ENCYCLOPAEDIC DICTIONARY OF PHYSICS

Volume 6

RADIATION, CONTINUOUS
to STELLAR LUMINOSITY

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RADIATION, CONTINUOUS. A stream of waves (or particles), the amplitude (or number) of which remains significant over a wide range of frequency (or energy) — as opposed to line radiation. The term is most commonly used to describe continuous electromagnetic radiation, emitted when an unbound charged particle executes non-periodic oscillations (Hertz dipole), gyrates at high speed in a magnetic field (synchrotron radiation), is accelerated in the field of a nucleus (Bremsstrahlung or free-free emission), or is captured into a bound state by a nucleus (free-bound or recombination emission); in reverse, the latter two processes give rise to continuous absorption. At energies greater than 1 MeV, continuous emission and absorption also arise from pair annihilation and pair production respectively. In free-bound processes, neglecting recoil effects, the frequency ν of the emitted or absorbed radiation is related to the ionization energy χ_n of the bound state and to the kinetic energy $p^2/2m$ of the incident or liberated particle (most commonly an electron) by the equation

$$h\nu = \chi_n + p^2/2m, \qquad (1)$$

where h is Planck's constant, so that ν has a minimum value χ_n/h which may or may not be associated with an abrupt "edge" in the curve relating absorption coefficient to frequency.

Thermal radiation. In thermodynamic equilibrium at temperature T, the energy radiated at frequencies between ν and $\nu + \mathrm{d}\nu$ in unit time in all directions by a small mass Δm of material is

$$\varepsilon_\nu\,\mathrm{d}\nu = 4\pi\,\mathrm{d}\nu\,\varkappa_\nu\,\Delta m\,B_\nu(T), \qquad (2)$$

where $\varkappa_\nu$ is the mass absorption coefficient (defined by the fact that $\varrho\,\varkappa_\nu I_\nu\,\mathrm{d}x\,\mathrm{d}\omega$ is the energy absorbed per unit area in a solid angle $\mathrm{d}\omega$ from a beam of specific intensity I_ν in distance $\mathrm{d}x$ where ϱ is the mass-density) and $B_\nu(T)$ is a function of ν and T only. This is Kirchhoff's law, derived by considerations of detailed balancing between absorbing and emitting processes from either a macroscopic viewpoint (Kirchhoff) or a microscopic one (Einstein). The Kirchhoff-Planck function $B_\nu(T)\,\mathrm{d}\nu$ is proportional to the energy density $u_\nu(T)\,\mathrm{d}\nu$ in a thermal enclosure; $u_\nu(T)\,\mathrm{d}\nu$ is the product of the density of normal modes of oscillation $8\pi\,\nu^2\,\mathrm{d}\nu/c^3$ and the mean energy of a harmonic oscillator $h\nu/\{\exp(h\nu/kT) - 1\}$, where c is the velocity of light and k Boltzmann's constant. Hence

$$B_\nu(T) = (c/4\pi)\,u_\nu(T) = 2h\nu^3/c^2\{\exp(h\nu/kT) - 1\}. \quad (3)$$

Continuous radiation in astrophysics. γ-radiation generated by nuclear reactions in stellar interiors undergoes Thomson and Compton scattering by free electrons and bound-free and free-free absorption by heavy elements followed by re-emission at longer wave-lengths. The opacity is the mass **absorption co-efficient** for radiation integrated over all wavelengths and is given in local thermodynamic equilibrium by the formula for the Rosseland mean:

$$\frac{1}{\overline{K}} = \frac{\displaystyle\int_0^\infty \frac{1}{K_\nu}\frac{\mathrm{d}B_\nu}{\mathrm{d}T}\,\mathrm{d}\nu}{\displaystyle\int_0^\infty \frac{\mathrm{d}B_\nu}{\mathrm{d}T}\,\mathrm{d}\nu} \qquad (4)$$

Apart from electron scattering (dominant in the more massive stars), $\overline{K}$ is given approximately by the Kramers-Gaunt formula

$$K = 130\,N_e\,T^{-7/2}\,\frac{\bar{g}}{t}\,(1 - X - Y), \qquad (5)$$

where N_e is the electron density, X and Y are the abundances by mass of hydrogen and helium respectively, and $\bar{g}/t$ is a tabulated correction factor.

