units and initiate the process of conceptual reorientation.

Phase II:

In this phase, again lasting three years, provisions should be made to live with the new and the old units simultaneously. In this period all routine measurements, exposure reports, monthly reports should contain both the units. All radiation measuring instruments should be provided with relevant conversion charts pasted/tagged on them. Health Physicists/Radiation Safety Officers at all the radiation installations should ensure that both the stationary and portable instruments have conversion tables along with them. Instrument manufacturers and laboratories involved in the development of such instruments should be kept posted of information in this respect. In addition they should be given a firm date after which all the instruments made by them should be reading in the SI units only. Thus this period will be one of intensive activity and use of the two systems simultaneously will prepare the user for the final stage when the special radiation units will become a matter for the archives and only the SI units shall prevail.

Phase III:

In the third and final phase, the SI units should be given primacy and if found necessary old units may also be given side by side. All the instruments would now be changed to the new system of readings. This means that a large number of instruments in various institutes, laboratories, hospitals and colleges will have to be converted to read in the new units. This would involve a massive programme of recalibration, as mere rewriting on the dial will not be sufficient for the convenient use of these instruments. The continued use of conversion charts or tables would be undesirable. The Tables VI- IX give the existing scales, in special radiation units in some instruments, the corresponding values in the SI units and the suggested scale in SI units.

REFERENCES

1. Schneider,E.E., J.Phys. E: Scientific Instruments 10, 2 and 8 (1977).
2. Liden,K., STI/PUB 401, p.457; IAEA, Vienna (1975).
3. Measurement Techniques, 18, 157, 479, 465 and 504 (1975).
4. ICRU Report 19: Radiation Quantities and Units (1971).
5. Wyckoff,H.O.; Allisy,A., Liden,K., Phys. Med.Biol. 20, 1029 (1975).
6. Liden,K., Wyckoff,H.O., Allisy,A., Brit.J.Radiol.49, 476 (1976).
7. Jennings,W.A., Phys. Med. Biol. 18, 730 (1973).
8. ISO - Standard 1000-1973 (F).
9. British Standard BS 3763: (1976).
10. Day,M.J., Brit, J. Radiol. 47, 82, (1974).
11. ICRU: Report 20 (1971).
12. Taubert,R., Wagner,S., PTB-Mitteilungen 86, 2 and 102 (1976).
13. Herrmann,D., Report SAAS-202 (1976).
14. Boag,J.W. and Binks,C., Brit Inst. of Radiology Bulletin II 6 (1976).
15. Mayneord,W.V.; Phys. Med. Biol. 17, 1 (1976).
16. Harvey,J.F., Appld. Hlth. Phys. Abst. and Notes, 3, 15 (1977).

TABLE I

SI Prefixes

Prefix	Symbol	Value
Exa	E	10^{18}
Peta	P	10^{15}
Tera	T	10^{12}
Giga	G	10^{9}
Mega	M	10^{6}
Kilo	k	10^{3}
Hecto	h	10^{2}
Deca	da	10
Deci	d	10^{-1}
Centi	c	10^{-2}
Milli	m	10^{-3}
Micro	u	10^{-6}
Nano	n	10^{-9}
Pico	p	10^{-12}
Femto	f	10^{-15}
Atto	a	10^{-18}

TABLE II

Radiological SI Derived Units

Quantity	SI Unit	Symbol	Present equivalent	Proposed new name for SI Units	Symbol
Activity	Reciprocal second	s^{-1}	2.703×10^{-11} Ci	becquerel	Bq
Absorbed dose	Joule per kilogram	$J.Kg^{-1}$	100 rad	gray	Gy
Absorbed dose rate	Watt per kilogram OR Joule per kilogram per second	$W.kg^{-1}$ $J.kg^{-1}s^{-1}$	100 rad s^{-1}	gray per second	
Exposure	Coulomb per kilogram	$C.kg^{-1}$	$\approx$ 3876 R		
Exposure rate	Ampere per kilogram OR coulomb per kilogram per second	$A.kg^{-1}$ $C.kg^{-1}s^{-1}$	3876 R s^{-1}		
Dose equivalent	Joule per kilogram	$J.kg^{-1}$	100 rem	sievert	Sv

