INTERNATIONAL STANDARD

ISO 11537

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Non-destructive testing — Thermal neutron radiographic testing — General principles and basic rules

Essais non destructifs — Essai de neutronographie thermique — Principes généraux et règles de base

Reference number
ISO 11537:1998(E)

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO Technical Committees. Each member body interested in a subject for which a Technical Committee has been established has the right to be reprensented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

Draft International Standards adopted by the Technical Committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

International Standard ISO 11537 was prepared by Technical Committee ISO/TC 135, *Non-destructive testing*, Subcommittee SC 5, *Radiation methods*.

Annexes A, B and C of this International Standard are for information only.

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Introduction

This International Standard is intended to provide guidelines for the production of neutron radiographs that possess consistent quality characteristics, and as an aid to the user in determining the suitability of thermal neutron radiographic inspection for a particular application.

Recommended practices are stated without detailed discussion of the technical background for the preference.

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Non-destructive testing — Thermal neutron radiographic testing — General principles and basic rules

Radiation protection - Health warning

Exposure of any part of the human body to neutrons, X- or gamma rays can be injurious to health. It is therefore essential that whenever neutron radiographic equipment or radioactive sources are used, adequate precautions should be taken to protect the radiographer and any other person in the vicinity.

Limits for the safe levels of neutron, X- or gamma radiation as well as the recommended practice for radiation protection are those valid in different countries. If there are no official regulations or recommendations in a country, the latest recommendations of the International Commission on Radiological Protection should be applied.

1 Scope

This International Standard specifies the basic practices and conditions that are to be observed for thermal neutron radiography of materials and components for flaw detection. It is concerned with techniques using photosensitive film as a recording medium. However, it recognizes that alternative methods of imaging may be used more widely in the future. The scope includes neutron production and collimation methods, converter screen selection, radiographic film, neutron radiographic inspection techniques and the type of material to be inspected. This practice is generally applicable to specific material combinations, processes and techniques.

2 Background material

A glossary of terms relating to neutron radiography is presented in annex A. Attenuation of neutrons in matter is presented in annex B.

3 Neutron radiography method

Neutron radiography and X-radiography share some similarities but produce different results when applied to the same object. Neutrons replace X-rays as the penetrating beam of radiation whose intensity is modulated by an object, resulting in a film image of the features of the object. Since the absorption characteristics of materials for X-rays and neutrons are very different, the two techniques generally tend to complement one another. Neutron and X-ray attenuation coefficients, presented in figure 1 as a function of atomic number, are a measure of this difference.

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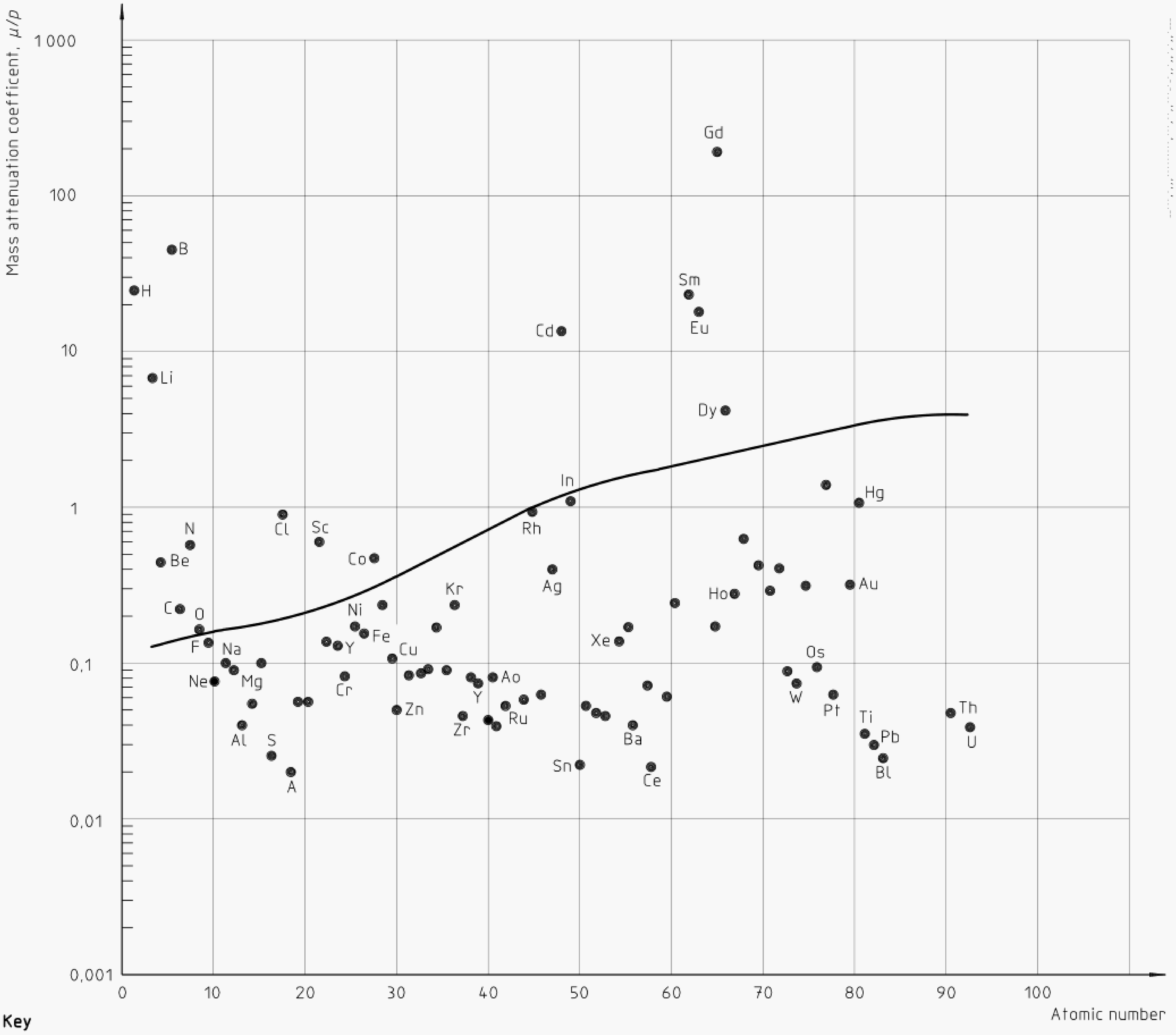