In stellar atmospheres, the main sources of opacity are photoionization of neutral hydrogen (for effective temperatures $> 10^4\,^\circ$K, with Thomson scattering above $2 \times 10^4\,^\circ$K), photoionization of H⁻ (between $10^4\,^\circ$K and $3500\,^\circ$K), and excitation and dissociation of molecules (below $3500\,^\circ$K).

When there are marked departures from thermodynamic equilibrium (e.g. in the presence of diluted radiation, with a total energy density lower than would correspond to the temperature derived from the spectral energy distribution), (2) is no longer applicable. In planetary nebulae, for example, continuous stellar radiation shortward of the fundamental ionization limits of the constituents (mainly hydrogen, λ 912) is absorbed and re-emitted in lines and continua of higher series. This fluorescence cycle represents the tendency for material in contact with diluted radiation to absorb high frequencies and re-emit lower ones (Rosseland's theorem), thus reducing the departure from thermodynamic equilibrium.

See also: Bremsstrahlung. Fluorescence. Gamma rays.

See Index for location of terms not found in this volume

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<div align="right">B. E. J. PAGEL</div>

RADIATION, CORPUSCULAR.

Radiation consisting of entities which are normally throught of as particles rather than waves, e.g. α rays, β rays, neutron radiation, atomic and molecular rays.

RADIATION DAMPING.

Gradual reduction in the amplitude of the harmonic motion of a quasistatically bound charge due to radiation reaction on the charge. In the equation of motion of the charge, a force proportional to the velocity of the charge and in the opposite direction to the motion (the reaction force) must be included and this is known as the damping term.

RADIATION, EFFECTS OF, ON DIELECTRICS.

Radiation causes both long-term effects, altering the physical structure of the dielectric and leading ultimately to breakdown, and the short-term effect of raising the conductivity under and subsequent to irradiation.

At dose rates of 1 rad min^{-1} and above, the conductivity rises in less than 1 min to its equilibrium value which is given by

$$\sigma = kR^\Delta$$
$$0 \cdot 5 \leqslant \Delta \leqslant 1$$

where σ is the conductivity in Ω^{-1}cm^{-1}, R the dose rate in rad min^{-1} and k and Δ are constants of the material studied.

At dose rates from 10^{-2} to 10^{10} rad min^{-1} most results can be expressed to within two orders of magnitude by the relation

$$\sigma = 10^{-18} R.$$

This relation applies for both organic and inorganic insulators. Polythene becomes more conductive than other dielectrics studied, and the relation which it follows,

$$\sigma = 4 \times 10^{-17} R^{0 \cdot 7}$$

sets an upper limit to the induced conductivity in good insulators at dose rates up to 10^4 rad min^{-1}.

The induced conductivity decays by some 50 per cent within 2 min and subsequently falls according to a bimolecular law

$$1/\sigma_t = 1/\sigma + bt.$$

Typical values for b in Ω cm hr^{-1} are: polythene, 10^{16}; polystyrene, 10^{17}. This slow decay is important since the charge on electrostatic ion chambers previously exposed to radiation may leak away through the polystyrene dielectric if there is a long interval between time of use and time of reading.

Both the induced conductivity and the fully recovered natural conductivity of a dielectric changes by a factor of 10 or less after exposure to reactor radiation up to 10^{18} nvt. Loss of electric strength occurs at the same time as the physical structure fails, that is, at doses greater than 10^{18} nvt for polythene, but at about 10^{16} nvt for teflon.

The electric strength changes little with large doses. Polyvinylchloride improves by 25 per cent for a total dose of 10^8 rad, while polythene shows only a somewhat larger spread about the mean field at the same dose, but the electric strength is maintained at temperatures $> 100°C$ because of the now cross-linked structure.