TABLE III

Exposure and Exposure Rate

Special Units	SI Units	SI Units	Special Unit
1 µR	0.258 nC/kg	1 nC/kg	3.88 µR
1 mR	0.258 µC/kg	1 µC/kg	3.88 mR
1 R	0.258 mC/kg	10 µC/kg	3.88 cR
10 R	0.258 cC/kg	100 µC/kg	3.88 dR
100 R	0.258 dC/kg	1 mC/kg	3.88 R
1 kR	0.258 C/kg	10 mC/kg	3.88 daR
10 kR	0.258 da C/kg	100 mC/kg	3.88 h R
100 kR	0.258 hC/kg	1 C/kg	3.88 k R (≈ 3876 R)
1 M R	0.258 kC/kg	1 kC/kg	3.88 MR
1 mR/h	0.0717 nA/kg = 0.258 µC/kg·h	1 A/kg = 1 C/kg·s 1 mA/kg = 1mC/kg·s	3.88 kR/s 3.88 R/s
1 mR/m	4.30 nA/kg = 0.258 µC/kg·m	1 µA/kg = 1 µC/kg·s 1 nA/kg = 1 nC/kg·s	3.88 mR/s 3.88 µR/s
1 R/h	0.0717 µA/kg = 258 µC/kg·h	0.278 nA/kg = 1 µC/kg·h	3.88 mR/h
1 R/m	4.30 µA/kg = 258 µC/kg·m		
5 R/s	1.29 mC/kg·s		

TABLE IV

Activity and Activity Concentration

Special Unit	SI Unit	SI Unit	Special Unit
a) Activity:			
1 M Ci	0.037 E Bq	1 E Bq	27 M Ci
1 K Ci	0.037 P Bq	1 P Bq	27 k Ci
1 Ci	0.037 T Bq	1 T Bq	27 Ci
1 m Ci	0.037 G Bq	1 G Bq	27 m Ci
1 µ Ci	0.037 M Bq	1 M Bq	27 µ Ci
1 n Ci	0.037 K Bq	1 k Bq	27 n Ci
1 p Ci	0.037 Bq	1 Bq	27 p Ci
1 f Ci	0.037 m Bq	1 m Bq	27 f Ci
1 a Ci	0.037 µ Bq	1 µ Bq	27 a Ci
b) Surface Activity			
1 m Ci/Cm^2	0.37 TBq/m^2	1 TBq/m^2	2.7 Ci/cm^2
1 µ Ci/cm^2	0.37 G Bq	1 $TGBq/m^2$	2.7 µ Ci/cm^2
1 n Ci/cm^2	0.37 M Bq	1 M Bq/cm^2	2.7 n Ci/cm^2
1 p Ci/cm^2	0.37 k Bq	1 k Bq/m^2	2.7 Ci/cm^2
		1 Bq/m^2	2.7 f Ci/cm^2

TABLE IV (CONTD.)

Special Unit	SI Unit	SI Unit	Special Unit
c) Volume activity:			
1 μ Ci/cm^3	37 G Bq/m^3	1 T Bq/m^3	27 μCi/cm^3
1 n Ci/cm^3	37 M Bq/m^3	1 G Bq/m^3	27 n Ci/cm^3
1 p Ci/cm^3	37 k Bq/m^3	1 M Bq/m^3	27 p Ci/cm^3
1 f Ci/cm^3	37 Bq/m^3	1 k Bq/m^3	27 f Ci/cm^3
1 a Ci/cm^3	37 m Bq/m^3	1 Bq/m^3	27 a Ci/cm^3
d) Specific activity:			
1 Ci/g	37 T Bq/kg	1 E Bq/kg	27 k Ci/g
1 mCi/g	37 G Bq/kg	1 P Bq/kg	27 Ci/g
1 μCi/g	37 M Bq/kg	1 T Bq/kg	27 m Ci/g
1 nCi/g	37 k Bq/kg	1 G Bq/kg	27 μ Ci/g
1 pCi/g	37 Bq/kg	1 M Bq/kg	27 n Ci/g
		1 k Bq/kg	27 p Ci/g
1 fCi/g	37 m Bq/kg	1 Bq/kg	27 f Ci/g
1 aCi/g	37 μ Bq/kg	1 m Bq/kg	27 a Ci/g

