TECHNICAL REPORT

Determination of lead equivalent values according to IEC 61331-1:2014 — Report and short guidelines for testing laboratories

L. Büermann

Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany
E-mail: ludwig.bueermann@ptb.de

ABSTRACT: Materials used for the production of protective devices against diagnostic medical X-radiation described in the international standard IEC 61331-3 need to be specified in terms of their lead attenuation equivalent thickness according to the methods described in IEC 61331-1. In May 2014 the IEC published the second edition of these standards which contain improved methods for the determination of attenuation ratios and the corresponding lead attenuation equivalent thicknesses of lead-reduced or lead-free materials. These methods include the measurement of scattered photons behind the protective material which were hitherto neglected but are becoming more important because of the increasing use of lead-reduced or even lead-free materials. They can offer the same protective effect but are up to 20% lighter and also easier to dispose of.

The new method is based on attenuation ratios measured with the so-called “inverse broad beam condition”. Since the corresponding measurement procedure is new and in some respects more complex than the methods used in the past, it was regarded as being helpful to have a description of how such measurements can reliably be performed. This technical report describes in detail the attenuation ratio measurements and corresponding procedures for the lead equivalent determinations of sample materials using the method with the inverse broad beam condition as carried out at the Physikalisch-Technische Bundesanstalt (PTB). PTB still offers material testing and certification for the German responsible notified body. In addition to the description of the measurements at PTB, a short technical guide is provided for testing laboratories which intend to establish this kind of protective material certification. The guide includes technical recommendations for the testing equipment like X-ray facilities, reference lead sheets and radiation detectors; special procedures for the determination of the lead attenuation equivalent thickness; their uncertainties and the necessary contents of the test certificate.

KEYWORDS: Inspection with x-rays; Dosimetry concepts and apparatus; Radiation monitoring; X-ray generators and sources
1 Introduction

In May 2014 the International Electrotechnical Commission (IEC) published the second edition of the international standard IEC 61331 [1–3] entitled “Protective devices against diagnostic medical X-radiation”. This standard consists of three parts:
Part 1: determination of attenuation properties of materials [1]

Part 2: translucent protective plates [2]

Part 3: protective clothing, eyewear and protective patient shields [3]

Part 1 of the standard describes different methods to measure the attenuation ratio $F$. $F$ is the ratio of the air kerma rate in the centre of a specified X-radiation beam of specified radiation quality, with the attenuating material under consideration outside the beam, to the value at the same position and under the same conditions with this attenuating material placed in the beam. This report deals with the improved methods to determine the attenuation ratio $F_{IB}$ of materials according to the “inverse broad beam condition (IB)” described in clause 4.4 of part 1. This special method shall be used for the determination of the lead attenuation equivalent values $\delta_{IB}$ of materials used for the manufacturing of some of the special types of protective clothing, eyewear and protective patient shields described in part 3. Among other things, part 3 defines the requirements on the lead equivalent values of such materials which shall be determined with methods described in part 1.

Since the measurement procedure according to the “inverse broad beam condition” is new and in some respects more complex than the methods used in the past, it was regarded as being helpful to have a description of how such measurements can reliably be performed. The Physikalisch-Technische Bundesanstalt (PTB) still offers this kind of material characterization as a service for the German notified body in charge of the approval of these types of protective clothing. Section 2 of this report describes in detail how PTB performs the attenuation measurements according to the “inverse broad beam condition”. The determination of the lead equivalent values of materials under test is described in section 3. A detailed description of the evaluation of uncertainties of the lead equivalent values is presented in section 4. Finally, section 5 presents a short guide for testing laboratories which intend to offer such services.