The power factor of polythene increases with dose at low frequencies but not at high frequencies. This can be attributed to double-bond formation. Typical values are:

unirradiated, $\tan \delta = 2 \times 10^{-4}$;

irradiated, 80 Mrads,

3×10^9 cps	25–200°C	$\tan \delta = 2 \times 10^{-4}$
3×10^5 cps	25–125°C	$\tan \delta = 10 \times 10^{-4}$
10^3, 10^4 cps	-160–$0°C$	$\tan \delta = 4 \times 10^{-4}$
10^3, 10^4 cps	20–75°C	$\tan \delta = 12 \times 10^{-4}$

The changes in $\tan \delta$ were found to depend upon the impurity concentration but the dielectric constant showed little variation throughout.

In thick samples under electron irradiation considerable charge can be built up at a depth corresponding to the range of the electrons and later released by bringing an earthed conductor nearby. This results in extensive treeing, rendering the material useless.

Electromotive forces of a few volts can be developed across non-symmetric electrode-dielectric systems, but the magnitude depends upon the materials used, the geometry of the system, the total dose received and the existing dose rate, so little generalization can be made.

There are reports that polyacrylonitrile and similar compounds may be converted into usable high temperature semiconductors under doses of 10^{22} eV g^{-1}.

Apart from the conductivity, little is known of the effective values of the electrical parameters of materials during irradiation, and few dielectrics have been as extensively studied as polythene.

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<div align="right">H. J. WINTLE</div>

RADIATION FROM CLOUDS OF PARTICLES.

The treatment of radiation from powdered-coal or atomized-oil flames, from dust particles in flames and from flames made luminous by the thermal decomposition of hydrocarbons to soot involves the evaluation of radiation from clouds of particles. The phenomena involved are very complex and the bibliography should be consulted for details.

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<div align="right">B. GAY</div>

RADIATION FROM GASES.

In the infra-red region of the spectrum, certain heteropolar gases show discontinuous bands, due to interatomic vibration and changes in rotational energy levels. These gases include sulphur dioxide, ammonia, hydrocarbons, and carbon monoxide, and, most important in industrial furnace heating, carbon dioxide and water vapour. The most convenient method of dealing with the problem of heat transfer by gas radiation is given by Hottel. The various shapes of enclosure, containing a radiation gas, can be evaluated using the concept of equivalent radius together with curves. prepared from experimental data. If a hemisphere, containing gas, radiates to a black element of area at the centre of the base, the net heat exchange may be expressed by the equation

$$q = \sigma(\varepsilon g\, T_G^4 - \alpha g_1 T_1^4)$$

where q = net heat exchange
     σ = Stefan–Boltzmann's constant
     ε_g = emissivity of the gas
     α_{g1} = absorptivity of the gas for radiation from surface
     T_g = gas temperature
     T_1 = surface temperature.

Families of curves are given for ε_g, which is the sum of contributions due to CO_2 and H_2O, slightly reduced by a correction factor, allowing for the spectral overlap of CO_2 and H_2O bands. Each portion is evaluated at T_g and a parameter, P_cL or P_wL, where

     P_c = partial pressure of CO_2
     P_w = partial pressure of H_2O
     L = radius of hemisphere considered.

Allowance is made for the total pressure of the gas which also affects the emissivity. The absorptivity of a gas is affected by the temperature of the source of the radiation and by the gas temperature. Methods are given to calculate absorptivities from the emissivity charts. However, it is often convenient to consider the gas to be grey, i.e. the absorptivity to be equal to the emissivity for radiation from any source, or to consider it to be real, i.e. consisting of a grey component, whose absorptivity is zero. These treatments are also discussed.

The concept of equivalent radius allows this method to be applicable to more practical and varied shapes of gas enclosure. The body is replaced by an equivalent hemisphere, such that the radiation from the gas in the hemisphere to the black element at the centre of the base is equal to the radiation from the gas enclosure to any particular surface element or elements. Factors have been calculated, which convert a characteristic gas enclosure dimension to an equivalent radius, L, for use in the curves, mentioned above. These factors are generally listed with the curves.