TABLE V

Absorbed Dose and Dose Equivalent

Special Unit	SI Unit	SI Unit	Special Unit
1 M rad	10 k Gy	1 M Gy	100 M rad
1 k rad	10 Gy	1 k Gy	100 k rad
1 rad	10 m Gy	1 Gy	100 rad
1 m rad	10 μ Gy	1 m Gy	100 m rad
1 μ rad	10 n Gy	1 μ Gy	100 μ rad
		1 n Gy	0.1 μ rad
1 rem	10 m Sv	1 Sv	100 rem
5 rem	50 m Sv	1 m Sv	0.1 rem

TABLE VI

GM Survey Meter

Present Scale sp. radiation units mR/h	Corresponding value in SI units	Suggested Scale in SI units	Corresponding value in mR/h
1. 0-0.2	0-0.0516 µC/kg h OR 0-0.0143 nA/kg	0-50 nC/kg h OR 0-15 pA/kg	0-0.194 0-0.208
2. 0-2.0	0-0.516 µC/kg h OR 0-0.143 nA/kg	0-500 nC/kg h OR 0-150 pA/kg	0-1.94 0-2.08
3. 0-20	0-5.16 µC/kg h OR 0-1.434 nA/kg	0-5.0 µC/kg h OR 0-1.5 nA/kg	0-19.4 0-20.8

TABLE VII : Gun Monitor

1. 0-50	0-12.90 µC/kg h OR 0-3.59 nA/kg	0-15 µC/kg h OR 0-4 nA/kg	0-58.2 0-55.6
2. 0-500	0-129 µC/kg h OR 0-35.85 nA/kg	0-150 µC/kg h OR 0-40 nA/kg	0-582 0-556
3. 0-5000	0-1.29 mC/kg h OR 0-358.5 nA/kg	0-1.5 mC/kg h OR 0-400 nA/kg	0-5820 0-5560

TABLE VIII

THIS Detector

Present Scale sp. radiation units	Corresponding value in SI units	Suggested Scale in SI units	Corresponding value in sp. radiation units
1. 0-10 mR/h	0-2.58 μC/kg h OR 0-0.717 nA/kg	0-2.50 μC/kg h OR 0-0.5 nA/kg	0-9.7 mR/h 0-6.9 "
2. 0-100 mR/h	0-25.8 μC/kg h OR 0-7.17 nA/kg	0-25 μC/kg h OR 0-5.0 nA/kg	0-97.0 " 0-69.5 "
3. 0-1 R/h	0-258 μC/kg h OR 0-71.7 nA/kg	0-250 μC/kg h OR 0-50 nA/kg	0-970 " 0-695 "
4. 0-10 R/h	0-2.58 mC/kg h OR 0-717 μA/kg	0-2.5 mC/kg h OR 0-0.5 μA/kg	0-9.7 R/h 0-6.9 "
5. 0-100 R/h	0-25.8 mC/kg h OR 0-7.17 μA/kg	0-25 mC/kg h OR 0-5.0 μA/kg	0-97 " 0-69 "
6. 0-1000 R/h	0-258 mC/kg h OR 0-71.7 μA/kg	0-250 μC/kg h OR 0-50 μA/kg	0-970 " 0-690 "

TABLE IX

Integrated Exposure Meter

(Pocket Dosemeter, Condenser, R meter)