Key

- ● neutrons (λ = 0,146 mm)
- —— X-rays (V_{THT} = 125 kV)

Figure 1 — A comparison of mass attenuation coefficients for thermal neutrons and X-rays

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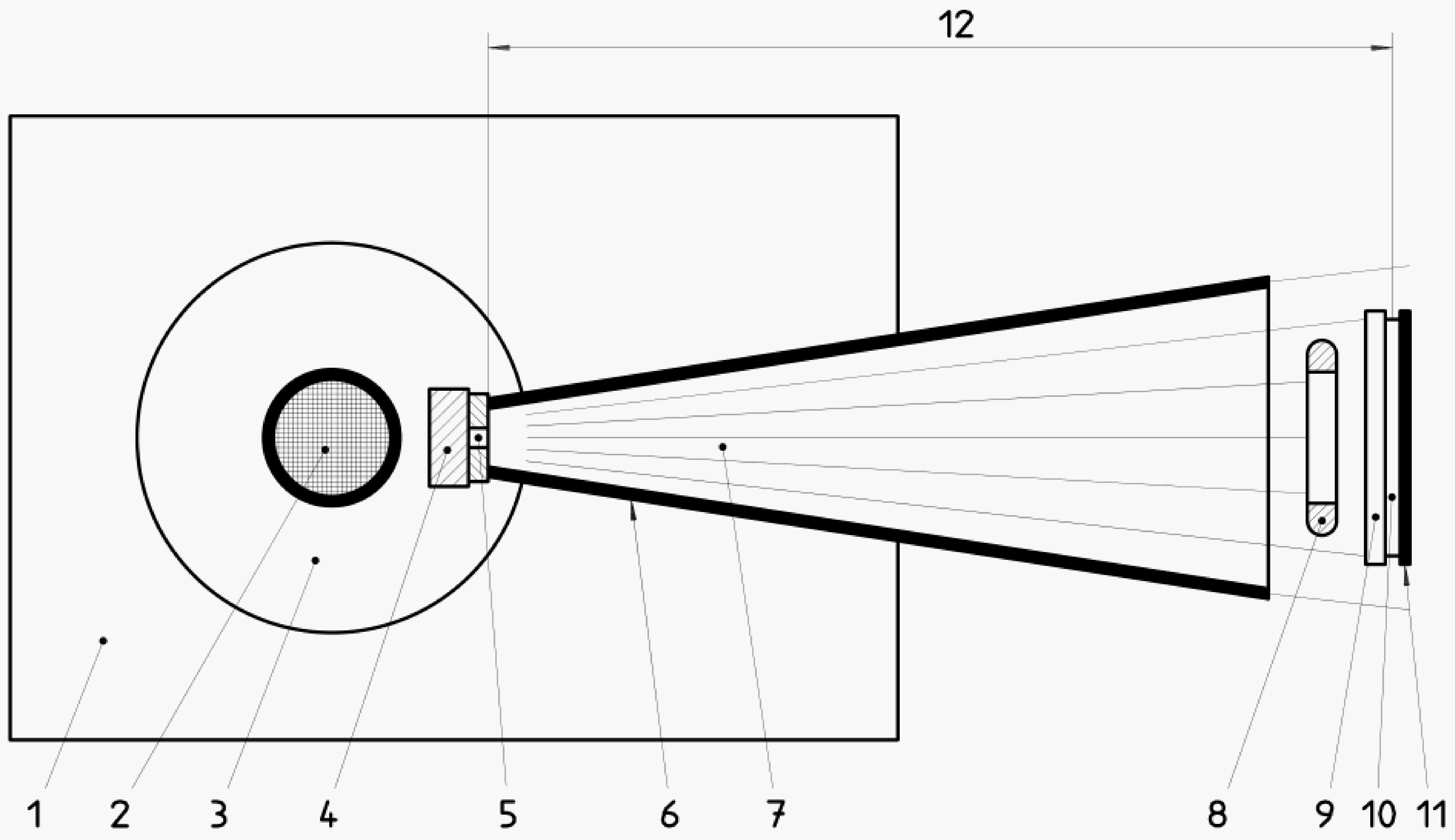
4 Facilities

