

The Health Physicist's Companion

Health Physicist's Companion

Settings Help

Nuclide Selection | Nuclide Data | Nuclide Assessment | Physical Data | Units | Serial Decay | X-ray Sets

Quick Find : Element Nuclide, A or Z

Run Query

New Query

13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.07	17 Cl 35.45	18 Ar 39.95
31 Ga 69.72	32 Ge 72.59	33 As 74.92	34 Se 78.96	35 Br 79.9	36 Kr 83.8
49 In 114.8	50 Sn 118.7	51 Sb 121.8	52 Te 127.6	53 I 126.9	54 Xe 131.3
81 Tl 204.4	82 Pb 207.2	83 Bi 209.0	84 Po (210)	85 At (210)	86 Rn (222)

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Introduction

Thank you for purchasing the Health Physicist's Companion (HPC).

We believe that it is an invaluable aid to radiation safety professionals who need simple yet comprehensive access to nuclide and other health physics related information.

When you first launch the Health Physicist's Companion, you are presented with the application's main form. This consists of a number of tabbed pages which each deal with an aspect of radiation-related information or calculation.

When you move between pages, your entered data are retained until you either return to the original page and select the <Reset><Clear Page> or <Reset><Clear All> menu option. The <Reset> menu is located in the menu bar at the top of the main form.

Some pages are only accessible when a radionuclide is selected in the Nuclide Selection page; for example, the Nuclide Assessment and Nuclide Data pages are only accessible when you have selected a radionuclide.

When entering numerical data in calculation fields, you can use the 'e' or 'E' character to denote standard form values. For example, the value 1090.99 would be entered as 1.09099e3 and 0.0099 as 9.9e-3. The Health Physicist's Companion uses standard form for calculation results that can not otherwise be displayed within the space available in a field.

If you have difficulties operating the Companion, contact Syberad at: hpc_help@syberad.co.uk

Chapter 1 - Nuclide Selection Page

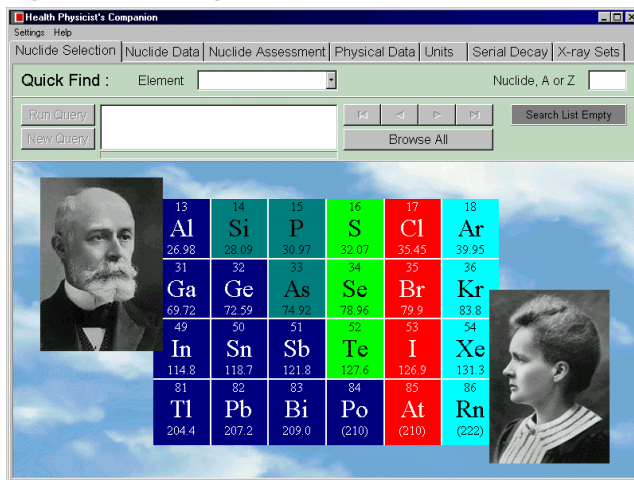
The Nuclide Selection page is where you select a nuclide for processing. On this page, you can access a database of over 2850 nuclides.

Getting started

When you first run the Health Physicist's Companion, the application opens with the Nuclide Selection page displayed as the default; here you enter search/selection criteria to locate the nuclides you are interested in.

The Nuclide Selection page is linked to the Nuclide Data, Nuclide Assessment and Serial Decay pages; it is therefore not possible to view these pages until a radionuclide has been selected.

Figure 1 - Opening screen-shot of the Companion



Information about the components shown in Figure 1

There are three ways of locating nuclides in the database:

1. Searches using the common element name.

Use this drop-down list field to choose an element; they are listed alphabetically by name. You can use the mouse, scroll-bar or cursor keys to navigate to the element of your choice. Alternatively, you can type directly into this control to make the selection cursor move to the nearest matching element as you type.

2. Searches using the abbreviated element name, atomic number or mass number

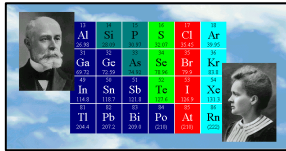
Enter an abbreviated element name, atomic mass number or atomic number for which you want to locate matching entries, for example, 'Ca' for calcium. The number of nuclides for the selected element is shown in the box below:

3. Searches using structured query language (SQL)

Enter an SQL search string here and then click the 'Run Query' button to execute the query. To clear the search string, click the 'New Query' button. For more information about SQL, see page 78.

Click this button to display all nuclides in the database.

Click these buttons to move backwards and forwards through the nuclides that match your selection criteria.



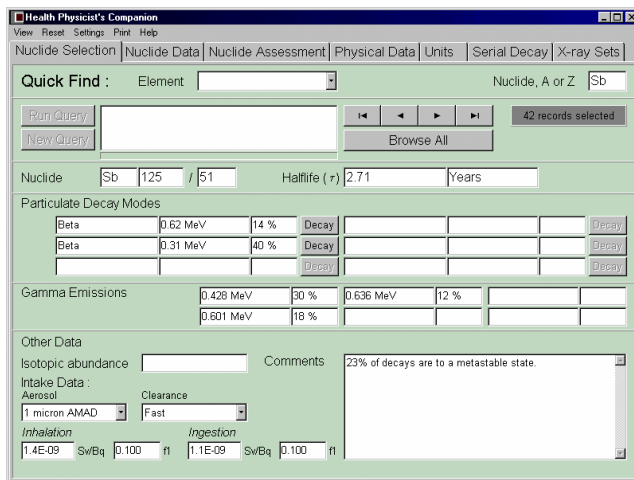
Double-click anywhere in this image to open the Health Physicist's Companion help system.

Entering data

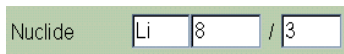
Once you have entered valid nuclide selection criteria, the data display panel appears; an example is shown in Figure 2.

If you have selected a series of nuclides, you can display them as a grid by double-clicking anywhere on the page background; double-clicking the page again, reinstates the single record display mode.

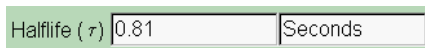
Figure 2 - Single record display



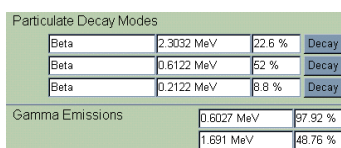
Information about the components shown in Figure 2



These three fields display the abbreviated nuclide name, the atomic mass number and the atomic number for the currently selected nuclide.



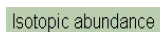
Displays the selected radionuclide's half-life.



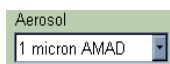
These fields display the decay modes for the selected radionuclide, their transition energies, in MeV, and the percentage decay by each mode.



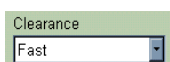
This button is enabled if there is a daughter nuclide for the adjacent decay mode; clicking it makes the corresponding daughter the currently selected nuclide.



If the currently selected nuclide is naturally occurring, the percentage abundance is displayed here.



Select the aerosol size for which to display dose per unit radioactivity inhaled. AMAD refers to the particle size measurement quantity, activity median aerodynamic diameter (see page 78).



The dosimetric lung model described by ICRP¹ in Publication 68⁽¹⁷⁰⁾, allows radioactive materials to be grouped into three lung clearance rate categories namely, fast, medium and slow.

¹ ICRP - International Commission on Radiological Protection.

- Inhalation*
 Sw/Bq

Effective dose, per unit radioactivity inhaled, in sieverts per becquerel. Values are consistent with ICRP, Publication 68. Effective dose is defined in ICRP, Publication 60⁽¹⁶⁰⁾; this quantity replaces effective dose equivalent defined in Publication 26⁽¹¹⁰⁾.
- f1

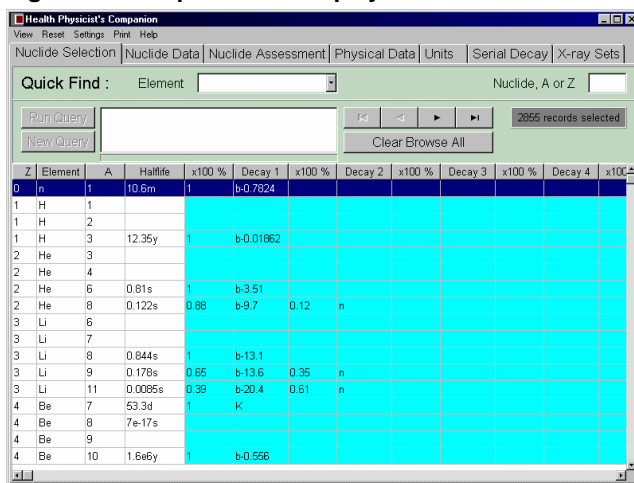
Clearance fraction assumed in the lung model described by ICRP² in Publication 68⁽¹⁷⁰⁾.
- Ingestion*
 Sw/Bq

Effective dose, per unit radioactivity ingested, in sieverts per becquerel. Values are consistent with ICRP, Publication 68.
- f1

Transfer fraction assumed in the intestinal tract (gut) model described by ICRP in Publication 68.
- Comments

This field displays miscellaneous notes about the currently selected nuclide.

Figure 3 - Multiple record display



Information about the components shown in Figure 3

Z | **Element** | **A** | **Halflife** | **x100 %** | **Decay 1** | The nuclide database's data field formats are shown in the table below.

Display Grid Column Heading	Detail
Element	Abbreviated element name
A	Atomic mass number
Z	Atomic number
Halflife	Radionuclide half-life (if applicable) where: y=years, d=days, h=hours, m=minutes and s=seconds
Decay (n)	Decay mode and energy in MeV where: b- beta K electron capture a alpha p proton IT isomeric transition b+ positron m metastable state SF spontaneous fission n neutron
Gamma (n)	Gamma emission energy in MeV
X100%	Percentage decay by mode(n)

² ICRP - International Commission on Radiological Protection.

Display Grid Column Heading	Detail
Inhale 5 micron (slow)	Dose per Bq inhalation of a 5 micron AMAD aerosol
Inhale 1 micron (slow)	Dose per Bq inhalation of a 1 micron AMAD aerosol
Inhale f1 (slow)	Fractional clearance value
Ingestion (slow)	Dose per Bq ingestion
Ingestion f1 (slow)	Fractional transfer value
Inhale 5 micron (med.)	Dose per Bq inhalation of a 5 micron AMAD aerosol
Inhale 1 micron (med.)	Dose per Bq inhalation of a 1 micron AMAD aerosol
Inhale f1 (med.)	Fractional clearance value
Ingestion (med.)	Dose per Bq ingestion
Ingestion f1 (med.)	Fractional transfer value
Inhale 5 micron (fast)	Dose per Bq inhalation of a 5 micron AMAD aerosol
Inhale 1 micron (fast)	Dose per Bq inhalation of a 1 micron AMAD aerosol
Inhale f1 (fast)	Fractional clearance value
Ingestion (fast)	Dose per Bq ingestion
Ingestion f1 (fast)	Fractional transfer value
Abundance	Fractional abundance for a naturally occurring isotope
Notes	Notes about the selected nuclide
Frac. Metastable	Fractional generation of the nuclide from its principal parent

The references to 'slow', 'medium' and 'fast' in the inhalation and ingestion fields refer to the definitions given in ICRP³, Publication 68⁽¹⁷⁰⁾ for uptake rates. Type S (slow) denotes an uptake rate by the exposed tissue of 0.1% in 10 minutes (7000 days for 99.9% uptake), type M (medium) an uptake rate of 10% in 10 minutes (140 days for 90% uptake) and type F (fast) an uptake rate of 100% in 10 minutes.

f1 values refer to the fraction of an intake which is taken up systemically following ingestion and to the fraction cleared to the gut by the 'pulmonary ciliary escalator' following inhalation; these values are consistent with ICRP, Publication 68. f1 values are a critical determinant of personal dose and are highly dependent upon chemical form and, in the case of inhalation, upon particle size. The values quoted in IAEA Safety Series 115⁽³⁾ and used by the Health Physicist's Companion are those for either 'worst case' or commonplace radionuclide compounds (see Annexes E and F of ICRP 68).

Double-click anywhere in the grid or form background to 'toggle' between single and multiple nuclide display modes.

Element	Z	A	Halflife	x100 %	Decay 1
n	0	1	10.6m	1	b-0.7824
H					
H					
H			85y	1	b-0.01862
He					
He					
He				1	b-3.51
He	2	8	0.122s	0.88	b-9.7

The grid headings can be mouse-dragged⁴ to new positions, thereby allowing you to alter the order of columns in the grid; you can also use mouse-dragging to resize the columns by dragging their boundaries. In either case, the changes you make are stored in the registry and reinstated each time you run the Health Physicist's Companion.

You can 'toggle' on and off any combination of grid options by right-clicking anywhere in the grid to display a pop-up menu. When you do this, the options shown in the figure to the left are available.

You can edit the data stored in the nuclide database by clicking the 'Edit Data' menu item. When this option is activated, the navigator button bar at the top-right of the page changes to include editing functions; turn on the 'Show Component Pop-Up Hints' option in the 'Settings' menu to get information about the function of each navigator button.

³ ICRP - International Commission on Radiological Protection.

⁴ Mouse-Dragging - is a Microsoft Windows term for a technique of moving or resizing an object on the screen. It's achieved by selecting a screen object such as a grid or table heading with the mouse and then, simultaneously, moving the mouse whilst keeping its left button depressed.

Any changes you make to the database are permanent, so make sure that you have backed-up the 'Nuclides.dbf', 'Nuclides.mdx' and 'Nuclides.dbt' files in the 'DataFiles' sub-directory of the directory in which the Health Physicist's Companion is installed, before proceeding. Alternatively, if you purchased the software on CD, you can reinstate original data files from there. Any changes you make to data in the database must conform to the specification described in the table below.

NB. During data editing of a particular record, the database is automatically updated when you select a new record.

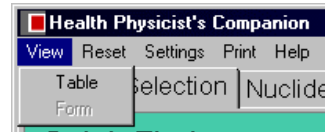
Database Field Name	Data Description	Display Grid Column Heading
ELEMENT	Nuclide name	Element
A	Atomic mass number	A
Z	Atomic number	Z
HALFLIFE	Nuclide Halflife	Halflife
ABUNDANCE	Fractional Abundance	Abundance
DECAY1	Fractional decay by mode 1	x100%
BETAALPHA1	Particulate Decay mode 1	Decay 1
DECAY2	Fractional decay by mode 2	x100%
BETAALPHA2	Particulate Decay mode 2	Decay 2
DECAY3	Fractional decay by mode 3	x100%
BETAALPHA3	Particulate Decay mode 3	Decay 3
DECAY4	Fractional decay by mode 4	x100%
BETAALPHA4	Particulate Decay mode 4	Decay 4
DECAY5	Fractional decay by mode 5	x100%
BETAALPHA5	Particulate Decay mode 5	Decay 5
DECAY6	Fractional decay by mode 6	x100%
BETAALPHA6	Particulate Decay mode 6	Decay 6
DECAY7	Fractional decay by gamma mode 1	x100%
GAMMA1	Gamma mode 1	Gamma 1
DECAY8	Fractional decay by gamma mode 2	x100%
GAMMA2	Gamma mode 2	Gamma 2
DECAY9	Fractional decay by gamma mode 3	x100%
GAMMA3	Gamma mode 3	Gamma 3
DECAY10	Fractional decay by gamma mode 4	x100%
GAMMA4	Gamma mode 4	Gamma 4
DECAY11	Fractional decay by gamma mode 5	x100%
GAMMA5	Gamma mode 5	Gamma 5
DECAY12	Fractional decay by gamma mode 6	x100%
GAMMA6	Gamma mode 6	Gamma 6
NOTES	Miscellaneous Notes	Notes
METSCALER	Fractional Yield	Fract. Metastable
RESPAMAD5S	Dose per Bq inhaled (5 micron AMAD)	Inhale 5 microns slow
RESPAMAD1S	Dose per Bq inhaled (1 micron AMAD)	Inhale 1 microns slow
RESPSF1	Lung clearance factor (f1)	Inhale f1 (slow)
INGESTS	Dose per Bq ingested	Ingestion (slow)
INGESTSF1	Gut transfer factor (f1)	Ingestion f1 (slow)
RESPAMAD5M	Dose per Bq inhaled (5 micron AMAD)	Inhale 5 microns medium
RESPAMAD1M	Dose per Bq inhaled (1 micron AMAD)	Inhale 1 microns medium
RESPMF1	Lung clearance factor (f1)	Inhale f1 (medium)
INGESTM	Dose per Bq ingested	Ingestion (medium)
INGESTMF1	Gut transfer factor (f1)	Ingestion f1 (medium)
RESPAMAD5F	Dose per Bq inhaled (5 micron AMAD)	Inhale 5 microns fast
RESPAMAD1F	Dose per Bq inhaled (1 micron AMAD)	Inhale 1 microns fast
RESPFF1	Lung clearance factor (f1)	Inhale f1 (fast)
INGESTF	Dose per Bq ingested	Ingestion (fast)
INGESTFF1	Gut transfer factor (f1)	Ingestion f1 (fast)

Using the menus

The menu bar at the top of the page is specific to the page being displayed. When the Nuclide Selection page is selected, the following options are available.

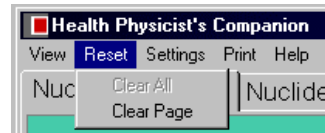
Choose:

'Form' to display data for each nuclide that matches your selection criteria or 'Table' to display a data grid of all nuclides that match your selection criteria.



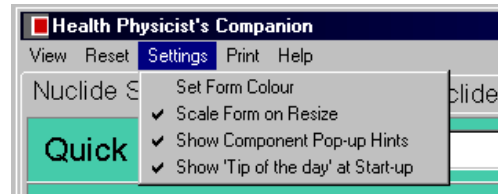
Choose:

'Clear page' to clear data in the currently selected page or 'Clear All' to clear data in all pages.



Choose:

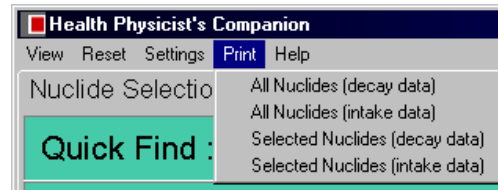
'Set Form Colour' to change the background colour of the main form; 'Scale Form on Re-size' if you want all components on the form to resize automatically when you change the size of the form; 'Show Component Pop-Up Hints' if you want to view a small help dialogue as you move the mouse over components within the form or 'Show Tip of the Day at Start-up' if you want to view a useful hints dialogue every time you run the Health Physicist's Companion.



NB. New settings are permanently stored so that, each time you use the Health Physicist's Companion, your preferences are reinstated.

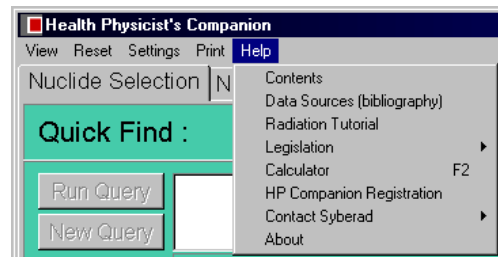
Choose:

To print a table of all nuclides in the database, select 'All Nuclides (decay data)' or 'All Nuclides (intake data)'. To print a table of nuclides you have selected for display, select 'Selected Nuclides (decay data)' or 'Selected Nuclides (intake data)'.



Choose:

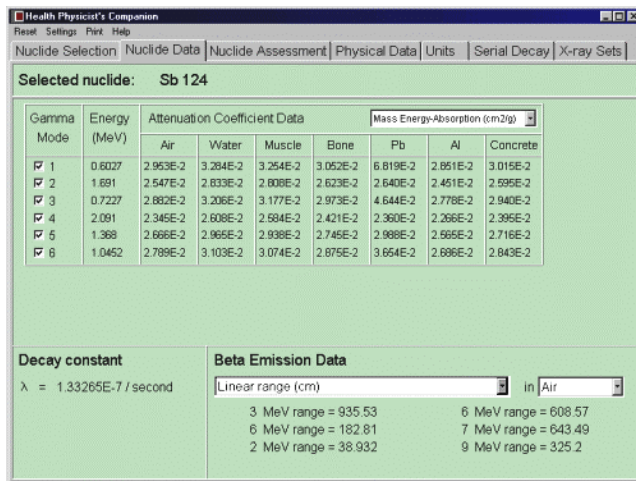
'Contents' to display the Companion's help contents, index and search dialogue; 'Data Sources' for information about the data sources the Companion uses for its calculations; 'Radiation Tutorial' for summary information about ionising radiation; 'Legislation' for information about ionising radiation legislation in the United Kingdom; 'Calculator' to open the HP Calculator utility; 'HP Companion Registration' to register your copy of the Health Physicist's Companion with Syberad; 'Contact Syberad' for information about how to contact Syberad or 'About' for information on the version of the Health Physicist's Companion you currently have installed on your PC.



Chapter 2 - Nuclide Data Page

The Nuclide Data page displays additional information about the radionuclide that is selected in the Nuclide Selection page; an example is shown in Figure 4. It is not possible to access this page until you have selected a radionuclide.

Figure 4 - Screen-shot of the Nuclide Data page



Information about the components shown in Figure 4

Gamma Mode This column allows you to select or deselect gamma emissions for use by the Nuclide Assessment page calculator.

Energy (MeV) This column shows the selected radionuclide's gamma emission energies in mega-electronvolts (MeV).

1 Tick (check) this box if you want to include this gamma emission in any calculations you set up in the Nuclide Assessment page; the default setting is ticked (checked). NB. The default is set whenever you change the selected nuclide in the Nuclide Selection page.

Air	Water	Muscle	Bone	Pb	Al	Concrete
2.953E-2	3.284E-2	3.254E-2	3.052E-2	6.819E-2	2.851E-2	3.015E-2
2.547E-2	2.833E-2	2.808E-2	2.623E-2	2.640E-2	2.451E-2	2.595E-2
2.882E-2	3.206E-2	3.177E-2	2.973E-2	4.644E-2	2.778E-2	2.940E-2
2.345E-2	2.608E-2	2.584E-2	2.421E-2	2.360E-2	2.266E-2	2.395E-2
2.666E-2	2.965E-2	2.938E-2	2.745E-2	2.988E-2	2.565E-2	2.716E-2
2.789E-2	3.103E-2	3.074E-2	2.875E-2	3.654E-2	2.686E-2	2.843E-2

This table shows the absorption coefficients for the selected radionuclide's gamma emissions.

You can display either the mass attenuation coefficient or the mass energy-absorption coefficient by selecting the appropriate quantity and display unit in the drop-down field at the top-right of the page.

Decay constant Displays the decay constant (λ) for the currently selected radionuclide. The decay constant takes the unit s^{-1} .

$$I = \frac{\log_e 2}{\text{Radionuclide halflife}}$$

Where radionuclide half-life is measured in seconds.

Beta Emission Data

The fields at the bottom-right of the form allow you to display data about the following quantities.

All data computed by the Calculator are based on a fractional decay value of unity for each beta particle emission energy exhibited by the selected radionuclide. You should scale computed values by the applicable fractional decay value shown in the Nuclide Selection page to obtain a final estimate of these quantities.

Attenuation

Linear range (cm)

Beta particle linear range, in centimetres, is computed from the decay transition's maximum emission energy $E_{(max)}$.

Mass thickness range as:

grammes per square centimetre
grammes per square metre
kilogrammes per square centimetre
kilogrammes per square metre

NB. Beta emission ranges, in units of mass-thickness, are largely independent of shield type, this field is therefore not displayed when these units are selected.

The empirical formulae used by the Calculator to compute beta particle range have the form:

$$R = 412E^{1.265-0.0954 \ln E}$$

For $0.01 \leq E \leq 2.5$

$$R = 530E - 106$$

For $E > 2.5$

Where:

R = beta particle range for energy $E_{(max)}$ in mg cm^{-2} and E = beta particle energy $E_{(max)}$ in MeV.

Dose rate

Dose rate constants for both beta $E_{(max)}$ and $E_{(average)}$ can be displayed and are given in sieverts per hour per unit activity.

NB. Calculated values do not take account of beta emission fractional decay; 100% decay by each beta mode exhibited by the selected nuclide is assumed.

The data used by the calculator were sourced from ICRP, Publication 51⁽¹⁴⁵⁾, 1987 (Table 26, page 44); these were developed from Monte Carlo calculations for a 30 cm thick, semi-infinite slab phantom exposed to mono-energetic radiation in a parallel beam geometry. These data should therefore be applied with caution to other exposure geometries, such as close proximity exposure to a point source (i.e. a non parallel beam), and exposure to beta radiation fields which are, by their very nature, multi-energetic. However, from a radiation protection perspective, the figures computed by the Calculator will err on the side of safety for most exposure geometries.

The skin dose rate value is taken to be the maximum equivalent dose rate arising in any tissue exposed to the radiation field. Due to the way in which beta particles are absorbed in the body, the maximum dose rate occurs in superficial tissues such as the skin. Beta particles of energies less than 70 keV are unable to penetrate the dead, cornified layer of the epidermis (assumed to have a mass thickness of 7mg cm^{-2} or linear thickness of 0.07mm), the Calculator therefore does not compute data for energies below this value.

The deep dose rate value is taken to be that arising in tissue at a depth of 10 mm. Whole-body effective dose is usually measured at this depth using some form of personal dosimeter and so this value gives a useful indication of the beta radiation field contribution to whole-body exposure. Beta particle energies below 2 MeV aren't able to penetrate tissue to a depth of 10 mm; deep dose values are therefore not computed for energies below this value.

In practice, dose rates greatly depend upon clothing type; attenuation factors typically range between 3-5 for light clothing but may be as high as 1000 for heavy clothing.

Contamination dose rate

Skin dose arising from contamination is difficult to measure and so is usually calculated.

The dose rate constants computed by the Calculator apply to that sustained by the basal layer of the skin (assumed to be 70 µm in depth) when exposed to beta particles or electrons. The gamma contribution to the dose rate is generally only a few per cent for most beta/gamma radionuclides.

The Calculator uses the dose rate constants listed in the table below. These are given as dose equivalent to the skin in units of µSv per hour per becquerel per square centimetre.⁽⁶¹⁾

Radionuclide	Dose Equivalent - µSv h ⁻¹ (Bq cm ⁻²) ⁻¹
H-3	0
C-14	0.32
F-18	1.90
Na-22	1.70
Na-24	2.20
Al-26	1.80
P-32	1.90
P-33	0.86
S-35	0.35
Cl-36	1.80
K-40	1.50
K-42	2.20
K-43	1.90
Ca-45	0.84
Ca-47/Sc-47	3.50
Sc-46	1.40
Sc-47	1.50
Cr-51	0.02
Mn-52	0.76
Mn-54	0.06
Mn-56	2.40
Fe-52	1.10
Fe-55	0.02
Fe-59	0.97
Co-56	0.55
Co-57	0.12
Co-58	0.30
Co-60	0.78
Ni-63	0
Ni-65	2.20
Cu-64	1.00
Cu-67	1.30
Zn-65	0.08
Ga-66	1.60
Ga-67	0.35
Ga-68	1.80
As-76	2.10
Se-75	0.14
Br-77	0.01
Br-82	1.50
Rb-87	1.90
Sr-85	0.06
Sr-89	1.80
Sr-90/Y-90	3.50
Y-90	2.00
Zr-95/Nb-95	1.60
Mo-99/Tc-99m	1.90
Tc-99m	0.25

Radionuclide	Dose Equivalent - $\mu\text{Sv h}^{-1} (\text{Bq cm}^{-2})^{-1}$
Tc-99	1.20
Ru-103/Rh-103m	0.78
Ru-106/Rh-106	2.20
Ag-110m	0.68
Ag-111	1.80
Cd-109	0.54
In-111	0.38
In-113m	0.73
In-115m	1.30
Sn-125	2.30
Sb-122	2.20
Sb-124	2.20
Sb-126	1.80
Te-123m	1.10
Te-132	0.78
I-123	0.38
I-124	0.52
I-125	0.02
I-131	1.60
Cs-131	0.01
Cs-134	1.40
Cs-137	1.60
Ba-133	0.13
Ba-140/La-140	3.80
La-140	2.10
Ce-139	0.49
Ce-141	1.80
Ce-143	2.00
Pr-143	1.70
Pm-147	0.60
Sm-153	1.60
Eu-152	0.92
Eu-154	2.10
Eu-156	1.20
Er-169	1.10
Yb-169	1.00
Re-186	1.80
Re-188	2.30
Ir-192	1.90
Au-198	1.70
Hg-197	0.09
Hg-203	0.90
Tl-201	0.27
Tl-204	1.60
Pb-210	0.01
Po-210	6.90E-07
U-235	0.18
U-238	2.30E-03
Pu-238	3.70E-03
Pu-239	1.40E-03
Am-241	0.02
Cm-244	2.20E-03
Cf-252	3.20E-03

Data reproduced by kind permission of Nuclear Technology Publishing ⁽⁶¹⁾

For other radionuclides, the dose rate constant is based on an empirical 'rule of thumb' of 2.4 micro-sieverts per hour per becquerel per square centimetre.