Sp. radiation units	Corresponding value in SI units	Suggested Scale in SI units	Corresponding value in sp. radiation units
1. 0-100 mR	0-25.8 µC/kg	0-25 µC/kg	0-97 mR
2. 0-250 mR	0-64.5 µC/kg	0-50 µC/kg OR 0-80 µC/kg	0-194 mR 0-310 mR
3. 0-500 mR	0-129 µC/kg	0-100 µC/kg OR 0-150 µC/kg	0-388 mR 0-502 mR
4. 0-1 R	0-250 µC/kg	0-250 µC/kg	0-970 mR
5. 0-10 R	0-2.58 mC/kg	0-2.5 mC/kg	0-9.7 R
6. 0-100 R	0-25.8 mC/kg	0-25 mC/kg	0-97 R

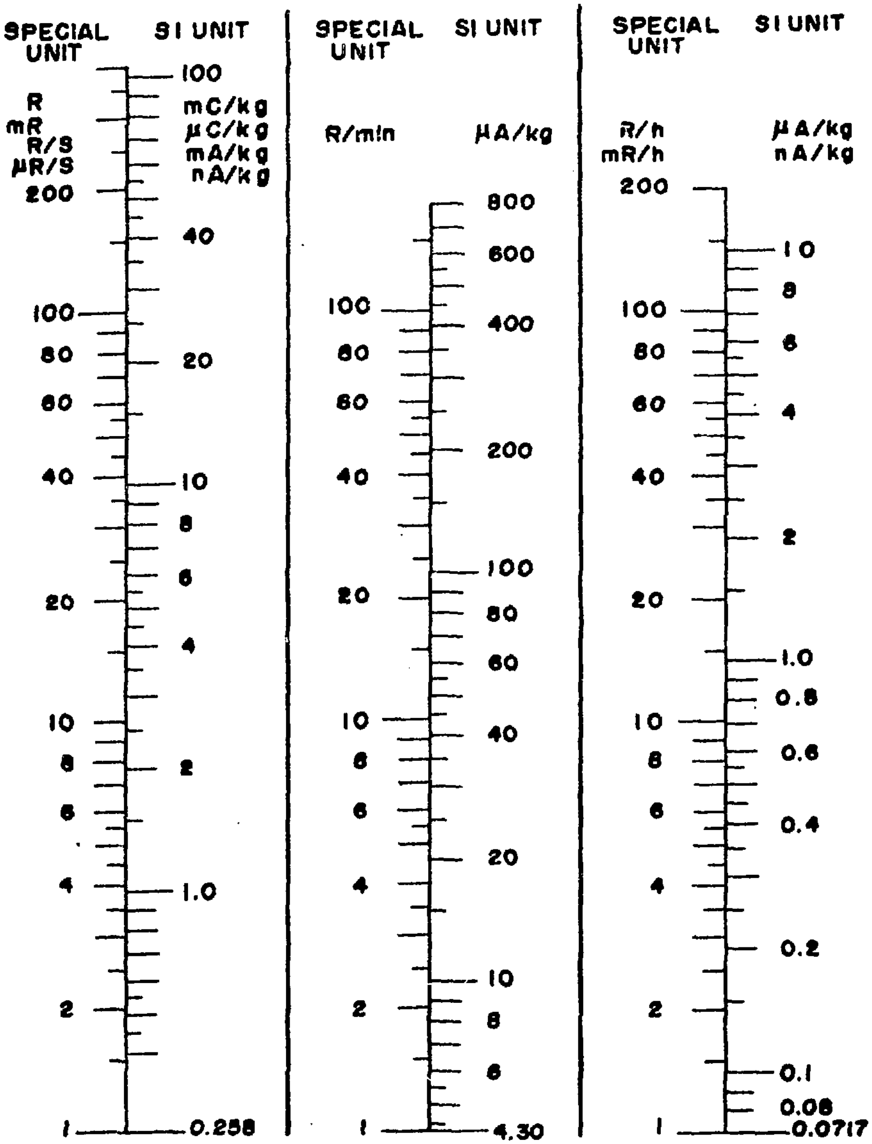

FIG. I. NOMOGRAM SHOWING EXPOSURE AND EXPOSURE RATE EQUIVALENCE IN SPECIAL AND SI UNITS.