2 Attenuation measurements

2.1 X-ray facility and radiation qualities

The X-ray facility named XG160 used for the attenuation measurements described in this report is controlled by a unit of the type MGC41, manufactured by YXLON International X-Ray GmbH. The converter-type generator is of the type XGG, operates at a frequency of 40 kHz and yields a constant potential that can be varied between 10 kV and 160 kV in steps of 20 V. The high voltage ripple is 5 V/mA. The unipolar X-ray tube of the type Comet MXR 165 has a tungsten anode with an angle of 30° and a 4 mm beryllium exit window. The maximum anode load is 6000 W but the maximum anode current is limited to about 90 mA at 60 kV. The tube current can be varied in steps of 0.1 mA. The emission angle is 45°. The high voltage is measured invasively with a frequency compensated voltage divider manufactured at PTB and traceable to the PTB primary standard for dc high voltage. A high-purity Ge spectrometer was used to measure the X-ray spectra shown in figure 1 from which the characteristic beam parameters shown in table 1 were deduced. The radiation qualities according to IEC 61331-1 were obtained by the use of 2.50 mm Al (purity 99.99%) added filtration. The first half-value layers (HVL) in units of mm Al are listed in table 1 and are compared with those published in table 1 of IEC 61331-1. It is obvious that the HVL values
Figure 1. Normalized photon fluence spectra $\phi_E/\phi$ of the radiation qualities according to IEC 61331-1 obtained from measurements with a high-purity germanium detector at a distance of 1 m from the focus. $\phi_E/\phi$ is the number of photons contained in energy bin $E$ normalized to the total number of photons contained in the spectrum.

obtained here are different from those given in the IEC standard. The reason for the deviation is that the IEC values were obtained from an X-ray tube with an anode angle of 21° and a tube exit window of 7 mm Be which is also operated at PTB. Note that the HVL values given in the standard are nominal values. Actual values depend on the special X-ray facility used and may differ from the nominal values (see 5.5.1). In this report the PTB codes (Al 30 – Al 150) listed in table 1 will be used as abbreviation for these radiation qualities.

2.2 Set-up for attenuation measurements

Attenuation measurements were performed for narrow and inverse broad beam conditions as described in clauses 4.2 and 4.4 of IEC 61331-1:2014.

2.2.1 Narrow beam conditions

The narrow beam condition set-up according to clause 4.2 of standard IEC 61331-1 was realized at the XG160 X-ray facility as shown in figure 2. A plane parallel transmission ionization chamber manufactured at PTB with very thin graphitized polyethylene windows is used as a monitoring chamber. The aperture $a_2$ limits the size of the circular shaped beam cross section, whereas $a_3$ is not beam limiting but protects the monitoring chamber against backscattered radiations. At a 1 m distance from the focal spot, beam diameters of 4 cm, 8 cm, 10 cm and 15 cm can be realized. The test object attenuating the beam is located at a distance of about 55 cm from the focal spot, and aperture $a_4$ protects the air kerma detector D which is positioned at a 1 m distance from the focus.
Table 1. Parameters of the radiation qualities according to IEC 61331-1 as realized at the PTB X-ray facility named XG 160.

| PTB code | Tube voltage nominal | Added filtration | 1st HVL (XG 160) | 1st HVL (IEC) | Ratio of the HVLs | Mean Energy (fluence) |
|----------|----------------------|------------------|------------------|---------------|------------------|----------------------|
| Al 30    | 30                   | 2.5              | 0.99             | 0.99          | 1.00             | 23.6                 |
| Al 40    | 40                   | 2.5              | 1.41             | 1.44          | 0.98             | 28.4                 |
| Al 50    | 50                   | 2.5              | 1.76             | 1.81          | 0.97             | 32.5                 |
| Al 60    | 60                   | 2.5              | 2.06             | 2.14          | 0.96             | 36.1                 |
| Al 70    | 70                   | 2.5              | 2.43             | 2.44          | 1.00             | 39.7                 |
| Al 80    | 80                   | 2.5              | 2.73             | 2.77          | 0.99             | 43.1                 |
| Al 90    | 90                   | 2.5              | 3.05             | 3.10          | 0.98             | 46.2                 |
| Al 100   | 100                  | 2.5              | 3.37             | 3.44          | 0.98             | 49.0                 |
| Al 120   | 120                  | 2.5              | 3.70             | 3.79          | 0.98             | 51.6                 |
| Al 120   | 120                  | 2.5              | 4.01             | 4.13          | 0.97             | 54.0                 |
| Al 130   | 130                  | 2.5              | 4.33             | 4.48          | 0.97             | 56.2                 |
| Al 140   | 140                  | 2.5              | 4.65             | 4.82          | 0.96             | 58.3                 |
| Al 150   | 150                  | 2.5              | 4.98             | 5.17          | 0.96             | 60.4                 |

Figure 2. Schematic drawing of the narrow-beam-condition set-up as realized at the X-ray facility XG160 at PTB. X: X-ray source; W: X-ray tube window; S: shutter; a1–a4: apertures, a2 is beam limiting; F: added filtration (2.5 mm Al); M: monitoring chamber; T: test object; D: air kerma detector.

against photons scattered from the test object. The sensitive cross sectional area of the air kerma detector D is fully covered by the X-ray beam.