NB. This 'rule of thumb' does not take account of beta emission fractional decay; 100% decay by each beta mode exhibited by the selected nuclide is assumed.

Energy Flux

The Calculator computes values in joules per second per square metre.

NB. Calculated values do not take account of beta emission fractional decay; 100% decay by each beta mode exhibited by the selected nuclide is assumed.

By convention, beta decay transitions are specified in terms of the maximum energy, E(max), that can be imparted to the ejected electron; this ensures that, in radiation protection calculations, beta hazards are never under-estimated. As a rough guide, the average beta particle energy, E(av), for a given decay transition is typically around a third of E(max).

2.3 MeV range = 935.53
 0.6 MeV range = 182.81
 0.2 MeV range = 38.932

Displays the calculated range for each of the currently selected radionuclide's beta emissions. The unit for this quantity is selected in the drop-down list field at the top-right of the form.

Air Sets the material to be used for beta emission range calculation. The Calculator uses the following density values:

Air - (1 bar, 20° C, 50% relative humidity & 0.04% CO ₂)	1.184 x 10 ⁻³	g cm ⁻³
Water	1.000	"
Plastic - (polyvinylchloride - PVC)	1.300	"
Aluminium	2.698	"

Linear range (cm) Select the quantity for which you wish to view data relating to each of the beta decay energies of the currently selected radionuclide. All data computed by the Calculator are based on a fractional decay value of unity for each beta particle emission energy exhibited by the selected radionuclide. You should scale computed values by the applicable fractional decay value shown in the Nuclide Selection page to obtain a final estimate of these quantities.

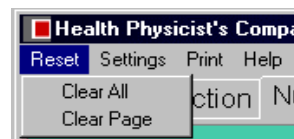
Mass Energy-Absorption (cm²/g) Sets the absorption coefficient unit for the display of calculated data.

Using the menus

The following menu options are available on this page:

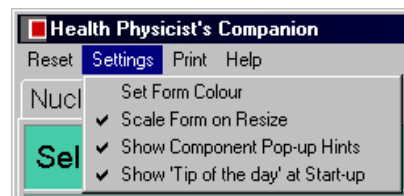
Choose:

'Clear page' to clear data in the currently selected page or 'Clear All' to clear data in all pages.



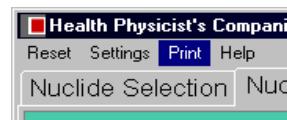
Choose:

'Set Form Colour' to change the background colour of the main form; 'Scale Form on Resize' if you want all components on the form to resize automatically when you change the size of the form; 'Show Component Pop-Up Hints' if you want to view a small help dialogue as you move the mouse over components within the form or 'Show Tip of the Day at Start-up' if you want to view a useful hints dialogue every time you run the Health Physicist's Companion.



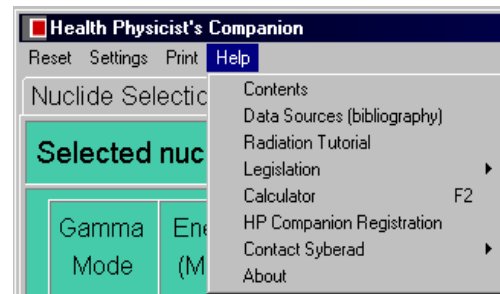
NB. New settings are stored for reinstatement each time you use the Health Physicist's Companion.

Prints a screen-shot of the data in the displayed page.



Choose:

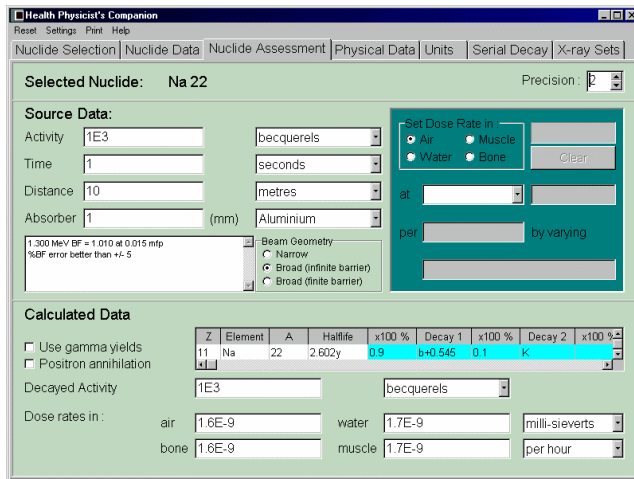
'Contents' to display the Companion's help contents, index and search dialogue; 'Data Sources' for information about the data sources the Companion uses for its calculations; 'Radiation Tutorial' for summary information about ionising radiation; 'Legislation' for information about ionising radiation legislation in the United Kingdom; 'Calculator' to open the HP Calculator utility; 'HP Companion Registration' to register your copy of the Health Physicist's Companion with Syberad; 'Contact Syberad' for information about how to contact Syberad or 'About' for information on the version of the Health Physicist's Companion you currently have installed on your PC.



Chapter 3 - Nuclide Assessment Page

The Nuclide Assessment page allows you to complete decayed radioactivity, gamma emission dose rate and shielding calculations; an example is shown in Figure 5. You can also carry out 'capped' dose rate calculations using this page.

Figure 5 - Screen-shot of the Nuclide Assessment page



Information about the components shown in Figure 5

Activity Quantity radioactivity of the source. The Calculator assumes that this value relates to a point source.

Time Exposure time. Enter zero if you want dose calculations to be based upon the activity value entered in the field above. If this activity value is that after decay has taken place, and you want to know the activity at some time in the past, enter the time value as a negative number.

Distance Distance between the measurement or exposure plane and the radioactive source.

Absorber Absorber/shield thickness in millimetres.

becquerels Radioactivity unit used in calculations.

seconds Exposure time unit used in calculations.

metres Distance unit used in calculations.

No Shield Shield material used in dose rate calculations. Density values are as follows.

Material	Density (kg m ⁻³)
lead	11343
aluminium	2698
concrete	2360
barytes concrete (high density)	3210
uranium	19050
iron	7873
tin	7285
copper	8933
bismuth	9803
glass (lead)	4360
polystyrene	1065
polythene	1375
polyvinyl chloride (PVC)	1350
air	1.2
water	1000

Beam Geometry
 Narrow
 Broad (infinite barrier)
 Broad (finite barrier)

Beam geometry to be used in dose calculations.

1.300 MeV BF = 1.026 at 0.067 mfp
 %BF error better than +/- 5

Displays the calculated build-up factor for each selected gamma emission (i.e. selected in the Nuclide Data page) of the currently selected radionuclide (i.e. selected in the Nuclide Selection page) together with the shield thicknesses, in mean free paths, at which the largest curve-fit errors occur.

The mean free path length is numerically equal to the reciprocal of the linear attenuation coefficient applicable to a particular photon (or particle) energy; it is also sometimes referred to as the relaxation length. The dimensionless product of the linear attenuation coefficient and linear shield thickness, gives the shield's 'depth' in mean free paths.

NB. The linear attenuation coefficient μ is not the same quantity as the mass attenuation or mass energy-absorption coefficients. See Chapter 11 for more information on these quantities.

Use gamma yields Tick (check) this box to scale dose rates in accordance with the fractional decay coefficients for each of the selected radionuclide's gamma decay modes. When left unticked (unchecked), a fractional decay value of unity is assumed for each gamma decay mode. This tick (check) box is also relevant to the 'Positron annihilation' tick (check) box, see below.

NB. You can exclude individual gamma decay modes for the selected radionuclide by going to the Nuclide Data page and de-selecting the relevant emission tick (check) boxes.

Positron annihilation If the selected radionuclide exhibits positron decay modes, tick (check) this box to include positron annihilation dose rates. Positrons have a range in matter comparable to that of beta particles and are ultimately 'converted' to 0.511 MeV photon pairs when they encounter an electron in an absorbing medium. Therefore, from a practical health physics standpoint, annihilation should be included in dose calculations in circumstances where positron range is smaller than the thickness of the radioactive material's substrate or encapsulation. For open sources and surface contamination assessments, this assumption will be invalid because annihilation will principally occur at some distance from the radioactive material, typically in air, or in the detection medium itself.

If 'Use gamma yields' is also ticked (checked), the dose due to annihilation is scaled by the total fractional decay for all positron modes exhibited by the selected radionuclide; this value is added to the total gamma dose (if applicable) shown in the fields at the bottom of the form. If 'Use gamma yields' is unticked (unchecked), a fractional decay value of unity is assumed for positron decay.

Z	Element	A	Halflife	x100 %	Decay 1	x100 %	Decay 2	x100 %
42	Mo	99	66.02h	0.82	b-1.21	0.17	b-0.436	0.01

The data formats for the nuclide database's fields are as follows.


Column Heading	Detail
Element	Abbreviated element name
A	Atomic mass number
Z	Atomic number
Halflife	Radionuclide half-life (if applicable) where: y=years, d=days, h=hours, m=minutes and s=seconds
Decay (n)	Decay mode and energy in MeV where: b- beta K electron capture a alpha p proton IT isomeric transition b+ positron m metastable state SF spontaneous fission N neutron
Gamma (n)	Gamma emission energy in MeV
X100%	Percentage decay by mode(n)
Inhale 5 micron (slow)	Dose per Bq inhalation of a 5 micron AMAD aerosol

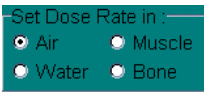
Column Heading	Detail
Inhale 1 micron (slow)	Dose per Bq inhalation of a 1 micron AMAD aerosol
Inhale f1 (slow)	Fractional clearance value
Ingestion (slow)	Dose per Bq ingestion
Ingestion f1 (slow)	Fractional transfer value
Inhale 5 micron (med.)	Dose per Bq inhalation of a 5 micron AMAD aerosol
Inhale 1 micron (med.)	Dose per Bq inhalation of a 1 micron AMAD aerosol
Inhale f1 (med.)	Fractional clearance value
Ingestion (med.)	Dose per Bq ingestion
Ingestion f1 (med.)	Fractional transfer value
Inhale 5 micron (fast)	Dose per Bq inhalation of a 5 micron AMAD aerosol
Inhale 1 micron (fast)	Dose per Bq inhalation of a 1 micron AMAD aerosol
Inhale f1 (fast)	Fractional clearance value
Ingestion (fast)	Dose per Bq ingestion
Ingestion f1 (fast)	Fractional transfer value
Abundance	Fractional abundance for a naturally occurring isotope
Notes	Notes about the selected nuclide
Frac. Metastable	Fractional generation of the nuclide from its principal parent

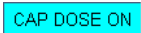
The references to 'slow', 'medium' and 'fast' in the inhalation and ingestion fields refer to the definitions given in ICRP, Publication 68⁽¹⁷⁰⁾ for uptake rates. Type S (slow) denotes an uptake rate by the exposed tissue of 0.1% in 10 minutes (7000 days for 99.9% uptake), type M (medium) an uptake rate of 10% in 10 minutes (140 days for 90% uptake) and type F (fast) an uptake rate of 100% in 10 minutes.

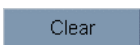
f1 values refer to the fraction of an intake which is taken up systemically following ingestion and to the fraction cleared to the gut by the 'pulmonary ciliary escalator' following inhalation; these values are consistent with ICRP, Publication 68. f1 values are a critical determinant of personal dose and are highly dependent upon chemical form and, in the case of inhalation, upon particle size. The values quoted in IAEA Safety Series 115⁽³⁾ and used by the Health Physicist's Companion are those for either 'worst case' or commonplace radionuclide compounds (see Annexes E and F of ICRP 68).


The grid headings can be mouse-dragged⁵ to new positions, thereby allowing you to alter the order of columns in the grid; you can also use mouse-dragging to resize the columns by dragging their boundaries.


 Displays the calculated decayed radioactivity for the entered data. The adjacent drop-down list field selects the quantity radioactivity unit to be used by the Calculator.

 Specifies the absorber or target material for 'capped' dose rate calculations.

 This panel tells you when the 'capped' dose rate option is enabled.

 Click this button to clear the 'capped' dose rate calculation fields and reinstate the original quantity radioactivity, time, distance and absorber values.

 Dose value used in 'capped' dose rate calculations.

 'Capped' dose rate unit used in calculations.

 Dose rate time unit used in calculations.

⁵ Mouse-Dragging - is a Microsoft Windows term for a technique of moving or resizing an object on the screen. It's achieved by selecting a screen object such as a grid or table heading with the mouse and then, simultaneously, moving the mouse whilst keeping its left button depressed.

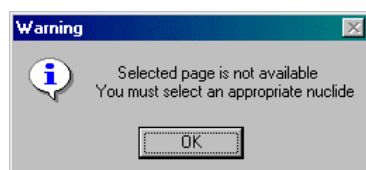
Activity Variable the Calculator adjusts to set the 'capped' dose rate.

air	<input type="text" value="0.027"/>	water	<input type="text" value="0.03003180212"/>
bone	<input type="text" value="0.02780565371"/>	muscle	<input type="text" value="0.02976678445"/>

These fields display calculated dose rates for air, water, bone and muscle.

Calculated value display precision. Dose calculator precision is not affected by the value selected in this spin box; calculated data are simply rounded to this precision for the purpose of display.

The Nuclide Assessment page is only accessible after you have selected a radionuclide in the Nuclide Selection page. If you try to access the page when a radionuclide is not selected, the following message box appears.



When you access the Nuclide Assessment page for the first time, the user-input fields are empty and no calculated data are displayed. As you enter or amend these fields, calculated results appear and are updated automatically.

The 'Use decay ratios' tick-box (check-box) at the bottom of the page allows you to include fractional decay values in dose rate calculations. When this box is unticked (unchecked), the Calculator assumes a value of unity for each of the selected radionuclide's photon emissions that you want included in calculations. You can specify which gamma emissions to include in calculations by going to the Nuclide Data page and ticking (checking) the appropriate boxes.

The nuclide assessment calculator operates in real time; it updates all calculated results, relevant to your data entries, as you make them and will recalculate dose rates when you select a new radionuclide in the Nuclide Selection page.

How do I calculate decayed radioactivity?

To display a calculated decayed radioactivity, you must enter two data values: an initial quantity radioactivity and a decay time. Use the drop-down list fields next to these edit fields to select the units you want the nuclide assessment calculator to use in its calculations.

Decayed radioactivity can be displayed in becquerels or curies; use the drop-down list field next to the decayed radioactivity field to select the unit you wish to use.

How do I calculate dose rates?

The Health Physicist's Companion contains comprehensive mass energy-absorption and mass attenuation coefficient data which are accessible from the Physical Data page. These data are used by the Calculator to determine dose rates and shielding performance; mass energy-absorption coefficient data are used in dose rate calculations and mass attenuation coefficient data in shielding calculations. The Calculator is able to compute dose rates, arising from exposure to an isotropic source, in four materials: air, water, bone and muscle.

The Calculator evaluates and sums the dose rates for each of the selected radionuclide's photon emissions you have selected for assessment in the Nuclide Data page. Results are then scaled by the applicable fractional decay factor that applies to each emission (if you have selected this option) and displayed in the fields at the bottom-right of the page. Calculation precision is determined by the value you select in the spin-box at the top-right of the page.

The Calculator infers absorbed dose rate in gray (Gy) from an evaluation of the product of the photon energy flux density ($\text{J m}^{-2} \text{s}^{-1}$), at a hypothetical spherical surface located at your entered distance value, and the applicable mass energy-absorption coefficient ($\text{m}^2 \text{kg}^{-1}$). For low linear energy transfer (LET) radiation such as gamma and x-rays, absorbed dose is numerically equal to equivalent dose in sieverts (Sv) and so, since this quantity is of most interest in radiation protection, the Calculator displays dose rates in sieverts rather than gray. See Chapter 12 for more information.

The dose rate computation essentially yields the total charged particle kinetic energy *production rate* per unit mass (kerma rate), rather than the energy absorption rate (absorbed dose), resulting from

photoelectric, Compton and pair/triplet production interactions in the absorbing material (i.e. the detection medium). In most radiation protection scenarios, if electronic equilibrium has been established in the absorbing material, kerma rate is essentially numerically equal to absorbed dose rate. However, in this regard, the following caveats apply:

- Unlike kerma, the absorbed dose computation made by the Calculator includes adjustment for bremsstrahlung and x-ray fluorescence 'losses' from the charged particle fluence generated by the primary photon fluence (the so-called 'uncollided' photon fluence). This essentially arises from differences in the definitions of the mass energy-transfer and mass energy-absorption coefficient. See Chapter 11 for more information.
- Rayleigh scatter (coherent scatter) is not included in the absorbed dose computation because it doesn't produce significant charged particle kinetic energy within the absorbing medium.
- The mass energy-absorption coefficient definition only includes photon interaction cross-sections for primary absorption processes. The effect upon charged particle production rate of Compton-scattered photon absorption and positron annihilation photon absorption following pair/triplet production interactions (so-called 'collided' photon fluence interactions) is not included in the Calculator's dose rate computations.

However, for irradiation geometries of typical interest to radiation protection professionals, the contribution to absorbed dose in low atomic number (Z) absorbers, such as soft tissue, of the 'collided' photon fluence is not significant at energies below a few MeV. This is because operational dose quantities such as personal dose equivalent are defined in relation to target volumes that are superficial (0.07 and 1000 mg cm^{-2}) and, in terms of the way in which such quantities are measured (i.e. by film badge, TLD or portable monitor), to target volumes that are relatively small compared to the average mean free path of the 'collided' photon fluence.

- In most radiation protection scenarios, apart from the need to always consider electronic equilibrium factors, soft tissue absorbed dose is largely independent of target volume location within the body at primary photon energies up to 0.5MeV .

At photon energies greater than 0.5MeV , deep tissue absorbed dose increasingly begins to fall below that for superficial tissue as the effect of primary photon attenuation becomes more dominant than 'collided' photon fluence build-up effects.

- The absorbed dose build-up factor resulting from 'collided' photon fluence interactions within target volumes is always significant in medical applications such as radiotherapy dose planning; here absorbed dose contours throughout a patient's body need to be accurately determined in order to achieve an appropriate balance between treatment efficacy and patient post-irradiation survival.

Charged particle or electronic equilibrium (CPE) is the condition whereby the photoelectron fluence, caused by a beam of photons as it propagates through a finite element of an absorbing medium, is solely a function of the beam's photon fluence and not a function of the element's position relative to any boundary of the absorbing medium.

Photoelectrons produced by the absorption of photons that are propagating through matter will have random trajectories and may not follow the trajectories of the photons that give rise to them. It follows therefore that the photoelectron fluence within a finite element of an absorbing medium is comprised of photoelectrons that have been created within it and those that have entered it from surrounding elements. The photoelectron fluence will therefore increase up to a maximal value as a photon beam begins to enter a more dense material and, conversely, will reduce to a minimal value when it begins to enter a less dense material (so-called beam entry and exit effects).

As a general rule, CPE can be considered to have been established in a detection or target material once its thickness exceeds the mean free path of the most energetic photoelectrons generated within it. For 1 MeV photoelectrons, this distance is approximately 400mm in air and 0.5mm in water.

NB. Dose rate calculations made by the Health Physicist's Companion for gamma emitting radionuclides assume that CPE has been established in the detector or target material. If this is not true for the irradiation geometry of interest, computed dose rates will be inaccurate. In practice, most

radiation detectors are designed to establish electronic equilibrium within their own detection volume and so, if you only want to know the dose rate at an operational location such as a work area, you may use the Calculator's dose rate results without further consideration. However, if you want to correctly infer dose rates in superficial tissue, you must know to what extent the radiation field is in 'electronic equilibrium'.

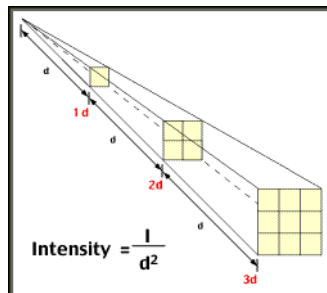
Including positron annihilation effects in dose calculations

For radionuclides that exhibit positron decay modes, you can include the positron annihilation contribution to dose rate in your calculations. To do this, select the 'Positron Annihilation' tick (check) box. This box is only enabled when the selected radionuclide exhibits positron decay modes.

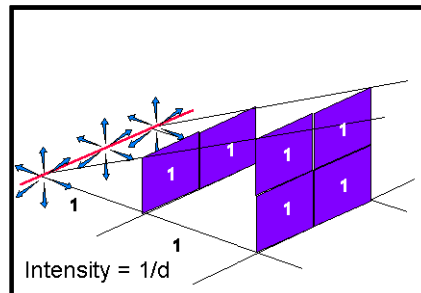
Positrons have a limited range in matter and are ultimately 'converted' to 0.511 MeV photon pairs when they encounter an electron in an absorber. Therefore, from a practical health physics standpoint, annihilation should be included in dose calculations in circumstances where positron range is smaller than the thickness of the radioactive material's substrate or encapsulation. For open sources and surface contamination assessments, this assumption will be invalid because annihilation will principally occur at some distance from the radioactive material, typically in air, or in the detection medium itself.

If 'Use gamma yields' is also ticked (checked), the dose due to annihilation is scaled by the total fractional decay for all positron modes exhibited by the selected radionuclide; this value is added to the total gamma dose (if applicable) shown in the fields at the bottom of the form. If 'Use gamma yields' is unticked (unchecked), a fractional decay value of unity is assumed for positron decay. For more information about absorbed dose rate calculation, see Chapter 11.

You should bear in mind that the Calculator determines dose rates at a hypothetical surface rather than an actual volume; dose rates will therefore be overestimated for 'targets' that have a significant thickness in relation to their distance from the source. This effect is due to the inverse square law⁶, see diagrams below.



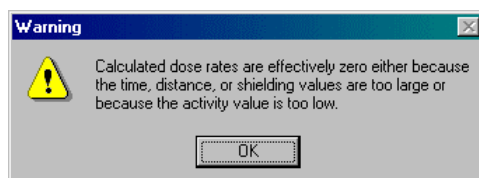
Point Source



Line Source

To calculate dose rates, you must enter a valid quantity radioactivity, decay time, source-to-exposure point separation distance and, optionally, a shield thickness. Calculated dose rates are based on the decayed radioactivity, not the original radioactivity. If you want to exclude radioactive decay, enter zero in the decay time field.

Calculated dose rates can be displayed in a number of dose and time units; use the drop-down list fields next to the dose rate fields to select the units you want the Calculator to use.



If the Calculator can't determine valid dose rates for all four 'target' materials, the error box shown-left is displayed.

When you close this message box, the dose rate fields will not be displayed; instead, an error message will flash on the screen. See Figure 6.

⁶ Inverse Square Law - Used to describe the way in which the radiation field produced by a point source reduces in inverse proportion to the square of the distance (D) separating it from the measurement point or surface; i.e. radiation intensity is proportional to D^{-2} .

Figure 6 - Dose calculation error

Health Physicist's Companion

Reset Settings Print Help

Nuclide Selection | Nuclide Data | Nuclide Assessment | Physical Data | Units | Serial Decay | X-ray Sets

Selected Nuclide: Co 60 Precision: 2

Source Data:

Activity: 1 becquerels

Time: 1E3 years

Distance: 1 metres

Absorber: 7E4 (mm) Aluminium

Beam Geometry:

Narrow

Broad (infinite barrier)

Broad (finite barrier)

Set Dose Rate in:

Air Muscle

Water Bone

Clear

Calculated Data

Z	Element	A	Half-life	x100 %	Decay 1	x100 %	Decay 2	x100 %
27	Co	60	5.271y	0.9992	b-0.3178	0e-4	b-1.4911	5e-5

Decayed Activity: 7.8E-58 becquerels

CALCULATED DOSES OUT OF RANGE. AMEND YOUR DATA ENTRIES

How do I calculate shielding requirements?

The dose rate calculator allows you to evaluate the effect of shielding placed between the source and the measurement location. You can enter a shielding thickness in millimetres in the 'Absorber' field and select a shielding material at any time during calculations; the effect upon calculated dose rates is computed in real time as you enter and edit shielding data. The shielding densities used by the Calculator are as follows.

Material	Density (kg m ⁻³)
lead	11343
aluminium	2698
concrete	2360
barytes concrete (high density)	3210
uranium	19050
iron	7873
tin	7285
copper	8933
bismuth	9803
glass (lead)	4360
polystyrene	1065
polythene	1375
polyvinyl chloride (PVC)	1350
air	1.2
water	1000

The Calculator allows you to specify any of three shield irradiation geometries; 'Narrow', 'Broad (infinite barrier)' and 'Broad (finite barrier)'.

'Narrow' refers to the exposure condition that typically arises when a thin shield is irradiated by a collimated beam; this geometry is often referred to as narrow-beam irradiation. For this irradiation geometry, the Calculator evaluates shielding attenuation as follows.

$$\text{Fractional transmission of 'uncollided' fluence (i.e. primary beam extinction)} = N_0 e^{-mm_x}$$

Where:

$$N_0 = \text{Initial photon fluence}$$

$$m = \text{Mass attenuation coefficient applicable to the photon energy (m}^2 \text{ kg}^{-1}\text{)}$$

$$m_x = \text{Mass thickness of the absorbing material (kg m}^{-2}\text{)}$$

This computation only takes account of interaction processes that directly remove primary photons from the radiation field namely, photoelectric absorption, Compton scatter and pair and triplet

production. Narrow-beam attenuation is therefore primarily an interaction probability function of photons interacting with the shielding material for the first time (so-called 'uncollided' beam interactions).

Partial energy absorption events, such as Compton scatter and pair/triplet production interactions, are not completely accounted for in the 'narrow' attenuation calculation because these processes produce 'secondary' photons which have yet to interact with the shielding material.

'Broad (finite barrier)' and 'Broad (infinite barrier)' are two irradiation geometries that typically arise in thick shields and in circumstances where the beam incident on a shield is uncollimated. Both exposure conditions are often referred to as broad-beam irradiation. For this irradiation geometry, the Calculator evaluates attenuation in the same way as for the 'narrow' irradiation condition, but then applies a build-up factor to take account of the effect on total photon energy fluence, at the measurement location, of radiation arising from previous photon interactions (so-called 'collided' beam or secondary interactions).

Beam build-up occurs in shields principally because gamma and x-ray attenuation involves scattering processes such as Compton scatter and, at photon energies above 1.022MeV, positron annihilation photon production (following pair/triplet interactions). Charged particle absorption processes which lead to photon production, for example bremsstrahlung and x-ray fluorescence, will also contribute to radiation field build-up within a shield.

The photon fluence in any finite element of an absorbing medium is therefore the sum of 'uncollided' originally incident photons and Compton, positron annihilation, x-ray fluorescence and bremsstrahlung photons that have been scattered into the element from interactions that have taken place in the material around it. The fluence within any finite element of an absorbing medium is therefore higher than it would be if there were no material around it (i.e. if the absorbing medium were not physically extended).

Specifically, the build-up factor is defined as:

The ratio of the total value of a specified radiation quantity at any point to the contribution to that value arising from radiation reaching the point without having undergone a collision.