A neutron radiography facility typically includes a source of thermal neutrons, a neutron beam collimator, a conversion screen, film and an exposure cassette. A schematic diagram of a representative neutron radiography facility is shown in figure 2.



Key

1	Shielding	7	Divergent neutron beam
2	Neutron source	8	Object
3	Moderator	9	Film
4	Gamma filter	10	Emulsion
5	Aperture - diameter (*D*)	11	Conversion screen
6	Collimator	12	Length (*L*)

Figure 2 — Typical neutron radiography facility with divergent collimator

5 Neutron sources

Neutron sources suitable for thermal neutron radiography can be classified into three general categories:

— radioactive isotopes;

— sealed tubes and accelerators of particles; and

— nuclear reactors.

Each of these sources produces high-energy neutrons that require moderation (slowing down) to thermal energies. This can be accomplished by surrounding the neutron source with beryllium, graphite, water, oil, plastic or some other moderator material.

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5.1 Isotopic sources

Isotopic sources have the advantage of being small and portable but because of their relatively low neutron yield require long exposure times to achieve a given radiographic quality. Many isotopic sources have been used for neutron radiography and the most common of these are shown in table 1. Californium (^{252} Cf) is one of the most popular isotopic sources used for thermal neutron radiography because of its low neutron energy and small physical size which permit efficient moderation and high total neutron yield.

Table 1 — Radioactive sources for neutron radiography

Radiation source	Reaction	Half-life	Remarks
^{241}Am-^{242}Cm-Be	(α, n)	163 days	high neutron yield but short half-life
^{241}Am-Be	(α, n)	458 years	gamma easily shielded, very long half-life
^{210}Po-Be	(α, n)	138 days	low gamma background, short half-life
^{124}Sb-Be	(γ, n)	60 days	high gamma background, short half-life, high neutron yield, easily moderated
^{252}Cf	spontaneous fission	2,65 years	small size, high neutron yield, long half-life, and easy moderation of neutron energies make this an attractive portable source

5.2 Accelerator sources

Sealed tubes and low-voltage accelerators utilizing the ^{3}H(d,n)^{4}He reaction, high-energy X-ray machines utilizing the (x, n) reaction, and Van de Graaff accelerators and cyclotrons using charged-particle neutron reactions have been used as neutron sources for thermal neutron radiography. The targets of these accelerators are surrounded by materials that will moderate the neutrons to thermal energies. The thermal neutron fluence rate of accelerator sources before collimation can be as high as 10^{9} neutrons cm^{-2} sec^{-1}.

5.3 Nuclear reactors

Nuclear reactors are a preferred neutron source for thermal neutron radiography because of their high neutron yield. The high neutron intensity makes it possible to provide a tightly collimated beam and high-resolution radiographs can be produced with a relatively short exposure time. Some of the disadvantages of using nuclear reactors for neutron radiography are the high cost of installation and operation, lack of portability, and vulnerability to strict and complex regulation.

6 Neutron collimators

Neutrons are emitted in all directions from a source and are further scattered randomly by the moderator. A means of collimating thermal neutrons into a beam is provided to produce a high quality neutron radiograph. A well collimated thermal neutron beam coupled with the ability to place the object being inspected close to the imaging system will provide the best radiographic resolution.

6.1 General collimator design considerations

Neutron collimators utilize materials having a high cross section for the absorption of thermal neutrons such as boron or cadmium. These materials should be applied to maximize the number of neutrons reaching the imaging system directly form the source and minimize the number of neutrons scattered back into the beam. Often, a combination of materials is used to achieve the best neutron collimation and to mask out unwanted secondary radiation from the beam. It is sometimes necessary to use materials, such as lithium carbonate, that produce neutron capture decay products that will not result in fogging of the imaging film. Materials that have a high neutron scattering cross section, such as hydrogeneous materials, or materials that emit radiation during neutron capture that may fog the imaging film should not be used indiscriminately near

