Practical Radiation Protection

Jos van den Eijnde
Klazien Huitema
Lars Roobol

Fifth, completely revised edition

Syntax Media – Amersfoort, the Netherlands

Preface

Dear reader,

This revised, fifth edition of *Practical Radiation Protection* provides insight into the hazards of applying ionising radiation and the practical methods to control these hazards. The book is a translation of the ninth edition of *Praktische Stralingshygiëne* (2022), with some corrections to the Dutch text.

The book is intended for anyone who works with open sources, sealed sources or X-ray equipment.
It is aimed at radiation protection officers (RPOs) working with
- industrial radiography equipment
- measurement and control applications
- dispersible radioactive substances at C and D level
- medical applications.

It fulfils the course requirements for the RPOs in these sectors, as laid down in Appendix 5.2 Part A of the *Regulations on basic safety standards for radiation protection*. The necessary depth of knowledge differs per sector; throughout the training the lecturer will guide you on this.

In addition the book may be used for
- radiation workers in these settings
- radiation protection experts
- anyone with an interest in this issue (managers, policy makers, journalists, etc.).

New to the fifth English edition is that – in addition to the basic knowledge – in-depth paragraphs have been included; these are not part of the course requirements. An extensive literature list has also been added. The book is now entirely in full colour.

Content, and changes in content compared to the fourth English edition

Chapter 2 gives an updated overview of the applications of ionising radiation in the Netherlands. New in this chapter is the treatment of the decay chain of uranium and radon.
Chapter 3, on interaction of radiation with matter and shielding of radiation, gives some more information on high-energy electrons and presents and discusses half-value layers in the easy-to-apply unit cm.

Chapter 4, on the relevant quantities and units, was Chapter 5 in the previous edition. New in this chapter are the extensive treatment of the ambient dose equivalents and an update of the RIVM-overview of the various sources of radiation exposure in the Netherlands.
In Chapter 5 (Chapter 4 in the previous edition), on radiation detection, the text is formulated more precisely.
New in Chapter 6, on effects and risks, is a closer look at the non-lethal cancers and at risk assessment.
In Chapter 7, on regulations and ethics, more attention is paid to the division of tasks within the company, and in particular to the tasks of the Radiation Protection Officer.
In Chapter 8 on the dose calculations, the ambient dose equivalent is used in the formulas and in the rules of thumb, and the text on the skin dose has been extended.
Chapter 9, originally called ‘Sealed sources and X-ray equipment’, is now called ‘Industrial Radiography and Measurement and Control Applications’. It has been expanded and completely rewritten to make this book useful for these applications.
In Chapter 10, Section 10.5 on removal of airborne activity, has been rewritten.
Chapter 11 on medical applications is virtually unchanged.

Acknowledgement
We would like to thank colleagues and former colleagues for providing substantive input and comments, and in particular: M. van Bourgondiën, T. van Dillen, B. Godthelp, R. de Goede, M. Huikeshoven, K. van Kammen, E. Luijkx, W. Moerman and T. Meeuwsen.

The content of this book is the responsibility of the authors and not of the institutions where they work or of the colleagues who have commented.

Authors
Drs. Jos van den Eijnde used to work as Radiation Protection Expert level 2, as Certified Safety Expert and as head of a Safety Health and Environment department. He was affiliated to the radiation protection unit of Amsterdam UMC as a guest employee until January 1, 2024. He is now retired.
Dr. Lars Roobol is a Radiation Protection Expert level 2 and works as head of the department ‘Radiation research, knowledge and policy’ at the Dutch National Institute for Public Health and the Environment (RIVM).
Dr. Klazien Huitema is a Radiation Protection Expert level 2, and works as head of the radiation protection education and training department at TU Delft | Stralingsonderwijs.

Leiderdorp, Stompetoren, Dordrecht, March 2024

Table of Contents

Some of these products might end up in by-products from industrial processes that use raw materials coming from the Earth's crust. This is called naturally occurring radioactive material (NORM). This is briefly discussed in Section 2.9.
For these natural sources, less strict regulations apply. However, if a natural radiation source is used for its radioactive properties, the Dutch law regards it as a 'source', and the regulations for 'sources' apply. For workers exposed to natural radiation during their work, the dose is seen as an occupational dose.
When the natural radiation source is used for its fissile or fertile properties, the regulations for fissile or fertile materials are also applicable.