At shield thicknesses significantly less than the mean free path of the incident photon energy, the shielding calculator produces the most accurate results for narrow-beam geometries; this is because empirically determined build-up factors are not used in calculations. However, once the shield thickness exceeds the mean free path, build-up phenomena can no longer be disregarded if absorbed dose calculation accuracy is to be maintained at a few percent. Attenuation calculation in thick shields using narrow-beam geometry considerations will lead to significant overestimates of shield performance; the error may be several orders of magnitude for very thick shields. So, it's important to use broad-beam geometry where appropriate.

The build-up factors used by the Calculator were derived from geometric progression (G-P) fitting function data published in the American Nuclear Society standard, ANS-6.4.3⁽⁴⁹⁾. This standard tabulates G-P fitting function coefficients for various materials and for primary photon energies ranging between 15keV and 15MeV. These values were derived from comparisons with build-up data obtained from Monte Carlo photon transport codes developed by NIST⁽⁶⁾. This method depends on the fact that the radiation exposure build-up factor B, in an absorber of thickness x mean free paths, when exposed to a point isotropic source of emission energy E (MeV), can be approximated by functions of the form:

$$B_{(E,x)} = 1 + \frac{(b-1)(k^x - 1)}{(k-1)} \quad \text{for } k \neq 1 \qquad B_{(E,x)} = 1 + (b-1)x \quad \text{for } k = 1$$

Where:

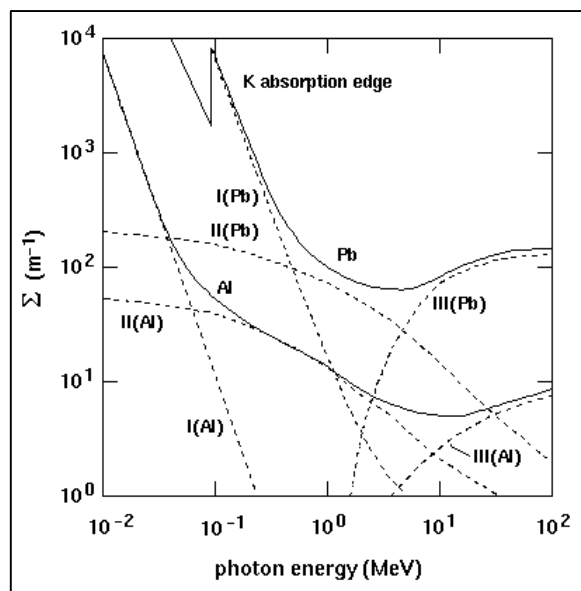
$$k_{(E,x)} = cx^a + d \left[\frac{\tanh\left(\frac{x}{X_k} - 2\right) - \tanh(-2)}{1 - \tanh(-2)} \right]$$

In these expressions a, b, c, d and X_k are empirically determined coefficients published in the ANS standard⁽⁴⁹⁾ and X the thickness of the shielding material in mean free paths.

The Calculator uses a comprehensive set of G-P coefficient values to calculate the radiation exposure build-up factor that applies to the data you have entered in the Nuclide Assessment page; the accuracy of these calculations is generally better than +/-5%. Information about curve-fit errors is displayed in the memo fields next to the 'Beam Geometry' radio buttons.

Build-up factors for high atomic number (Z) materials, at photon energies that are close to electron shell binding energies (especially K-shell binding energies) of the absorbing medium, can become very large indeed. This is due to the discontinuous nature of absorption cross-sections at these energies. Here absorption cross-sections can be so large that a significant proportion of the total primary photoelectron fluence, created by photoelectric interactions within the absorbing material, is 'converted' into fluorescence x-rays as k-shell ionization vacancies are filled by electrons from lower energy shells. This has the effect of converting short-range photoelectrons into much more penetrating electromagnetic radiation, thereby significantly reducing overall attenuation within the absorbing material. In lead and uranium, the critical photon energies, at which build-up by these processes is most pronounced, occur at the K-shell ionization potentials of 0.088 and 0.16 MeV respectively. Great care should therefore be exercised when interpreting the effect of build-up at these photon energies.

At high photon energies (i.e. above 0.5MeV) in high Z absorbers, bremsstrahlung radiation becomes an important contributor to radiation field build-up for, like x-ray fluorescence, the process involves the 'conversion' of photoelectron fluence into a more penetrating photon fluence.



The figure to the left depicts the absorption cross-sections for photons in aluminium (Al) and lead (Pb). Curves labelled 'I' show the partial cross-sections due to photoelectric absorption and curves labelled 'II' the partial cross-sections due to Compton scatter. The curves labelled 'III' show partial cross-sections for pair production.

NB. The Calculator assumes that photon energies at the shield are the same as those for the selected radionuclide's gamma emission energies. This is normally true for shielding bonded to or placed in close proximity to a radioactive source. However, at large shield-to-source separation distances and especially at low photon energies, this assumption may be invalidated by air attenuation which tends to degrade the mean photon energy of an emission as a result of Compton scatter. However from a health physicist's perspective, air attenuation does not compromise safety because it leads to an under-estimate of shielding effectiveness.

Mathematical formula used by the dose calculator (overview)

The formula used by the Calculator to determine absorbed dose rates [D_r] is shown overleaf. It consists of three components: dose rate determination in the target material (i.e. air, water, bone and muscle), shield attenuation correction (if the user has selected this option) and, finally, radiation field build-up correction for the shield (if present).

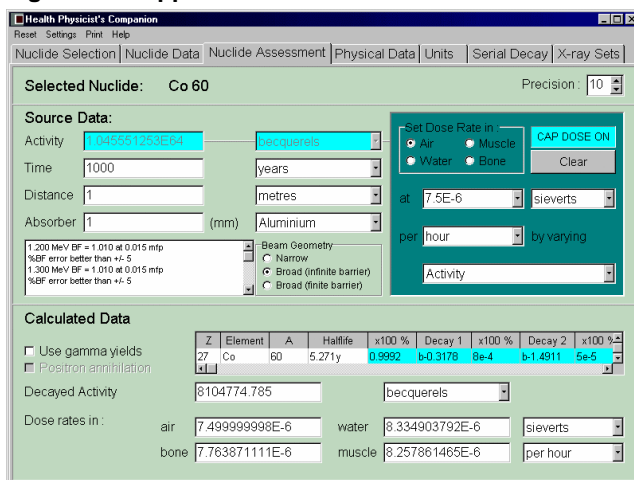
$$D_r = \sum_i \left[\frac{\overbrace{A_{(Bq)} E_i f_i}^{\text{Energy(i) Dose Rate}}}{4 p d^2} \overbrace{m_{(en) i}}^{\text{Shield Absorption}} \times e^{-m_i m_x} \times B_{(E,x)} \right]$$

Where:

- $A_{(Bq)}$ = Source radioactivity in becquerels (Bq)
- E_i = Energy, in joules (J), of photon emission 'i'
- f_i = Fractional decay coefficient for photon emission 'i'
- d = Distance between source and measurement location (m)
- $m_{(en) i}$ = Mass energy-absorption coefficient for photon emission 'i' ($m^2 \text{ kg}^{-1}$)
- m_i = Mass attenuation coefficient for photon emission 'i' ($m^2 \text{ kg}^{-1}$)
- m_x = Mass thickness of shielding material (kg m^{-2})
- $B_{(E,x)}$ = G-P Build-up factor for photon energy E (MeV) in a shield of thickness x mean free paths

How do I carry out 'capped' dose rate calculations?

Figure 7 - 'Capped' dose rate calculation

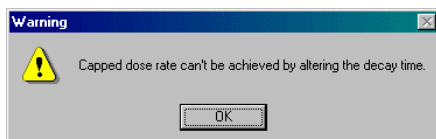


The dose rate calculator allows you to calculate the quantity radioactivity, time, distance, or absorber thickness needed to achieve a 'capped' dose rate of your choosing. The target dose rate can be set in four materials: air, water, bone, and muscle and in any combination of units.

The screen-shot in Figure 7 shows a 'capped' dose rate calculation where source radioactivity is the variable quantity.

If the 'capped' dose rate can't be achieved by altering the parameter you have chosen as the variable, the following type of message box is displayed.

NB. 'Capped' values are determined by an iterative approximation process and so you might not see the exact 'capped' dose rate value replicated in the calculation fields at the bottom of the page.



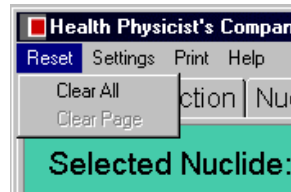
If you enter 'capped' values that lie outside the Calculator's numerical range or if they are inconsistent with the source data you have entered, the message box shown to the left will display. When this occurs, click the okay button and amend the 'capped' dose rate entries accordingly.

Using the menus

The following menu options are available on this page.

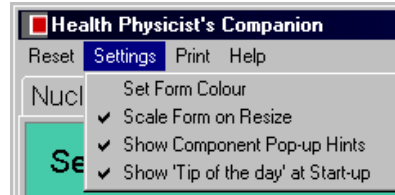
Choose:

'Clear page' to clear data in the currently selected page or 'Clear All' to clear data in all pages.



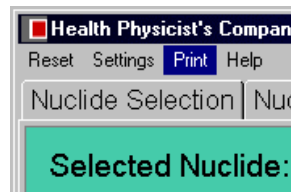
Choose:

'Set Form Colour' to change the background colour of the main form; 'Scale Form on Resize' if you want all components on the form to resize automatically when you change the size of the form; 'Show Component Pop-Up Hints' if you want to view a small help dialogue as you move the Mouse over components within the form or 'Show Tip of the Day at Start-up' if you want to view a useful hints Dialogue every time you run the Companion.



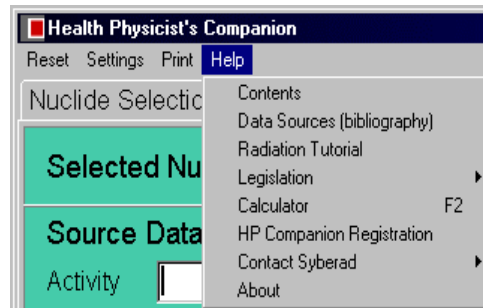
NB. New settings are permanently stored so that, each time you use the Health Physicist's Companion, your preferences are reinstated.

Prints a screen-shot of the data in the displayed page.



Choose:

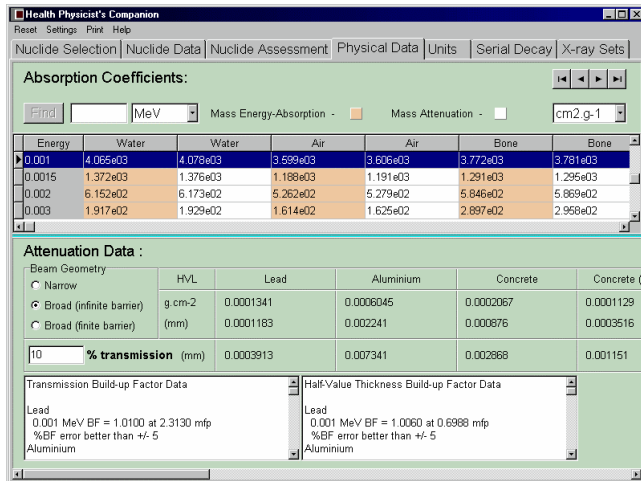
'Contents' to display the Companion's help contents, index and search dialogue; 'Data Sources' for information about the data sources the Companion uses for its calculations; 'Radiation Tutorial' for summary information about ionising radiation; 'Legislation' for information about ionising radiation legislation in the United Kingdom; 'Calculator' to open the HP Calculator utility; 'HP Companion Registration' to register your copy of the Health Physicist's Companion with Syberad; 'Contact Syberad' for information about how to contact Syberad or 'About' for information on the version of the Health Physicist's Companion you currently have installed on your PC.



Chapter 4 - Physical Data Page

The Physical Data page allows you to look up mass energy-absorption and mass attenuation coefficients for various photon energies and to calculate the shielding mass-thickness needed to achieve a beam transmission value that you specify. The layout of this page is shown in Figure 8.

Figure 8 - Screen-shot of the Physical Data page



Information about the components shown in Figure 8

Find Click this button to move the record pointer to the entry that is the nearest match to the search value in the adjacent field. Photon energy values must be within the following ranges:

MeV - 1 keV to 100 MeV
 joules - 1×10^{-16} to 1.6×10^{-11} J

NB. The 'Find' button is only enabled for entries that fall within these ranges.

MeV Absorption coefficient energy unit.

cm².g-1 Absorption coefficient unit used to display data in the table (grid).

Navigation buttons Use these buttons to browse the coefficient database.

Table Displays the absorption coefficients for a number of materials irradiated at various photon energies. Right-click anywhere in the grid to access the grid display options menu. Double-click anywhere in the grid to 'toggle' between full-screen and minimized views. You can also manually resize the grid by using the left-mouse button to 'drag' the blue horizontal line (splitter-bar) at the bottom of the grid to a new position.

Energy	Water	Water
0.001	4.065e03	4.078e03
0.0015	1.372e03	1.376e03

Beam Geometry Beam geometry to be used in attenuation calculations. See pages 23-25 for more information about irradiation conditions

- Narrow
- Broad (infinite barrier)
- Broad (finite barrier)

% transmission (mm) The shield thickness, in mm, required to achieve the transmission value, in a number of materials, is displayed in the table columns to the right of this field. The calculations completed here can be adjusted to take account of radiation field build-up effects by selecting an appropriate irradiation geometry in the field above.

HVL	Lead	Aluminium
g.cm-2	0.0005438	0.0003165
(mm)	0.0004794	0.001173

Displays half-value layer (HVL) data for various 'target' materials. HVL is also referred to as the half-value thickness (HVT).

Calculations completed here can be adjusted to take account of radiation field build-up effects by selecting an appropriate irradiation geometry in the control next to this table (grid).

Half-Value Thickness Build-up Factor Data	
Lead	0.002 MeV BF = 1.0060 at 0.6988 mfp
	%BF error better than +/- 5
Aluminium	

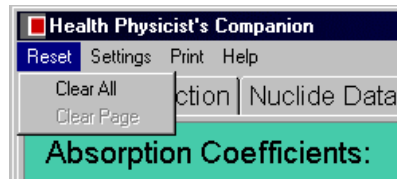
These two fields display information about calculated build-up factors for the selected photon energy together with the shield thicknesses, in mean free paths, at which the largest curve-fit errors occur.

Using the menus

The following menu options are available on this page.

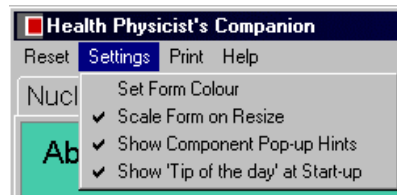
Choose:

'Clear page' to clear data in the currently selected page or 'Clear All' to clear data in all pages.



Choose:

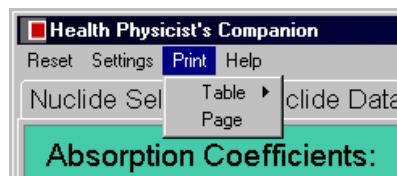
'Set Form Colour' to change the background colour of the main form; 'Scale Form on Resize' if you want all components on the form to resize automatically when you change the size of the form; 'Show Component Pop-Up Hints' if you want to view a small help dialogue as you move the mouse over components within the form or 'Show Tip of the Day at Start-up' if you want to view a useful hints dialogue every time you run the Health Physicist's Companion.



NB. New settings are permanently stored so that, each time you use the Health Physicist's Companion, your preferences are reinstated.

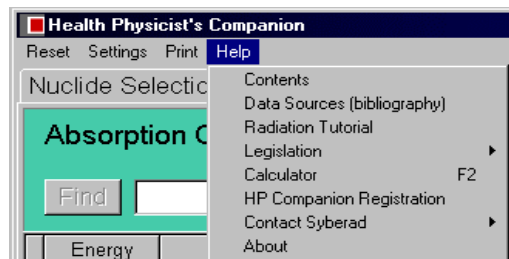
Choose:

'Table' to print a table of mass energy-absorption or mass attenuation coefficient data or, 'Page' to print a screen-shot of the data currently displayed in the form.



Choose:

'Contents' to display the Companion's help contents, index and search dialogue; 'Data Sources' for information about the data sources the Companion uses for its calculations; 'Radiation Tutorial' for summary information about ionising radiation; 'Legislation' for information about ionising radiation legislation in the United Kingdom; 'Calculator' to open the HP Calculator utility; 'HP Companion Registration' to register your copy of the Health Physicist's Companion with Syberad; 'Contact Syberad' for information about how to contact Syberad or 'About' for information on the version of the Health Physicist's Companion you currently have installed on your PC.



Chapter 5 - Units Page

The Units page enables you to convert radiation quantities and to complete radon exposure assessments; an example is shown in Figure 9.

Figure 9 - Screen-shot of the Units page

Information about the components shown in Figure 9

curies curie (Ci) - CGS unit of quantity radioactivity. Equivalent to 3.7×10^{10} atomic disintegrations per second.

sieverts sievert (Sv) - SI unit of radiation dose. The sievert is a specially weighted measure of radiation absorbed dose. As defined in ICRP⁷, Publication 26⁽¹¹⁰⁾, 1976, the sievert denoted two dose quantities namely, dose equivalent (the radiation absorbed dose in gray weighted for radiation type) and effective dose equivalent (the dose equivalent in Sv weighted for exposed tissue(s)).

Following the publication of ICRP's latest radiation protection recommendations in Publication 60, 1990⁽¹⁶⁰⁾, the dose equivalent quantity was replaced by equivalent dose. For more information about these new dose quantities, see Chapter 12.

curie.MeV curie mega-electronvolt (Ci MeV) - A derived quantity, numerically equal to radioactive source energy-emissivity (MeV s^{-1}); it is often used as an alternative way of specifying radioactivity.

This quantity is convenient for the assessment of external⁸ radiation hazards caused by personal exposure to materials that contain an indeterminate number and concentration of radionuclides having similar gamma emission energies and therefore absorption cross-sections.

The curie electronvolt is often used in the assessment of gamma-emitting radionuclides in gaseous discharges which contain significant quantities of 'inert gas' radioisotopes, for example, xenon, krypton and argon. It therefore has extensive application in the nuclear industry. Here, inexpensive and reliable gamma detectors, such as energy-compensated geiger counters, can be placed in gaseous discharge stacks and calibrated in terms of time-integrated energy emission (Ci MeV h). This provides an effective means of total discharge assessment of radionuclides that present only an external gamma radiation hazard to people.

⁷ ICRP - International Commission on Radiological Protection.

⁸ The curie electronvolt is not useful for the hazard assessment of radionuclides that cause internal exposure, i.e. those that are taken up systemically by an exposed person.

joule (J) - SI unit of energy.

becquerel (Bq) - SI unit of quantity radioactivity. Equivalent to one atomic disintegration per second.

rem - roentgen equivalent man - CGS unit of dose (ICRP, Publication 26⁽¹¹⁰⁾, 1976 defines these quantities). This unit has largely been replaced by its SI equivalent, namely, the sievert (Sv).

$$1 \text{ rem} = 0.01\text{Sv.}$$

becquerel joule (Bq J) - A derived quantity numerically equal to radioactive source energy-emissivity (J s^{-1}); it is often used as an alternative way of specifying radioactivity.

This quantity is convenient for the assessment of external⁹ radiation hazards caused by personal exposure to materials that contain an indeterminate number and concentration of radionuclides having similar gamma emission energies and therefore absorption cross-sections.

The becquerel joule is often used in the assessment of gamma-emitting radionuclides in gaseous discharges which contain significant quantities of 'inert gas' radioisotopes, for example, xenon, krypton and argon. It therefore has extensive application in the nuclear industry. Here, inexpensive and reliable gamma detectors, such as energy-compensated geiger counters, can be placed in gaseous discharge stacks and calibrated in terms of time-integrated energy emission (Bq J h). This provides an effective means of total discharge assessment of radionuclides that present only an external gamma radiation hazard to people.

electronvolt (MeV) - Unit of energy equivalent to $1.6021773 \times 10^{-19}$ joules (J)

Selects the radon isotope on which to base calculations. Radon is a colourless, odourless, gaseous radioactive element of atomic number 86 and mass numbers in the range 198 to 227. All isotopes are radioactive; the most important being those that arise in the primordial decay series of Uranium and Thorium. The radon isotope formed in the thorium series is often referred to as thoron.

Important Radon Isotopes:

Isotope	Series Name	
Rn 222	Uranium series	(4N+2) - Uranium 238 parent
Rn 220	Thorium series	(4N) - Thorium 232 parent
Rn 225	Neptunium series	(4N+1) - Plutonium 241 parent
Rn 219	Actinium series	(4N+3) - Uranium 235 parent

Enter a radon exposure time in this field. The radon Calculator converts exposure time values into Working Level Months (WLM) for the purpose of calculation. Since this quantity is based upon occupational (i.e. worker) exposure considerations, you should note the following equivalencies when entering an exposure time.

- 21.25 days = 1 WLM
- 170 hours = 1 WLM
- 10200 minutes = 1 WLM
- 612000 seconds = 1 WLM

If you want to calculate radon exposure for the general population, you should use the hours, minutes or seconds time quantities: the months and days time quantities are inappropriate for this purpose because they are based on 8 hour (i.e. a work shift) rather than 24 hour daily exposure.

⁹ The curie electronvolt is not useful for the hazard assessment of radionuclides that cause internal exposure, i.e. those that are taken up systemically by an exposed person.

Equilibrium Factor Radon Gas Equilibrium Factor (F value) - A coefficient used to express the extent to which short-lived daughters of radon gas are in radioactive decay equilibrium with the radon parent.

As radon gas decays in a fixed volume of air, the quantity radioactivities of short-lived daughters increase over time until each daughter achieves decay equilibrium with the parent radon gas; at which point, daughter quantity radioactivities attain their maximal values.

Since radon daughters are collectively measured in terms of the potential alpha energy concentration in air (PAEC), it follows that the measured radon gas concentration, associated with this quantity, will be a function of the extent to which the short-lived daughters are in decay equilibrium with the parent radon gas. Therefore a measured PAEC value can be interpreted in terms of either the measured radon gas concentration actually giving rise to it or in terms of the concentration of radon gas which, if in equilibrium with its short-lived daughters, would give rise to a similar PAEC (the so-called equilibrium-equivalent radon gas concentration).

Numerically, the F value is defined as the ratio of equilibrium-equivalent radon gas concentration to measured radon gas concentration.

Set Exposure Time Select this option if you want to calculate the exposure time that equates a working level (WL) or potential alpha energy concentration in air value (PAEC) with a working level month (WLM) or activity exposure value.

The Radon Calculator converts exposure time values into Working Level Months (WLM) for the purpose of calculation. Since this quantity is based upon occupational (i.e. worker) exposure considerations, you should note the following equivalencies when entering an exposure time.

21.25 days	=	1 WLM
170 hours	=	1 WLM
10200 minutes	=	1 WLM
612000 seconds	=	1 WLM

If you want to calculate radon exposure for the general population, you should use the hours, minutes or seconds time quantities: the months and days time quantities are inappropriate for this purpose because they are based on 8 hour (i.e. a work shift) rather than 24 hour daily exposure.

Set Equilib Factor Select this option if you want to calculate the equilibrium factor that equates a radon gas concentration to its corresponding working level (WL) or potential alpha energy concentration in air value (PAEC).

Gas Conc. (Bq m⁻³) Radon/thoron Gas Concentration - Although the equivalent dose arising from radon gas exposure is trivial, its short-lived daughters, which can readily attach to respirable air particulates, may cause significant equivalent dose when inhaled.

Radon gas concentration is usually measured as becquerels per unit volume (Bq m⁻³) but may also be stated in terms of curies per unit volume (Ci m⁻³).

PAEC J m⁻³ MeV m⁻³ Radon Potential Alpha Energy Concentration in Air (PAEC). The PAEC is the time-integrated alpha radioactive decay energy produced by the short-lived daughters of radon, present in unit volume of air, during their total radioactive decay.

This quantity takes the SI units J m⁻³ or more commonly MeV m⁻³ and is equivalent to the historical quantity known as the working level (WL).

NB. 1 J m⁻³ is equivalent to 6.24x10¹² MeV m⁻³

Working Levels The working level (WL) is a radon measurement quantity. It was originally defined as any combination of short-lived radon daughters (Po218, Pb214, Bi214 and Po214), present in one litre of air at normal temperature and pressure, that had the potential to release 1.3x10⁵ MeV of alpha particle energy during their ultimate radioactive decay. The definition has since been widened to include the short-lived daughters of thoron (Po216, Pb214, Bi212 and Po212) and has been standardized at a value of 1.3x10⁸ MeV m⁻³.

This amount of energy is approximately that released during the ultimate decay of short-lived daughters in equilibrium with 100 pico-curies (3.7 Bq) of radon gas.

Working Level Months The working level month (WLM) is used as a measure of time-integrated exposure to short-lived radon daughter isotopes; it has an equivalence with activity exposure and takes the SI units of $J s m^{-3}$. A working month is assumed to be 170 hours.

The WLM is a radon exposure quantity that is gradually falling into disuse because it is more difficult to measure operationally than radon gas concentration. However, since most historical epidemiological exposure data (viz. miners) are stated in terms of WLM, the use of this quantity is likely to persist for some time to come.

One WLM is equivalent to an activity exposure of $6.29 \times 10^5 Bq h m^{-3}$ of radon gas in decay equilibrium with its daughters or $4.63 \times 10^4 Bq h m^{-3}$ of thoron gas in decay equilibrium with its daughters.

Activity Exp. (Bq h m-3) Radon activity exposure is the derived quantity of time-integrated radon or thoron gas exposure. It takes the units $Bq s m^{-3}$. This quantity is often used as a substitute for the working level month (WLM).

Worker effective dose (mSv) **0.1342** Radon Detriment and Dose - The radon detriment field displays the life-time detriment associated with the radon activity exposure shown in the field above. It can be expressed as either a fatal cancer risk or as an effective dose in mSv.

The effective dose conversion factor used by the Calculator is 5.06 mSv per WLM for workers and 3.88 mSv per WLM for members of the public. The detriment per unit exposure to radon progeny is 0.08 per $J h m^{-3}$. These data were obtained from ICRP, Publication 65(167).

These cancer risk values are based upon the findings of epidemiological studies of highly exposed populations, such as miners (non-ferrous metal mining rather than coal mining), which sought to relate radon activity exposure (historically measured in WLM) to the incidence of lung cancer. The values are for general populations and therefore include smokers and non-smokers alike^(5a).

NB. It is not possible to select the dose to members of the public option when either 'days' or 'months' is the selected time unit. This is because the Radon Calculator assumes worker occupancies rather than 24 hour exposure for these time units.

4 Sets the display precision for calculated fields. The value you select determines the number of significant figures that will be used to display calculation results; it does not affect the precision of the calculation process itself.

Using the menus

The menu options available for this page are as follows.

Choose:

'Clear page' to clear data in the currently selected page or 'Clear All' to clear data in all pages.



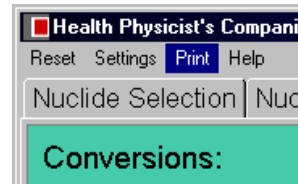
Choose:

'Set Form Colour' to change the background colour of the main form; 'Scale Form on Resize' if you want all components on the form to resize automatically when you change the size of the form; 'Show Component Pop-Up Hints' if you want to view a small help dialogue as you move the mouse over components within the form or 'Show Tip of the Day at Start-up' if you want to view a useful hints dialogue every time you run the Health Physicist's Companion.



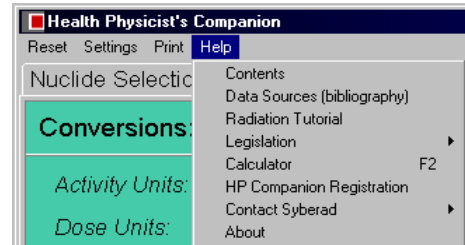
NB. New settings are permanently stored so that, each time you use the Health Physicist's Companion, your preferences are reinstated.

Prints a screen-shot of the data in the displayed page.