Data for emissivities of SO_2, CO, and NH_3 are presented in the same manner as that for CO_2 and H_2O. Since radiation, as a mode of energy transfer, depends on basic physical laws and upon the geometry of the system, it is not surprising that the subject has been extensively treated, mathematically. Gas radiation is no exception to this statement, and as early as 1923, Schack showed that the radiation transmitted through a non-luminous gas would follow an exponential law. For a more involved discussion, the reader is referred to Jacob's book: "Heat transfer". Thring compares the Hottel curves with an empirical formula based on German measurements.

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<div align="right">P. L. START and M. W. THRING</div>

RADIATION, HETEROGENEOUS.

Radiation consisting of several different frequencies, or a beam of particles of a variety of energies or containing different types of particles.

RADIATION INTENSITY.

Name given to the amount of energy passing per second through unit area at normal incidence and radiated into unit solid angle.

See also: Radiant energy.

RADIATION INTERCHANGE FACTOR.

Assume two large plane surfaces at respective temperature T_1 and T_2 facing each other closely in a vacuum. The heat flux density F passing between the two plates is given by

$$F = C[(T_1)^4 - (T_2)^4]$$

See Index for location of terms not found in this volume

where C is the radiation interchange factor between the two surfaces. It depends on their emissivities and reflectivities.

See also: Radiation of heat.

RADIATION, IONIZING. Ionizing radiation is defined by the British Standards Institution as any radiation, either electromagnetic or particulate, which is capable of producing ions, directly or indirectly, in its passage through matter.

As thus defined, the term includes X rays and gamma rays, alpha and beta particles, protons, deuterons and mesons, and neutrons. This is also consistent with the practice followed in recent U.K. Legislation.

RADIATION, IONIZING, ABSORPTION OF, IN BODY TISSUES. When penetrating electromagnetic radiation is absorbed in body tissues, its biological effects are essentially a consequence of the release of secondary charged particles. The nature of the process giving rise to these particles depends on the energy of the radiation and on the atomic composition of the tissue concerned: as the energy is increased the processes of photoelectric absorption, Compton effect, pair production and photonuclear disintegration will in turn occur.

When the ionizing radiation is itself corpuscular, however, we are concerned with the interaction between the primary particles and the tissue atoms. For electrons, energy may be absorbed by collision processes involving ionization or excitation, by scattering, by bremsstrahlung production or, for very high energies, by electrodisintegration of nuclei. For neutrons, the absorption is by elastic or inelastic scattering processes or by nuclear capture. For heavy charged particles (protons, deuterons, α particles) the usual process of absorption is by inelastic collisions with bound electrons of atoms in the tissue; radiation loss and scattering also occur but not to the same extent as for primary electrons of corresponding energy.

The table includes frequently used radiations of various types and indicates the approximate average range in aqueous tissue of the associated particles. Only an approximate estimate of the average range can be given since the ionizing particles usually have complex energy spectra. The extent of the range as compared with the size of the biological entity in question is fundamental to the consideration of energy absorption in irradiated tissues.

Although it is evident that ionizing radiation can bring about changes in tissue only by virtue of the energy absorbed, the biological effect also depends on the spatial distribution of the energy released along the tracks of ionizing particles. The linear spacing of ions is usually discussed in terms of the specific ionization or linear ion density, i.e. the number of ion pairs formed per unit length of track. In tissue, however, there is some uncertainty as to the average energy per ion pair produced and for this reason as well as to avoid the further uncertainty as to the part which may be played by excitation, the practice has arisen of discussing the spatial distribution of events along the tracks in terms of energy transferred per unit length or *linear energy transfer* (L.E.T.) expressed in keV per micron.

Energy absorption being thus fundamental to the interpretation of the biological consequences of irradiating body tissues, we are led to a consideration of radiation dosimetry. By international agreement (1953) the "absorbed dose" of any ionizing radiation is defined as the amount of energy imparted to matter by ionizing particles per unit mass of irradiated material at the place of interest. The *rad* is the unit of absorbed dose and is equal to 100 ergs per gramme.