- The radiation coming from the sun and outer space is called cosmic radiation. It consists of high-energy protons and heavy ions, and their resulting decay products. They expose astronauts and air crew (section 7.4.3) and reach ground level, resulting in a dose to everyone.
  Close to the earth, high in the atmosphere, the cosmic radiation forms tritium ^{3}H (tritium), ^{7}Be and ^{14}C (carbon 14); these radionuclides also reach ground level resulting in a dose to all persons.

The resulting dose from 'natural radiation' is treated in Section 4.3.5.

Sources with radioactive substances which are man-made are called artificial sources.

2.3 Decay chains and natural radiation sources

2.3.1 Decay chains

^{14}C has the simplest form of decay. It forms ^{14}N in one step, and ^{14}N is stable (not radioactive). A little more complicated is the decay of ^{99}Mo. This nuclide can decay to ^{99m}Tc, which decays to ^{99}Tc. But ^{99}Mo can also decay to ^{99}Tc directly, in one step. The ^{99}Tc eventually decays to ^{99}Ru, which is a stable nuclide. So ^{99}Mo decays after 2 or 3 steps into a stable nuclide.
In Figure 1.12, we have seen various forms of decay. The successive steps that are needed to finally arrive at a stable nuclide are called a decay chain. It turns out that the naturally occurring ^{232}Th, ^{235}U and ^{238}U have long decay chains. For example, the decay chain of ^{238}U has fourteen decay steps; it ends at the stable ^{206}Pb.