Choose:

'Contents' to display the Companion's help contents, index and search dialogue; 'Data Sources' for information about the data sources the Companion uses for its calculations; 'Radiation Tutorial' for summary information about ionising radiation; 'Legislation' for information about ionising radiation legislation in the United Kingdom; 'Calculator' to open the HP Calculator utility; 'HP Companion Registration' to register your copy of the Health Physicist's Companion with Syberad; 'Contact Syberad' for information about how to contact Syberad or 'About' for information on the version of the Health Physicist's Companion you currently have installed on your PC.



Chapter 6 - Serial Decay Page

Introduction

The Serial Decay page enables you to:

- View the decay series for the radionuclide selected in the Nuclide Selection page.
- Complete serial decay calculations to:
 - Calculate quantity radioactivities for decay series daughters and,
 - calculate maximal radioactivity 'in-growth' times for decay series daughters.

How do I start a decay tree build?

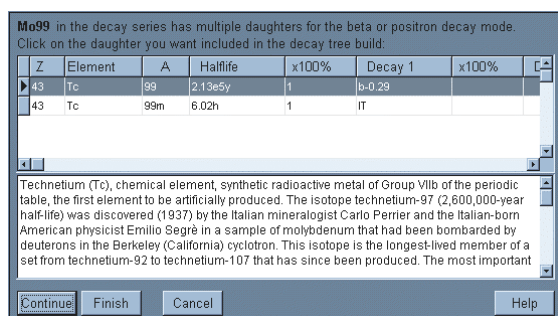
When you first access the Serial Decay page, the only enabled component is a button at the bottom-right of the page. Clicking this button will cause the Calculator to begin its work of finding and displaying data for all the daughters of the radionuclide selected in the Nuclide Selection page.

This process may take some time and you may be asked to make some daughter selections yourself if the Calculator finds metastable states. If this happens, the dialogue box shown below is displayed.

How do I stop a decay tree build?

During the decay tree build process, a progress dialogue box is displayed which shows, in real time, the number of daughters identified by the Calculator. If you want to quit the decay series build, you can press the escape key at any time during the display of this dialogue box.

Dealing with metastable states during a decay tree build



In the form to the left, we see that the parent radionuclide Mo99 has two daughters in the nuclide database for the decay mode currently being assessed by the Calculator; in this case, beta or positron decay. You therefore have the choice of using either the ground state or metastable daughter in the decay tree build. If you choose a metastable daughter that can only decay by isomeric transition to the ground state, the ground state daughter will also be included in the decay tree build. When you have selected the nuclide you want included in the

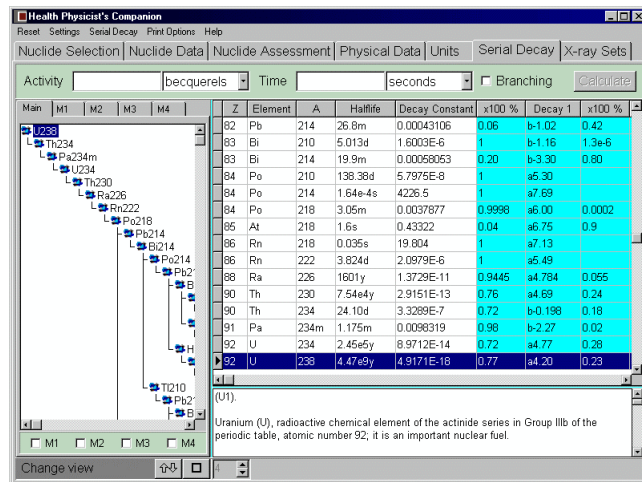
decay tree build, click the 'Continue' button. If you want to stop the build at the current daughter, click the 'Finish' button. To quit the decay series build altogether, click the 'Cancel' button.

NB. If you select the 'Finish' option, you will be able to view and print the decay tree up to the point at which you terminated the decay tree build, but you will not be able to complete serial decay and maximal daughter 'in-growth' calculations.

What can I do once the decay tree has been built and displayed?

When the Calculator has finished locating the daughters for the radionuclide that you have selected, the Companion displays a form similar to that shown in Figure 10.

Figure 10 - Screen-shot of the Serial Decay page



Information about the components shown in Figure 10

Activity This field is used in serial decay calculations. Here you enter the initial quantity radioactivity of the parent radionuclide shown in the decay tree below. The unit for this quantity is selected in the adjacent drop-down list field.

becquerels Selects the radioactivity unit to be used in calculations.

Time This field is used in serial decay calculations. Here you enter the decay time for the parent radionuclide shown in the decay tree below; the quantity radioactivities of the daughters in the decay series are calculated for this time value. The unit for this quantity is selected in the adjacent drop-down list field.

seconds Selects the decay time unit to be used in calculations.

Branching This tick-box (check-box) is used in serial decay calculations. If you want these calculations to take account of fractional decay coefficients, tick (check) this box.

If you leave this box unticked (unchecked), the Calculator uses fractional decay coefficients of unity (i.e. 100% decay for each mode) in the calculation of quantity radioactivities for each daughter in the decay series.

Calculate Click this button to calculate quantity radioactivities for the daughters in the decay tree. Computed values are based on the parent starting quantity radioactivity and decay time entered in the fields to the left of this button.

NB. Any serial decay calculations you carry out will only be applied to the primary branch of the decay tree.

Displays the decay series for the radionuclide that is currently selected in the Nuclide Selection page. You can use the cursor keys or the mouse to highlight the parent or a daughter; as you do this, the record cursor in the adjacent grid moves to the nuclide you have selected.

Double-click the parent or a daughter to expand or contract the decay tree below the point that is currently selected. Alternatively, you can fully expand or contract the decay tree, or zoom it to fill the entire page, by clicking the buttons in the change view panel.


Right-click anywhere in the decay tree to display the options pop-up menu. Here you can sort the decay tree in accordance with fractional decay constants, carry out 'equilibrium' calculations and customize the decay tree display. The display customization option allows you to display the element name, halflife or decay mode associated with each daughter in the decay series. Decay mode information for a particular daughter relates to the type of decay *giving rise* to it rather than the type of decay it undergoes to produce the next daughter in the decay series (see figure below). To resize the




Column Heading	Detail
Ingestion (med.)	Dose per Bq ingestion
Ingestion f1 (med.)	Fractional transfer value
Inhale 5 micron (fast)	Dose per Bq inhalation of a 5 micron AMAD aerosol
Inhale 1 micron (fast)	Dose per Bq inhalation of a 1 micron AMAD aerosol
Inhale f1 (fast)	Fractional clearance value
Ingestion (fast)	Dose per Bq ingestion
Ingestion f1 (fast)	Fractional transfer value
Abundance	Fractional abundance for a naturally occurring isotope
Notes	Notes about the selected nuclide
Frac. Metastable	Fractional generation of the nuclide from its principal parent

The references to 'slow', 'medium' and 'fast' in the inhalation and ingestion fields refer to the definitions given in ICRP¹⁰, Publication 68⁽¹⁷⁰⁾ for uptake rates. Type S (slow) denotes an uptake rate by the exposed tissue of 0.1% in 10 minutes (7000 days for 99.9% uptake), type M (medium) an uptake rate of 10% in 10 minutes (140 days for 90% uptake) and type F (fast) an uptake rate of 100% in 10 minutes.

f1 values refer to the fraction of an intake which is taken up systemically following ingestion and to the fraction cleared to the gut by the 'pulmonary ciliary escalator' following inhalation; these values are consistent with ICRP, Publication 68. f1 values are a critical determinant of personal dose and are highly dependent upon chemical form and, in the case of inhalation, upon particle size. The values quoted in IAEA Safety Series 115⁽³⁾ and used by the Health Physicist's Companion are those for either 'worst case' or commonplace radionuclide compounds (see Annexes E and F of ICRP 68).

The grid headings can be mouse-dragged¹¹ to new positions, thereby allowing you to alter the order of columns in the grid; you can also use mouse-dragging to resize the columns by dragging their boundaries. In either case, the changes you make are stored in the registry and reinstated each time you run the Health Physicist's Companion.

 This spin-box is used in serial decay calculations; use it to set the display precision for calculated serial decay values. The value you select determines the number of significant figures used to *display* calculation results; it does not affect the precision of the calculation process itself.


   Click this button to view the decay series for the radionuclide currently selected in the Nuclide Selection page. To quit the decay series build process at any time, press the <Escape> key. The two radio buttons to the left of this button allow the primary branch of the decay tree to be built from the daughters with either the highest or lowest probability of occurrence.


NB. The decay series is built by successive interrogation of the radionuclide database and so, for radionuclides that have a large number of daughters, this may take some time.

Using the decay tree window

The outline (tree) component to the left of the page displays diagrammatically the decay tree for the selected radionuclide. You can select a nuclide in the decay tree by either clicking its icon with the mouse or by using the keyboard cursor keys; double-clicking a daughter icon 'toggles' between expansion and collapse of the decay tree at the icon's position.

The two buttons just below the decay tree component have the following functions:

 'Toggles' between full-screen and split-screen views of the decay tree.

 'Toggles' between expanded and collapsed views of the decay tree.

¹⁰ ICRP - International Commission on Radiological Protection.

¹¹ Mouse-Dragging - is a Microsoft Windows term for a technique of moving or resizing an object on the screen. It's achieved by selecting a screen object such as a grid or table heading with the mouse and then, simultaneously, moving the mouse whilst keeping its left button depressed.

You can also right-click anywhere in the decay tree panel to display an options menu. This menu is also accessible from the 'Serial Decay' menu bar at the top of the page.

Using the nuclide data grid

As you move between daughters using the methods described above, you will notice that the grid pointer in the right-hand pane moves to the corresponding record in the nuclide database. This allows you to immediately identify the data that relate to the daughter you have selected in the decay tree.

You can 'toggle' between full and partial display of the grid (i.e. zoom and reduce it) by double-clicking anywhere within it. You can also adjust the relative proportions of the page taken up by the decay tree and data grid by mouse-dragging¹² the blue line (splitter-bar) that separates these two panes.

You can 'toggle' on and off any combination of display fields by right-clicking anywhere in the grid to display a pop-up menu. When you do this, the following options are available.

Element	A	Z	Halflife	Decay 1	x100%	Decay 2	x100%
Hg	206	80	4.31	0.63			
Tl	206	81		1			
Tl	207	81	53	1			
Pb	210	82		0.06	b-0.70	0.42	
Pb	210	82		0.63	0.19	b-0.016	0.81
Pb	206	82					

Serial decay calculations

You can complete serial decay calculations on the decay tree's major branch. Enter a decay time and parent starting quantity radioactivity in the edit boxes at the top of the page and then click the 'Calculate' button. Results are displayed in the decay tree window (see Figure 10 and figure below). The spin-box next to the

'Calculate' button allows you to select the precision that is used to display calculation results.

Any serial decay calculations you carry out will only be applied to the primary branch of the decay tree. Therefore, if the daughters for which you want to calculate serial decay values are not in the major branch of the decay series, you will need to re-sort and rebuild it.

Z	Element
82	Pb
82	Pb
83	Bi
83	Bi
84	Po
84	Po
84	Po
85	At
86	Rn

To do this, use the 'Sort' option in the decay tree pop-up menu (shown left) or the 'Serial Decay' menu accessible from the menu bar at the top of the page.

The Calculator uses the Bateman serial decay equations to compute daughter radioactivities; these equations produce accurate daughter activity values but are very processor intensive and may yield results that lie outside the number resolution of the software. When this occurs, the Health Physicist's Companion places a zero value in the corresponding daughter branch of

the decay tree and continues to compute results for the other daughters in the decay chain. However, this situation will only arise in circumstances where your entered decay time is many orders of magnitude different from that of the half-life of the parent radionuclide and where the decay series contains a radionuclide whose immediate daughter has a half-life that is many orders of magnitude different from its own. In this regard, serial decay calculations involving transuranic decay series may well suffer from this zero entry anomaly if your entered decay time is too small. To solve this problem, increase the decay time to a value that produces an entry for every daughter in the decay series.

You can also complete maximal 'in-growth' radioactivity calculations for any daughter or the entire decay series. To do this, first select a radionuclide other than the parent by clicking its icon in the decay tree window. Next, right-click the icon to display the options menu and select 'Equilibrium Calculations'. After you have chosen a calculation accuracy from this menu, the Calculator will compute the time taken for the selected daughter(s) to achieve maximal quantity radioactivities.

¹² Mouse-Dragging - is a Microsoft Windows term for a technique of moving or resizing an object on the screen. It's achieved by selecting a screen object such as a grid or table heading with the mouse and then, simultaneously, moving the mouse whilst keeping its left button depressed.

The Calculator assumes that, at time zero, only the parent is present.

In the case of long-chain decay series, it may take several minutes for the Calculator to compute maximal quantity radioactivities for each of the daughters in the decay series, especially if you choose the +/- 0.001 percent accuracy option. If you want to quit the calculation process before the Calculator has finished computing results, press the escape key at anytime.

NB. When the escape key is pressed, termination is delayed until the current daughter calculations have been completed (i.e. the nuclide whose decay series number is shown in the progress dialogue box). You may therefore have to wait a while for termination to occur.

The 'Branching' tick-box (check-box) at the top of the page is used in serial decay calculations. If you want these calculations to take account of fractional decay coefficients, tick (check) this box.

If you leave this box unticked (unchecked), the Calculator uses fractional decay coefficients of unity (i.e. 100% decay for each mode) in the calculation of quantity radioactivities for each daughter in the decay series.

Using the menu options

The menu options available for this page are as follows.

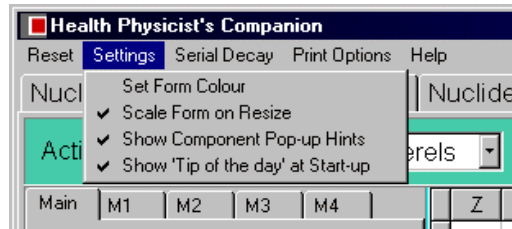
Choose:

'Clear page' to clear data in the currently selected page or 'Clear All' to clear data in all pages.



Choose:

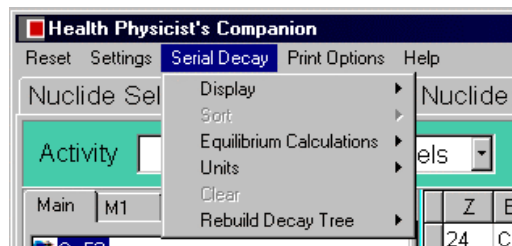
'Set Form Colour' to change the background colour of the main form; 'Scale Form on Resize' if you want all components on the form to resize automatically when you change the size of the form; 'Show Component Pop-Up Hints' if you want to view a small help dialogue as you move the mouse over components within the form or 'Show Tip of the Day at Start-up' if you want to view a useful hints dialogue every time you run the Health Physicist's Companion.



NB. New settings are permanently stored so that, each time you use the Health Physicist's Companion, your preferences are reinstated.

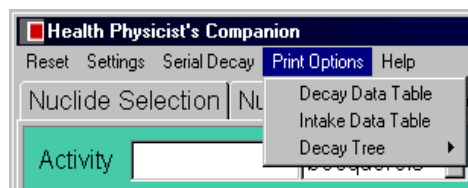
Choose:

'Serial Decay' to complete 'equilibrium' calculations. This menu is identical to the pop-up menu that is opened by right-clicking the decay tree pane.



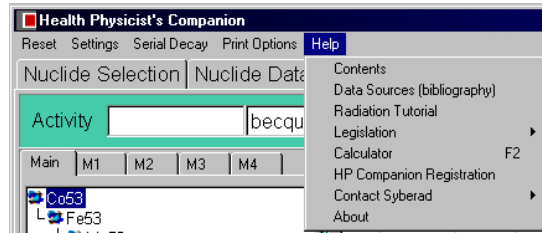
Choose:

'Decay Data Table' or 'Intake Data Table' to print a table of physical data relating to the daughters of the currently selected parent nuclide or, 'Decay Tree' to print a decay tree schematic for the currently selected parent nuclide.



Choose:

'Contents' to display the Companion's help contents, index and search dialogue; 'Data Sources' for information about the data sources the Companion uses for its calculations; 'Radiation Tutorial' for summary information about ionising radiation; 'Legislation' for information about ionising radiation legislation in the United Kingdom; 'Calculator' to open the HP Calculator utility; 'HP Companion Registration' to register your copy of the Health Physicist's Companion with Syberad; 'Contact Syberad' for information about how to contact Syberad or 'About' for information on the version of the Health Physicist's Companion you currently have installed on your PC.



Chapter 7 - X-ray Sets Page

What can I do with the x-ray calculator?

The X-ray page enables you to calculate typical x-ray dose rates, in soft tissue, for two types of x-ray set namely, constant potential¹³ and pulsed¹⁴.

The Calculator produces a table of dose rates for a tube electric current and measurement distance entered by the user. Data are displayed for a number of tube voltages and beam hardening filter materials.

Dose rates are computed from an empirical database of typical x-ray set outputs. Calculated values should therefore only be used as a *guide* to the dose rates likely to be produced in practice.

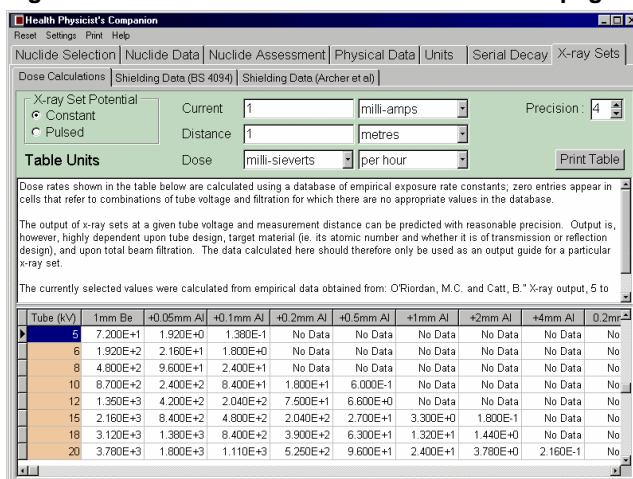
X-ray set output efficiency varies significantly between different makes and models, even in circumstances where generator designs are similar; cathode electron emissivity per unit current and photon production efficiency at the anode target are the main factors that affect output characteristics. The data generated by the Calculator should therefore be interpreted with these factors in mind.

The Calculator also enables x-ray transmission, through typical shielding materials, to be estimated.

How do I calculate x-ray dose rates?

An example of the dose rate calculator is shown in Figure 11.

Figure 11 - Screen-shot of the dose calculations page



Information about the components shown in Figure 11

Current X-ray tube electric current.

milli-amps X-ray tube electric current unit.

Distance Separation distance between the measurement/exposure location and the x-ray tube.

metres Distance unit used calculations.

milli-sieverts Dose unit to be used for the display of calculated dose rates.

per hour Time unit used for the display of dose rates.

¹³ Fully rectified and 'smoothed' x-ray tube voltage.

¹⁴ Half-wave rectified 'un-smoothed' x-ray tube voltage.

Tube (kV)	1mm Be	+ 0.05mm Al
4.0	3.0E+0	No Data
4.5	1.0E+1	No Data

This grid displays dose rate calculator results for various types of x-ray filtration. A zero entry in a cell indicates that the Calculator was unable to evaluate the dose rate for that combination of tube voltage and filtration: the Calculator's database doesn't contain dose rate constant values for every combination of tube voltage and filtration.

Filtration examples:


- 1mm Be Denotes a 1 mm thick beryllium filter.
- + 0.05mm Al Denotes a filter consisting of 1mm of beryllium and 0.05 mm of aluminium.


Column heading key:

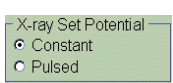
- +
 - **
- Denotes addition of the specified thickness of aluminium to 1mm of beryllium.
Denotes a reflection target.

Double-click anywhere in the grid to 'toggle' between zoomed and minimized table views. To manually resize the grid, use the left-mouse button to 'drag' the blue horizontal line (splitter-bar) at the top of the grid to a new position.

NB. Right-click anywhere in the grid to access the grid display options menu.

 Select the dose rate precision for the results shown in the table below.

 When this button is enabled, you can print a table of the dose rate values shown in the grid (table) at the bottom of the form.

 Selects the type of x-ray tube upon which to base calculations. Constant potential refers to a full-wave rectified and 'smoothed' tube power supply and 'Pulsed' to a half-wave rectified power supply.

Customizing the data grid

The data grid can be customized in several ways. Right-clicking anywhere in the grid opens a pop-up menu that allows you to select the fields the grid displays.

Tube (kV)	1mm Be	+0.05mm Al
		1.92e00
		2.16e01
		9.6e01
		2.4e02
		4.2e02
		8.4e02
18	3.12e03	1.38e03

Double-clicking the grid, 'toggles' between zoomed and minimized views of the data. You can also manually resize the data grid by using the left-mouse button to 'drag' the blue line (splitter-bar) at the top of the grid to a new position.

How do I use the shielding calculator?

The Health Physicist's Companion uses two sets of empirical data to calculate x-ray attenuation in various materials: those published in British Standard 4094 and those published by Archer et al⁽⁵²⁾.

For high energy x-ray beams, you should use the BS 4094 data set; the data published by Archer will give the most accurate results for low to intermediate energy, medical x-ray equipment.

Dose Rate Data Sources

Dose rate values are calculated from data published in the Handbook of Radiological Protection⁽⁴⁾, hereafter referred to as the RSAC publication. These data are also reproduced in British Standard 4094. The following figures from the British Standard and RSAC publication were used to define the curve-fit functions used by the Calculator.

Pulsed X-ray Tube Dose Rates

Tube (kV)	Reference	Total Beam Filtration
4 - 50	<p>BS4094, Figure 1. "X-ray output 4 kV to 50 kV pulsating potential". Data sourced from W.A Jennings, "Physical aspects of roentgen radiation from a beryllium window tube operated over the range 2 - 50 kVp for clinical purposes." Acta Radiologica, 33, 435-484 (1950).</p> <p>In the RSAC publication, the same data are shown in Figure 3.2(1) "Output of pulsating potential x-ray tubes (5-50 kV)".</p> <p><i>NB. Pulsating potential refers to half-wave rectification of the tube supply voltage.</i></p>	<p>1mm Be plus various thicknesses of Al up to 3.22mm.</p> <p>Tungsten reflection target.</p>

Constant Potential X-ray Tube Dose Rates

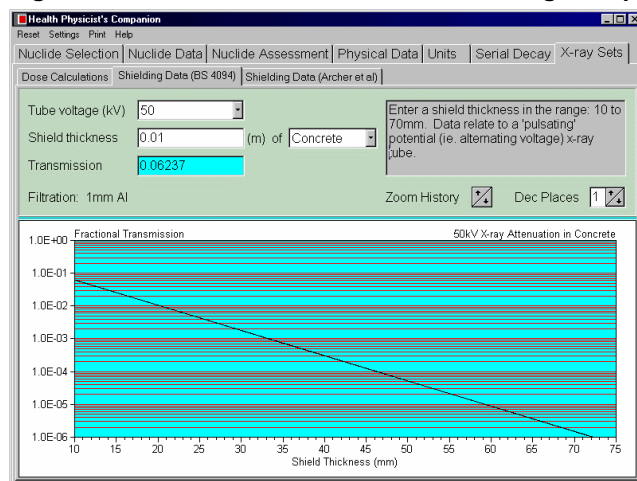
Tube (kV)	Reference	Total Beam Filtration
5 - 50	<p>BS4094, Figure 2. "X-ray output 5 kV to 50 kV constant potential". Data sourced from M.C Riordan and B Catt, "X-ray output, 5 to 50 kV, constant potential". RPS/I/32, Radiological Protection Service, Sutton (1968). In the RSAC publication, the same data are shown in Figure 3.2(2) "Output of constant pot. X-ray tubes (5-50 kV)".</p>	<p>1mm Be plus various thicknesses of Al up to 4 mm.</p> <p>Tungsten reflection target.</p>
50 - 200	<p>BS4094, Figure 3. "X-ray output 50 kV to 200 kV constant potential". Data sourced from H Glasser, E.H Quimby, L.S Taylor and J.L Weatherwax, "Physical foundations of radiology". Hoeber, New York (1954). In the RSAC publication, the same data are shown in Figure 3.2(3) "Output of constant potential x-ray tubes (50-200 kV)".</p> <p><i>NB. For half-wave generators, the output is approximately 30-50% of the value calculated for a constant potential x-ray set.</i></p>	<p>Various filtration. Tungsten reflection target.</p>
200 - 500	<p>BS4094, Figure 4. "X-ray output 200 kV to 500 kV constant potential". Data sourced from:</p> <p>For 0.5mm Cu filtration; G.W.C Kaye, and W Binks, "The emission and transmission of X and gamma radiation". British Journal of Radiology, 13, 193-212 (1940). For 3mm Cu filtration; W Miller and R.J Kennedy, "X-ray attenuation in lead, aluminium and concrete in the range 275 to 525 kilovolts". British Journal of Radiology, 65, 920-925 (1955). In the RSAC publication, the same data are shown in Figure 3.2(4) "Output of constant potential x-ray tubes (200-500 kV)".</p> <p><i>NB. For half-wave generators, the output is approximately 30 - 50% of the constant potential calculated value.</i></p>	<p>0.5 and 3 mm Cu. Tungsten reflection target.</p>

Tube (kV)	Reference	Total Beam Filtration
200 - 3000	<p>BS4094, Figure 5. " X-ray output 0.2 MV to 3 MV constant potential". Data sourced from:</p> <p>For 0.5mm Cu filtered reflection target; G.W.C Kaye and W Binks, "The emission and transmission of X and gamma radiation". British Journal of Radiology, 13, 193-212 (1940).</p> <p>For 2.3mm Pb filtration; A.A Petrauskas, L.C Van Atta and F.E Myers, "Measurements on X-ray production and absorption in the range 0.7 to 2.5 MV". Physical Review, 63, 389-399 (1943).</p> <p>For complex filtration; H.O Wyckoff, R.J Kennedy and W.R Bradford, "Broad and narrow beam attenuation of 500 to 1400 kV X-rays in lead and concrete." British Journal of Radiology, 51, 848-859 (1948). In the RSAC publication, the same data are shown in Figure 3.2(4) "Output of constant potential x-ray tubes (0.5 - 3 MV)".</p> <p><i>NB. For half-wave generators, the output is approximately 30 - 50% of the calculated value.</i></p>	<p>0.5 mm Cu. Tungsten reflection target.</p> <p>2.3 mm Pb equivalent total filtration. Gold transmission target.</p> <p>W+Cu+Brass+water. Tungsten transmission target. Lead equivalencies in (mm): 0.5MV = 5.0 0.6MV = 5.6 0.8MV = 6.2 1.0MV = 7.0 1.4MV = 7.8 2.0MV = 9.2 3.0MV = 10.0</p>

Using British Standard 4094 data for shielding calculations

The transmission values published in the British Standard are also cited in the Handbook of Radiological Protection (RSAC). An example is shown in Figure 12

Figure 12 - Screen-shot of the BS4094 Shielding Data page



Information about the components shown in Figure 12

X-ray tube operating voltage, in kilovolts.

Shield thickness in metres. The fractional x-ray transmission is automatically calculated and displayed in the field below as you type.

NB. Take note of the acceptable input range for the selected x-ray tube voltage. This is indicated in the panel at the top-right of the page.

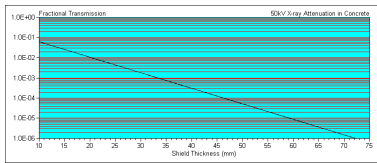
Shield material to be used in transmission calculations.

Enter a shield thickness in the range 10 to 70mm. Data relate to a pulsating potential (ie. alternating voltage) x-ray tube.


Displays information about the shield thickness acceptable input range.



Number of decimal places to display on the axes of the graph below.



Double-click anywhere in the graph to 'toggle' between zoomed and minimized views. To resize the graph manually, use the left-mouse button to 'drag' the blue line (splitter-bar) at the top of the graph to a new position.