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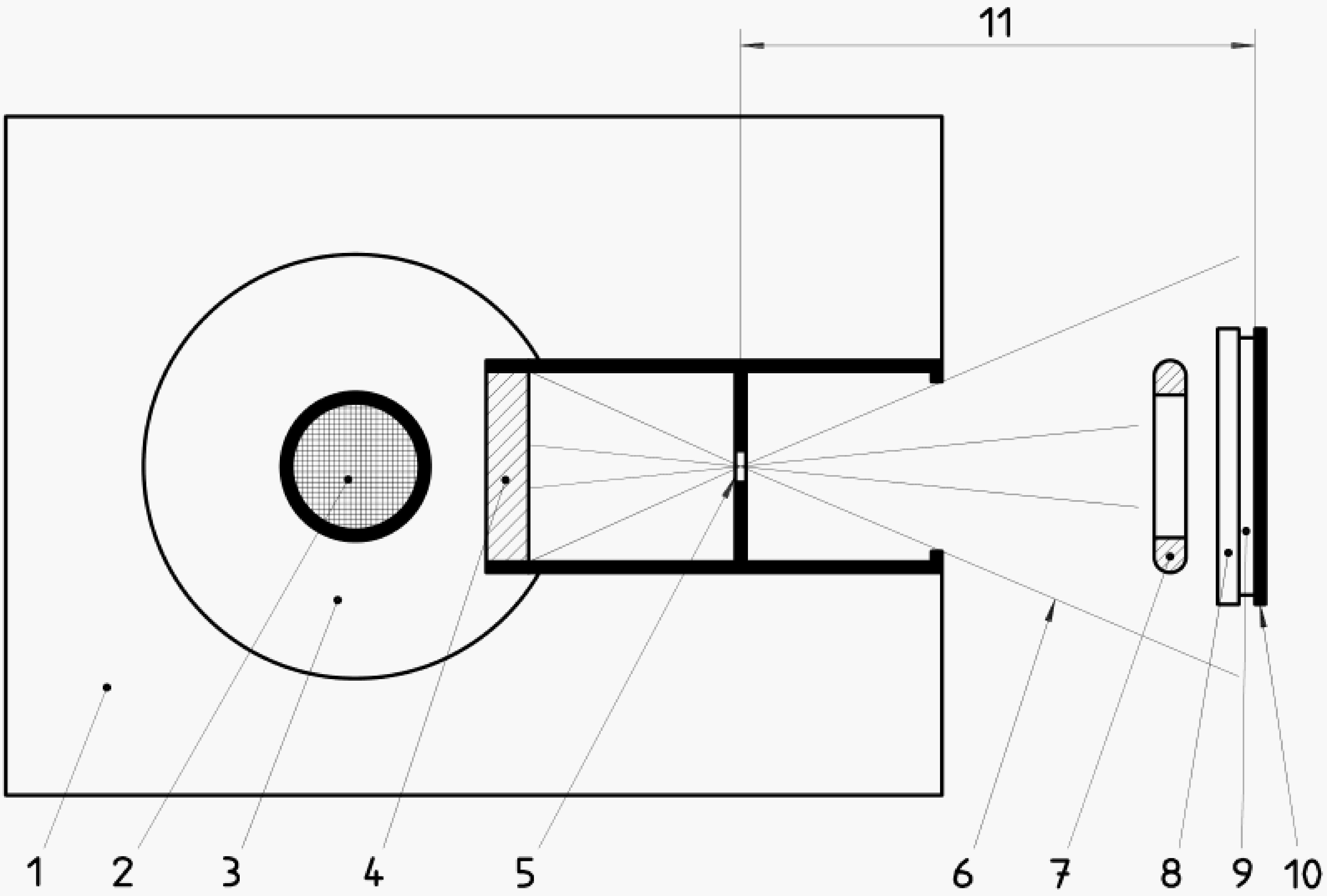
the imaging system. Examples of this latter class of materials include indium, dysprosium and cadmium. Film fogging may also result from the 470 keV gamma ray produced by neutron capture in boron.

The spatial resolution of a neutron radiography system is influenced by the length (*L*) of the collimator, the diameter, or longest dimension of the inlet aperture (*D*) and aperture shape. The ratio of *L*/*D* is used generally to describe the effective collimation of the system. For example, if the *L*/*D* ratio of a system is several hundred, one can expect the system to be capable of producing radiographs of higher resolution than a system having an *L*/*D* of 10. Although *L*/*D* is an important measure of system capability, other factors, such as object size and scattering characteristics, obviously affect the ultimate radiographic quality that can be achieved. In addition to the *L*/*D* value, the L value itself is important. Because the L value is finite, a separation, *l*, between the object and imaging device results in an unsharpness in the image described by magnification factor *L*/(*L*-*l*).

6.2 Collimator types

Although there have been many different collimator designs that have been used experimentally, few of these have survived for use in commercial neutron radiograph facilities. The need to radiography relatively large objects has led to the widespread use of the divergent collimator design shown in figure 2. The divergent collimator consists of a tapered channel made of neutron-absorbing material and originating at its small end (inlet aperture) at the source of highest neutron flux in the moderator.

