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Ionising Radiation in Non-destructive Testing, Part 1
Types of Radiation used for Radiographic Testing – Basic Properties and Mechanism of Image Recording

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Summary

Electromagnetic radiation, which is a special example of the electromagnetic field, has been present in the universe since its creation. Examples of radiation include radio waves, X-rays, and visible light. Depending on the frequency of the emitted electromagnetic wave, it can be ionising or non-ionising. Ionising radiation, due to its ability to penetrate matter, is often used in many areas of life. In industry, it is used for diagnostic purposes, e.g. in radiography.

Keywords: ionising radiation, non-destructive testing, industrial radiography

1. Introduction

Electromagnetic radiation, omnipresent in our lives, is a form of energy propagation where photons with corpuscular-wave properties travel at the speed of light. The quantum of energy, i.e. the energy of a single photon, is defined by the following correlation:

$$E = h \cdot \nu = h \cdot c/\lambda,$$

where:

E – photon energy,
h – Planck's constant,
ν – frequency of the wave in Hz,
c – speed of the electromagnetic wave (light),
λ – wavelength.

According to this correlation, the energy of a photon is directly proportional to the frequency of the wave and inversely proportional to its length. Thus, waves of higher frequency (lower length) have higher energy. This is important for the interaction of radiation with matter and for this reason, electromagnetic radiation is divided into non-ionising and ionising radiation. The spectrum of ionising and non-ionising electromagnetic radiation as a function of wavelength, frequency and photon energy is shown in Figure 1.

Ionising radiation has sufficient energy to remove tightly bound electrons from an atom, leading to the formation of ions, hence its name. This phenomenon can cause serious damage to living organisms; nevertheless, with proper protection, it can be used to benefit many areas of life. Its most obvious applications are nuclear power and medicine. However, radiation is also used in industry, particularly in diagnostics. The use of ionising radiation in industry is presented in broad terms, among others, in a study edited by Prof. A. Chmielewski and Z. Zimek [2], and due to the continuous development of research apparatus, this subject is covered in other publications [3, 6, 11, 12, 13, 14].

Ionising radiation can originate from the radioactive decay of naturally occurring isotopes or can be produced in nuclear reactors and accelerators. It can also be obtained by means of the X-ray tube or particle accelerators excluding nuclear processes. Radiation can be divided into:

- particle radiation, which includes α, β, and neutron radiation, and
- electromagnetic, which includes γ and X-rays.

γ and X-rays are commonly used in non-destructive testing – radiological (radiographic, radioscopic or radiometric – depending on the radiation detector used) [3]. The use of radiation offers many advantages in industrial diagnostics, guaranteeing, among other things, good detection of internal inconsistencies of objects, relatively easy interpretation of tests and obtaining a confirmation document that can be subjected to repeated verification.