You can also change graph scaling by using the zoom function. To do this, mouse-drag¹⁵ anywhere within the graph, starting at the lowest x and y co-ordinate you wish to display and then moving the mouse to the highest x and y co-ordinate you wish to display. As you do this, the mouse icon changes to a small square, with an arrow inside it, and the new 'zoomed' graph size is shown as an outline rectangle as you move the mouse. To make a displayed graph fill the entire page, double-click with the mouse anywhere within it; double-clicking again will revert the graph to its original size. Zoomed views, once created, can be selectively displayed by clicking on the 'Zoom History' buttons  above the displayed graph. These buttons are only effective once you have created a set of zoomed views by mouse-dragging within a displayed graph.

X-ray Set Shielding Data Sources (Industrial)

These data were obtained from British Standard 4094⁽⁵⁰⁾; the following figures were used to define the curve-fit functions used by the Calculator.

Concrete Shield Transmission Values

Tube (kV)	Reference	Total Beam Filtration
50	BS4094, Figure 8. "Transmission of 50 kV to 300 kV pulsating potential x-rays through concrete". Data sourced from E.D. Trout, J.P. Kelley and A.C Lucas, Radiology 72, 1959, pp 62-69. The same data are shown in the RSAC publication, Figure 4.3(1) "Broad beam transmission of x-rays (pulsating potential) through concrete (50-300kV)".	1.0 mm Al. Tungsten reflection target. <i>NB. Pulsating potential refers to half-wave rectification of the tube supply voltage.</i>
70	"	1.5 mm Al "
100	"	2.0 mm Al "
125	"	3.0 mm Al "
150	"	3.0 mm Al "
200	"	3.0 mm Al "
250	"	3.0 mm Al "
300	BS4094, Figure 13. "Transmission of 300 kV to 400 kV constant potential x-rays through concrete". Data sourced from W. Miller and R.J Kennedy, "X-ray attenuation in lead, aluminium and concrete in the range 275 to 525 kV", Radiology 65, 1955, pp 920-925. In the RSAC publication, the same data are shown in Figure 4.3(2) "Broad beam transmission of x-rays (constant potential) through concrete (300-400kV)".	3.0 mm Cu. Gold reflection target.

¹⁵ Mouse-Dragging - is a Microsoft Windows term for a technique of moving or resizing an object on the screen. It's achieved by selecting a screen object such as a grid or table heading with the mouse and then, simultaneously, moving the mouse whilst keeping its left button depressed.

Tube (kV)	Reference	Total Beam Filtration
400	"	3.0 mm Cu. Gold reflection target.
500	BS4094, Figure 14. "Transmission of 0.5 MV to 3.0 MV constant potential x-rays through concrete". Data sourced from H.O Wyckoff, R.J Kennedy and W.R Bradford, "Broad and narrow beam attenuation of 500 to 1400 kV X-rays in lead and concrete", Radiology 51, 1948, pp 849-859. In the RSAC publication, the same data are shown in Figure 4.3(3) "Broad beam transmission of x-rays (constant potential) through concrete (0.5-3MV)".	2.8 mm W + 2.8 mm Cu + 2.1 mm brass + 18.7 mm water. (Pb equivalent 5mm). Tungsten transmission target.
1000	"	"
2000	BS4094, Figure 14. "Transmission of 0.5 MV to 3.0 MV constant potential x-rays through concrete". Data sourced from W.W Evans, R.C Granke, K.A Wright and J.G Trump, "Absorption of 2 MeV constant potential roentgen rays by lead and concrete", Radiology 58, 1952, pp 560-567. In the RSAC publication, the same data are shown in Figure 4.3(3) "Broad beam transmission of x-rays (constant potential) through concrete (0.5-3MV)".	6.8 mm Pb equivalent. Van de Graff generator.
3000	BS4094, Figure 14. "Transmission of 0.5 MV to 3.0 MV constant potential x-rays through concrete". Data sourced from C.H Goldie, K.A Wright, J.H Anson, W.R Cloud and J.G Trump, "Radiographic properties of X-rays in the two to six million volt range", American Society for Testing Materials Bulletin, No. 201, 1954, pp 49-54. In the RSAC publication, the same data are shown in Figure 4.3(3) "Broad beam transmission of x-rays (constant potential) through concrete (0.5-MV)".	11 mm Pb equivalent. Van de Graff generator.

Lead Shield Transmission Values

Tube (kV)	Reference	Total Beam Filtration
50	BS4094, Figure 11. "Transmission of 50 kV to 200 kV constant potential x-rays through lead". Data sourced from W. Binks, "Protection in Industrial Radiology", British Journal of Radiology 16, 1943, pp 49-53. In the RSAC publication, the same data are shown in Figure 4.3(7) "Broad beam transmission of X-rays (constant potential) through lead (50-200kV)".	0.07 mm Cu or 2 mm Al. Tungsten reflection target.
75	"	0.07 mm Cu or 2 mm Al. Tungsten reflection target.
100	"	0.07 mm Cu or 2 mm Al. Tungsten reflection target
150	"	0.07 mm Cu or 2 mm Al. Tungsten reflection target.
200	"	0.07 mm Cu or 2 mm Al. Tungsten reflection target.

Tube (kV)	Reference	Total Beam Filtration
250	BS4094, Figure 12. "Transmission of 250 kV to 400 kV constant potential x-rays through lead". Data sourced from W. Binks, "Protection against x-rays and gamma rays in the industrial field", British Journal of Industrial Medicine 12, 1955, pp 153-161. In the RSAC publication, the same data are shown in Figure 4.3(8) "Broad beam transmission of x-rays (constant potential) through lead (250-400kV)".	0.5 mm Cu. Tungsten reflection target.
300	"	0.5 mm Cu. Tungsten reflection target.
400	BS4094, Figure 12. "Transmission of 250 kV to 400 kV constant potential x-rays through lead". Data sourced from W. Miller and R.J Kennedy, "X-ray attenuation in lead, aluminium and concrete in the range 275 to 525 kilovolts", Radiology 65, 1955, pp 920-925. In the RSAC publication, the same data are shown in Figure 4.3(8) "Broad beam transmission of x-rays (constant potential) through lead (250-400kV)".	3.0 mm Cu. Gold reflection target.
500	BS4094, Figure 15. "Transmission of 0.5 MV to 2.0 MV constant potential x-rays through lead". Data sourced from H.O Wyckoff, R.J Kennedy and W.R Bradford, "Broad and narrow beam attenuation of 500 to 1400 kV X-rays in lead and concrete", Radiology 51, 1948, pp 849-859. In the RSAC publication, the same data are shown in Figure 4.3(9) "Broad beam transmission of x-rays (constant potential) through lead (0.5-2 MeV)".	2.8 mm W + 2.8 mm Cu + 2.1 mm brass + 18.7 mm water (Pb equivalent 5 mm). Tungsten transmission target.
1000	"	2.8 mm W + 2.8 mm Cu + 2.1 mm brass + 18.7 mm water (Pb equivalent 7 mm). Tungsten transmission target.
2000	BS4094, Figure 15. "Transmission of 0.5 MV to 2.0 MV constant potential x-rays through lead". Data sourced from W.W Evans, R.C Granke, K.A Wright and J.G Trump "Absorption of 2 MeV constant potential roentgen rays by lead and concrete", Radiology 58, 1952, pp 560-567. In the RSAC publication, the same data are shown Figure 4.3(9) "Broad beam transmission of x-rays (constant potential) through lead (0.5-2 MeV)".	6.8 mm Pb equivalent. Van de Graff generator.

X-ray transmission generally reduces exponentially with increasing shield thickness, and so most of the curves you can view on this page of the Health Physicist's Companion are linear when plotted on logarithmic scales. The slight upward curvature of the low energy lead shield plots is due to 'beam hardening' effects at small shield thicknesses (i.e. the attenuation coefficient is initially higher than the average for the plot). As an x-ray beam enters a shield, low energy photons are absorbed more readily than those at the peak energy determined by the tube voltage. The effective attenuation coefficient therefore decreases with increasing shield thickness down to a value that is asymptotic with that for a mono-energetic x-ray beam of an energy equivalent to the tube voltage.

By contrast, some of the higher energy concrete shield plots show a slight downward curvature at small shield thickness values (i.e. the attenuation coefficient is initially lower than the average for the

plot). This is due to a quite different phenomenon; here we see the effect of radiation field build-up on the effective attenuation coefficient. The lead shield plots do not show this trend because 'beam hardening' effects in lead are more dominant at small shield thicknesses than in concrete.

X-ray Set Medical Shielding Data (Archer et al⁽⁵¹⁾)

An example of this page is shown in Figure 13. Shielding calculations using Archer's data are based on an empirical x-ray attenuation curve-fitting formula of the following form:

$$\text{Broad-beam attenuation} = \left[\left(1 + \frac{b}{a} \right) \exp(\alpha g x) - \frac{b}{a} \right]^{-\left(\frac{1}{g}\right)}$$

Where:

- x is the linear thickness of the shielding material and,
- α , β and γ are empirically determined coefficients applicable to the units of x .

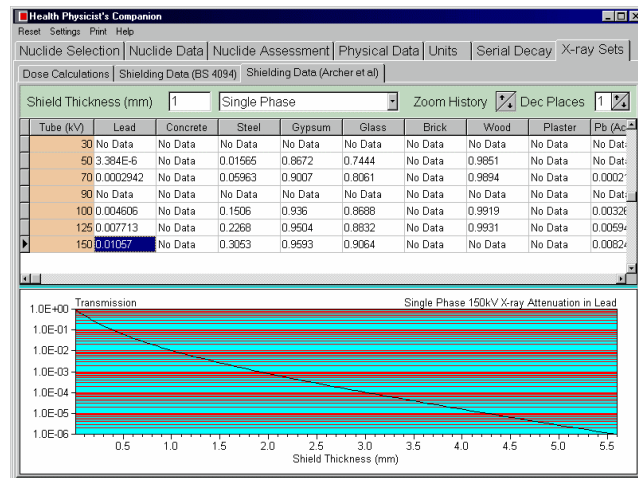
The materials for which Archer has determined appropriate coefficients are as follows.

Material	Density (g cm ⁻³)
Lead	11.35
Steel	7.40
Glass (plate)	2.56
Gypsum (wallboard)	0.75
Lead acrylic	1.60
Concrete	2.35
Brick	1.65
Wood	0.55
Plaster (barium)	Unspecified

The data published by Archer, and used by the Calculator, relate to single and multiple phase x-ray sets. Typical parameters for these equipment types are as follows.

Parameter	Single Phase	Three Phase
Max mA	300	1000 at 80 kVp
Max kVp	150	150
Tube insert	Maxiray 75	MX-100
Target angle	15 degrees	12.5 degrees
Focal spot size	2.0mm	1.5mm
Collimator	Machlett-Dudcon M	GE-Sentry Three
1 st Half Value Layer (100 kVp)	2.87mm Al	3.49mm Al
2 nd Half Value Layer (100 kVp)	7.12mm Al	8.79mm Al


Figure 13 - Screen-shot of the Archer Shielding Data page




Information about the components shown in Figure 13

Shield Thickness (mm) Shield thickness, in millimetres, used in transmission calculations. The fractional x-ray transmission values are automatically calculated and displayed in the grid (table) below.

Single Phase X-ray tube type; see descriptions earlier in this section.

 Click the up-arrow to go back to the previous zoomed view or the down-arrow to go to the next zoomed view. NB. These buttons are only effective once you have created a set of zoomed views by mouse-dragging within a displayed graph.

 Number of decimal places to display on the axes of the graph.

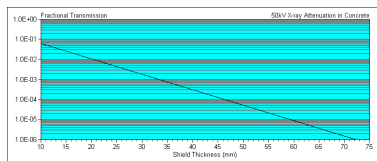
Tube (kV)	Lead	Concrete
30	No Data	No Data
50	1	No Data

Click on a cell within the grid to display the associated x-ray transmission curve. The value shown in each cell is the fractional transmission through a shield of the material denoted by the cell's column heading, at your entered thickness value, and at the x-ray tube voltage denoted by the cell's row heading.

When you enter a new shield thickness value or change the x-ray tube type in the two fields above the grid, the displayed transmission values are automatically updated.

The displayed graph is also updated as you change the selected cell in the grid. You can do this by either clicking a new cell with the mouse or by using the keyboard cursor keys.

NB. Each time the selected cell is changed, the zoom history buffer is cleared.



Double-click anywhere in the graph to 'toggle' between zoomed and minimized views.

To resize the graph manually, use the left-mouse button to 'drag' the blue line (splitter-bar) at the top of the graph to a new position.

How do I configure and print displayed graphs?

The graphs displayed in both the BS4094 and Archer shielding pages can be printed by clicking the right-mouse button anywhere within them and then selecting <Print Graph> when the pop-up menu displays.

You can also change graph scaling by using the zoom function. To do this, mouse-drag¹⁶ anywhere within the graph, starting at the lowest x and y co-ordinate you wish to display and then moving the mouse to the highest x and y co-ordinate you wish to display. As you do this, the mouse icon changes to a small square, with an arrow inside it, and the new 'zoomed' graph size is shown as an outline rectangle as you move the mouse.

Zoomed views, once created, can be selectively displayed by clicking on the 'Zoom History' buttons above the displayed graph.

To make a displayed graph fill the entire page, double-click with the mouse anywhere within it; double-clicking again will revert the graph to its original size.

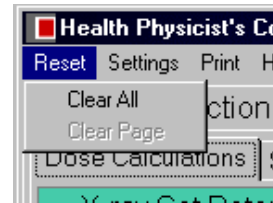
¹⁶ Mouse-Dragging - is a Microsoft Windows term for a technique of moving or resizing an object on the screen. It's achieved by selecting a screen object such as a grid or table heading with the mouse and then, simultaneously, moving the mouse whilst keeping its left button depressed.

Using the menus

The menu options available for this page are as follows.

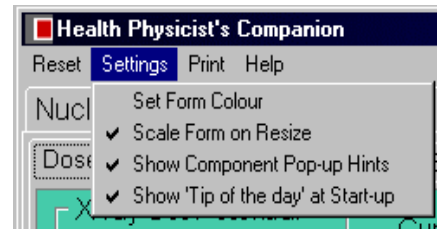
Choose:

'Clear page' to clear data in the currently selected page or 'Clear All' to clear data in all pages.



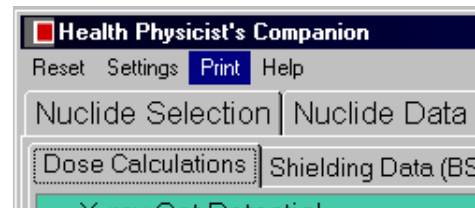
Choose:

'Set Form Colour' to change the background colour of the main form; 'Scale Form on Resize' if you want all components on the form to resize automatically when you change the size of the form; 'Show Component Pop-Up Hints' if you want to view a small help dialogue as you move the mouse over components within the form or 'Show Tip of the Day at Start-up' if you want to view a useful hints dialogue every time you run the Health Physicist's Companion.



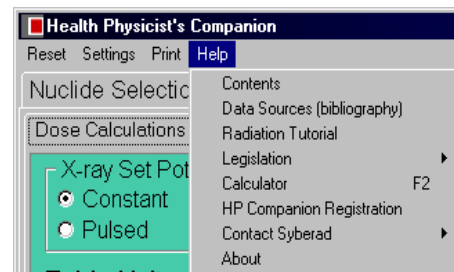
NB. New settings are permanently stored so that, each time you use the Health Physicist's Companion, your preferences are reinstated.

Prints a screen-shot of the data in the displayed page.



Choose:

'Contents' to display the Companion's help contents, index and search dialogue; 'Data Sources' for information about the data sources the Companion uses for its calculations; 'Radiation Tutorial' for summary information about ionising radiation; 'Legislation' for information about ionising radiation legislation in the United Kingdom; 'Calculator' to open the HP Calculator utility; 'HP Companion Registration' to register your copy of the Health Physicist's Companion with Syberad; 'Contact Syberad' for information about how to contact Syberad or 'About' for information on the version of the Health Physicist's Companion you currently have installed on your PC.



Chapter 8 - Radon and Thoron

Radon Hazards and Metrology

Radon is a colourless, odourless, gaseous radioactive element of atomic number 86 and mass numbers in the range 198 to 227. All isotopes are radioactive, the most important being those that arise in the primordial decay series of Uranium and Thorium. The radon isotope formed in the thorium series is often referred to as thoron.

Radon Isotopes:

Isotope	Decay Series Name	
Rn 222	Uranium series	(4N+2) - Uranium 238 parent
Rn 220	Thorium series	(4N) - Thorium 232 parent
Rn 225	Neptunium series	(4N+1) - Plutonium 241 parent
Rn 219	Actinium series	(4N+3) - Uranium 235 parent

The effective dose arising from exposure to radon (Rn222) and thoron (Rn 220) daughters is almost entirely due to their deposition in the lung during respiration and results in an increase in the risk of lung cancer. Estimates of the lung cancer risk have been made from epidemiological studies of cohorts known to have received significant radon daughters exposure namely, uranium and tin ore miners (ICRP, Publication 65⁽¹⁶⁷⁾).

Exposure of these miners has historically been expressed in terms of working levels (WL); this was originally defined as any combination of radon daughters, and later by extension thoron daughters, present in 1 litre of air at normal temperature and pressure which had the potential to release 1.3×10^5 MeV of alpha particle energy during their ultimate decay. This energy approximates to that released by radon daughters in secular equilibrium with 100 pico-curies (pCi) [3.7Bq] per litre of radon 222 gas.

Historically, time-integrated radon daughter exposure has been measured in working level months (WLM), where a month is taken to be 170 hours (i.e. the number of hours worked by industrial workers during a typical month). For radon gas in decay equilibrium with its daughters (i.e. the equilibrium factor is unity), the WLM is equivalent to an activity exposure of 6.29×10^5 Bq hours per cubic metre for radon and 4.63×10^4 Bq hours per cubic metre for thoron.

The potential alpha energy concentration in air (PAEC) is defined as the time-integrated alpha particle energy released during the total decay of all the short-lived radon daughters present in a unit volume of air. It is measured in units of energy per unit volume, normally as MeV per cubic metre.

For a given PAEC measurement, the equilibrium-equivalent radon gas concentration is that volumetric concentration of radon gas, which in secular equilibrium with its daughters, has the given PAEC. The difference between measured radon gas concentration and its corresponding equilibrium-equivalent concentration is therefore a measure of the degree to which a radon daughter mixture is in secular equilibrium with its parent radon gas. This difference is usually expressed as the ratio of equilibrium-equivalent concentration to measured radon gas concentration and is referred to as the equilibrium factor (F).

In domestic properties in the UK, F values are typically 0.5. Therefore, a radon gas concentration of 20 Bq per cubic metre in the home corresponds to an equilibrium-equivalent concentration of only 10 Bq per cubic metre. The primary determinant of the F value is environmental ventilation rate. Stagnant air environments, such as underground caves, tend to have very high F values (i.e. radon daughters are significantly equilibrated with the parent radon gas), whereas environments which have greater ventilation, such as homes, tend to have lower F values.

The estimation of radiation dose to the lungs resulting from exposure to radon daughters, expressed as WLMs, greatly depends upon the degree to which these radionuclides are attached to aerosols in respirable air and the degree to which they are in decay equilibrium with one another. Aerosol deposition in lung tissue depends upon particle diameter, breathing rates and occupancy. These factors make it very difficult to interpret epidemiological data, for conditions such as lung cancer, in

terms of effective dose. These problems are compounded by the difficulty in equating domestic radon daughter exposures with those arising in workplaces such as mines; equilibrium factors and exposure levels are of a quite different order in each of these environments.

In the UK, the National Radiological Protection Board (NRPB, 1990) recommends that action should be taken to reduce radon levels in homes if its gas concentration exceeds 200 Bq per cubic metre; this corresponds to an equilibrium-equivalent concentration of 100 Bq per cubic metre.

The Radon Calculator

The radon calculation fields are located at the bottom of the Units Page; their layout is shown in the diagram below.

You can't complete radon quantity calculations until you have entered a valid exposure time and radon gas equilibrium factor. Once you have done this, you can enter values in any of the radon quantity fields at the bottom-right of the page; all dependent quantities will be updated automatically as you type.

The Calculator can determine the following quantities:

- Radon Gas Concentration
- Potential Alpha Energy Concentration in Air (PAEC)
- Working level (WL)
- Working level month (WLM)
- Activity Exposure and
- Cancer risk.

These quantities have a serial relationship (as laid out in the Units page); each is related to the other by a scaling coefficient. For some quantities, these coefficients are also dependent upon the selected radon isotope, i.e. radon 222 or radon 220 (thoron). For more information, see the Radon Schematic on page 54.

The equilibrium factor is used to convert PAEC into an equivalent radon gas concentration. It should be set to unity for radon daughters that are known to be in complete equilibrium with their parent radon isotope. The radon gas concentration will have two values for any given PAEC, one for radon and another for thoron. If you have both radon gas concentration and PAEC data, you can calculate the equilibrium factor by clicking the 'Set Equilib Factor' check-box and entering the PAEC and radon gas concentration values.

The exposure time is used to convert working level and PAEC into a working level month (WLM) value and to convert the radon or thoron gas concentration (as the case may be) into an activity exposure value.

NB. The radon calculator converts exposure time values into Working Level Months (WLM) for the purpose of calculation. Since this quantity is based upon occupational (i.e. worker) exposure considerations, you should note the following equivalencies when entering an exposure time.

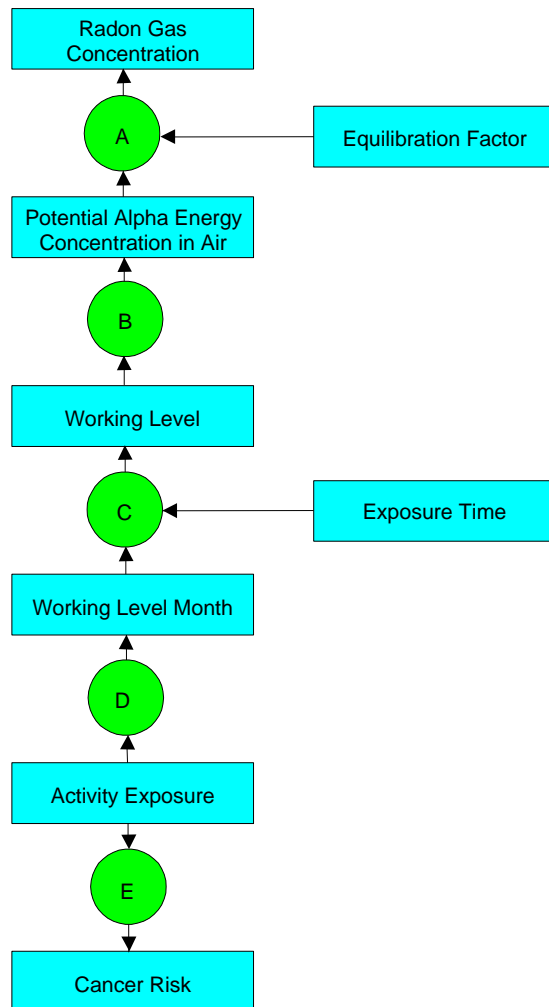
21.25	days	=	1	WLM
170	hours	=	1	WLM
10200	minutes	=	1	WLM
612000	seconds	=	1	WLM

If you want to calculate radon exposure for the general population, you should use the hours, minutes or seconds time quantities; the months and days time quantities are inappropriate for this purpose because they are based on 8 hour (i.e. a work shift) rather than 24 hour daily exposure.

Radon Calculator Schematic

The schematic below shows how the radon calculator computes radon quantities from your entered values. Each of the rectangular boxes represents a user-input field.

Radon Calculation Flow Diagram



When you change a value represented by a rectangular box in the schematic, the radon calculator updates all corresponding quantities. The algorithm works by incrementing the activity exposure from zero until your entered value is achieved. This programming design allows the use of a single coding method for the calculation of any entered radon quantity.

The circular symbols denote the calculation coefficients that are used; their values are as follows:

A - Radon gas concentration, in Bq per cubic metre, is equal to the product of coefficient A and the PAEC, in joules per cubic metre, divided by the equilibrium factor. Coefficient A has the value 1.81×10^8 for radon and 1.32×10^7 for thoron.

B - The working level is equal to the quotient of the PAEC, in MeV per cubic metre, and coefficient B. Coefficient B has the value 1.3×10^8 .

C - The working level month (WLM) is equal to the product of working level and the exposure time in months, where a month is 170 hours.

D - The activity exposure in Bq hours per cubic metre is equal to the time-integral of the radon or thoron gas concentration. For daughters in decay equilibrium with the parent radon or thoron gas, the activity exposure is equal to the product of coefficient D and the working level month value, where D has the value 6.29×10^5 for radon daughters and 4.63×10^4 for thoron daughters.

E - The lifetime cancer risk value is based upon the extrapolated probability of lung cancer death for both sexes. The figure includes smokers and non-smokers alike. Cancer risk is equal to the product of activity exposure, equilibrium factor and coefficient E.

For radon or thoron gas in decay equilibrium with its daughters, coefficient E has the value 4.5×10^{-10} and 6.1×10^{-9} respectively.

Cancer risk can also be expressed in terms of radon or thoron daughter time-integrated exposure; here the risk is 2.83×10^{-4} per WLM. For more information about radon quantity conversion coefficients, you should consult ICRP¹⁷, Publication 65⁽¹⁶⁷⁾.

NB. The radon calculator converts exposure time values into Working Level Months (WLM) for the purpose of calculation. Since this quantity is based upon occupational (i.e. worker) exposure considerations, you should note the following equivalencies when entering an exposure time.

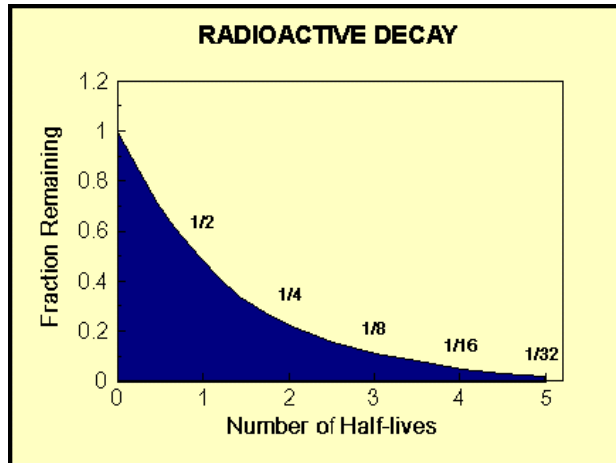
21.25	days	=	1	WLM
170	hours	=	1	WLM
10200	minutes	=	1	WLM
612000	seconds	=	1	WLM

If you want to calculate radon exposure for the general population, you should use the hours, minutes or seconds time quantities; the months and days time quantities are inappropriate for this purpose because they are based on 8 hour (i.e. a work shift) rather than 24 hour daily exposure.

¹⁷ ICRP - International Commission on Radiological Protection.

Chapter 9 - Radioactive Decay

Radioactive decay is a statistical exponential rate process. The number of atoms (N) likely to decay at any given moment (dN/dt) is proportional to the number of atoms present. The proportionality constant is given the Greek letter lambda (λ) and is referred to as the decay constant, its value varies greatly from one radionuclide to the next.



Radioactive decay can be represented mathematically as a first-order differential equation as follows:

$$Eq(1) \quad -\frac{dN}{dt} = \lambda N$$

This equation is readily integrated to give:

$$Eq(2) \quad N_{(t)} = N_0 e^{-\lambda t}$$

In which (N_0) is the number of atoms present at time (t) equals zero.

Equations 1 and 2 show that both the nuclear disintegration rate and the number of parent nuclei fall exponentially with time (see figure).

The time taken for the disintegration rate to reach half its original value, or for half the original number of atoms to disintegrate, is called the half-life ($t_{1/2}$). Equation (2) can therefore be restated in terms of half-life as follows:

$$Eq(3) \quad N_{(t)} = N_0 \left(\frac{1}{2}\right)^t \quad \text{where } t = \frac{t}{t_{1/2}}$$

The reciprocal of the decay constant (λ) gives the mean-life and is given the Greek letter tau (τ).