Another collimator type worthy of note is the pinhole collimator shown in figure 3. High resolution neutron radiography can be produced with systems utilizing pinhole collimators. The pinhole is fabricated from material such as cadmium, gadolinium or boron which have a very high attenuation for thermal neutrons.



Key

1 Shielding
2 Neutron source
3 Moderator
4 Gamma filter
5 Pinhole aperture diameter (*D*)
6 Diverging neutron beam
7 Object
8 Film
9 Emulsion
10 Conversion screen
11 Length (*L*)

Figure 3 — Typical neutron radiography facility with pinhole collimator

6.3 Beam filters

It is often desirable to minimize the gamma radiation that contaminates the neutron beam. This gamma radiation comes from the neutron source and can cause film fogging and reduced image contrast. Filters made of lead or bismuth may be installed near the collimator inlet to reduce this unwanted gamma radiation in the beam. When using a bismuth filter it is advisable to encase the filter in a sealed aluminium can to prevent the spread of alpha contamination due to the ^{210}Po producted by the neutron capture reaction in ^{209}Bi.

6.4 Neutron scattering

Back-scattered radiation from the walls or equipment can be reduced by masking the neutron beam to the smallest practical exposure area and by the careful use of neutron absorber and gamma shielding materials. Back-scattered radiation can be detected by placing a marker made of neutron absorbing material such as gadolinium and a marker made of gamma shielding material such as lead, on the back of the film cassette during neutron exposure. If back-scattered radiation is a problem, one or both of the markers will appear on the film. If backscattering is present, one should minimize materials that scatter or emit radiation in the exposure area (see 7.1). Gadolinium or some other suitable neutron absorber can be placed behind the detector to effectively minimize the influence of back-scattered neutrons on the image.

7 Imaging methods and conversion screens

Neutrons, as their name implies, carry no electrical charge and are therefore non-ionizing and produce little effect on radiographic film. To produce a neutron radiographic image on film it is necessary to employ a conversion screen that, upon neutron capture, will emit ionizing radiation or light that can expose the film as shown in figure 2. It is important that the conversion screen be in intimate contact with the film in order to produce the best quality radiograph. Since conversion screens are expensive and represent a sizeable investment, care should be taken to store them in an environment that will protect them from physical damage and corrosion. Storing dysprosium screens in a vacuum when not in use will minimize atmospheric corrosion and substantially lengthen their useful life.

7.1 Direct exposure method

In the direct exposure method, the film and the conversion screen are placed in a light-tight cassette and exposed to the neutron beam. The film is exposed by the emission of electrons from the conversion screen upon neutron capture. Gadolinium screens are preferred for most applications and are available either as a free standing foil or as a sapphire-coated, vapour-deposited gadolinium coating on an aluminium substrate. Gadolinium emits a 70 keV electron as the result of neutron interaction.

A second type of conversion screen is the light-emitting fluorescent screen such as gadolinium oxysulfide ($Gd_2O_2S:Gd_6$) or lithium fluoride/zinc sulfide ($^6LiF/ZnS$). It is recomended that the spectral response of the screen emission and film be matched for optimum results.

The direct film method using gadolinium metal screens provides high resolution and excellent contrast and has become the reference against which other neutron radiography techniques are compared. This method cannot be used if the neutron beam contains substantial gamma radiation or if the object is highly radioactive.

Other direct exposure methods are used but are beyond the scope of this International Standard.

7.2 Indirect exposure method

The indirect exposure method is used almost exclusively for the radiographic inspection of radioactive objects. This method is insensitive to gamma radiation and utilizes conversion screens, without film, that become temporarily radioactive when exposed to the neutron beam. The film image is made by placing the activated foil in a cassette or other light-tight device together with film after the neutron exposure is terminated. Beta particles emitted by the decay process of the activated foils sensitize the film which can then be processed. Dysprosium, indium, rhodium and gold are all candidates for indirect conversion screens. Dysprosium and indium are the best choice for most applications with dysprosium having the greater speed. Some materials such as gold are less desirable for production neutron radiography because of their relatively long half-life (2,7 days) which results in unacceptability long exposure and decay times.

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Indirect conversion screens should be exposed for a period of time not to exceed three half-lives of the material being used. Further irradiation provides no benefit since the activation rate and decay rate are nearly the same at that point. Three or four half-lives is also sufficient time to transfer the image from the activated foil to the film although they are sometimes left in contact overnight as a matter of convenience. X-ray image intensification screens may be used to increase the speed of the transfer process if desired. The indirect conversion screens can safely be reused without fear of double exposure after decaying for four half-lives.

7.3 Other imaging methods

Other imaging systems could be useful for some applications. However these are not addressed in detail in this International Standard which is concerned with film radiography.