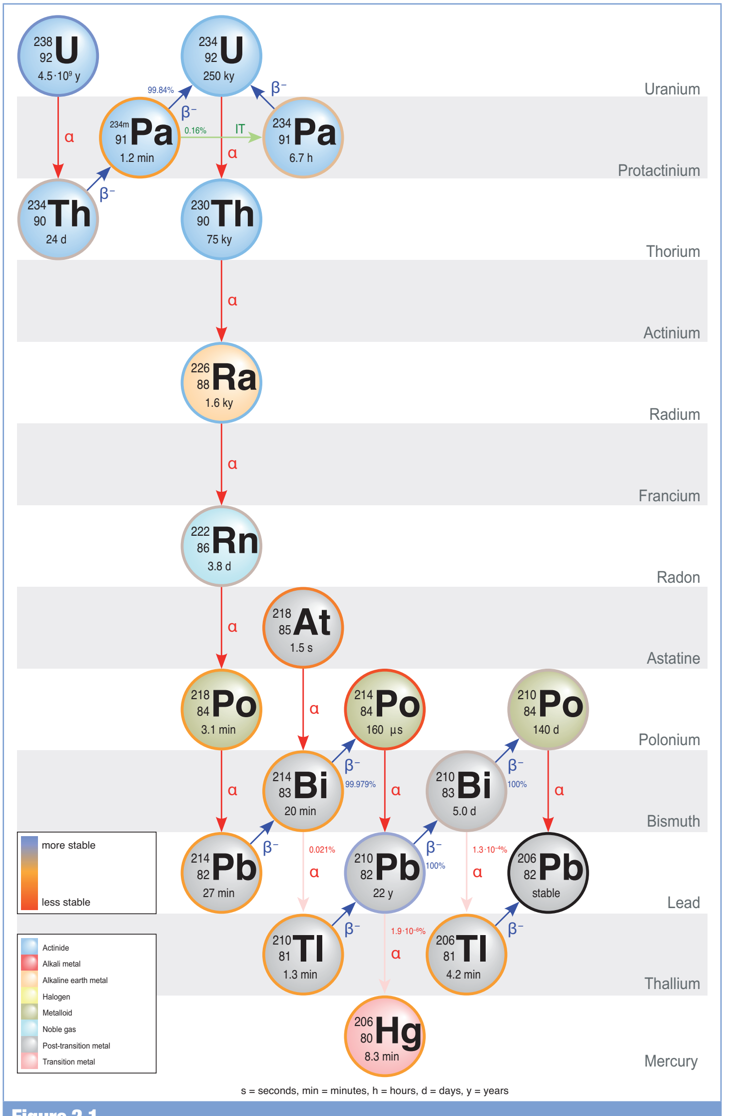


Figure 2.1

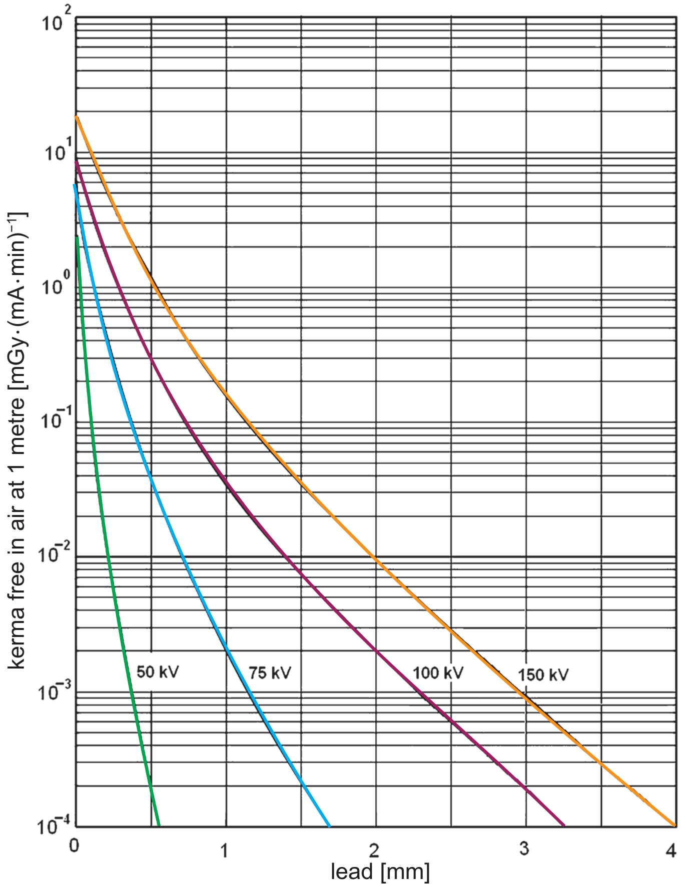
The decay chain of ^{238}U.

In the decay chain of ^{238}U (Figure 2.1), you can find some well-known nuclides:

- ^{226}Ra, known from the research of Marie Curie, and from the ‘luminous paint’ that was used to make the hands of watches light up green in the dark;
- ^{222}Rn, a noble gas and therefore volatile, in contrast to the other, mostly metallic nuclides in the decay chain. See Section 2.3.2 for more information on radon.

Scattering also depends on:

- the size of the irradiated surface;
- the distance from the irradiated surface to the worker;
- the angle at which the surface is irradiated;
- the type of material. If the irradiated material has a high Z, then the photoelectric effect is dominant (Figure 3.5), and much less scattering will occur than for material with a low Z.



kerma free in air per unit of charge ($mGy \cdot mA^{-1} \cdot min^{-1}$) at 1 metre of the focus of broad beam X-radiation traversing lead, density 11.35 g/cm^3, multipulse generator, tungsten anode

tube voltage	50 kV	75 kV	100 kV	150 kV
filtration	2 mm Al	2 mm Al	2 mm Al	2 mm Al
intersection with *y*-axis	2.6	6.1	9.6	18.3

Figure 9.3

Dependence of the dose on the high voltage and the shielding [4].

The foregoing clarifies why Section 8.5 stated that there are no rules of thumb for the dose rate for workers due to scattered X-rays. In practice, first one will use the data provided by the manufacturer, and additional measurements will have to be carried out for the specific application.
In Section 8.5, a scattering percentage of 0.05% was assumed for the discussed application. It will be clear that for other applications a different value will apply.

9.4.4 Shielding of X-radiation

Chapter 8 indicates that for photon radiation determining the reduction of the radiation field caused by shielding is difficult. Often Formulas 3.7 and 8.5 cannot be used, because the value of B (the build-up factor) in these formulas is often unknown. It was stated that then graphs are used to determine the effect of shielding.
For X-ray equipment too, the build-up factor is often unknown. But there is also another problem. X-rays have an energy spectrum. This means that for X-radiation there is not one single half-value layer that can be used in a formula.
Low-energy radiation will be much better absorbed than high-energy radiation. This means that the energy spectrum of the beam changes when passing through matter: the beam becomes 'harder'. The average energy of the photons in the beam increases. As a result the value of the half-value layers changes. It is therefore customary to number the half-value layers. The first half-value layer will be smaller than the second, the second will be smaller than the third, and so on.
So even more by X-rays as by γ emitters, graphs are used to determine the effectiveness of a shielding. Figure 9.3 is such a graph. More graphs can be found in Chapter 6 of the *CZO table book* [5].