The decay constant (λ) and half-life ($t_{1/2}$) have the following relationship:

$$Eq(4) \quad \lambda = \frac{\log_e 2}{t_{(1/2)}} = \frac{0.693}{t_{(1/2)}}$$

For radionuclides that decay by more than one process (decay mode), the total decay constant is the sum of the partial decay constants for each decay mode. Potassium-40 is an example of such a radionuclide; it decays 89% of the time by beta emission (β^-) and 11% of the time by electron capture. The partial half-life for a particular decay mode is the reciprocal of the partial decay constant for that mode multiplied by $\ln 2$ (0.693).

When a radionuclide decays, it transmutes into another nuclide (daughter) which itself may also be radioactive. Some radionuclides go through a series of such decays before reaching a stable daughter nuclide. This process is called serial radioactive decay or transformation.

Consider the case of a radionuclide decay chain in which the parent (generation 1) of decay constant (λ_1) decays into a radioactive daughter (generation 2) of decay constant (λ_2). If the second-generation radionuclide is not present at time equals zero, it will appear exponentially as its parent decays but, like its parent, will eventually decay away; equation (5) mathematically describes this situation. The relation of parent to daughter decay rate is a function of their respective decay constants.

The number N_2 of daughter nuclei existing at time (t) in terms of the number $N_{1(0)}$ of parent nuclei present at time equals zero is given by:

$$Eq(5) \quad N_{2(t)} = \lambda_1 N_{1(0)} \frac{e^{-\lambda_1 t} - e^{-\lambda_2 t}}{\lambda_2 - \lambda_1}$$

Where (e) is the logarithmic constant 2.71828.

The general equation for a chain of (n) generations with only the parent initially present (when time equals zero) is as follows:

$$Eq(6) \quad N_{n(t)} = N_{1(0)} \left(C_1 e^{-I_1 t} + C_2 e^{-I_2 t} + \dots + C_n e^{-I_n t} \right) I_1 I_2 \dots I_{n-1}$$

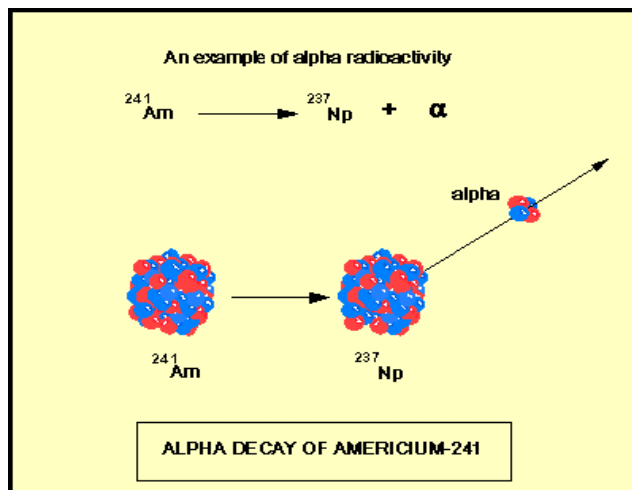
The coefficient values for equation (6) are given by:

$$Eq(7) \quad C_1 = \frac{1}{(I_2 - I_1)(I_3 - I_1) \dots (I_n - I_1)}$$

$$C_2 = \frac{1}{(I_1 - I_2)(I_3 - I_2) \dots (I_n - I_2)}$$

$$C_n = \frac{1}{(I_1 - I_n)(I_2 - I_n) \dots (I_{n-1} - I_n)}$$

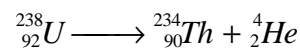
Alpha decay



In alpha decay, an energetic helium ion (alpha particle) is ejected, leaving a daughter nucleus of atomic number two less than the parent and of atomic mass number four less than the parent. Alpha decay is given the Greek symbol α .

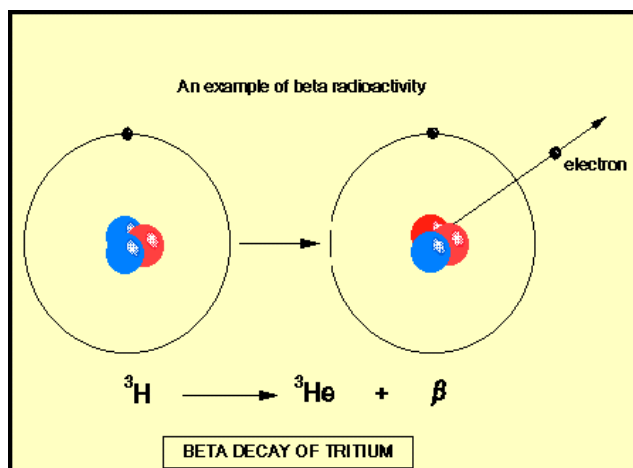
The energy released is given the symbol 'Q' and is measured in millions of electronvolts (MeV).

An example is the decay (symbolized by an arrow) of uranium 238 to a thorium daughter:



$$Q_a = 4.268 \text{ MeV} \quad t_{1/2} = 4.51 \times 10^9 \text{ years}$$

Beta decay

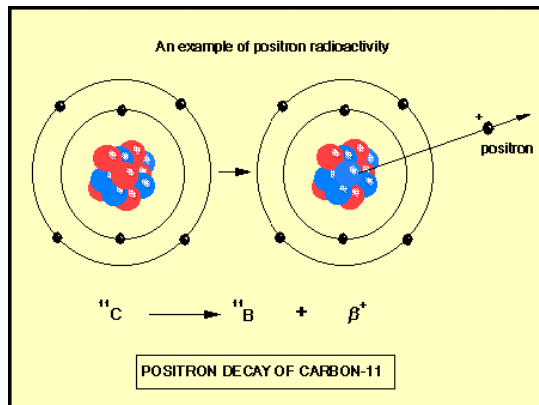


Beta decay is any of three processes of radioactive disintegration by which some unstable atomic nuclei spontaneously dissipate 'excess' nuclear energy and undergo a change of one unit of positive charge without any change in mass number. The three processes are called electron emission, positron (positive electron) emission, and electron capture.

In electron emission, an unstable nucleus ejects an energetic electron (of relatively negligible mass) and an anti-neutrino (with no rest mass). The energy needed to create the electron rest mass and its ejection kinetic

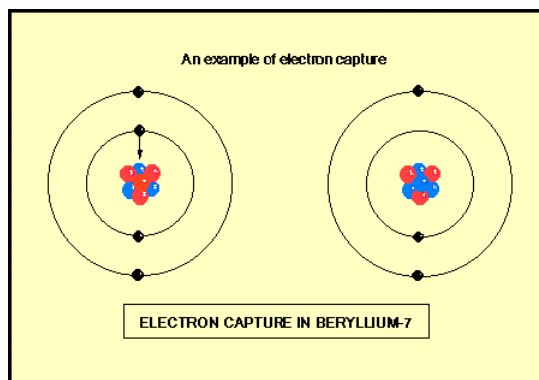
energy comes from the increase in nuclear binding energy that results from the conversion of one of the unstable nucleus' neutrons to a proton. Electron emission is therefore characterized by an increase in atomic number as the unstable nucleus decays to its daughter. For example, hydrogen-3 (atomic number 1, mass number 3) decays to helium-3 (atomic number 2, mass number 3). Electron emission by beta decay is given the Greek symbol β (see figure).

The energy lost by the nucleus is shared between the ejected electron and the anti-neutrino; relative energy proportions varying from one nuclear disintegration to the next. The electron emission spectra produced by radioactive materials that decay by this mode are therefore not mono-energetic but span a range, between a maximum value and zero, depending upon whether the ejected electron receives all or none of the available transition energy.



In positron decay, also called positive beta decay, a proton in the parent nucleus 'decays' into a neutron. The increase in binding energy created when this happens is used to create a positron (anti-electron) and a neutrino, which has no rest mass. Positive beta decay therefore produces a daughter nucleus of atomic number one less than the parent. Positron emission was first observed by Irène and Frédéric Joliot-Curie in 1934. As with electron emission, the transition energy is 'consumed' by the production of the positron rest mass with the remainder appearing as kinetic energy shared between the positron and neutrino. Positron spectra like electron emission spectra, are therefore not mono-energetic. Positron

emission is only energetically possible for transition energies that exceed the energy equivalence of two rather than one electron rest mass; this is because 'conversion' of a proton into a neutron itself requires the energy equivalent of one electron rest mass.

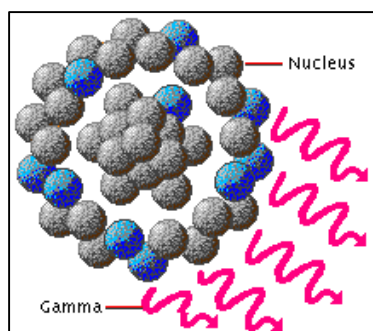


In electron capture, an electron orbiting the nucleus combines with a nuclear proton to produce a neutron, which remains in the nucleus, and a neutrino which is ejected. Most commonly, the electron is captured from the innermost (K) shell of electrons and, for this reason, the process is often called K-capture. As in positron emission, the nuclear positive charge and therefore atomic number decreases by one unit, and the mass number remains the same. Electron capture is a competing process with positron emission; most positron emitters will therefore exhibit some degree of electron capture. However, unlike positron decay, the minimum transition energy does not have to exceed

the energy equivalence of two electron rest masses because the electron rest mass needed to convert a proton to a neutron is gained from the orbital electron capture process. Electron capture is the only decay process that is energetically possible for some radioactive decay transitions and may therefore take place in the absence of positron emission.

In comparison with other forms of radioactivity, such as gamma and alpha decay, beta decay is a relatively slow process. Halfives for beta decay are never shorter than a few milliseconds.

Gamma decay



Gamma ray emission occurs in unstable nuclei which dissipate nuclear excitation energy by a spontaneous electromagnetic process (see figure). Gamma emission is denoted by the Greek symbol γ

Gamma decay also includes two other electromagnetic processes, namely, internal conversion and internal pair production.

In internal conversion, excess energy in a nucleus is directly transferred to one of its own orbiting electrons, thereby ejecting the electron from the atom. In internal pair production, excess energy is directly converted, within the electromagnetic field of a nucleus, into an electron and positron¹⁸ pair which are both then ejected from the nucleus.

Although gamma ray emission is the predominant process in gamma decay, internal conversion always accompanies it to some extent. However, at low nuclear excitation energies, internal conversion is often the predominant decay mode.

For internal pair production to be energetically possible, nuclear excitation energy must exceed the energy equivalent of the rest mass of two electrons, i.e. 1.02 MeV.

The unstable nuclei that undergo gamma decay are either the products of other types of radioactivity (e.g. alpha and beta decay) or of some other nuclear process, such as neutron capture in a nuclear reactor. Gamma decay is essentially the process by which nuclei that have undergone these decay or capture processes de-excite to the nuclear ground state.

Gamma emission half-lives range from immeasurably short (femto-seconds) to 200,000 years (Re186m). Excited nuclei, for which the half-life is measurable, are referred to as metastable isomers of their nuclear ground states.

Proton decay

Proton decay is a special class of rare beta (positron) decay that gives rise to heavy particle emission. In these processes, beta (positron) decay can cause excitation of the daughter nucleus which subsequently de-excites by the emission of a proton.

Pure proton radioactivity, discovered in 1970, is exhibited by an excited isomeric state of cobalt-53. This radionuclide decays by proton emission with a fractional radioactivity of 1.5 percent.

However, all radionuclides exhibiting proton decay in the HPC database, do so following an initial beta (positron) decay.

Neutron decay

Neutron decay is a special class of rare beta-decay that gives rise to heavy particle emission. In these processes, beta decay can partly cause excitation of the daughter nucleus which subsequently de-excites by the emission of a neutron.

All radionuclides exhibiting neutron decay in the Companion's database, do so following an initial beta decay.

Spontaneous fission

Spontaneous fission is a type of radioactivity associated with high atomic number radionuclides. In this process, a nucleus splits into two fragment nuclei of roughly half the parent mass. The process is only barely detectable since most radionuclides that exhibit it also decay by alpha emission. Uranium 238, uranium 235 and plutonium 239 are well-known examples of radionuclides that undergo spontaneous fission.

In the case of some of the heaviest artificial nuclei, for example fermium-256, spontaneous fission is the predominant mode of radioactive decay.

Nuclear fission releases huge amounts of energy; this is manifest as kinetic imparted to the nuclear fragments and ranges between 150 to 200 MeV.

When nuclear fission occurs, a few neutrons are also emitted. These particles typically have energies of a few MeV and are an important feature of nuclear chain reactions. Spontaneous fission should not be confused with induced fission, the process involved in nuclear reactors. Thermal neutron

¹⁸ A positron is a positively charged electron and, as such, is an anti-matter particle

capture-induced fission is a property of radionuclides that have odd mass numbers, for example uranium-235, plutonium-239, and other high atomic number isotopes with odd mass numbers.

Internal transition

Internal transition is the collective name for a number of decay processes whereby an excited nucleus undergoes de-excitation, usually to the ground state. Gamma photon emission and internal conversion are two examples of internal transitions.

Metastable and isomeric states

Most particulate decay processes, such as alpha and beta decay, involve nuclear transitions that leave the daughter nucleus in an excited state. However, de-excitation times are usually so short that the gamma photon produced by the nucleus, as it de-excites, appears concomitantly with the particulate emission. It is only when de-excitation is delayed, to the extent that the excited nucleus appears to have a quite different half-life from the particulate decay process giving rise to it, that the nucleus is considered to have completed an entirely separate internal transition.

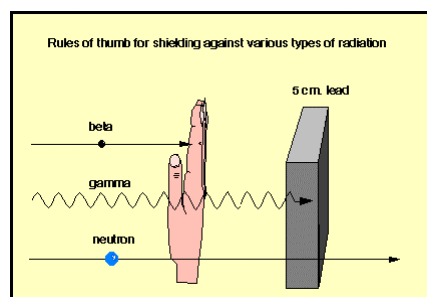
Radionuclides that exhibit this behaviour are called metastable or isomeric; a well-known example being the decay of Mo99 to Tc99 by beta emission. The increase in nuclear binding energy that occurs during this nuclide's decay is split between two temporally separate transitions: a beta decay to produce an excited isomer or metastable state of Tc99 (referred to as Tc99m) which then undergoes a 6 hour half-life internal transition, involving the production of a 141 keV gamma photon, to form Tc99.

Internal Conversion

Internal conversion is a nuclear de-excitation process that involves the transfer of nuclear excitation energy directly to an orbital electron, which is then ejected, from the atom. This is energetically possible because in quantum mechanical theory, orbital electrons have a finite probability of passing through the nucleus around which they are considered to be in 'orbit'. The probability of de-excitation by this process is however small compared to gamma transitions.

Ionising radiation attenuation in matter

Radiation absorption is summarized in the diagram below. For a detailed account of photon (i.e. gamma and x-ray) absorption processes, see Chapter 10.



Alpha radiation propagates only a few centimetres in air and is completely attenuated by a thin piece of paper. It can't penetrate the dead, cornified layer of the epidermis (skin) and so doesn't pose an external radiation hazard.

Beta radiation is more penetrating and may, depending upon energy, propagate several metres in air. Energies above 70 keV will penetrate to the upper layers of the epidermis and so this radiation can be a significant contributor to extremity and skin dose. Beta radiation is completely attenuated by a thin sheet of aluminium, but if high atomic number (Z) absorbers are used as a shield, the linear energy transfer may be high enough to cause bremsstrahlung radiation emission (see page 62), which is much more penetrating. It is therefore important to use low- Z materials, such as water and plastics, as shielding for this type of radiation.

Chapter 10 - Photon Absorption Processes

Photoelectric absorption

Photoelectric absorption is a phenomenon characterized by the ejection of charged particles when electromagnetic energy is absorbed in matter. Electrons are the particles that are typically ejected in photoelectric processes; any photon having an energy that exceeds an electron's atomic binding energy is capable of causing it to be ejected from the atom to which it is 'bound'. Gamma rays, x-rays, and visible and ultraviolet light are all capable of being absorbed in matter by photoelectric absorption.

Photoelectric absorption is a phenomenon that can't be explained using classical wave theory. This is because charged particle ejection energy is dependent upon electromagnetic radiation wavelength rather than intensity. In explaining the photoelectric effect, Einstein assumed that electromagnetic radiation was quantized, i.e. it propagates through matter as discrete energy 'packets' called photons. His theory suggested that a photon could penetrate matter, where it would collide with an atom and be absorbed; since all atoms have electrons, an electron would be ejected from the atom with great velocity by this absorption process. According to Einstein, each light quantum consists of an amount of energy equal to the product of Planck's universal constant (h) and its frequency (ν).

Gamma and x-ray photoelectric absorption cause atomic ionization as electrons from target material atoms are ejected. These electrons may themselves cause further ionization within the target material as they travel through it and are eventually captured by a positively charged atom; this phenomenon is called secondary ionization.

Ionization events may involve the innermost atomic energy shells of the atoms of the absorbing material; such electron 'vacancies' may then be filled by the de-excitation of an electron located in a lower energy shell. When this occurs, the increase in electron binding energy that results is converted into an x-ray photon which itself may cause further ionization events within the absorbing material. Another energetically possible way for electron de-excitation energy to be converted is in a process called Auger electron emission; here de-excitation energy is simultaneously transferred to one or a number of outer orbital electrons, causing them to be ejected from the target atom.

The Auger effect is generally but not exclusively observed at high photon energies; the 'filling' of an inner vacancy by the de-excitation of an orbital electron can be followed by a great number of different Auger transitions. This phenomenon, coupled with the development of high-resolution spectroscopy and improved methods for the study of low-energy electrons, makes the Auger effect an important tool in the exploration of many nuclear processes such as capture and internal conversion.

Compton scatter

Compton scatter is one of the ways in which gamma and x-ray radiation is absorbed in matter. It is characterized by an increase in emission wavelength and therefore a decrease in photon energy. It occurs when gamma photons are elastically scattered by electrons within the material through which they are propagating. Compton scatter is the principal way in which photons at gamma and x-ray energies are absorbed in matter. The effect has proved to be one of the cornerstones of quantum mechanics, a theory which explains both the wave and particle properties of radiation and matter.

The American physicist Arthur Holly Compton explained (1922; published 1923) this wavelength increase by considering x-rays as being composed of discrete pulses, or quanta, of electromagnetic energy, which he called photons. Photons have energy and momentum as well as wave characteristics, such as wavelength and frequency. A photon's energy is directly proportional to its frequency and inversely proportional to its wavelength.

In the Compton effect, individual photons collide with free and loosely bound single electrons present within the material through which they are propagating. In doing so, some photon energy and momentum is transferred to the electron causing it to recoil. At the instant of photon collision, a new photon, of less energy and momentum, is produced and scattered at an angle dependent upon the amount of energy lost to the recoiling electron.

Because of the relationship between energy and wavelength, a Compton scattered photon has a

wavelength that depends on the size of the scatter angle: the greater the angle of scatter, the longer the wavelength and therefore the lower the energy of the scattered photon. The increase in wavelength, referred to as the Compton shift, does not depend on the wavelength of the incident photon.

Compton scatter is often referred to as a form of incoherent scatter because it involves energy deposition within the propagating medium, it is therefore an inelastic interaction phenomenon (see Rayleigh scatter).

Compton scatter was discovered independently by Peter Debye in early 1923.

Pair production

Pair production is the formation or materialization of two electrons, one negative and the other positive (positron), from a pulse of electromagnetic energy travelling through matter, usually in the vicinity of an atomic nucleus.

Pair production involves the direct conversion of electromagnetic energy to matter. It is the principal way in which high-energy gamma rays are absorbed in matter. For pair production to be energetically possible, the mass equivalence of the photon energy must be at least that of two electrons.

The mass m of a single electron is equivalent to 0.511 MeV of energy (cf. Einstein's mass-energy equivalence formula; $E = mc^2$, in which c is a constant equal to the velocity of light). Therefore, to produce two electrons, photon energy must be at least 1.022 MeV. If photon energy is greater than this threshold, the excess is converted into kinetic energy that is shared equally between the electron and positron pair.

If pair production occurs in a track detector, such as a cloud chamber, to which a magnetic field is applied, the electron and the positron pair follow curved trajectories in opposite directions. In this way, pair production was first detected in 1933.

Positrons are anti-particles and so are annihilated when they encounter an electron in the material in which they are generated. This process leads to the production of two 511 MeV gamma photons that propagate in mutually opposite directions from the point of their production (to conserve momentum). Positron annihilation absorption cross-sections are very large and so positron mean free paths are very short; consequently, their range in matter is much shorter than that for electrons.

Internal pair production, a type of gamma decay, occurs when an excited nucleus that has at least 1.022 MeV of excess energy, directly ejects an electron-positron pair without first producing a gamma photon.

Rayleigh scatter

Dispersion (diffraction) of electromagnetic radiation by particles of matter that have a radius less than 1/10 of the radiation's wavelength is referred to as Rayleigh scatter. The process is named in honour of Lord Rayleigh, who published a paper describing the phenomenon in 1871.

In the case of ionizing electromagnetic radiation such as x-rays and gamma rays, the particles which cause Rayleigh scatter (diffraction) are the atoms of the material through which the photons are propagating.

Rayleigh scatter is an elastic photon interaction phenomenon often referred to as coherent scatter; it therefore does not cause energy deposition in a propagating medium, only a change in photon trajectories within it. Unlike Compton scatter, in which scatter angles approaching 180 degrees are commonplace (so-called backscatter), Rayleigh scatter seldom exceeds 90 degrees (i.e. interaction cross-sections for larger scatter angles are very small). The phenomenon is therefore often described as forward scatter.

A visible radiation example.

The angle through which sunlight is scattered by gas molecules found in the atmosphere varies

inversely as the fourth power of its wavelength; hence, blue light, which is at the short wavelength end of the visible spectrum, is scattered much more strongly than red light which has a longer wavelength. This results in the blue colour of the sunlit sky; in directions other than towards the Sun, the observer sees only scattered light.

Bremsstrahlung radiation

The production of x-rays when a charged particle is rapidly accelerated.

When a charged particle (e.g. beta radiation) passes close to a nucleus, the strong coulomb force causes the particle to deviate sharply from its original path. The change in direction is due to radial acceleration and the particle, in accordance with classical theory, loses energy by electromagnetic radiation at a rate proportional to the square of the acceleration.

The following empirical relationship may be used to estimate bremsstrahlung emission from beta radiation incident on an absorber:

$$f = 3.5 \times 10^{-4} ZE$$

Where:

- f = fraction of incident beta radiation kinetic energy that is converted into photons
- Z = the atomic number of the absorber
- E = the maximum kinetic energy (E_{\max}) of the beta radiation in MeV

Chapter 11 - Photon Absorption Coefficients

This chapter is taken from explanatory information produced by NIST⁽⁶⁾ for their published coefficients. These data are used by the Health Physicist's Companion by kind permission of NIST.

Introduction

The mass attenuation coefficient, μ/r [μ/ρ in English], and the mass energy-absorption coefficient, μ_{en}/r [μ_{en}/ρ in English], are basic quantities used in calculations of penetration and energy deposition by photons (x-ray, gamma ray, bremsstrahlung) in biological, shielding and other materials. These coefficients are defined in ICRU Report 33 (1980).

The mass attenuation coefficient

A narrow beam of mono-energetic photons with an incident intensity I_0 , penetrating a layer of material with mass thickness¹⁹ x and density r , emerges with intensity I given by the exponential attenuation law.

$$Eq(1) \quad \frac{I}{I_0} = e^{-\mu/r \cdot x}$$

Where:

$$\mu/r = \text{mass attenuation coefficient (m}^2 \text{ kg}^{-1}\text{)}$$

Equation (1) can be rewritten as:

$$Eq(2) \quad \frac{m}{r} = x^{-1} \times \log_e \left(\frac{I_0}{I} \right)$$

from which μ/r can be obtained from measured values of I_0 , I and x .

The various experimental arrangements and techniques from which μ/r can be obtained, particularly in the crystallographic photon energy/wavelength regime, have recently been examined and assessed by Creagh and Hubbell (1987, 1990) as part of the International Union of Crystallography (IUCr) X-Ray Attenuation Project. This has led to new tables of μ/r in the 1992, *International Tables for Crystallography* (Creagh and Hubbell, 1992).

The μ/r data used in the Health Physicist's Companion rely heavily on theoretical values for the total cross-section per atom, σ_{tot} , which is related to μ/r according to:

$$Eq(3) \quad \frac{m}{r} = \frac{S_{tot}}{nA}$$

In Eq. (3), u is the atomic mass unit in grammes ($1/12$ of the mass of an atom of nuclide ^{12}C - $1.6605402 \times 10^{-24}$ g), A , the relative atomic mass of the target element, and σ_{tot} [σ_{tot} in English] the total photon interaction cross-section.

The mass attenuation coefficient μ/r , is numerically equivalent to the quotient of the linear attenuation coefficient μ (m^{-1}) and the density (kg m^{-3}) of the absorbing material to which it applies.

The total cross-section can be written as the sum over contributions from the principal photon interactions:

$$Eq(4) \quad S_{tot} = S_{pe} + S_{coh} + S_{incoh} + S_{pair} + S_{trip} + S_{ph.n.}$$

¹⁹ Mass thickness is defined as mass per unit area; it is numerically equal to the product of an absorber's linear thickness (m) and density (kg m^{-3})

Where σ_{pe} is the atomic photoelectric cross-section, σ_{coh} and σ_{incoh} the coherent (Rayleigh) and incoherent (Compton) scatter cross-sections, respectively, σ_{pair} and σ_{trip} the cross-sections for electron-positron production in the fields of the nucleus and of the atomic electrons, respectively, and $\sigma_{ph.n.}$ the photonuclear cross-section.

Photonuclear absorption of a photon by the atomic nucleus usually results in the ejection of one or more neutrons and/or protons. This interaction can contribute as much as 5-10% to the total photon interaction cross-section but in a fairly narrow energy region, usually somewhere between 5 and 40 MeV. The absorption cross-section greatly depends upon where the giant resonance of the target nuclide falls (see, Hayward, 1970; Fuller and Hayward, 1976; and Dietrich and Berman, 1988; also the illustrative tables in Hubbell, 1969, 1982). The effects of this interaction can be observed in measurements of the total attenuation coefficients (see, Gimm and Hubbell, 1978).

The data used by the Health Physicist's Companion are calculated according to:

$$Eq(5) \quad m/r = (s_{pe} + s_{coh} + s_{incoh} + s_{pair} + s_{trip})/nA$$

Values for the relative atomic mass A , of target elements are taken from Martin (1988); values for the individual contributing cross-sections are those found in the current NIST⁽⁶⁾ database (see Berger and Hubbell, 1987), as outlined below.

Atomic photoelectric effect. For photon energies from 1 keV to 1.5 MeV, values of the photoelectric cross-section, σ_{pe} , are those calculated by Scofield (1973), based on his solution of the Dirac equation for the orbital electrons moving in a static Hartree-Slater central potential. No re-normalisation was performed using those factors given by Scofield for the elements with $Z = 2$ to 54 to convert to values expected from a relativistic Hartree-Fock model. This represents a break with the practice by Hubbell (1977, 1982) and Hubbell et al. (1980) in which this re-normalisation had been done.

Absorption-edge fine structure can be experimentally observed using continuum-energy photon sources and high-resolution detectors (see Faessler, 1955; Deslatters, 1969; Hubbell et al., 1974; Lytle et al., 1984; and Del Grande, 1986, 1990), and the observed variations are subject to chemical, phase and other environmental effects, such as temperature (Lytle, 1963). The cross-sections in the vicinity of absorption edges are assumed to have simple sawtooth shapes. Values at the edge have been obtained by extrapolation of the near-edge sub-shell cross-sections of Scofield (1973) to the threshold edge energies given by Bearden and Burr (1967), according to the same procedure used by Berger and Hubbell (1987) to prepare the NIST database.

The interpolation procedures used for the present NIST tables are slightly different from those used by Berger and Hubbell; a cubic Hermiter interpolant for the individual sub-shell cross-sections rather than a cubic spline for the total photoelectric effect cross-section has been used, this results in occasional small differences in the vicinity of M- and N-shell edges of high-Z elements.