Table 2 — Some Representative Thermal Neutron Detector Materials

Element	Nuclear reaction	Product half-life	Cross-section[1)] barns	Method of radiography
Boron	$^{10}B(n, \alpha)^{7}Li$	prompt	3 837	direct[2)]
Dysprosium	$^{164}Dy(n,\gamma)^{165}Dy$	139 min	1 000	indirect
Gadolinium	$^{155}Gd(n,\gamma)^{156}Gd$ $^{157}Gd(n,\gamma)^{158}Gd$	prompt prompt	61 000 254 000	direct direct
Gold	$^{197}Au(n,\gamma)^{198}Au$	2,7 d	99	indirect
Indium	$^{115}In(n,\gamma)^{116m}In$	54 min	65	indirect
Lithium	$^{6}Li(n,\alpha)^{3}H$	prompt	940	direct[2)]
Rhodium	$^{103}Rh(n)^{104}Rh$	42 s	139	indirect

1) Cross-sections are for the reaction and isotope shown for thermal neutrons (source BNL-325, 3rd edition, volume I, 1973).

2) These detectors are often used for track-etch neutron radiography.

8 Film

Nearly any photo-sensitive film may be used for neutron radiography but it is recommended that industrial radiographic film be used for most applications, either direct or indirect, for best results. Single-sided films produce the best resolution. In applications requiring the additional speed of a film having emulsion on both sides some resolution may be sacrificed. The recommendations and practices that apply to the manual or automatic processing of radiographic films can also be applied generally to the processing of radiographic films used for neutron radiography.

9 Cassettes

9.1 General

Cassettes are required for exposure of the film and conversion screens in the direct method, for exposure of the conversion screens in the indirect method, and for the decay transfer process in the indirect method. Vacuum cassettes are highly recommended for all applications involving film, as these ensure that the film and conversion screens are in intimate contact and thus prevent film flaws due to poor contact.

9.2 Material of construction

Materials used in the fabrication of cassettes to be used in the neutron beam should be selected with care to avoid image degradation caused by neutron scattering or secondary radiation from the cassette. The cassettes should be fabricated from

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aluminium or magnesium, both of which are relatively transparent to neutrons. If commercially available cassettes are to be used, they should be free from plastic materials and the face-plate should be made of thin aluminium (Al. 99,0 Cu (1100) reactor grade or Al.Mg.1Si.Cu-TF (6061T6) aluminium are recommended). Cassettes having o-rings or other hydrogeneous gasket materials should be avoided entirely or at least considered carefully.

For the indirect screen-to-film exposure, the cassette material is not a critical consideration because the cassette is never exposed to the neutron beam, therefore there are no neutrons to be scattered and no secondary radiation to consider. Inexpensive commercially-available flexible vacuum cassettes can even be used for this purpose.

10 Applications for thermal neutron radiography

Although there are many similarities between X- and neutron radiography, the dissimilarities between the two techniques make them each valuable in their own respective domain. Neutron radiography is particularly useful in some specific applications as shown in the following. For additional information see annex C.

10.1 Detection of low-density materials surrounded by high-density materials

Thermal neutron radiography is useful for the detection and inspection of lighter elements encased in a more dense material such as metal. A classic demonstration is the neutron radiography of a wax-coated string embedded in several inches of lead. Although lead is very difficult to penetrate with X-rays, it is easily penetrated by a neutron beam. Examples of this type of application include the inspection of ordnance and other explosive devices, location and measurement of hydrogen in metals, detection of moisture or liquids in metal containers, inspection of adhesive bonding of honeycomb structures, verification of the location of o-rings and gaskets within an assembly, detection of corrosion in aircraft structures, studies of fluid flow in systems, and the detection of fission products in nuclear fuel elements.

10.2 Detection of materials having similar densities

Thermal neutron radiography can be used effectively when objects consist of similar density materials that would be difficult to image with X-rays. Whereas X-rays interact with elements of increasing density in a fairly linear fashion, neutrons interact more randomly as shown in figure 1. Because of this phenomenon, some materials having very similar densities have totally different responses to neutrons and can be differentiated on a neutron radiograph. Examples of these applications include neutron radiographic evaluation of cadmium and silver brazing materials, migration of materials in solid-state electronic components, electrolyte migration in batteries, diffusion between light and heavy water, and absorption of moisture by concrete. For example, contrast agents such as gadolinium may be used to pre-impregnate the core material of investment castings and thus enable residue particles within core galleries to be detected using neutron radiography. This technique is used routinely to aid in the inspection of gas-cooled turbine blades.

10.3 Differentiation between isotopes of the same element

Neutron attenuation is governed by the nuclear cross section of the material, which may vary even between isotopes of a given element, rather than density or any other physical or chemical property of the material. For example, because of the strong difference in neutron absorption between ^{235}U and ^{238}U, fuel pellets having different concentrations (enrichment) of the fissionable ^{235}U isotope can easily be identified in a neutron radiograph. Another example is ^{113}Cd which is the only isotope of cadmium with a high thermal neutron attenuation. Also, one can differentiate between isotopes such as hydrogen and deuterium.

10.4 Inspection of highly radioactive materials

Indirect neutron radiography is insensitive to gamma radiation either form the neutron beam or from a radioactive object. Therefore this technique is extremely useful in the nuclear industry for in-service inspection.