2.2.2 Inverse broad beam conditions

The inverse broad beam condition set-up according to clause 4.4 of the IEC standard was realized at the XG160 X-ray facility as shown in figure 3. The set-up is exactly the same as that shown in
figure 2 except for the additional aperture $a_5$ in front of the air kerma detector D which limits the beam size close to the entrance window of the plane parallel shaped air kerma detector in a way that the cross sectional area of the sensitive volume of the detector is only partly irradiated according to the conditions described in the standard. At PTB the aperture $a_5$ is of size $2 \text{ cm} \times 2 \text{ cm}$. The lower drawing in figure 3 complies with the description in the standard whereas the upper drawing shows the test object positioned behind aperture $a_5$ far away from the air kerma detector. The reason for this additional set-up option for the test object is to allow a measurement of the build-up factor $B$. $B$ is obtained from the ratio of the air kerma rate measurements when the test object is close to the detector (as shown in the lower picture) and when the test object is positioned far away from the detector (as shown in the upper picture). Section 2.3 explains why this type of measurement of $B$ was chosen as an additional option.

2.3 Radiation detectors

There are different types of ionization chambers which are suited for measurements in narrow beam and/or inverse broad beam conditions. The description is therefore divided into two sections.

2.3.1 Narrow beam conditions

For the attenuation measurements under narrow beam conditions shown in this report, the PTB primary air kerma standard of the type “Fasskammer (FK)” was used [4]. The FK is a cylindrical free-air ionization chamber [5] and measures the air kerma rate independently of the photon energy for X-ray beam qualities produced with tube voltages in the range from about 30 kV to 300 kV. The entrance window of the FK can be varied by a set of circular apertures of diameters ranging from 8 mm to 30 mm. For the measurements presented in this report, an aperture diameter of 10 mm was used.

Alternatively, any other radiation detector can be used for this type of measurement, which is calibrated in terms of air kerma, and complies with the conditions described in clause 4.2 of standard IEC 61331-1. The air kerma response as a function of the photon energy of such a detector must be known and it is very beneficial if the response is flat. An example of a suitable detector is the ionization chamber of the type 34069 manufactured by the Physikalisch-Technische Werkstätten (PTW) in Freiburg, Germany. This chamber is a shadow-free plane parallel chamber used for absolute dosimetry in diagnostic radiology and mammography. The diameter of the sensitive volume is 30.4 mm and the walls consist of graphitized PMMA of a thickness 0.32 mm and an area density of 38 mg/cm$^2$. The air kerma response of this chamber was measured at the calibration facilities of PTB as a function of the ISO 4037 narrow-spectrum series [6] for tube potentials between 10 kV and 200 kV (coded N 10 to N 200). The result is shown in figure 4 where the relative response is plotted as a function of the air-kerma-weighted mean energy ranging from 8 keV (N 10) to 166 keV (N 200). Note that this is equivalent to the Al HVL range from about 0.05 mm to 19.4 mm indicated in figure 4 by the blue colored figures.

Table A.4 in IEC 61331-1 contains the first HVL in mm Al of the radiation qualities described in table 1 as a function of additional lead filters of different thicknesses from 0.125 mm to 2 mm. These values are in the range from 1.0 mm Al (Al 30, without any additional lead filters) to 13.8 mm Al (Al 150 with additional 2 mm lead filter). To get an idea of the change in the spectral fluence of the non-attenuated and attenuated radiation beam qualities these were calculated and plotted against the air-kerma-weighted mean energies as shown in figure 5. It is obvious that the response of the
Figure 3. Schematic drawings of the inverse-broad-beam-condition set-up as realized at the X-ray facility XG160 at PTB. X: X-ray source; W: X-ray tube window; S: shutter; a1–a5: apertures, a5 (square shaped, 2 cm × 2 cm) is beam limiting; F: added filtration; M: monitoring chamber; T: test object; D: air kerma detector. The set-up as shown in the upper and lower part are referred to as IB-AP and IB-AT, respectively, where IB is an abbreviation of inverse broad beam geometry, AP stands for attenuated primary and AT, attenuated total.