Scofield's (1973) photoeffect calculations were limited to photon energies of 1.5 MeV and below. His data were extended to higher energies (where the photoelectric cross-section is quite small) by connecting them to the high-energy asymptotic values of Pratt (1960) through use of a semi-empirical formula (Hubbell, 1969).

Coherent and incoherent scatter. Values for the coherent (Rayleigh) scatter cross-section, σ_{coh} , are taken from Hubbell and Overbo (Øverbo) (1979). These were calculated by numerical integration of the Thomson (1906) formula weighted by $F^2(q, Z)$, where $F(q, Z)$ is the relativistic Hartree-Fock atomic form factor and q is the momentum transfer. The compilation of $F(q, Z)$ by Hubbell and Overbo was based on piecing together, over the different ranges of q and Z , values given by Pirenne (1946) for $Z = one$, and those of Doyle and Turner (1968), Cromer and Waber (1974) and Overbo (1977, 1978) for the other elements.

Values for the incoherent (Compton) scatter cross-section, σ_{incoh} , are from Hubbell et al. (1975), obtained from numerical integration of the Klein-Nishina (1929) differential formula weighted by the incoherent scattering function $S(q, Z)$. For their compilation of $S(q, Z)$, Hubbell et al. pieced together results given by Pirenne (1946) ($Z = 1$), Brown (1970a, 1970b, 1971, 1972, 1974) ($Z = 2 - 6$, with configuration interaction) and by Cromer and Mann (1967) and Cromer (1969) ($Z = 7 - 100$, from a

non-relativistic Hartree-Fock model). Radiative and double-Compton corrections from Mork (1971) were applied to the integrated values for σ_{incoh} .

Electron-positron pair and triplet production cross-sections. Cross-sections for the production of electron-positron pairs (e^- , e^+) in the field of the atomic nucleus, σ_{pair} , and for the production of triplets ($2e^-$, e^+) in the field of the atomic electrons, σ_{trip} , are taken from the compilation of Hubbell et al. (1980). Their synthesis combined the use of formulae from Bethe-Heitler theory with various other theoretical models to take into account screening, coulomb, and radiative corrections. Different combinations were used in the near-threshold, intermediate and high-energy regions to obtain the best possible agreement with experimental cross-sections (Gimm and Hubbell, 1978).

The mass energy-absorption coefficient

The methods used to calculate the mass energy-absorption coefficient, μ_{en}/ρ [mu_{en}/rho in English], are described perhaps more clearly through the use of an intermediate quantity, the mass energy-transfer coefficient, μ_{tr}/ρ [mu_{tr}/rho in English].

The mass energy-transfer coefficient, μ_{tr}/ρ , when multiplied by the photon energy fluence, gives the dosimetric quantity kerma. As discussed in depth by Carlsson (1985), kerma has been defined (ICRU 1980) as, and is an acronym for, the sum of the kinetic energies of all those primary charged particles released by uncharged particles (here photons) per unit mass. Thus, μ_{tr}/ρ doesn't take into account the kinetic energy released by subsequent absorption of secondary photon radiations (e.g. Compton-scatter photons), produced at the initial photon-atom interaction site, and by convention, doesn't take into account the quanta of radiation arising from the annihilation of positrons (assumed to have come to rest) produced in pair and triplet production interactions.

NB. Care must therefore be exercised when using mass energy-transfer and mass energy-absorption data to infer radiation absorbed dose. The extent to which these unaccounted for secondary radiations contribute to absorbed dose will depend upon the irradiation geometry and the physical extent and composition of the medium of interest.

μ_{tr}/ρ is defined as:

$$\text{Eq(6)} \quad \mu_{\text{tr}}/\rho = (f_{pe} S_{pe} + f_{\text{incoh}} S_{\text{incoh}} + f_{\text{pair}} S_{\text{pair}} + f_{\text{trip}} S_{\text{trip}}) / nA$$

In Eq.(6), coherent scatter has been omitted because of the negligible energy transfer associated with it, and the factors f represent the average fractions of the photon energy E that is transferred to kinetic energy of charged particles in the remaining types of interactions.

These energy-transfer fractions are given by:

$$\text{Eq(7)} \quad f_{pe} = 1 - (X/E)$$

where X is the average energy of fluorescence radiation (characteristic x-rays) emitted per absorbed photon;

$$\text{Eq(8)} \quad f_{\text{incoh}} = 1 - (\langle E' \rangle + X) / E$$

where E' is the average energy of the Compton-scattered photon; and

$$\text{Eq(9)} \quad f_{\text{pair}} = 1 - 2mc^2 / E$$

where mc^2 is the rest energy of the electron; and

$$\text{Eq(10)} \quad f_{\text{trip}} = 1 - (2mc^2 + X) / E$$

The fluorescence energy X in Eq.(7), (8), and (10) depends on the distribution of atomic-electron vacancies produced in the process under consideration and is, in general, evaluated differently for

photoelectric absorption, incoherent scatter, and triplet production. Moreover, X is assumed to include the emission of "cascade" fluorescence x-rays associated with the complete atomic relaxation process initiated by the primary vacancy, the significance of which has been pointed out by Carlsson (1971).

The mass energy-absorption coefficient involves the further emission of radiation produced by the charged particles in travelling through the medium, and is defined as:

$$Eq(11) \quad \mu_{en}/r = (1 - g)\mu_r/r$$

The factor g in Eq.(11) represents the average fraction of the kinetic energy of secondary charged particles (produced in all the types of interactions) that is subsequently lost in radiative (photon-emitting) energy-loss processes as the particles slow to rest in the absorber. The evaluation of g is accomplished by integrating the cross-section for the radiative process of interest over the differential track length distribution established by the particles in the course of slowing down. In the continuous-slowing-down approximation, the track length distribution is replaced by the reciprocal of the electron or positron total stopping power of the absorber. Even assuming Bragg additivity for the stopping power (that now appears in the denominator of the integral), simple additivity for μ_{en}/r or, as suggested by Attix (1984), for g is formally incorrect. When the numerical values of g are relatively small, the errors in μ_{en}/r incurred by using simple additivity schemes are usually small, a consequence partially mitigating the use of additivity, particularly for photon energies below 20 MeV. However, additivity has not been used in the data used by the Health Physicist's Companion.

For the calculation of g , the radiative (bremsstrahlung) stopping powers used are based on the results by Seltzer and Berger (1985, 1986) and Kim et al. (1986), and are very slightly different from the values used in ICRU 37 (1984). The collision stopping powers, evaluated according to the prescriptions in ICRU 37 (1984), include departures from simple Bragg additivity due to chemical-binding, phase, and density effects, as reflected in the choice of the mean excitation energy I and density r for the medium.

Photoelectric Absorption. The radiative losses for photoelectrons have been evaluated according to:

$$Eq(12) \quad g_{pe} = \left[f_{pe} E \frac{\mu_{pe}}{r} \right]^{-1} \sum_i w_i \sum_n \left[\frac{\mu_{pe}}{r} \right]_{n,i} (E - B_{n,i}) Y(E - B_{n,i})$$

where μ_{pe}/r is the total photoeffect mass attenuation coefficient for an incident photon of energy E in the medium, $(\mu_{pe}/r)_{n,i}$ is the corresponding coefficient for the n th atomic electron sub-shell of the i th elemental constituent, $B_{n,i}$ is the binding energy of that sub-shell and,

$$Eq(13) \quad Y(T) = Y_b(T) + Y_x(T)$$

is the total radiative yield. The total radiation yield has been evaluated as the sum of two components. The bremsstrahlung yield, $Y_b(T)$, is the mean fraction of the initial kinetic energy T of an electron (or positron) that is converted to bremsstrahlung energy as the particle slows down to rest; and the x-ray energy yield, $Y_x(T)$, usually very much smaller than $Y_b(T)$, is the mean fraction of the initial kinetic energy converted to fluorescence emission due to ionization by the electron (or positron) in the course of its slowing down. The very small radiative losses for the associated Auger electrons have been neglected.

Incoherent (Compton) Scatter. For incoherent scatter:

$$Eq(14) \quad g_{incoh} = \left[f_{incoh} E \frac{\mu_{incoh}}{r} \right]^{-1} \int_{E_{min}}^E \left[\sum_i \frac{w_i}{nA_i} S(q, Z_i) \right] \times \frac{dSKN}{dE'} (E - E') Y(E - E') dE'$$

where $S(q, Z_i)$ is the incoherent scattering factor, taken from the compilation of Hubbell et al. (1975), $d\sigma_{KN}/dE'$ is the Klein-Nishina cross-section differential in the Compton-scattered photon energy E' ,

$E_{\min} = E / (1 + 2E/mc^2)$ is the minimum energy of the scattered photon (corresponding to 180 degrees scatter), and $Y(T)$ is the total radiation yield.

Pair and Triplet production. The radiative losses from electrons and positrons created in pair and triplet processes, including the effects of positron annihilation in flight, have been evaluated according to:

$$Eq(15) \quad g_{pair} = \left[\int_{pair} E m_{pair}(E) / \mathbf{r} \right]^{-1} \int_0^{E-2mc^2} \left\{ \sum_i W_i \left[\frac{\mathbf{m}_{pair}}{\mathbf{r}} \right]_i P_{pair,i}(T_+) \right\} \\ \times \left\{ (E - 2mc^2 - T_+) Y - (E - 2mc^2 - T_+) + T_+ [Y_+(T_+) + \mathbf{h}(T_+)] \right\} dT_+$$

where $P_{pair,i}(T_+) dT_+$ is the probability that the positron from a pair-production interaction with the i th constituent atom will have a kinetic energy between T_+ and $(T_+ + dT_+)$. $Y_-(T_+)$ and $Y_+(T_+)$ are the total radiation yields for the electrons and positrons, respectively, and $\eta(T_+)$ is the correction for positron annihilation in flight. Pair spectra have been evaluated using Bethe-Heitler theory in conjunction with screening and Coulomb corrections. The annihilation-in-flight correction has been derived on the basis outlined in Berger (1961), and has been evaluated using the two-quanta annihilation-in-flight cross-section of Bethe (1935) plus estimates for the one-quantum annihilation-in-flight cross-section.

Computation of g_{trip} proceeds similarly, but using the threshold for triplet production of $4mc^2$ instead of $2mc^2$ in Eq.(15), and using the Wheeler-Lamb (1939) expressions for the screening corrections to the triplet spectra.

Chapter 12 - Dose Quantities

A number of dose quantities are defined by ICRP²⁰; these are summarized below. Regulation of ionising radiation in the European Union is required to be based on these quantities (Directive 96/29/Euratom).

Radiation Absorbed Dose

SI unit - gray (Gy). This quantity is defined in ICRP, Publication 60⁽¹⁶⁰⁾.

$$1 \text{ Gy} = 1 \text{ J Kg}^{-1}$$

The gray has largely replaced the CGS unit of radiation absorbed dose, namely the rad.

$$\begin{aligned} 1 \text{ rad} &= 0.01 \text{ J kg}^{-1} \\ &= 10 \text{ mGy} \end{aligned}$$

Equivalent dose [H_T] - is the absorbed dose, in tissue or organ [T] weighted for the type and quality of radiation [R]. It is given by:

$$H_{T,R} = W_R \cdot D_{T,R}$$

where:

$D_{T,R}$ is the absorbed dose averaged over the tissue or organ [T], due to radiation [R] and
 W_R is the radiation weighting factor for radiation [R].

When the radiation field is composed of types and energies with different values of [W_R], the total equivalent dose [H_T] is given by:

$$H_T = \sum_R W_R \cdot D_{T,R}$$

Effective dose [E] - is generally defined by the relationship:

$$E = \sum_T W_T \cdot H_T \qquad E = \sum_T W_T \cdot \sum_R W_R \cdot D_{T,R}$$

This represents the sum of the weighted equivalent doses in all the tissues and organs of the body from external radiation, where:

$D_{T,R}$ is the absorbed dose averaged over the tissue or organ [T], due to radiation [R];
 W_R is the radiation weighting factor for radiation [R] and
 W_T is the tissue weighting factor for tissue or organ [T].

The total effective dose [E] usually includes the 50-year committed effective dose [$E_{(int)}$] arising from ingested or inhaled radionuclides (so-called internal radiation). These doses are calculated using radionuclide-specific dose per unit intake values (Annex III of Directive 96/29/Euratom gives default values). Both effective dose and equivalent dose are given in sieverts (Sv).

Estimation of personal doses

Where the effective dose from external radiation is estimated from personal monitoring, the operational dose quantity **personal dose equivalent $H_p(d)$** is normally used to demonstrate compliance with dose limits. Personal dose equivalent is the dose in soft tissues at an appropriate depth d , in mm, below a specified point in the body and is given in sieverts.

²⁰ ICRP - International Commission on Radiological Protection.

If doses are to be estimated from area monitoring results, the relevant operational quantities are: **ambient dose equivalent $H^*(d)$** and **directional dose equivalent $H'(d,W)$**

where d is the depth in mm under the surface of the ICRU²¹ sphere. For strongly penetrating radiation, a depth of 10 mm is appropriate and for weakly penetrating radiation, a depth of 0.07 mm for the skin and 3 mm for the eye is normally used. W - is the angle of incidence.

Ambient dose equivalent is the dose equivalent at a point in a radiation field that would be produced by the corresponding expanded and aligned field in the ICRU sphere at a depth, d , on the radius opposing the direction of the aligned field. It is given in sieverts.

Directional dose equivalent is the dose equivalent at a point in a radiation field that would be produced by the corresponding expanded field, in the ICRU sphere at a depth, d , on a radius in a specified direction, W . It is given in sieverts.

The ICRU sphere is a convention introduced by the International Commission on Radiation Units and Measurements to approximate the human body as regards energy absorption from ionizing radiation; it consists of a 30 cm diameter tissue-equivalent sphere with a density of 1 g cm^{-3} and a mass composition of 76.2% oxygen, 11.1% carbon, 10.1% hydrogen and 2.6% nitrogen.

Expanded field: A theoretical expanded field derived from an actual field at a reference point which, throughout the volume of interest, has fluence, directional and energy distributions identical to that of the actual field at the reference point.

Expanded and aligned field: A radiation field in which the fluence, directional and energy distributions are the same as that for an expanded field but in which the fluence is unidirectional.

The fluence F , is the quotient of dN by da , where dN is the number of particles which enter a sphere of cross-sectional area da .

The quality factor Q , is a function of linear energy transfer (L) in water and is used to weight the absorbed dose at a point in such a way as to take into account the quality of a radiation in a specified tissue or organ.

Unrestricted linear energy transfer (L) is the quotient of dE by dl , where dE is the mean energy lost by a particle of energy E in traversing a distance dl in water.

The relationship between the quality factor, $Q(L)$, and the unrestricted linear energy transfer, L , is as follows.

Unrestricted linear energy transfer, L , in water (keV mm^{-1})	$Q(L)$
< 10	1
10-100	$0.32L - 2.2$
> 100	300

Tissue weighting factors

Appropriate values of tissue weighting factor [W_T], to be used to weight the equivalent dose in a tissue or organ [t], where necessary, are as follows.

Tissue or organ	Tissue weighting factor, W_T
Gonads	0.20
Bone marrow (red)	0.12
Colon*	0.12
Lung	0.12
Stomach	0.12

²¹ International Commission on Radiation Units

Tissue or organ	Tissue weighting factor, W_T
Bladder	0.05
Breast	0.05
Liver	0.05
Oesophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surface	0.01
Remainder	(**)(***)0.05

(*) Dose to the colon is taken to be the mass-weighted average dose to the upper and lower large intestines.

(**) For the purposes of calculation, the remainder is composed of the following additional tissues and organs: adrenals, brain, small intestine, kidneys, muscle, pancreas, spleen, thymus, uterus and extrathoracic airways.

(***) The equivalent dose to the remainder tissues is normally calculated as the mass-weighted mean dose to the ten organs and tissues listed above. In the exceptional case in which the most highly irradiated remainder tissue or organ receives the highest equivalent dose of all organs, a weighting factor of 0.025 (half of remainder) is applied to that tissue or organ and 0.025 to the mass-weighted equivalent dose in the rest of the remainder tissues and organs.

Radiation weighting factors

Where required for a direct estimate of [E], values of radiation weighting factor [W_R] depend upon the type and quality of the external radiation field as follows.

Type and energy range	Radiation weighting factor, W_R
Photons, all energies	1
Electrons and muons, all energies	1
Neutrons, energy , 10 keV	5
> 10 keV to 100 keV	10
> 100 keV to 2 MeV	20
> 2 MeV to 20 MeV	10
> 20 MeV	5
Protons (not recoil protons) > 2 MeV	5
Alpha particles, fission fragments, heavy nuclei	20

In calculations involving neutrons, it may be difficult to apply step function values. In these cases, it is preferable to use:

$$W_R = 5 + 17e^{-\left(\log_e(2E)\right)^{2/6}}$$

where [E] is the neutron energy in MeV.

Chapter 13 - The Discovery of Radioactivity

Becquerel, Antoine Henri



Becquerel was a member of a scientific family which extended through several generations; his grandfather Antoine-César Becquerel (1788-1878), father, Alexandre-Edmond Becquerel (1820-91), and son, Jean Becquerel (1878-1953), were all famous scientists in their own right.

Education and training

After his early schooling at the Lycée Louis-le-Grand, Henri Becquerel received his formal scientific education at the École Polytechnique (1872-74) and engineering training at the École des Ponts et Chaussées (Bridges and Highways School; 1874-77). In addition to his teaching and research posts, Becquerel was for many years an engineer in the Department of Bridges and Highways and was appointed chief engineer in 1894. His first academic post came in 1876 when he was appointed assistant teacher at the École Polytechnique, a post he held until he succeeded to the chair of physics at the polytechnique in 1895. Concurrently with these posts, he was assistant naturalist to his father at the museum, where he also assumed the physics professorship upon his father's death.

Electricity, magnetism, optical phenomena, and energy were major areas of physical investigation during the 19th century. For several years the young Becquerel's research was concerned with the rotation of plane-polarized light by magnetic fields, a subject first studied by Michael Faraday and which Henri's father had also studied. Henri later concerned himself with infrared radiation, examining among other things, the spectra of different phosphorescent crystals under infrared stimulation. In this regard, he extended the work of his father by studying the relationship between absorption and emission of light in uranium compounds.

By 1896 Henri was an accomplished and respected physicist and had become a member of the prestigious Académie des Sciences. His expertise with phosphorescent materials, familiarity with uranium compounds, and his general skill in laboratory techniques, especially in photography, were together to make his discovery of radioactivity possible.

Study of radiation

At the end of 1895, Wilhelm Röntgen discovered x-rays. Becquerel undertook to investigate whether there was a fundamental connection between this invisible radiation and visible light. To test this hypothesis, he placed phosphorescent crystals upon a photographic plate that had been wrapped in opaque paper so that only a penetrating radiation could reach the emulsion. He exposed his experimental arrangement to sunlight for several hours, thereby exciting the crystals in the customary manner. Upon development, the photographic plate revealed silhouettes of the mineral samples, and in subsequent experiments, the image of a coin or metal cutout that had been interposed between the crystals and paper wrapping. Becquerel reported this discovery to the Académie des Sciences at its session on February 24, 1896, noting that certain salts were particularly able to create this effect.

His conclusion was that something very similar to X-rays was being emitted by these luminescent substances as well as visible radiation. Later, Becquerel learned that his uranium salts continued to eject penetrating radiation even when they were not made to phosphoresce by the ultraviolet radiation present in sunlight. To account for this phenomenon, he postulated the existence of a long-lived form of invisible phosphorescence, which he interpreted as a unique case of metallic phosphorescence.

During 1896, Becquerel published seven papers on this phenomenon, which he called radioactivity but in subsequent years, he showed very little interest in this new discovery. This was an index of both his and the scientific world's interest in the subject, for the period saw studies of numerous radiations (e.g. cathode rays, X-rays, Becquerel rays, "discharge rays," canal rays, radio waves, the visible spectrum, rays from glow-worms, fireflies, and other luminescent materials), it was therefore no surprise that Becquerel did not regard his radioactive discovery as significant. The far more popular X-rays could take sharper shadow photographs and more quickly than the use of any radioactive material. It required the extension in 1898 of radioactivity to another known element, (by Gerhard Carl

Schmidt and independently by Marie Curie), and the discovery of new radioactive materials, polonium and radium (by Pierre and Marie Curie and their colleague, Gustave Bémont), to awaken the world and Becquerel to the significance of his discovery.

Curie, Marie



Maria Skłodowska Curie was born in Warsaw, Poland on November 7 1867 but spent her adult life as a physicist in France. With Henri Becquerel and her husband, Pierre, she was awarded the 1903 Nobel Prize for Physics and won the prize again in her own right in 1911 for her work in the field of chemistry.

From childhood, she was remarkable for her prodigious memory and at the age of 16, she won a gold medal on completion of her secondary education at the Russian lycée. Because her father, a teacher of mathematics and physics, lost his savings through bad investment, she had to take work as a teacher and, at the same time, took part clandestinely in the nationalist "free university," reading in Polish to women workers.

At the age of 18, she took a post as governess, where she suffered an unhappy love affair. From her earnings, she was able to finance her sister Bronia's medical studies in Paris, on the understanding that Bronia would in turn later help her to get an education.

In 1891, Marie went to Paris and began to follow the lectures of Paul Appel, Gabriel Lippmann, and Edmond Bouty at the Sorbonne. There she met physicists who were already well-known; Jean Perrin, Charles Maurain, and Aimé Cotton. Marie worked far into the night in her students' garret subsisting on bread, butter and tea. Her studies were well rewarded when, in 1893, she came first in the licence of physical sciences and it was in the spring of that year, that she met her future husband Pierre Curie.

Pierre and Marie married in 1895; this event marked the start of a partnership that was soon to achieve results of world significance, in particular the discovery of polonium in the summer of 1898 (so-called by Marie in honour of her native land) and radium a few months later. Following Henri Becquerel's discovery (1896) of a new phenomenon (which she later called "radioactivity"), Marie Curie, looking for a subject for a thesis, decided to find out if the property discovered in uranium was exhibited by other materials. She soon discovered that thorium was another example of a radioactive material; the radioactivity of thorium was discovered at the same time by G.C. Schmidt.

In her search for other radioactive materials, Marie's attention was drawn to a mineral whose activity was greater than that of pure uranium and which could only be explained by the presence in the mineral of small quantities of an unknown substance of very high radioactivity. Pierre and Marie worked together to try to isolate this substance. This research culminated in the discovery of two new elements, polonium and radium.

While Pierre Curie devoted himself chiefly to the physical study of the radiations produced by these newly discovered radionuclides, Marie Curie struggled to obtain pure radium in its metallic state; this she achieved with the help of the chemist A. Debierne, one of Pierre Curie's pupils. For her work in the separation of radium, Marie received her doctorate of science in June 1903 and, with Pierre, was awarded the Davy Medal of the Royal Society. In 1903, Pierre and Marie shared the Nobel Prize for Physics with Becquerel.

The birth of her two daughters, Irène and Ève, in 1897 and 1904 respectively did not interrupt Marie's intensive scientific work. She was appointed lecturer in physics at the École Normale Supérieure for girls in Sèvres (1900) and introduced there a method of teaching based on experimental demonstrations. In December 1904, she was appointed chief assistant in the laboratory directed by Pierre Curie.

The sudden death of Pierre Curie (April 19, 1906) was a bitter blow to Marie, but it was also a decisive turning point in her career: henceforth she was to devote all her energy to completing alone the scientific work that he had undertaken. On May 13, 1906, she was appointed to the professorship that had been left vacant following her husband's death; she was the first woman to teach in the Sorbonne.

In 1908, she became titular professor, and in 1910, her fundamental treatise on radioactivity was published. In 1911, she was awarded the Nobel Prize for Chemistry, for the isolation of pure radium. In 1914, she saw the completion of the building of the laboratories of the Radium Institute (Institut du Radium) at the University of Paris.

Throughout World War I, Marie, with the help of her daughter Irène, devoted herself to the development of the use of X-radiography. In 1918, the Radium Institute, the staff of which Irène had joined, began to operate in earnest; it was to become a universal centre for nuclear physics and chemistry. Marie, now at the highest point of her fame and, from 1922, a member of the Academy of Medicine, devoted her researches to the study of the chemistry of radioactive substances and to the development of medical applications for these materials.

In 1921, accompanied by her two daughters, Marie Curie made a triumphant journey to the United States, where President Warren G. Harding presented her with a gram of radium bought as the result of a collection among American women. She gave lectures, especially in Belgium, Brazil, Spain, and Czechoslovakia. She was made a member of the International Commission on Intellectual Co-operation by the Council of the League of Nations. In addition, she had the satisfaction of seeing the Curie Foundation in Paris develop and the inauguration in 1932 in Warsaw of the Radium Institute, of which her sister Bronia became director.

One of Marie Curie's outstanding achievements was to have understood the need to accumulate intense radioactive sources, not only for the treatment of illness but also to maintain an abundant supply for research in nuclear physics; the resultant stockpile was an unrivaled instrument until the appearance after 1930 of particle accelerators. The existence in Paris at the Radium Institute of a stock of 1.5 grams of radium in which, over a period of several years, radium D and polonium had accumulated, made a decisive contribution to the success of the experiments undertaken in the years around 1930 and in particular of those performed by Irène Curie in conjunction with Frédéric Joliot, whom she had married in 1926.

This work prepared the way for the discovery of the neutron by Sir James Chadwick and above all the discovery in 1934 by Irène and Frédéric Joliot-Curie of artificial radioactivity. A few months after this discovery Marie Curie died from leukemia which had been caused by her radiation exposure. Her contribution to physics had been immense, not only in her own work, the importance of which had been demonstrated by the award to her of two Nobel Prizes, but because of her influence on subsequent generations of nuclear physicists and chemists.

In 1995, Marie Curie's ashes were enshrined in the Pantheon in Paris; she was the first woman to receive this honour for her own achievements.

Chapter 14 - X-rays Tutorial

Any electromagnetic radiation of an extremely short wavelength produced by the deceleration of charged particles or by electron energy transitions in atoms. The wavelengths of x-rays range from about 0.005 to a few tens of nanometres.

Like other forms of electromagnetic radiation (for example, gamma rays, ultraviolet, visible light, infrared, and radio waves), x-rays have the same speed in vacuo - 300,000 km per second [186,000 miles per second] and exhibit phenomena consistent with their wavelike nature, for example interference, diffraction, and polarization.

X-rays were discovered in Würzburg, Germany, on November 8, 1895, by Wilhelm Conrad Röntgen. Röntgen made his discovery while investigating the effects of cathode rays produced by electrical discharges through gases at low pressures. Cathode rays are electrons that are emitted from the negative electrode, or cathode, of a discharge tube.

Although many scientists had studied the properties of cathode rays, Röntgen discovered an effect that had escaped these earlier investigators namely, that a surface coated with barium platinocyanide placed outside a discharge tube would emit light (fluoresce) even when it was shielded from the direct visible and ultraviolet light of the gas discharge. He deduced that an invisible radiation from the tube passed through the air and caused the screen to fluoresce. He named these strange new rays x-rays to indicate their unknown nature.

General x-ray phenomena

When a beam of x-rays passes through matter, it becomes a source of secondary x-rays and electrons as the primary beam is absorbed. The intensity of these secondary radiations is weak compared with the intensity of the primary x-ray beam some of which may escape from the material.

Two types of secondary x-rays are produced when a beam of x-rays strikes a material namely, scattered x-rays, which are characterized by an energy that is nearly the same as the primary beam, and fluorescence x-rays, which are less energetic than the primary x-ray emission.

Scattered x-rays are primary x-rays that have had their direction and sometimes their energy altered by passing through matter. X-ray scatter occurs by two interaction processes: Compton absorption and Rayleigh scatter.

In the case of Compton absorption, some of the primary x-ray photon energy is absorbed by an electron within the target material causing it to be ejected from the nucleus to which it is bound (photoelectric effect); the remaining x-ray photon energy appears as a new lower energy photon which has a different trajectory to that of the original x-ray photon.

In the case of Rayleigh scatter, the incoming x-ray photon is simply made to change its path in the presence of electrons within the target material, very little energy is lost from the x-ray photon in this process.