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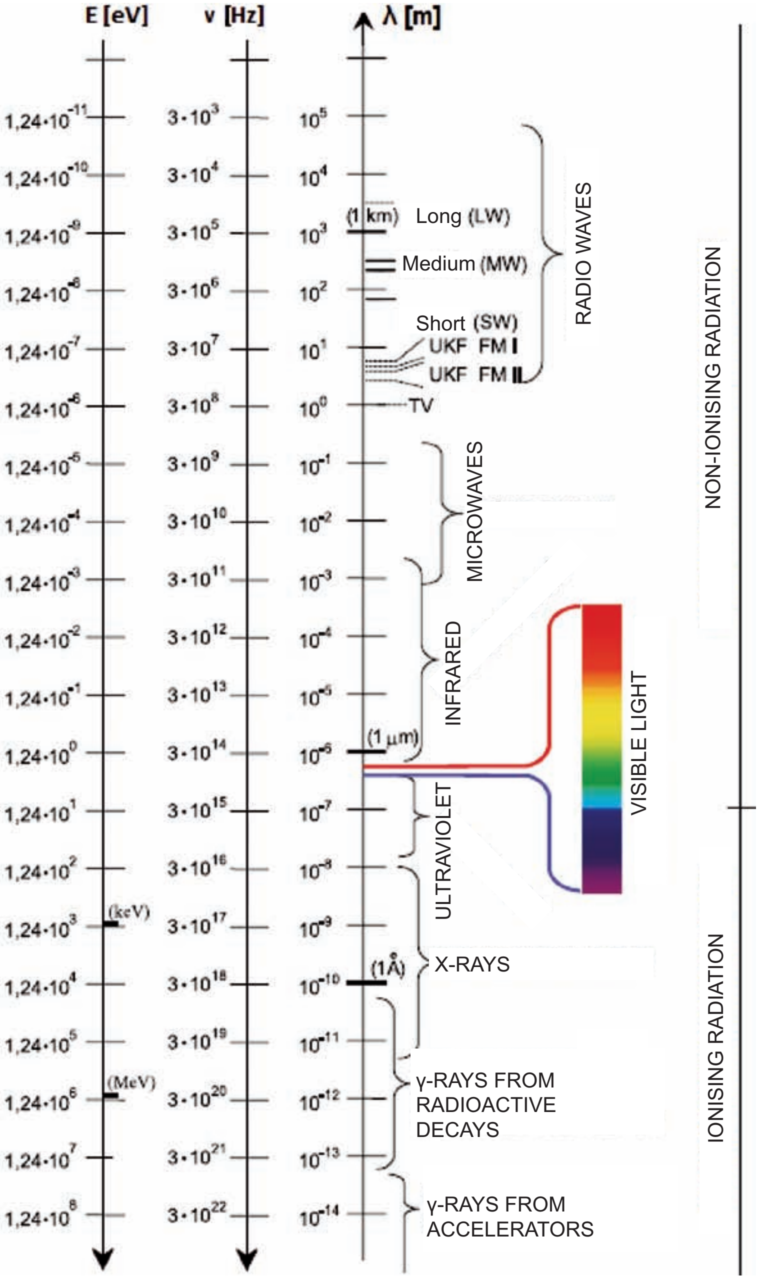

Fig. 1. Spectrum of electromagnetic radiation depending on the wavelength, frequency of the wave, and energy of the photon [1]

2. Properties of radiation used in radiology

γ and X-rays used in radiology have the following properties:

- penetrates through matter,
- propagates in space in a straight line,
- does not deflect in a magnetic or electric field,
- causes excitation and ionisation phenomena in matter, and photochemical phenomena in photographic film,
- has a harmful impact on living organisms.

The fundamental difference between X-rays and gamma rays used in diagnostic methods is not the wavelength, but the source of their formation (Fig. 2). X-rays are produced by fast electrons striking solid matter, while gamma rays are produced within the atomic nucleus due to nuclear processes [4].

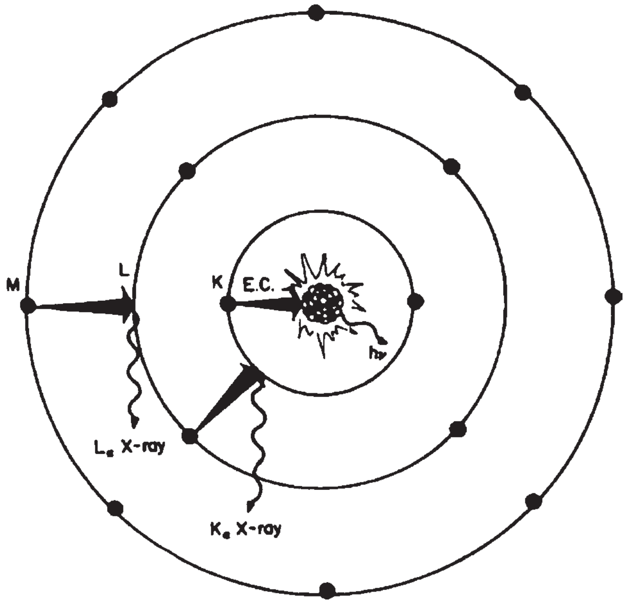

Fig. 2. Diagram showing radioactive decay with electron capture and accompanying emission of gamma-ray quanta (hv) and X-rays [5]