PTW 34069 chamber shown in figure 4 is sufficiently flat in this HVL range. It can moreover be expected that this chamber is capable of measuring the air kerma rate ratio of the non-attenuated and attenuated radiation beams with a relative standard uncertainty of less than 2% as required in the standard even if the response is not corrected for its energy dependence. It is however recommended to apply such a correction because it is known and it improves the precision of the measurement.
2.3.2 Inverse broad beam conditions

According to clause 4.4.3 of standard IEC 61331-1, flat ionization chambers shall be used for measurements under inverse broad beam conditions. The flat ionization chamber shall be calibrated in terms of air kerma under the same irradiation conditions. For the measurements presented in this report, chamber type 34060 manufactured by PTW in Freiburg, Germany, was used. This chamber is a shadow-free plane parallel chamber used for absolute dosimetry in diagnostic radiology. The diameter of the sensitive volume is 91.4 mm and the walls consist of graphitized PMMA of a thickness of 0.52 mm and an area density of 62 mg/cm$^2$. The air kerma response of this chamber was measured at the calibration facilities of PTB as a function of the ISO 4037 narrow-spectrum series [6] for tube potentials between 20 kV and 200 kV (coded N 20 to N 200). Measurements were conducted under narrow beam conditions (as shown in figure 2) and under inverse broad beam conditions (as shown in figure 3). The results are shown in figure 6 where the relative responses are plotted as a function of the air-kerma-weighted mean energy ranging from 15.8 keV (N 20) to 166 keV (N 200). From figure 6 it is obvious that the energy response under the usual conditions when the whole chamber is completely irradiated (as shown in figure 2) is significantly different from the response measured under inverse broad beam conditions when only the inner part of the sensitive volume is irradiated (as shown in figure 3). Similar energy response curves were measured for the comparable ionization chamber types PTW 34060 S/N 68, Keithley 96020C S/N 1477022 and PTW Type 7733 S/N 4775 as shown in figure 7.

In clause 4.4.3 of the IEC standard it is required that the quotient of the air kerma rates measured in the non-attenuated beam (without the test object in the beam) and attenuated (with the test object in the beam) shall be known with a relative standard uncertainty of not more than 2%. Due to the fact that the spectral photon fluences of the non-attenuated and attenuated radiation qualities are significantly different as was shown in figure 5, it will be necessary to correct for the energy response of the detector if used under inverse broad beam conditions. Moreover, filtered beams at
Figure 5. Normalized photon fluence spectra $\phi_E/\phi$ of the radiation qualities Al 80 (top chart) and Al 120 (lower chart) without and with 0.25 mm, 0.35 mm, 0.50 mm and 1.0 mm additional lead filters. $\phi_E/\phi$ is the number of photons contained in energy bin $E$ normalized to the total number of photons contained in the spectrum.

The entrance window of the flat detector under these conditions will contain scattered photons from the test object as shown in figure 8 for a layer of 0.25 mm of lead. These transmission spectra were calculated using the flurznrc user code [7] of the EGSnrc code system [8]. One possibility to solve this problem is to calculate the mean response of the detector weighted with the corresponding photon fluence spectrum. However, this method requires knowledge of the photon fluence spectra which are usually not available at testing laboratories.
Figure 6. Relative response $R/R_0$ of the ionization chamber type PTW 34060 plotted as a function of the mean energy of the ISO 4037 narrow-spectrum series [6] N 20 to N 200. $R_0$ is the response at N 40. The blue colored figures relate to the corresponding first half-value layers in units of mm Al. Usually, the whole sensitive volume of the chamber is covered by the radiation beam as shown in figure 2 ("usual response"). The response changes significantly if the chamber is only partly covered by the incident radiation beam as shown in figure 3 ("response in IBG").