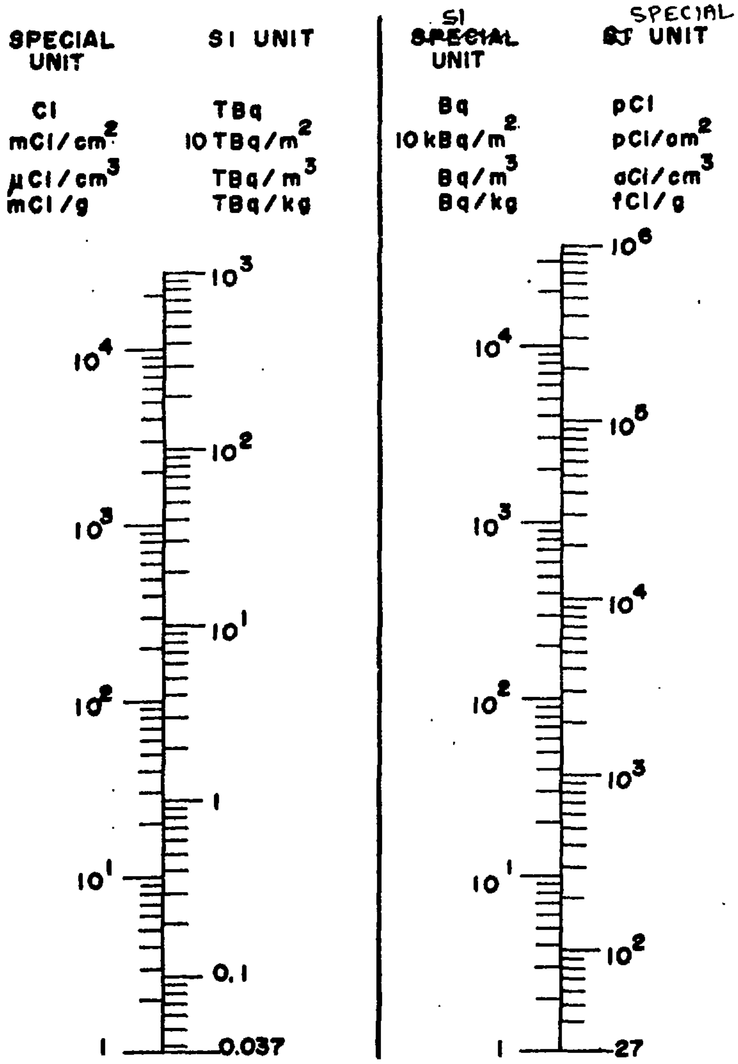

FIG. 2. NOMOGRAM SHOWING ACTIVITY AND ACTIVITY CONCENTRATION EQUIVALENCE IN SPECIAL AND SI UNITS.