The direct measurement of energy absorption, however, presents formidable difficulties and only recently have calorimetric methods become, in certain limited applications, a practicable procedure. The principal method of dosimetry has in fact been indirect, based on the measurement of ionization in a volume of gas, usually air, contained within a cavity ionization chamber. The relationship between energy absorption and the ionization produced in such a cavity situated within an irradiated medium has been considered in detail by Gray. He showed that for a solid medium traversed by secondary electrons, the presence of a small gas-filled cavity would not affect either the angular or the energy distribution of the secondary electrons at the site of the cavity, provided its dimensions were so small that the electrons lost only a small fraction of their energy in crossing it. Under such conditions the relationship between E, the energy released by the electrons per gramme of the

Primary radiation	Energy range (MeV)	Ionizing particle in tissue	Average range of ionizing particles in low Z material g/cm² or cm of aqueous tissue
β rays	0·015–5	Electron	10^{-4}–1·0
Electron beams	2–20	Electron	1–10
γ rays	0·05–2·9	Electron	5×10^{-4}–0·6
X rays	0·01–0·4	Electron	10^{-4}–5×10^{-3}
X rays	1–10	Electron	5×10^{-2}–1·2
X rays	10–30	Electron	1·2–3·5
Fast neutrons	0·1–10	Proton	10^{-4}–6×10^{-2}
Slow neutrons	0·1 eV	0·6 MeV proton (+ 2·2 MeV γ ray)	10^{-3} (protons) 0·5 (electrons)
Proton beams	5–400	Proton	3×10^{-2}–10^2
α rays	5–10	α particle	3×10^{-3}–10^{-2}

(from F. W. Spiers in *Radiation Dosimetry*)

medium, and the ionization within the cavity defined by J_G, the number if ion pairs formed per gramme of gas, is

$$E = J_G \varrho W \qquad (1)$$

in which W is the mean energy expended per ion pair produced and ϱ is the ratio of the mass stopping powers in medium and in gas. Substitution of known values of ϱ and W and of measured values of J_G in equation 1 will thus determine the absorbed dose in the medium in terms of rads. Equation 1 may also be applied to ionizing particles other than electrons provided the basic conditions for the validity of the theory are satisfied.

The practical unit of dosage in terms of ionization produced in air, the *röntgen*, was defined in 1937 as "the quantity of X or γ radiation such that the associated corpuscular emission per 0·001293 gramme of air (1 ml at N.T.P.) produces, in air, ions carrying 1 e.s.u. of quantity of electricity of either sign". Since by this definition the energy of secondary electron emission is fully utilized, the röntgen measures energy absorption per gramme of air. It involves the release of

$$\frac{1 \text{ e.s.u.}}{\text{electronic charge in e.s.u.}} = \frac{1}{4 \cdot 8 \times 10^{-10}} \text{ ion pairs}$$

each of which requires, on the average $W = 34\,\text{eV}$ or $5 \cdot 5 \times 10^{-11}$ ergs.

Hence energy absorption in air per r $= \dfrac{5 \cdot 5 \times 10^{-11}}{4 \cdot 8 \times 10^{-10} \times 0 \cdot 001293} = 88\,\text{ergs/g}$

$= 0 \cdot 88$ rads.

(The previously accepted value of 32·5 eV for W gave 84 ergs/g for the energy absorption in air per r.)

For irradiation of tissues of known real mass absorption coefficients μ, the energy absorption per gramme is

$$E_{\text{tissue}} = 0 \cdot 88 \frac{\mu_{\text{tissue}}}{\mu_{\text{air}}} \text{ rads per röntgen.}$$

The real rather than total absorption coefficients are here appropriate since we are concerned with the fraction of radiation energy transferred to secondary charged particles.