By contrast, fluorescence x-rays are characteristic of the target material in which they are generated. Fluorescence x-rays are generated when electrons are ejected (photoelectric absorption) from some of the atoms of the target material, leaving them in an ionized state. These electron shell vacancies are then able to be filled by the de-excitation of lower energy electrons (i.e. from higher orbital shell's) with concomitant production of a characteristic x-ray photon. The two main types of fluorescence x-rays that can be produced in most of the elements are known as the K and L characteristic x-rays.

Dual nature of x-rays

Early experiments with x-rays led to observations that were difficult to explain unless one thinks of them as consisting of waves. Other experiments however, indicated that x-rays consist of particles. This dual nature is not restricted to x-rays; indeed, it is a general property of all forms of energy and matter. X-rays (and the other forms of electromagnetic radiation) should therefore be considered as both particles and waves; that is, as consisting of small packets of electromagnetic wave quanta, or photons.

X-rays as waves

According to classical electromagnetic theory, the deceleration of electrons will produce electromagnetic radiation, in the same way that accelerated electrons in a radio antenna produce radio waves. The failure of magnetic fields to deflect an x-ray beam seems to confirm this classical idea of the origin of x-rays. Conclusive evidence for the existence of waves is established if diffraction and interference phenomena are observed, both of which depend on the superposition of waves. In addition, if polarization effects are observed, the transverse (vibration at right angles to direction of propagation) nature of the wave is established. In the case of light, these effects were well-known in 1895 when x-rays were discovered. However, Röntgen's early experiments failed to reveal these effects in the case of x-rays.

In 1906, a British physicist, Charles Glover Barkla, demonstrated that when x-rays are scattered in certain directions by a block of carbon they are polarized. From these experiments it appeared likely that x-rays were transverse electromagnetic waves, perhaps of the same nature as light but having only a different wavelength.

Many scientists attempted to show the wave nature of x-rays by passing them through narrow slits and looking for diffraction fringes, and there was some evidence that x-ray wavelengths were about 0.1 nm. In 1912, a German physicist, Max Theodor Felix von Laue, conceived of a way of measuring the wavelength of x-rays. Laue used the idea that, in crystals, atoms are regularly arranged throughout the crystal structure with spacings of about 0.1 nm and concluded that the atoms of a single crystal would serve as a grating for the diffraction of x-rays. Laue's coworkers directed a narrow-beam of x-rays at a crystal of zinc sulfide and placed a photographic plate behind it. The resulting photograph consisted of a dark central spot and a complex but symmetrical pattern of dots; the central spot was the result of x-rays passing directly through the crystal, whereas the dots were produced by diffraction from the atoms of the zinc sulfide crystal. These experiments established that x-rays are waves with wavelengths of the order of 0.1 nm and confirmed that crystals have their atoms arranged in regular structures, called a lattice.

Shortly after Laue's experiment, an English physicist, William Lawrence Bragg, devised another technique for diffracting x-rays. By considering how x-rays are scattered from atoms in a crystal lattice, he concluded that, when an x-ray of wavelength λ strikes a crystal of interplanar spacing d at an angle with respect to the crystal plane, constructive interference would occur when the product of an integer number n (called order of diffraction) and the wavelength is equal to twice the lattice spacing times the diffraction angle: $n\lambda = 2d \sin \theta$. This equation is known as Bragg's law and is the principle of operation of x-ray crystal-diffraction spectrometers.

Using this theory, Bragg obtained a distribution of the intensity of ionization in a detector as a function of angle. This distribution indicated that x-rays consisted of two types, a line spectrum characteristic of the target material used in the x-ray tube and a continuous spectrum.

From the crystal spacing d , which Bragg obtained from the geometry of the crystal lattice, the density of the crystal, and mass of a single atom, he was able to calculate the wavelengths of characteristic x-ray lines and was able to show that these wavelengths varied approximately as the inverse square of the atomic mass number of the absorber.

These experiments confirmed the earlier results of Barkla, who, by using the fact that short-wavelength x-rays are absorbed to a lesser extent than long-wavelength x-rays, found two regions of strong maxima. In 1911 Barkla named the long-wavelength maxima the L series and the short-wavelength maxima the K series.

In 1923, the reflection of x-rays from a polished surface of glass was demonstrated by an American physicist, Arthur Holly Compton. He found that, for angles of less than 10 minutes of arc, a strong reflected beam could be observed in the direction predicted by the specular-reflection law. The final proof of the wave nature of x-rays, their diffraction by a ruled grating, was observed in 1925. Because the line spacing of a ruled grating is accurately known, this method has been used to determine the absolute value of x-ray wavelengths.

X-rays as particles

The particle nature of x-rays is graphically demonstrated in the photoelectric and Compton effects. In

an attempt to explain blackbody radiation (radiation from a theoretically perfectly non-reflecting, or completely absorbing [i.e., "black"] body), Max Planck postulated that energy is radiated in small packets, or quanta, with an energy given by $h\nu$, in which ν is the frequency of the radiation and h a constant (now called Planck's constant). One of the most important successes of Planck's postulate, in addition to explaining blackbody radiation, was its use by Einstein in explaining the photoelectric process.

A second series of experiments that demonstrated the particle nature of x-rays was carried out in 1922-23 by Compton. Using an x-ray spectrometer, he measured the wavelength of x-rays scattered from light elements. In addition to scattered x-rays that had the same wavelength as the primary beam, he found a second, or "modified", peak at a longer wavelength. The intensity and wavelength of this second peak were functions of the scatter angle from the sample. The explanation of this effect (now known as the Compton effect) was given by Compton and independently by a Dutch scientist, Peter Debye. They proposed that a primary x-ray photon could be considered as a small ball that could collide with one of the electrons in the scattering material in a manner similar to the collision of two smooth elastic balls of different mass. The photon would then lose some of its energy to the recoiling electron and would be of longer wavelength. By assuming that conservation of energy and momentum (mass times velocity) would hold in the collision between a photon and an electron, they were able to derive the shift of the wavelength of the scattered x-ray to give the modified peak at a longer wavelength.

Chapter 15 - Using the Health Physicist's Companion

Nuclide Database Structure

The Companion's nuclide database has the following field and displayed data structure.

Detail	Field Name	Displayed Name
Abbreviated element name	ELEMENT	Element
Atomic mass number	A	A
Atomic number	Z	Z
Radionuclide half-life (if applicable) where: y=years, d=days, h=hours, m=minutes and s=seconds	HALFLIFE	Half-life
Decay mode and energy in MeV where: b- beta b+ positron K electron capture m metastable state a alpha SF spontaneous fission p proton N neutron IT isomeric transition	BETAALPHA1...6	Decay(1...6)
Gamma emission energy in MeV	GAMMA1...6	Gamma(1...6)
Fractional decay	DECAY1...12	X100%
Dose per Bq inhalation of a 5 micron AMAD aerosol	RESPAMAD5S	Inhale 5 μ (slow)
Dose per Bq inhalation of a 1 micron AMAD aerosol	RESPAMAD1S	Inhale 1 μ (slow)
Fractional clearance value	RESPSF1	Inhale f1 (slow)
Dose per Bq ingestion	INGESTS	Ingestion (slow)
Fractional transfer value	INGESTSF1	Ingestion f1 (slow)
Dose per Bq inhalation of a 5 micron AMAD aerosol	RESPAMAD5M	Inhale 5 μ (med.)
Dose per Bq inhalation of a 1 micron AMAD aerosol	RESPAMAD1M	Inhale 1 μ (med.)
Fractional clearance value	RESPMF1	Inhale f1 (med.)
Dose per Bq ingestion	INGESTM	Ingestion (med.)
Fractional transfer value	INGESTMF1	Ingestion f1 (med.)
Dose per Bq inhalation of a 5 micron AMAD aerosol	RESPAMAD5F	Inhale 5 μ (fast)
Dose per Bq inhalation of a 1 micron AMAD aerosol	RESPAMAD1F	Inhale 1 μ (fast)
Fractional clearance value	RESPFF1	Inhale f1 (fast)
Dose per Bq ingestion	INGESTF	Ingestion (fast)
Fractional transfer value	INGESTFF1	Ingestion f1 (fast)
Fractional naturally occurring isotopic abundance	ABUNDANCE	Abundance
Notes about the selected nuclide	NOTES	Notes
Nuclide fractional generation from the principal parent*	METSCALER	Fract. Metastable

*The Metscaler field stores the fractional daughter yield for parent radionuclides that decay to both a metastable and ground state. The default value for this field is unity but for metastable/ground state daughter 'pairs', the field value obeys the following rules:

1. If the parent always decays to the ground state, the ground state daughter Metscaler field value is unity and the metastable daughter Metscaler field value is zero. For example, Ne24 decays exclusively to the Na24 ground state, hence the Metscaler field values are zero for Na24m and unity for Na24.
2. If the parent always decays to a metastable state, the ground state Metscaler field value is zero and the metastable Metscaler field value is unity. For example, Cd115 always decays to In115m rather than to the In115 ground state, hence the Metscaler field values are unity for In115m and zero for In115.

3. If the parent decays partially to both the metastable and ground state daughters, both Metscaler fields are set to the fractional decay value that respectively applies. For example, Ga75 has a 99% fractional decay to Ge75 and a 1% fractional decay to Ge75m, hence the Metscaler field values are 0.99 and 0.01 respectively.

NB. In the Serial Decay Page, for radionuclides that either behave as item 3 or have indeterminate metastable/ground state fractional decay values, the user is given the choice of including either daughter nuclide in the serial decay tree build.

The references to 'slow', 'medium' and 'fast' in the inhalation and ingestion fields refer to the definitions given in ICRP²², Publication 68⁽¹⁷⁰⁾ for uptake rates. Type S (slow) denotes an uptake rate by the exposed tissue of 0.1% in 10 minutes (7000 days for 99.9% uptake), type M (medium) an uptake rate of 10% in 10 minutes (140 days for 90% uptake) and type F (fast) an uptake rate of 100% in 10 minutes.

f1 values refer to the fraction of an intake which is taken up systemically following ingestion and to the fraction cleared to the gut by the 'pulmonary ciliary escalator' following inhalation; these values are consistent with ICRP, Publication 68. f1 values are a critical determinant of personal dose and are highly dependent upon chemical form and, in the case of inhalation, upon particle size. The values quoted in IAEA Safety Series 115⁽³⁾ and used by the Health Physicist's Companion are those for either 'worst case' or commonplace radionuclide compounds (see Annexes E and F of ICRP 68).

AMAD refers to the aerosol particle size measurement quantity, activity median aerodynamic diameter.

For poly-disperse (i.e. those having a range of particle sizes) aerosols, the AMAD corresponds to the particle diameter above which 50% of the total aerosol radioactivity occurs. AMAD is typically used in measurements of aerosols that cause exposure by inertial impaction and sedimentation within exposed tissues such as the lung. It therefore has limited application to aerosols that have AMAD values below 0.5 microns.

Using Data Display Grids

You can view nuclide data in 'scrollable' grids in both the Nuclide Selection and Serial Decay pages. In the Nuclide Selection page, you access the grid by double-clicking anywhere in the form background; to revert to single nuclide record display, double-click anywhere within the grid. In the Serial Decay page, the nuclide data grid is permanently displayed.

To configure the layout of a nuclide display grid, right-click anywhere within it to access the display options menu. Grid headings can be mouse-dragged²³ to new positions, thereby allowing you to alter the order of columns; you can also use mouse-dragging to resize columns by dragging their boundaries. In either case, the changes you make are stored in the registry and reinstated each time you run the Health Physicist's Companion.

Querying the Database

The Health Physicist's Companion uses Structured Query Language (SQL) to complete nuclide searches. SQL is an industry-standard database querying language that allows the user to build complex conditional database queries. The language also allows query results to be grouped and sorted for presentation in accordance with sophisticated criteria.

²² ICRP - International Commission on Radiological Protection.

²³ Mouse-Dragging - is a Microsoft Windows term for a technique of moving or resizing an object on the screen. It's achieved by selecting a screen object such as a grid or table heading with the mouse and then, simultaneously, moving the mouse whilst keeping its left button depressed.

SQL statements have the following general syntax:

[COMMAND][FIELD NAME CRITERIA][DATABASE TABLE NAME][FILTER CRITERIA]

Filter criteria are standard operators such as:

< less than > greater than <= less than or equal to >= greater than or equal to
 = equal to **AND** Boolean operator **OR** Boolean operator

The % symbol can also be used as a 'wildcard' anywhere in a search string but you must use the comparator keyword 'like' or 'not like' rather than '=' with this symbol.

Decay mode fields contain two data elements; a type prefix and a mode energy in MeV. The decay type prefixes are listed below:

a	alpha particle decay	b-	beta (electron) decay
b+	beta (positron) decay	K	electron capture (often referred to as K-capture)
p	proton decay	n	neutron decay
IT	isomeric transition	SF	Spontaneous fission
y	gamma emission		

The half-life field contains two data elements; a decay time value and a time base suffix. The time base suffixes are listed below:

y = years d = days h = hours m = minutes s = seconds

Field entry examples:

y1.0 = 1 MeV gamma photon	a5.34 = 5.34 MeV alpha emission
b-2.3 = 2.3 MeV beta emission	1.79e6y = half-life of 1.79 million years

Examples of SQL queries:

- select * from nuclides where betaalpha1 like 'b-%'**
locates all nuclides that have a beta emission first decay mode.
- select * from nuclides where betaalpha1 = 'b-'**
locates nuclides that have a beta emission first decay mode and no specified emission energy.
- select * from nuclides where betaalpha1 > 'a2.3' and betaalpha1 like 'a%'**
locates all alpha emitting nuclides for which the emission energy is greater than 2.3 MeV.
- select * from nuclides where half-life > '2d' and half-life like '%d'**
locates all nuclides having a half-life, measured in days, greater than 2 days.

Tips on Entering Data in Calculation Fields

When entering numerical data in calculation fields, you can use the 'e' or 'E' character to denote standard form values. For example, the value 1090.99 could be entered as 1.09099e3 and 0.0099 as 9.9e-3. The Health Physicist's Companion uses standard form for calculation results that can not otherwise be displayed within the space available in a field.

Screen Optimization

You can optimize the Health Physicist's Companion for VGA or SVGA (640x480 or 800x600 pixels) display by disabling the 'Always-on-top' or enabling the 'Auto-hide' property of the Taskbar.

However, if your PC supports screen resolutions > greater than SVGA, you should consider changing to a higher setting.

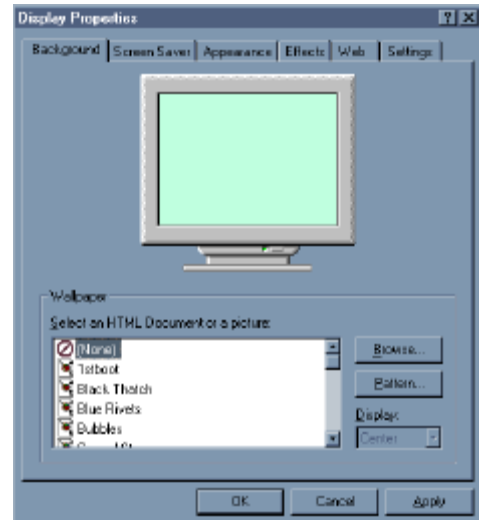
The following notes show you how to make these changes.

Increasing the screen resolution

Changing to a higher screen resolution is the preferred option for optimizing the display of the Health Physicist's Companion; but remember that you will only be able to do this if your PC supports these higher resolutions.

To choose another resolution setting, use your mouse to right-click anywhere on the Desktop, i.e. the screen background where all the programme icons are displayed. Then select the 'Properties' option from the pop-up menu.

You will now see the dialogue shown to the right.

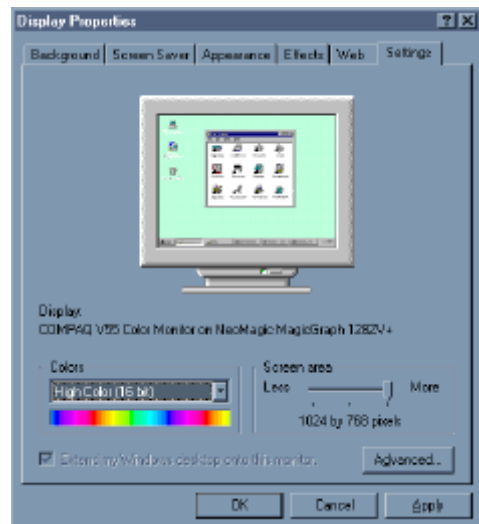


Select the 'Settings' tab from this dialogue and then move the 'Screen area' slider control (shown right) to a higher setting.

Click the 'OK' button to close this dialogue and up-date the screen resolution setting.

On Windows 95 systems, you may be prompted to restart you PC in order to give effect to the resolution change.

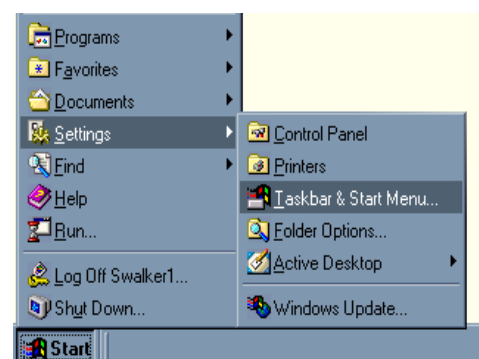
Remember that your monitor and display adapter determine whether you can change your screen resolution.



Changing the Taskbar properties

Click the 'Start' button, point to 'Settings' and then click 'Taskbar & Start Menu...' (shown right).

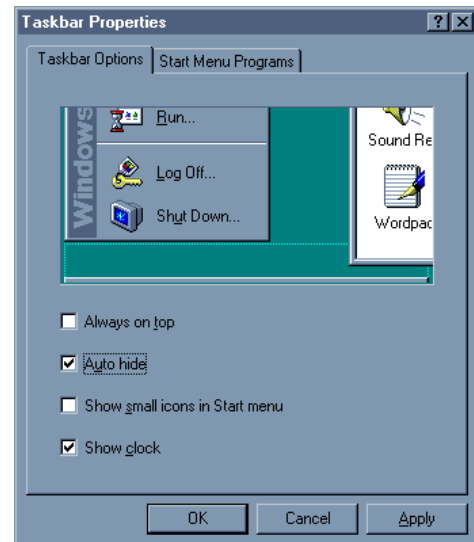
NB. You can also access the Taskbar dialogue (shown below) by right-clicking on any blank area of the Taskbar and selecting 'Properties' from the pop-up menu.



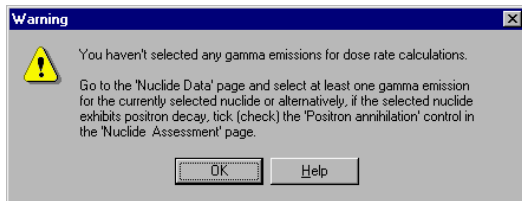
In the dialogue shown to the right, tick (check) the 'Auto-hide' option or untick (uncheck) the 'Always on top' option. Click the 'OK' button to close the dialogue and give effect to the changes you have made.

Tips

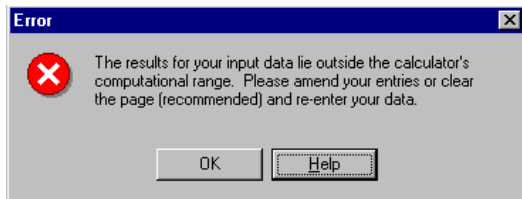
When set to 'Auto-hide', the Taskbar can be redisplayed by pointing to the area of your screen where it is normally displayed. For example, if your Taskbar is normally located at the bottom of your screen, point to that area. Instead of using the 'Auto-hide' setting, you can temporarily hide the Taskbar by pointing to the top of it and dragging downwards when a two-headed arrow appears. To redisplay the Taskbar, drag its visible edge upwards.



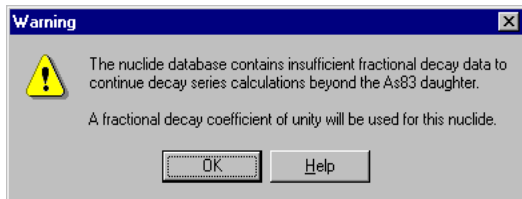
Message Dialogues



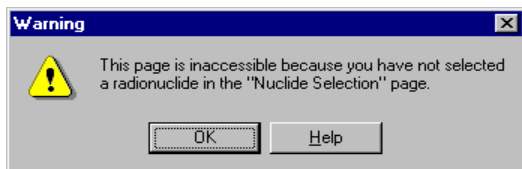
This message box is displayed by the Nuclide Assessment page whenever you try to complete dose rate calculations on a radionuclide for which you have not selected any gamma emissions in the Nuclide Data page. The selections you make in the Nuclide Data page remain in effect until you either clear all pages or select a different nuclide. Selection of a different nuclide defaults all gamma emissions to 'selected'.



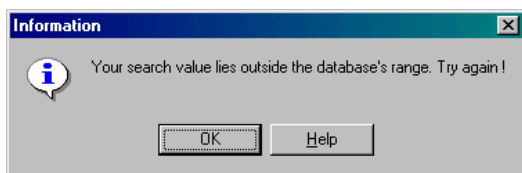
This message box is displayed when the Dose Calculator can't complete dose rate calculations in the Nuclide Assessment page. This problem may arise from errors in the nuclide database or because your entered data in the Nuclide Assessment page has produced an unrecoverable arithmetic error in the Dose Calculator. Contact Syberad if you find that the problem persists.



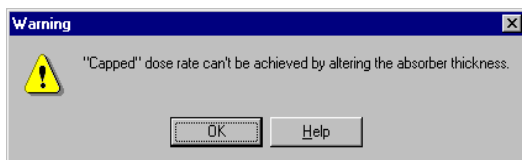
This message box is displayed by the Serial Decay page. The error occurs during serial decay calculations when the nuclide database doesn't contain a fractional decay coefficient for a particular decay mode and the user has selected the 'Branching' option. By deselecting the 'Branching' option, the Calculator is forced to substitute a fractional decay coefficient of unity (i.e. 100%) for all decay modes.



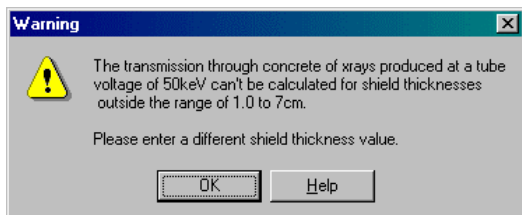
This message box is displayed when you try to select the Nuclide Assessment, Nuclide Data or Serial Decay pages before having first selected a radionuclide in the Nuclide Selection page.



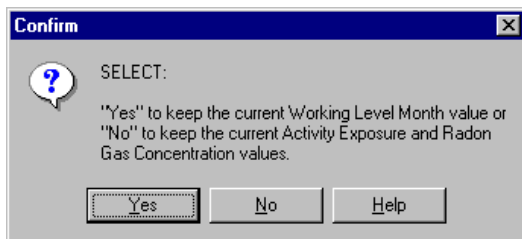
This message box is displayed when you try to locate absorption coefficient data in the Physical Data page that are not in the Companion's database.



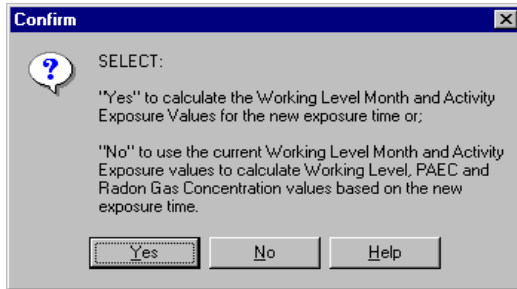
This message box is displayed by the Nuclide Assessment page when you try to calculate the absorber thickness needed to achieve your entered 'capped' dose rate. The error occurs when the 'capped' dose rate can't be achieved even when the absorber thickness is set to zero.



This message box is produced by the X-ray Sets page when you try to calculate a transmission value, for a particular tube voltage and shield thickness, for which there are no empirical data contained in the database.

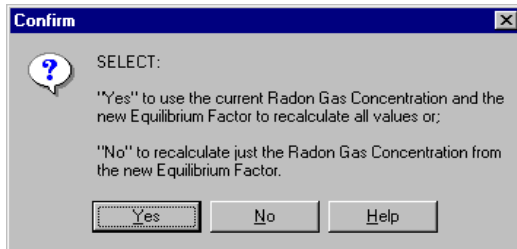


This dialogue box is produced by the Radon Calculator in the Units page. It occurs when you select a different radon isotope for radon data that are already being displayed. When you do this, the calculated radon data can be updated in two ways; either by keeping the original working level month value and calculating a new value for activity exposure and radon gas concentration (the YES option) or by keeping the existing activity exposure and radon gas concentration values and updating the working level month value (the NO option).



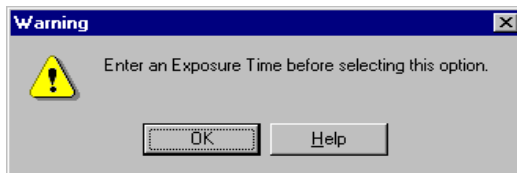
This dialogue box is produced by the Units page.

It occurs when you change the exposure time for radon data that are already being displayed. When you do this, the Radon Calculator can update the calculated data in two ways; either by keeping the original radon gas concentration, PAEC and working level values (the YES option) or by keeping the original activity exposure and working level month (WLM) values (the NO option).



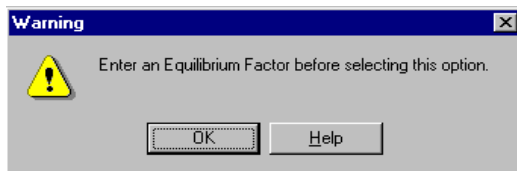
This dialogue box is produced by the Units page. It occurs when you change the equilibrium factor for radon data that are already being displayed.

When you do this, the Radon Calculator can update the calculated data in two ways; either by keeping the original radon gas concentration value and recalculating all other values (the YES option) or by recalculating only the radon gas concentration (the NO option).

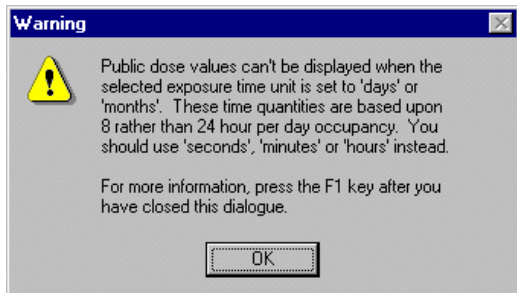


This dialogue box is produced by the Radon Calculator in the Units page.

It occurs when you select the 'Set Equilibrium Factor' tick-box (check-box) before entering an exposure time. The Calculator can't enter this calculation mode until a valid exposure time has been entered.



This dialogue box is produced by the Radon Calculator in the Units page. It occurs when you select the 'Set Exposure Time' check-box before entering a radon gas equilibrium factor. The Calculator can't enter this calculation mode until a valid equilibrium factor has been entered.



This warning message is displayed by the Radon Calculator in the Units page when you try to select the public dose option, in the detriment field at the bottom-right of the page, with either 'days' or 'months' as the selected exposure time unit. The warning is given because public exposures should be based upon 24-hour occupancy rather than the 8-hour per day figure assumed by the Radon Calculator when you select either of these exposure time units. To overcome this problem, select either the 'seconds', 'minutes' or 'hours' time unit.

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Data reproduced in the HP Companion are by kind permission of the BNL.
- 2 ENSDF data are also available from:
 - The Nuclear Energy Agency (Paris, France) of the Organization for Economic Development and Cooperation (OECD). World-wide-web url: www.nea.fr
 - The Nuclear Data Section (NDS) of the International Atomic Energy Agency, Vienna, Austria. World-wide-web url: <http://www-nds.iaea.or.at/ripl/>
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These data are consistent with those published by the International Commission on Radiological Protection (ICRP²⁴) in Publication 68, Volume 24 No.4 1994, ISSN 0146-6453. World-wide-web url: www.icrp.org
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