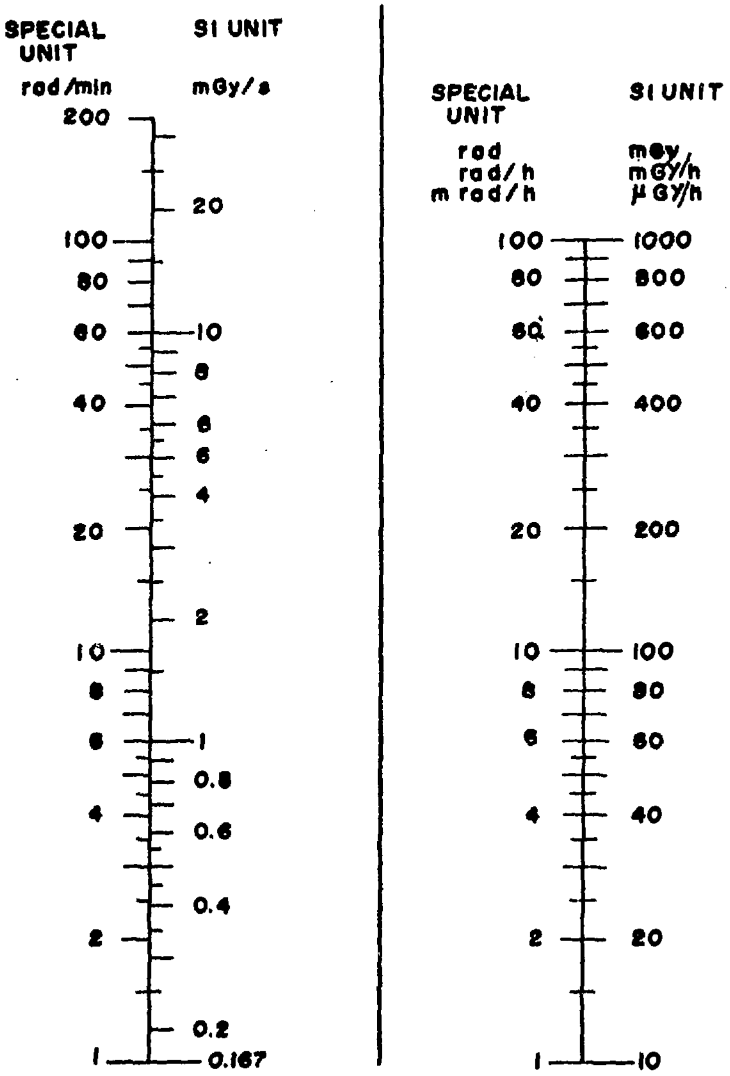

FIG.3. NOMOGRAM SHOWING THE ABSORBED DOSE RATE EQUIVALENCE IN SPECIAL AND SI UNITS.

Appendix

SI Units for other Physical Radiation Quantities.

A.1a Energy imparted (ε) or mean energy imparted to matter $(\bar{\varepsilon})$ by ionizing radiation in a volume element, sometimes called the integral dose.
The special unit for the above quantity is gram-rad (g.rad) and the SI unit joule (J).

A.1b Specific energy imparted (ε / m) has the special unit rad and the SI unit joule per kilogram (J kg^{-1}).

A.2 The SI unit of fluence Φ of particles which enter a sphere of unit cross-sectional area is no. of particles per metre^2 (- m^{-2}.)

A.3 The SI unit of flux density or fluence rate i.e. fluence per unit time is no. of particles per metre^2 per sec.

$$\varphi \longrightarrow m^{-2}\ s^{-1}$$

A.4 The SI unit of energy fluence Ψ is the energies of all particles which enter a sphere of unit cross-section and hence is joule per metre^2

$$\Psi \longrightarrow J\ m^{-2}$$

A.5 The SI unit of energy flux density or energy fluence rate is the change in energy fluence per unit time i.e. joule per metre^2 per sec

$$\psi \longrightarrow Jm^{-2}\ s^{-1} \longrightarrow Wm^{-2}$$
$$\text{or} = 10^3\ \text{erg cm}^{-2}\ s^{-1}$$

Thus the SI unit is 1000 times compared to the CGS unit and since

$$1\ \text{erg} = 6.25 \times 10^5\ \text{MeV}$$
$$1\ Wm^{-2} = 6.25 \times 10^8\ \text{MeV cm}^{-2}\ s^{-1}$$

The SI unit becomes very large compared to the special unit MeV. cm^{-2}. s^{-1}.