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11 Improved contrast

Certain materials having high neutron attenuation can be useful for tagging other materials to increase their contrast in a neutron radiograph. An example is the use of gadolinium-oxide which is a powder that can be wiped on to a machinist's scale to make it highly visible in a thermal neutron radiograph. Other contrast agents include cadmium, boron or even water or oil.

12 Image quality indicators

Future ISO standards will describe devices and techniques used to characterize the total system response for a thermal neutron radiography facility. The methods described therein can be used as a basis for establishing repeatability and quality criteria between a vendor and customer.

13 Neutron activation

Some materials become radioactive when exposed to the neutron beam during radiography. Depending on their neutron capture cross section and half-life, this may result in radiation that may persist for hours or days following neutron exposure. Although this secondary radiation can have a detrimental effect on the film used for neutron radiography, causing fogging and loss of contrast, the major consideration is to prevent personnel exposure. Some consideration shall be given to the neutron characteristics of materials used in the radiography facility and the objects being radiographed. Also, radiation surveys of the object shall be performed following neutron exposure. Using a short decay time is all that is required before normal handling can resume.

Cassettes can become activated especially if used repeatedly during a short interval of time. Monitoring of radiation levels can result in a cassette management scheme that will minimize exposure to personnel. It is important to keep activated cassettes away form unexposed film.

Conversion screens such as gadolinium, boron or lithium used for direct neutron radiography usually have low activation properties and seldom cause problems. Conversion screens used for indirect neutron radiography are chosen specifically for their high activation capabilities. These screens become radioactive during exposure and shall be handled with care, especially after neutron exposure and until the screens are loaded into the film cassette. The cassette is usually effective in shielding out most of the radiation from these screens.

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Annex A
(informative)

Glossary of terms related to neutron radiography

activation: Process of causing a substance to become artificially radioactive by subjecting it to bombardment by neutrons or other particles.

attenuation coefficient: Term related to the rate of change in the intensity of a beam of radiation as it passes through matter (see linear and mass absorption coefficient).

attenuation cross section: Probability, expressed in barns, that a neutron will be totally absorbed by the atomic nucleus.

barn: Unit of area expressing nuclear cross sections (1 barn = $10^{-24} cm^2$).

cadmium ratio: Ratio of the response of two identical neutron detectors, usually activation types such as indium or gold, one exposed bare to the beam and the other cadmium covered (the cadmium covered detector records primarily neutrons having an energy above 0,5 eV and the ratio is a measure of thermalization in the neutron spectrum).

cassette: Light-tight device for holding film or conversion screens and film in close contact during exposure.

contrast agent: Material added to a component to enhance details by selective absorption of the incident radiation.

conversion screen: Device that converts the imaged neutron beam to radiation or light that exposes the radiographic film.

cross section: Apparent cross-sectional area of the nucleus as calculated on the basis of the probability of occurrence of a reaction by collision with a particle. It does not necessarily coincide with the geometrical cross-sectional area πr^2. It is given in units of area.

direct exposure imaging: In the direct exposure imaging method, the conversion screen and image recorder are simultaneously exposed to the neutron beam.

electron volt: Kinetic energy gained by an electron after passing through a potential difference of 1 V.

gamma ray: Electromagnetic radiation having its origin in an atomic nucleus.

half-life: Time required for one half of a given number of radioactive atoms to undergo decay.

half-value layer: Thickness of an absorbing material required to reduce the intensity of a beam of incident radiation to one-half of its original intensity.

indirect exposure: Method in which only a gamma-insensitive conversion screen is exposed to the neutron beam. After exposure, the conversion screen is placed in contact with the image recorder.

isotope: One of a group of nuclides of the same element having the same number of protons (Z) in the nucleus, but differing in the number of neutrons, resulting in differing values of atomic weight (A).

***L/D* ratio:** Ratio of the distance from the entrance aperture to the image plane (L) to the diameter of the entrance aperture (D). It is one measure of resolution capability of a neutron-radiographic system.

linear attenuation coefficient: Measure of the fractional decrease in radiation beam intensity per unit of distance travelled in the material (cm^{-1}).

mass attenuation coefficient: Measure of the fractional decrease in radiation beam intensity per unit of surface density ($cm^2 . g^{-1}$).

moderator: Material used to slow fast neutrons. Neutrons are slowed down when they collide with atoms of light elements such as hydrogen, deuterium, beryllium and carbon.

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neutron: Neutral elementary particle having a mass close to 1. In the free state outside of the nucleus, the neutron is unstable having a half-life of approximately 10 min.

neutron radiography: Process of making a durable image of the internal details of an object by the selective attenuation of a neutron beam by the object.

thermal neutron: Neutrons of these energies are produced by slowing down of fast neutrons until they are in thermal equilibrium with their environment.

total cross section: Sum of the absorption and scattering cross sections.

vacuum cassette: Light-tight device having a flexible entrance window which, when operated under a vacuum, holds the film and conversion screen in intimate contact during exposure.