3. X-ray

X-ray tubes (Fig. 3) or, in the case of high-energy photons, particle accelerators are used to produce X-rays. The radiation produced in an X-ray tube is the result of inhibition at the anode of electrons emitted by the cathode and accelerated in an electric field. The electric field is generated by applying a high voltage (50–400kV) to the anode and cathode. With increasing voltage, the X-ray energy increases:

$$E_k = \frac{1}{2} m \cdot v^2 = e \cdot U,$$

where:

E_k – kinetic energy,
m – mass of the electron,
v – velocity of the electron,
c – charge of the electron,
U – potential difference.

X-rays obtained, for example, in an X-ray tube by decelerating accelerated electrons on a material with an atomic number greater than 20, have a continuous characteristic, on which peaks from the characteristic radiation of the anode (accelerated electrons knock electrons out of the anode atoms) are also visible. The material of the anode affects the course of this characteristic. An example of the spectral distribution for tungsten is shown in Figure 4. The electron knockout spots on the lower electron shells remain empty until filled by electrons from the higher shell. As an electron passes from the higher state, it emits a quantum of X-ray radiation. X-rays can also be produced as a result of electron capture (see Fig. 2), i.e. when the nucleus captures an electron located on the K shell, resulting in a vacant spot onto which electrons from higher shells fall and an X-ray quantum is emitted (e.g. iron ^{55}Fe).

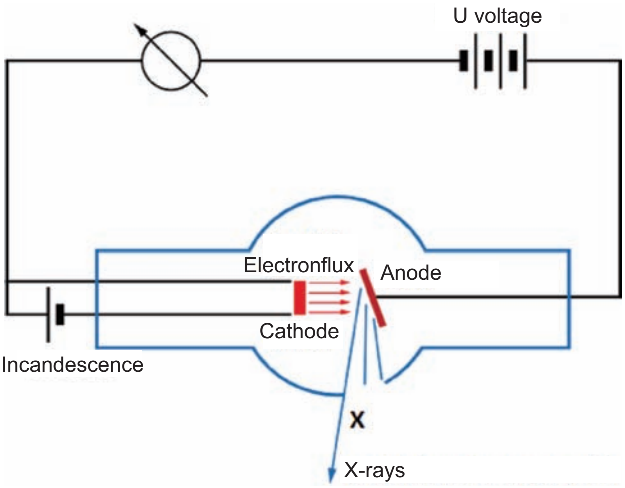

Fig. 3. Simplified diagram of the operation of an X-ray tube [Author's own elaboration]

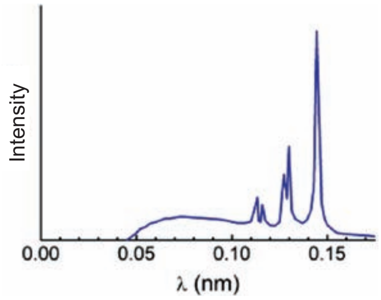

Fig. 4. X-ray spectrum of tungsten; intensity is expressed in terms of signal amplitude (number of counts per second) [7]

The penetrability of radiation depends on its energy, i.e.: the higher the energy, the greater its penetrability. With regard to the ability of radiation to penetrate matter, a further division was made into: soft radiation with a wavelength of 0.1 to 10 nm and hard radiation up to 100 pm. The DIN 6809 standard for clinical dosimetry [6] relates these terms to the voltage of the X-ray tube (Table 1).

Table 1

Scale of radiation hardness depending on acceleration voltage according to DIN 6809

Determination	Acceleration voltage [kV]
Very soft	Below 20
Soft	20–60
Medium hard	60–150
Hard	150–400
Very hard	400–3000
Ultra-hard	Above 3000

[Authors' own elaboration].