A.6 Mass attenuation coefficient μ/ρ for indirectly ionising particles

$$\mu/\rho = dN/N \Big/ \rho dl$$

is the fraction of particles which experience interaction in traversing a distance dl in a medium of density ρ

Alternatively $\mu/\rho = N_A \sigma / M$

N_A = Avogadro number, M = Molecular weight

The SI unit is $m^2\ kg^{-1}$. Compared to $cm^2\ g^{-1}$, m^2kg^{-1} is 10 times larger.

However, if the linear absorption coefficient $\mu\ (cm^{-1})$ is used the SI unit (m^{-1}) is 100 times larger.

A.7 Mass energy transfer coefficient

$$\mu_{tr}/\rho = 1/\rho dl \cdot dE_{tr}/E$$

where dE_{tr}/E is the fraction of incident energy that is transferred to kinetic energy of charged particles by interactions in traversing a distance dl in a medium of density ρ. The SI unit is $m^2\ kg^{-1}$. μ_{tr} is slightly less than μ.

A.8 Mass energy absorption coefficient μ_{en}/ρ which accounts for any loss through bremsstrahlung of the energy transferred to the secondary charged particles has the same SI unit as above vis m^2kg^{-1}.

A.9 Total mass stopping power of a material for charge particles

$$S/\rho = 1/\rho \cdot dE/dl$$

is the energy lost by charged particles of specified energy in traversing a distance dl in a medium of density ρ. The SI unit is $Jm^2\ kg^{-1}$.

$$1\ Jm^2\ kg^{-1} = 10^8\ erg\ cm^2\ g^{-1}$$

$$= 6.25 \times 10^{13}\ MeV\ cm^2\ g^{-1}.$$

Conversely

$$1 \text{ MeV cm}^2 \text{ g}^{-1} = 1.6 \times 10^{-14} \text{ J m}^2 \text{ kg}^{-1}$$
$$= 16.0 \text{ f J m}^2 \text{ kg}^{-1}$$

A.10 Linear Energy Transfer, LET

The special unit of LET is keV per micron. The SI unit is joule per metre

$$1 \text{ J m}^{-1} = 6.25 \times 10^9 \text{ keV } \mu^{-1}$$

Conversely

$$1 \text{ keV } \mu^{-1} = 1.6 \times 10^{-10} \text{ J m}^{-1}$$
$$= 0.16 \text{ n Jm}^{-1}$$

Again it is evident that the SI unit for LET is too large and prefixes nano, or even pico would be required for normal values. In table A.1 LET values in both special and SI units are given.

A.11 Specific exposure rate constant which has replaced the specific gamma ray constant, Γ_δ of a nuclide emitting photons is

$$\Gamma_\delta = l^2/A \, (dx/dt)_\delta$$

where $(dx/dt)_\delta$ is the exposure rate due to photons of energy greater than δ, at a distance l from a point source of this nuclide having an activity A. The special unit of Γ_δ is $\text{R m}^2\text{h}^{-1}\text{Ci}^{-1}$.

The SI unit is $\text{cm}^2 \text{ kg}^{-1}$. In the SI unit Ci is replaced by Bq and R by C kg^{-1}. Thus $1 \frac{\text{cm}^2}{\text{kg}} = \text{const.} \frac{\text{Rm}^2}{\text{Ci h}}$

$$= \frac{\text{Rm}^2 \times 3.7 \times 10^{10} \times 3600}{2.58 \times 10^{-4} \text{ Ci h}}$$

$$= 0.516 \times 10^{18} \quad \frac{\text{Rm}^2}{\text{Ci h}}$$

$$\text{or } \frac{1\ Cm^2}{Ci\ h} = 1.94 \times 10^{-18}\ \frac{Cm^2}{kg}$$

$$= 1.94\ a\ Cm^2\ kg^{-1}$$

$$= 1.94\ a\ Cm^2\ kg^{-1} \times \frac{3600}{Bq\ h}$$

$$= 6.97\ f\ Cm^2\ kg^{-1}\ Bq^{-1}\ h^{-1}$$

In this case again the SI unit is very inconvenient. The fully converted SI unit besides being too big so that the smallest permitted prefix is used does not give the feeling of an exposure rate constant (since activity and time cancel out). When instead of second, hour is used as the unit of time the whole unit becomes too long and cumbersome, for example $\frac{1\ Rm^2}{Ci\ h}$ = 6.97 femto coulomb metre squred per kilogram per becquerel per hour.