9.5 Regulations for IR and MCA

In this section the regulations are discussed in the following order:

- Organisational regulations (as discussed in Chapter 7), relevant for both IR and MCA, in Section 9.5.1.
- Legally prescribed regulations for the workplace (as discussed in Section 7.6), relevant for both IR and MCA, in Section 9.5.2.
- Workplace measures for both IR and MCA that are not specifically legally prescribed, but that the RPO and the radiation worker can and often must take themselves, as an elaboration on the optimisation/ALARA obligation, in Section 9.5.3.

The elaboration of workplace regulations and measures for specifically IR follows in Section 9.6 and for MCA in Section 9.7.

Measures

An overview of measures is included in the *Praktijkrichtlijn Stralingsbescherming Niet-Destructief Onderzoek* (Practice Guide on Radiation Protection Non-Destructive Testing) [19]. It is made by a committee of the trade association, KINT: the four Dutch NDT companies worked together in this committee. The Practice Guide is an elaboration of the *IAEA Specific Safety Guide SSG-11* [20].

When the source is applied 'in the field' (and not in the bunker), many additional measures are needed, in addition to the measures mentioned in Section 9.5. Some important measures are presented below. (Please note that the measures for high-activity sealed sources must also be taken, in particular security measures and measures to control incidents/calamities.)

- A comprehensive management system.
  Given the complexity of the work and the relatively high hazards, high demands are placed on the management system. Routine inspections, audits and controls are part of this. Close consultation with the client is also necessary, about the measures to be taken at the location.
- Measures to control conventional risks.
  The practices often have to be carried out in hard-to-reach and hazardous places, for example in roadside gullies (Figure 9.5), in basements and at height in a structure. It is also often necessary to work outside normal working hours, so as not to disrupt the progress of normal production caused by the enclosure requirements.
  This results in additional non-radiation related risks, which must be assessed in advance, for which appropriate measures are required and which are described in the radiation RI&E and/or in the general RI&E.
- Additional requirements for supervision.
  At the workplace, the work must be done by a worker who has completed the RPO training. This person is called the radiographer. An assistant radiographer must also be present. So the work is never done alone! Often, the assistant has followed an RPO training too.
- Regular checks and measurements.
  Routine checks must be performed in order to detect abnormal conditions in good time. An overview of these checks can be found in the aforementioned *Practice Guide* [19].
  A real-time dosimeter is used, worn by anyone entering a controlled area and during the transport of the sources. This dosimeter is worn in addition to the mandatory personal dosimeter (with monthly, or biweekly readings). An alarm monitor with an audible signal and a survey meter must also be used, to check the exposure rate at the perimeter of the enclosure and to check at the end of the procedure whether the source is returned to a safe position in its source container.

Afbeelding 9.5

Welding seam check in hard-to-reach areas.

9.6.4 Special applications of HAS sources

The ionisation capability of ionising radiation is used to kill germs by irradiating food with a ^{60}Co or ^{137}Cs source with an activity up to 400,000,000 GBq. Irradiation sources are also used in scientific research, e.g. with a ^{137}Cs activity of 100,000 GBq.
In the food irradiation facility, the irradiation space is only accessible through a labyrinth. In scientific research, the sources are kept in a highly-shielded casing. The irradiation space and the shielded casing are secured with interlocks that immediately provide the necessary measures if a person would open a door, and would risk exposure.

9.6.5 IR applications with X-ray equipment

Welding seams

If possible, the material to be examined is taken to an X-ray equipment in a bunker. This bunker is equipped with all safeguards to keep the dose, and in particular the risk of a calamity dose, as low as reasonably achievable.
When it is necessary to take photos of welds in the field with X-ray equipment, a directional tube or a panoramic tube is used. They can have a high voltage of 350 kV, a tube current of up to 6 mA and a dose rate of 6 to 20 $Sv \cdot h^{-1}$ at 1 m. This dose rate is even higher than with the application with sealed sources, as described in Section 9.6.3. The risk and measures described in that Section 9.6.3 also apply when using the X-ray equipment.

Other applications

At airports and at postal and courier companies, different types of ‘small’, fixed X-ray baggage scanners are used to check passengers’ suitcases and hand luggage. The maximum high voltage of these systems is 160 kV.