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Annex B
(informative)

Thermal neutron linear attenuation coefficients using average scattering and thermal absorption cross sections for the naturally occurring elements[1)]

Element		Cross-section barns [2)]		Linear attenuation coefficient
Atomic No.	Symbol	Scattering	Absorption	cm^{-1}
1	H	20,49	0,333	gas
2	He	0,76	0,007	gas
3	Li	0,95	70,5	3,31
4	Be	6,15	0,007 6	0,76
5	B	4,27	767	101,79
6	C	4,74	0,003 5	0,55
7	N	10,03	1,9	gas
8	O	3,761	0,001 9	gas
9	F	3,64	0,096	gas
10	Ne	2,415	0,039	gas
11	Na	3,025	0,53	0,09
12	Mg	3,414	0,063	0,150
13	Al	1,413	0,231	0,10
14	Si	2,043 7	0,171	0,11
15	P	3,134	0,172	0,12
16	S	0,978 7	0,53	0,06
17	Cl	15,8	33,5	gas
18	A	0,647	0,675	gas
19	K	2,04	2,1	0,05
20	Ca	2,93	0,43	0,08
21	Sc	22,4	27,2	1,99
22	Ti	4,09	6,09	0,58
23	V	4,8	5,08	0,71
24	Cr	3,38	3,07	0,54
25	Mn	2,2	13,3	1,24
26	Fe	11,35	2,56	1,18
27	Co	6	37,18	3,93
28	Ni	17,8	4,49	2,04
29	Cu	7,78	3,78	0,98
30	Zn	4,08	1,11	0,34
31	Ga	6,5	2,9	0,48
32	Ge	8,37	2,3	0,47
33	As	5,43	4,5	0,46
34	Se	8,56	11,7	0,74
35	Br	6,1	6,9	0,31

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Element		Cross-section barns 2)		Linear attenuation coefficient
Atomic No.	Symbol	Scattering	Absorption	cm^{-1}
36	Kr	7,5	25	gas
37	Rb	6,4	0,38	0,07
38	Sr	10	1,28	0,20
39	Y	7,67	1,28	0,27
40	Zr	6,4	0,185	0,28
41	Nb	6,37	1,15	0,42
42	Mo	5,59	2,55	0,53
43	Tc	–	20	1,43
44	Ru	6,5	2,56	0,67
45	Rh	5,0	145	10,89
46	Pd	4,2	6,9	0,75
47	Ag	5,08	63,3	4,01
48	Cd	5,6	2 520	117,0
49	In	2,45	193,8	7,52
50	Sn	4,909	0,626	0,16
51	Sb	4,2	5,1	0,31
52	Te	3,74	4,7	0,25
53	I	3,54	6,2	0,23
54	Xe	4,3	23,9	gas
55	Cs	20	29,15	0,42
56	Ba	3,42	1,2	0,07
57	La	10,13	8,97	0,51
58	Ce	9	0,63	0,28
59	Pr	2,54	11,5	0,41
60	Nd	16	50,5	1,89
61	Pm	–	8 400	251,79
62	Sm	38	5 670	171,76
63	Eu	–	4 565	94,82
64	Gd	172	48 890	1 483,88
65	Tb	6,92	23,4	0,95
66	Dy	105,9	940	33,13
67	Ho	8,65	64,7	2,35
68	Er	9	259,2	5,49
69	Tm	6,3	105	3,70
70	Yb	23,4	35,5	1,43
71	Lu	6,8	76,4	2,82
72	Hf	10,3	104,1	5,14
73	Ta	6,12	20,5	1,47
74	W	4,77	18,4	1,46
75	Re	11,3	89,7	6,86
76	Os	15	16	2,21
77	Ir	14,2	425,3	30,86

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Element		Cross-section barns 2)		Linear attenuation coefficient
Atomic No.	Symbol	Scattering	Absorption	cm^{-1}
78	Pt	12,4	10,3	1,5
79	Au	7,84	98,65	6,14
80	Hg	26,5	372,3	16,21
81	Tl	10,01	3,43	0,47
82	Pb	11,26	0,171	0,38
83	Bi	9,3	0,033 8	0,26
84	Po	–	–	—
85	At	–	–	—
86	Rn	–	–	gas
87	Fr	–	–	—
88	Ra	–	12,8	0,17
89	Ac	–	890	23,77
90	Th	12,97	7,37	0,62
91	Pa	–	210	8,41
92	^{235}U	14,3	680,9	33,75
	^{238}U	9,38	2,68	0,58
93	Np	–	–	density unknown
94	Pu	–	1 756 (absorption + fission)	85,96

1) Updated with data primarily from *Neutron Cross Sections: Neutron Resonance Parameters and Thermal Cross Section.* S.F. Mughabghad, Academic Press, Inc., San Diego, 1981.

2) All cross section values are the most probable values.

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Annex C
(informative)

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