In table A-2 Γ_δ for some radio nuclides are given in SI units.

A.12 Mean energy $\overline{W}$ expended in a gas per ion pair formed

$$\overline{W} = E/N$$

where N is the number of ion pairs formed when a directly ionizing particle of energy E is completely stopped by the gas. The special unit of $\overline{W}$ is ev and the SI unit, J.

The SI unit for $\overline{W}$ is thus astronomically large since

$$1\ ev = 1.6 \times 10^{-12}\ erg.$$

$$\text{and } 1\ J = 10^7\ erg$$

$$= 6.25 \times 10^{18}\ ev$$

Conversely

$$1\ ev = 1.6 \times 10^{-19}\ J$$

$$= 0.16\ f\ J$$

$\bar{W}_{air}$ = 33.7 ev for x-rays

= $33.7 \times 1.6 \times 10^{-19}$ J

= 53.97×10^{-19} J

= 5.397 a J

Similarly

$\bar{W}_{CH4}$ = 26.8 ev for X-rays

= 4.288 a J

$\bar{W}_{A}$ = 26.1 ev

= 4.176 a J

$\bar{W}_{O_2}$ = 30.7 ev

= 4.912 a J

A.13 Absorbed Dose in Air and Tissue

In radiation protection work the following relations are commonly used:

Exposure X_R in air gives an absorbed dose of

D_{air} (rad) = 0.87 X (R) (1 MeV x-rays)

Similarly for tissue D_{tissue}(rad) = 0.96 X (R)

In SI units

$$D_{air} = \bar{W}_{air} / e \, . \, X$$

$$= \frac{33.73 \text{ ev } 1.602 \times 10^{-9} \text{ J/ev}}{1.602 \times 10^{-19} \text{ C}} X \, .$$

$$= 33.73 \text{ J C}^{-1} X$$

$$= 33.7 \frac{\text{Gy}}{\text{C}} \text{kg}^{-1} X (\text{C kg}^{-1})$$

or D_{air}(Gy) = 33.7 X(C/kg)

D_{tissue}(Gy) = 37.2 X

or X (Exposure) = 1 C kg^{-1} (= 3876 R)

then D_{tissue} = 37.2 Gy

= 3720 rad (1 Gy = 100 rad) Cf 3876 R.

Therefore for tissue 1 C $\text{kg}^{-1} \approx$ 37 Gy corresponding to

1 R $\approx$ 1 rad.

TABLE A-1

LET and QF

LET (L_∞ in water)		QF
Special Unit kev/µm	SI Unit	
3.5	0.56 n Jm^{-1}	1
7.0	1.12 n Jm^{-1}	2
23	3.68 n Jm^{-1}	5
53	8.48 n Jm^{-1}	10
175	28.0 n Jm^{-1}	20

TABLE A-2

Exposure Rate Constant

Isotope	Exposure rate constant	
	Special unit Rm^2/Ci	SI Unit
^{60}Co	1.23	2.38 a $\frac{Cm^2}{kg}$ = 8.57 f $Cm^2kg^{-1}Bq^{-1}h^{-1}$
^{137}Cs	0.30	0.58 a Cm^2/kg = 2.09 f Cm^2kg^{-1} Bq^{-1} h^{-1}
^{192}Ir	0.51	0.99 a Cm^2/kg = 3.55 f $Cm^2kg^{-1}Bq^{-1}h^{-1}$
^{226}Ra (in equilibrium)	0.84	1.63 a Cm^2/kg = 5.84 f $Cm^2kg^{-1}Bq^{-1}h^{-1}$