Another possibility is a two step procedure measurement. First, the attenuation ratio $F_N$ ($N =$ narrow beam conditions) is measured using the set-up according to clause 4.2 of the IEC standard and as shown in figure 2. Next, two air kerma rate measurements are carried out using the inverse broad beam set-up as shown in figure 3. One measurement is conducted with the test object far away from the entrance window of the flat ionization chamber (figure 3, upper part); this signal is denoted as $\dot{K}_{AP}$. Using this geometry assures that the radiation detector measures the attenuated transmitted primary (AP) photons but no scattered radiation. Another measurement is done with the test object close to the entrance window of the flat ionization chamber (figure 3, lower part), this signal is denoted as $\dot{K}_{AT}$. In this configuration the radiation detector will detect both the attenuated transmitted primary photons and the scattered photons from the test object ($AT =$ attenuated total). Obviously, the build-up factor is obtained by the ratio $B = \dot{K}_{AT}/\dot{K}_{AP}$. Finally, the inverse broad beam attenuation ratio is evaluated as $F_{IB} = F_N/B$. The advantage of this kind of measurement is that the flat ionization chamber under the conditions of the inverse broad beam geometry is irradiated with the filtered (attenuated) beam quality in both measurements which are set up as shown in the upper and lower parts of figure 3. Consequently, the significant differences in the spectral photon fluences of the attenuated and non-attenuated beams as shown in figure 5 can be avoided when $B$ is measured. Another advantage is that $F_N$ and $B$ are evaluated separately which is important additional information about the material under test.
Figure 7. Relative response $R/R_0$ of three different plane parallel diagnostic ionization chambers (see text) measured with the ISO 4037 narrow-spectrum series [6] N 20 to N 150 at inverse broad beam conditions as shown in figure 3. $R_0$ is the response at N 40. The blue colored figures relate to the corresponding first half-value layers in units of mm Al.

Clearly, the photon fluence spectra of the attenuated beam at the entrance window of the flat ionization chamber will be different if the test object is far away or close to the window (see figure 3) because in the latter case scattered photons are added to the spectrum. However, the influence of these differences in the spectral photon fluences on the change in the mean detector response is less significant than those obtained by a measurement with and without the test object in the beam under inverse broad beam conditions. To obtain an estimate, the difference in the mean air kerma response of the radiation detector used (see figure 6, PTW 34060, response in IBG) was calculated based on the corresponding transmission photon fluence spectra as shown in figure 8. This calculation was performed for the case that the Pb sheet is close to ($R_1$) or far away from ($R_2$) the entrance window of the detector D. Results of the ratios $R_1/R_2$ are listed in table 2. Obviously the largest relative difference in $R_1$ and $R_2$ is no more than 0.7% which is acceptable and will be included in the uncertainty estimation (section 4).

2.4 Lead sheets

High-purity (99.94%) lead sheets produced by the PLANSEE Composite Materials GmbH company, Austria were used for the measurements presented in this report. The thicknesses and their uncertainties are listed in table 3. The sheets were square shaped with a size of about 5 cm $\times$ 5 cm.
Figure 8. Normalized photon fluence spectra $\phi_E/\phi$ of the radiation qualities Al 90 (top chart) and Al 150 (lower chart) each filtered with additional 0.25 mm of lead. $\phi_E/\phi$ is the number of photons contained in energy bin $E$ normalized to the total number of photons contained in the spectrum. The red spectrum contains only transmitted primary photons expected at the entrance window of the air kerma detector D in the IB-AP set-up shown in the upper part of figure 3. The green spectrum contains both the transmitted primary photons and the scattered photons expected at the entrance window of the air kerma detector D in the IB-AT set-up shown in the lower part of figure 3. The small peaks between 10 keV and 15 keV are the L-fluorescence lines and those around 80 keV are the K-fluorescence lines of lead.