(Since by definition the röntgen was not suitable for corpuscular radiation, Parker (1948) suggested the **röntgen equivalent physical** (rep) defined originally as the dose to any medium to give an energy absorption of 84 ergs/g, i.e. the same as the absorption in 1 g of air exposed to 1 r of hard X or γ rays (for $W = 32 \cdot 5\,\text{eV}$). It later became general to take the rep as 93 ergs/g so that its value is the same as for 1 r of γ rays per gramme of aqueous tissue and it is then equivalent to the energy unit of Gray (1939). The rad now replaces these earlier units.)

Values of E_{tissue} for bone, soft tissue and fat were derived by Spiers from his experimental determinations of the mass absorption coefficients of these media and are illustrated in the figure. It will be seen that there is only a small variation in the energy ab-

sorption per gramme of aqueous tissue per röntgen over the range 0·01–1 MeV and this provides justification for the use of the röntgen as a dosage unit within the energy range of "conventional" radiotherapy. The usefulness of the röntgen as a unit of dose becomes dubious, however, when the secondary electron emission is not in equilibrium with the primary radiation as, for example, at interfaces (such as a skin surface irradiated with high energy X rays) or within heterogeneous media, such as bone. Even in
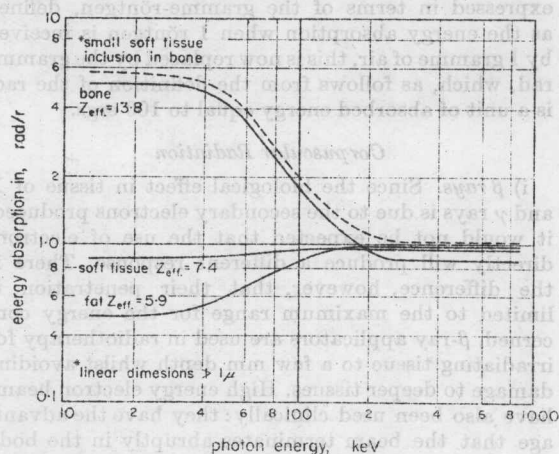
Energy absorption in body tissues (derived from data in F. W. Spiers)

the range up to 1 MeV, it is clear from the figure that the energy absorption per röntgen in bone and in fat is quite different from that for soft tissue especially at the lower quantum energies. For very high energy radiations (above a few MeV) absorption due to pair production becomes important and since it is proportional to the square of the atomic number, differences between bone, soft tissue and fat will again appear though they are not so marked as in the lower energy range illustrated in the figure.

The implications of the differences in energy absorption between bone and soft tissue have been further studied by Spiers and by Wilson in attempts to derive the dosage to the living soft tissue structures contained within the canals which traverse the inorganic bone matrix. The number of ion pairs released per röntgen in a small soft tissue inclusion within a bone cavity is derived from the electron emissions of bone and soft tissue at various radiation energies in relation to the size of cavity considered. The analysis indicates that only for wave-lengths generated at 1 MeV and above (an X-ray tube operated at 1 MeV with suitable filter gives a mean photon energy of rather less than 0·5 MeV) does the ionization in the living tissue structures within bone approximate to that in other soft tissues. At lower radiation energies the ionization within the bone cavities may be several times that in other soft tissues for the same

dose expressed in röntgens (vide dotted curve in the figure). It is thus clear that if it is required to irradiate a tumour in or near bone, the higher energy of radiation ($\sim 1\,\mathrm{MeV}$) should be selected to avoid considerable non-uniformity of dosage and its possible harmful consequences.

In considering the absorption of energy by the body as a whole, the concept of **integral dose,** first introduced by Mayneord, is valuable. It refers to the dose to tissue integrated over the mass irradiated. Originally expressed in terms of the gramme-röntgen, defined as the energy absorption when 1 röntgen is received by 1 gramme of air, this is now replaced by the gramme rad, which, as follows from the definition of the rad, is a unit of absorbed energy equal to 100 ergs.