4. Gamma ray

The gamma ray used in radiographic non-destructive testing is obtained as a result of energy transformations of atomic nuclei of elements that have been artificially excited to radiation, e.g.: cobalt, iridium, ytterbium and other isotopes. The general formulation of the gamma transformation is as follows:

$$ {}^{A}_{Z}X^{*} \rightarrow {}^{A}_{Z}X + \gamma , $$

where:

A – atomic number,
Z – mass number,
X* – excited element.

A schematic diagram of the γ transformation is shown in Figure 5.

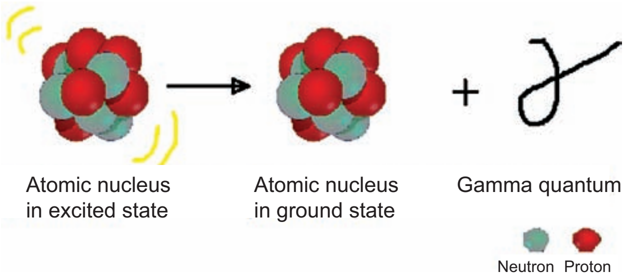

Fig. 5. Schematic diagram of gamma transformation, general principle [Author's own elaboration]

The decay process of a radioactive source can often be accompanied by the emission of alpha, beta or electron particles, as for example in the record for cobalt [10]:

$$ Co_{27}^{60} \rightarrow \beta + \gamma + Ni_{28}^{20} . $$

These are usually several or multi-stage processes, as perfectly illustrated in the diagram for Iridium-192 (Fig. 6).

As time passes, the activity of the radioisotope decreases, as indicated by a parameter called the half-life. The basic parameters of selected radioactive sources are shown in Table 2.

Gamma-emitting equipment used in radiographic inspection during non-destructive testing of materials or industrial objects is called gamma ray projector.

5. Obtaining a test result

The detection of inconsistencies in the materials under test is based on the analysis of changes in X-ray and gamma-ray intensity after passing through the test object according to the correlation [3, 6]:

$$ dI(x) = -\mu \cdot I(x)dx. $$

The radiation intensity after passing through a material of thickness g is:

$$ I = I_0 \cdot e^{-\mu \cdot g} $$

where:

μ – linear coefficient of attenuation,
g – thickness of test material,
I_0 – output radiation intensity,
I – intensity of radiation after passing through the material.

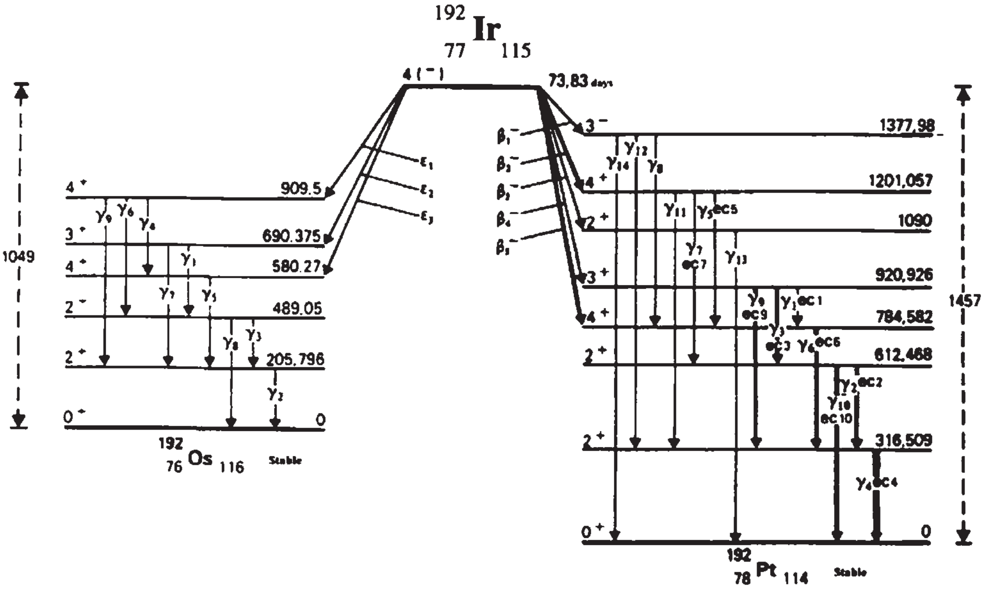

Fig. 6. Decomposition of iridium-192 [8, 9]