2.5 Measurement conditions and procedures

The irradiation area at PTB is temperature controlled at around 20 °C and is stable over the duration of a measurement to better than 0.1 °C. Three thermistors, calibrated with an uncertainty of 20 mK,
Table 2. Ratio $R_1/R_2$ of the chamber response if the 0.25 mm Pb sheet is close ($R_1$) or far away ($R_2$) from the entrance window of the detector D shown in the lower (IB-AT) and upper (IB-AP) part of figure 3, respectively.

| Quality code | $R_1/R_2$ |
|--------------|-----------|
| Al 50        | 1.007     |
| Al 60        | 1.004     |
| Al 70        | 1.001     |
| Al 80        | 1.001     |
| Al 90        | 1.000     |
| Al 100       | 1.001     |
| Al 110       | 1.002     |
| Al 120       | 1.004     |
| Al 130       | 1.004     |
| Al 140       | 1.005     |
| Al 150       | 1.004     |

Table 3. Thicknesses of the lead sheets and their uncertainties.

| Thickness/µm | Uncertainty/µm |
|--------------|----------------|
| 100          | 1              |
| 147          | 2              |
| 187          | 3              |
| 244          | 5              |
| 297          | 4              |
| 332          | 5              |
| 531          | 7              |
| 710          | 20             |
| 810          | 20             |
| 1454         | 20             |
| 2015         | 50             |

measure, respectively, the temperature of the air inside the PTB standard and of the ambient air close to the monitoring and transfer chambers. The ambient air pressure is measured using a barometer (Setra capacitance-sensing circuit system) calibrated with an uncertainty of 6 Pa. All ionization current measurements are corrected for air temperature and pressure. There is no air humidity control in the laboratory but the relative humidity cannot exceed 60%. Variations in the humidity are taken into account by a type B relative standard uncertainty of 4 parts in $10^4$ for the PTB air kerma standard and similarly for the secondary standard ionization chamber calibration. No humidity correction is applied to the ionization current measured with ionization chambers.

3 Determination of lead equivalent values

3.1 Lead attenuation curves at narrow beam conditions

The attenuation ratio $F_N$ was measured as described in 2.3.1 for three of the reference lead sheets listed in table 3 with thicknesses of 244(5) µm, 332(5) µm and 531(5) µm. Values were also calculated by using the measured photon fluence spectra shown in figure 1 and the application
of linear mass-attenuation coefficients of lead from the NISTIR 5632 [9] tables of X-ray mass attenuation coefficients according to the description in clause 4.5.4 of the IEC standard. Results are shown in figure 9. Measured values agreed with calculated ones within better than 1%. These results demonstrate the high precision of the measurements.

Based on this good agreement between measurements and calculations, using the calculated $F_N$ values for the other lead sheets of table 3 with different thicknesses was justified. Results are summarized in table 4. It turned out that the measured data could be fitted perfectly by a second order polynomial $y(x) = b_0 + b_1 x + b_2 x^2$, where $y = t_{pb}$ is the thickness of lead and $x = \ln(F_N)$. An example of such a fit is shown in figure 10. Lead equivalent values $\delta_N$ of materials under test are now easily obtained by a single measurement of $F_N$ and inserting $x = \ln(F_N)$ in the polynomial. This is shown graphically in figure 10. Note that curves as shown in figure 10 need to be measured for each reference radiation quality needed for the test. Such curves are specific to the X-ray facility used and may differ for other facilities as already mentioned in section 2.1. Therefore, it is mandatory to use the same X-ray facility for the reference measurements with lead and for the material sheet under test.

### 3.2 Lead attenuation curves at inverse broad beam conditions

The build-up factor $B$ was measured as described in 2.3.2 for the reference lead sheets listed in table 3 up to thicknesses of 710 $\mu$m and for the reference radiation qualities from Al 50 to Al 150. Results are listed in table 5.

![Figure 9](image.png)

**Figure 9.** Measured and calculated attenuation ratios $F_N$ of three different lead sheets measured under narrow beam conditions as a function of the tube high voltage of the IEC reference radiation qualities listed in table 1.
Table 4. $F_N$ values of the reference lead sheets for radiation qualities Al 50 to Al 150.