Corpuscular Radiation

i) *β rays.* Since the biological effect in tissue of X and γ rays is due to the secondary electrons produced, it would not be expected that the use of electrons directly will produce a different response. There is the difference, however, that their penetration is limited to the maximum range for the energy concerned. β-ray applicators are used in radiotherapy for irradiating tissue to a few mm depth whilst avoiding damage to deeper tissues. High energy electron beams have also been used clinically: they have the advantage that the beam terminates abruptly in the body so that the integral dose is less than it would be for the same tumour dose delivered by X or γ radiations. The radiation fields can be made very uniform and the integral doses are readily assessed; doses in rads to bone, muscle and fat are nearly the same at the energies used.

ii) *Heavy charged particles.* Examples of heavy charged particles which have been used in biological experiments include protons, deuterons, α particles, fission and nuclear recoils, and cosmic-ray primaries. Heavy particles often have greater biological effectiveness than light ones because of the considerable difference in ion density. Thus β particles from a radium salt incorporated in tissue would give an average of 7 ions per micron whilst the accompanying α particles would give rise to some 500 times this ion density; if the biological results of equal doses (i.e. equal total ionization) are compared, the α's are found to be several times more effective than the β's. The absorption of proton beams in tissue has been studied both theoretically and experimentally. The information thus obtained is also germane to considerations of the neutron irradiation of tissue as indicated below. Examples of biological effects due to fission fragments or recoil nuclei are the neutron irradiation of tissue incorporating U or Li respectively, causing intense localized ionization along the short tracks of the heavy recoil particles.

iii) *Neutrons.* When fast neutrons (of energy more than a few keV) irradiate soft tissue, most of the energy absorbed (of the order of 90 per cent) is by elastic scattering with the hydrogen nuclei which

constitute about two thirds of the total, and recoil protons are thus produced. Other collisions give rise to recoil oxygen and carbon nuclei. The ion density for the secondary heavy particles is far higher than for electrons of the same energy because of the much lower velocities of the former; hence the greater biological effectiveness of neutrons. At rather higher energies, inelastic scattering and capture are also possible both accompanied by γ-ray emission but this does not appreciably affect the dose distribution because of the low cross-section for such reactions. Those neutrons which are reduced to thermal energies, however, will produce protons from $^{14}\mathrm{N}(n, p)$ reactions and γ rays from nγ reactions with hydrogen. The emission of γ radiation then tends to spread the total dosage through a greater volume. At very high energies (of the order of $100\,\mathrm{MeV}$), the carbon, oxygen and nitrogen nuclei may disintegrate in star formation but the biological consequences of such reactions have yet to be explored.

Radiations from Internally Administered Isotopes

The absorption of radiations from sources of radioactivity within the body forms the basis of the therapeutic use of administered isotopes and also of consideration of the permissible levels of ingested or inhaled radioactivity. The dose to tissue from an incorporated radioisotope depends on the type and energy of radiation, on the rate of radioactive decay and on the rates of biological uptake, concentration in and elimination from the tissue.

Consideration of α emitters applies to cases of accidental ingestion, e.g. of radium salts followed by α irradiation of bone within which radium is accumulated. Theoretical estimates of the dosage resulting from such deposition have been supported by studies employing autoradiography and track-counting techniques.

With β emitters the dose is delivered within the tissue in which the isotope is incorporated and its value in rads per $\mu\mathrm{C/g}$ may be estimated from the average effective life (including biological elimination as well as physical decay) of the radioisotope and the mean energy released per disintegration.

With γ emitters, the dosage is spread throughout a larger volume and attempts have been made to calculate the doses to organs concerned for various models simulating actual distributions in the body.

For isotopes emitting both β and γ radiation the dosage from the former will usually predominate because of the short range and complete absorption of the β particles. The γ-ray contribution must, however, be considered when the integral dose to the whole body is required.

The establishment for different isotopes of the maximum permissible burdens which the body may safely tolerate has been based on calculations of the type indicated, together with knowledge of the metabolism of the substances concerned.

See also: Radiation, biological effects of. Radio-isotopes, biological and medical applications of.