Table 2

Basic parameters of selected radioactive sources [3]

Radiation source	Half-life	Gamma ray energy [MeV]	Chronic radiation exposure		Range of steel thicknesses tested [mm]
			$\frac{\mathrm{R\ m^2}}{\mathrm{Ci[2]\ h}}$	$\frac{\mathrm{C[3]\ m^2}}{\mathrm{kg}}$	
Co-60	5.3 years	1.33;1.17	1.35	$2.615 \cdot 10^{-18}$	30–200
Cs-137	30 years	0.66	0.31	$6.005 \cdot 10^{-19}$	15–120
Ir-192	74 days	0.206–0.612	0.46	$8.910 \cdot 10^{-19}$	6–60
Yb-169	31.8 days	0.063–0.309	0.123	$2.421 \cdot 10^{-19}$	1.5–15
Tm-170	130 days	0.052–0.084	0.004	$1.937 \cdot 10^{-21}$	5–40

As a medium for recording the test result, traditional radiography uses X-ray films with a photosensitive emulsion applied to a polyester or cellulose triacetate substrate. The silver compounds contained in the emulsion decompose after the passage of radiation, creating the so-called latent image. After photochemical treatment of the film, the image is revealed as changes in optical density according to the following correlation:

$$D = \log (i_o/i),$$

where:

D – optical density of radiograph

I_o – intensity of incident radiation,

I – the intensity of the radiation passing through the material; the optical density of the radiograph is directly proportional to the intensity of the radiation incident on the film.

Defects in the test object usually have a lower density than the surrounding material, and radiation is absorbed less in those areas. Inconsistencies are revealed as dark spots or lines (depending on the geometry of the defect). Figure 7 illustrates the principle of recording material inconsistencies using the radiographic method.

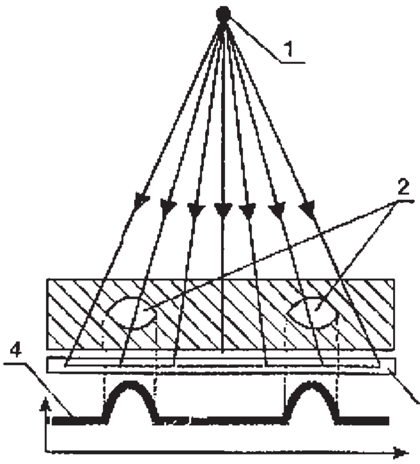

Fig. 7. Recording of material inconsistencies using the radiographic method [3]: 1) X- or gamma-ray source, 2) incompatibilities, 3) radiographic film cassette, 4) change in optical density in the radiograph

6. Conclusion

The article presents basic information on the radiation used in radiography. It discusses the methods of producing radiation and its basic properties that enable the use of radiation in non-destructive radiographic testing.

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[2] In the SI system, the basic unit of activity (number of decays per unit time) is the becquerel (Bq). In a source with an activity of one becquerel, one radioactive decay occurs in one second (1 Bq = 1 s^{-1}). The historical unit of activity is the kyur (Ci). 1 Ci represents the activity of 1g of ^{226}Ra and corresponds to: 1 Ci = $3.7 \cdot 10^{10}$ Bq = 37 GBq.

[3] Formerly, the unit of radiation was the roentgen (R), however, the definition of the roentgen changed over time and in 1937 the ICRU (International Commission on Radiological Units) modified this definition (ICRU, 1938) which is still in force today. An exposure dose of 1 R, via the emission of secondary particles, induces in 1 cm^3 of dry air under normal conditions (in air of 1.293 mg) the formation of so many ion pairs of each sign that their charge is equal to 1 esu (1 esu = $3.336 \cdot 10^{-10}$ C); 1 R = $2.58 \cdot 10^{-4}$ C/kg.

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