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RADIATION, IONIZING, FILTERS FOR. A filter is a layer of material, usually a metal, placed in the path of a beam of ionizing radiation in order:

(a) to alter the spectral distribution of a beam of a single type, e.g. X rays;

or (b) to alter the relative strengths of the components of a mixed beam, e.g. α, β, and γ rays emitted by a radium source;

or (c) to alter the spatial distribution of the radiation by absorbing one portion of the beam more than another. Such filters—in contrast to (a) and (b) types—are non-uniform in thickness; examples are *wedge filters* and *beam-flattening* filters used in radiotherapy. This type of filter will not be considered further in the present article.

X-ray filters. In *X-ray therapy* the purpose of filtration is to remove the softer components of the radiation which would otherwise irradiate the skin and superficial tissues but would contribute little to the treatment of a deep-seated tumour. Again, in *diagnostic radiology*, filtration helps to avoid unnecessary dosage to the patient and reduced the amount of unwanted scattered radiation at the film; the latter consideration also applies to *industrial radiology.*

The action of a filter depends on the fact that long wave-lengths are in general, more heavily absorbed than are short. Approximately, the linear absorption coefficient is proportional to the cube of the wavelength. The effect of filtration on the spectral distribution of an X-ray beam is illustrated in Fig. 1. Such curves are not, however, of practical value in routine radiology, and a more useful approach is *via* the **half-value-layer** or *half-value-thickness* (H.V.L. or H.V.T.) of the radiation. This is defined as the thickness of a given material which reduces the beam intensity to one half of its initial value. It is the normal method of specifying beam quality in radiology. The H.V.L. is determined by measuring an absorption curve of the radiation in the chosen material, and reading off the thickness corresponding to 50 per cent absorption. Sometimes the *second H.V.L.* is quoted also; i.e. the further layer which absorbs 50 per cent

of the radiation *incident on it*, since although radiations of different spectral distributions can have the same first H.V.L., their second H.V.L.'s will not be identical. An example of the relationship between H.V.L. and filtration is shown in Fig. 2.
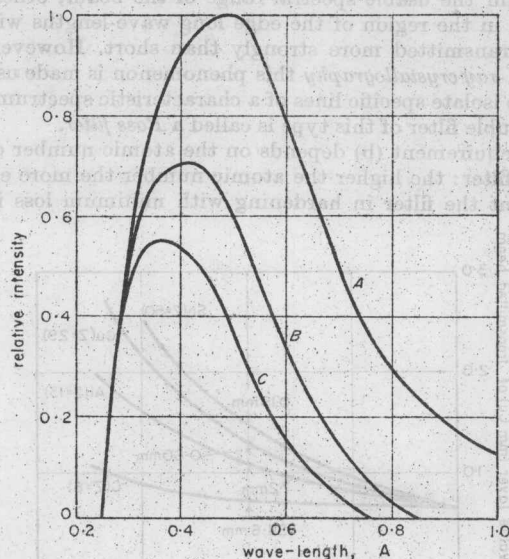

Fig. 1 Spectral distribution curves of 50 kV X rays. A: Unfiltered; B: Filter 1·0 mm Al; C: Filter 2·0 mm Al.
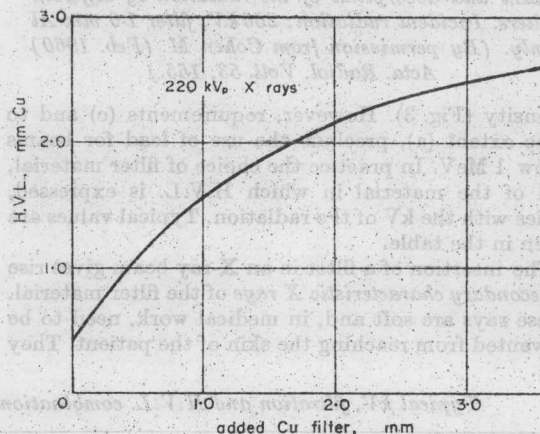

Fig. 2. Relationship between half-value-layer and filtration for a 220 kV X-ray beam, initial filter 1·0 mm Al only.

The choice of a filter for a given application is necessarily a compromise, the requirements being:

(a) the filter thickness should be neither too thin for mechanical stability nor too thick for convenience; actual thicknesses of a fraction of a mm to several mm are suitable;