| t/µm | Al 50 | Al 60 | Al 70 | Al 80 | Al 90 | Al 100 | Al 110 | Al 120 | Al 130 | Al 140 | Al 150 |
|------|-------|-------|-------|-------|-------|--------|--------|--------|--------|--------|--------|
| 100  | 17.42 | 10.73 | 7.56  | 5.87  | 4.82  | 4.22   | 3.83   | 3.53   | 3.30   | 3.10   | 2.93   |
| 147  | 41.25 | 20.87 | 13.03 | 9.25  | 7.15  | 6.07   | 5.41   | 4.93   | 4.54   | 4.22   | 3.95   |
| 187  | 79.47 | 34.24 | 19.43 | 12.85 | 9.49  | 7.90   | 6.97   | 6.30   | 5.77   | 5.33   | 4.94   |
| 244  | 187.30| 64.66 | 32.21 | 19.44 | 13.53 | 11.02  | 9.62   | 8.65   | 7.88   | 7.21   | 6.63   |
| 297  | 393.70| 111.1 | 49.31 | 27.48 | 18.19 | 14.57  | 12.65  | 11.34  | 10.28  | 9.37   | 8.55   |
| 332  | 629.60| 155.9 | 64.21 | 34.03 | 21.84 | 17.31  | 15.00  | 13.43  | 12.15  | 11.04  | 10.04  |
| 531  | 7448  | 895.3 | 245.8 | 100.1 | 54.59 | 41.28  | 35.46  | 31.78  | 28.68  | 25.80  | 23.03  |
| 710  | 57900 | 3700  | 717.1 | 235.0 | 111.60| 81.29  | 69.51  | 62.57  | 56.68  | 50.84  | 44.82  |

Figure 10. Polynomial fit to the $\ln(F_N)$ values for the radiation quality Al 80. Lead equivalent values $\delta_N$ of a test object are obtained as shown in the figure.

Table 5. Measured build-up factors $B$ for the reference lead sheets for radiation qualities Al 50 to Al 150.

| t/µm | Al 50 | Al 60 | Al 70 | Al 80 | Al 90 | Al 100 | Al 110 | Al 120 | Al 130 | Al 140 | Al 150 |
|------|-------|-------|-------|-------|-------|--------|--------|--------|--------|--------|--------|
| 100  | 1.23  | 1.21  | 1.19  | 1.17  | 1.16  | 1.16   | 1.17   | 1.17   | 1.18   | 1.18   | 1.18   |
| 147  | 1.24  | 1.21  | 1.21  | 1.17  | 1.16  | 1.16   | 1.16   | 1.18   | 1.19   | 1.19   | 1.20   |
| 187  | 1.26  | 1.22  | 1.20  | 1.18  | 1.16  | 1.16   | 1.18   | 1.20   | 1.21   | 1.22   | 1.22   |
| 244  | 1.29  | 1.26  | 1.23  | 1.20  | 1.19  | 1.21   | 1.23   | 1.25   | 1.27   | 1.28   | 1.28   |
| 297  | 1.30  | 1.26  | 1.23  | 1.21  | 1.19  | 1.21   | 1.24   | 1.27   | 1.28   | 1.29   | 1.30   |
| 332  | 1.37  | 1.31  | 1.27  | 1.24  | 1.22  | 1.24   | 1.27   | 1.30   | 1.32   | 1.33   | 1.33   |
| 531  | 1.47  | 1.35  | 1.32  | 1.28  | 1.26  | 1.29   | 1.33   | 1.38   | 1.41   | 1.43   | 1.44   |
| 710  | 1.45  | 1.40  | 1.35  | 1.31  | 1.34  | 1.39   | 1.44   | 1.48   | 1.51   | 1.51   | 1.52   |
Results for three thicknesses plotted against the tube high voltage are shown in figure 11. From the graph it becomes obvious that the build-up factor increases with an increasing thickness of the lead sheet and depends strongly on the radiation quality. Increasing $B$-values with lead thickness can be explained by the decreasing fraction of air kerma contributions from transmitted non-attenuated primary photons relative to those from the scattered photons. Regarding the quality dependence, $B$ decreases from Al 50 to a minimum value at Al 90 and increases from Al 90 to Al 150. The physical interpretation of this behaviour can be undertaken by looking at the transmission photon fluence spectra as shown for Al 90 and Al 150 in figure 8. From Al 50 to Al 90 the scattered photons are composed of photons arising from L-fluorescence emission and incoherent scattering. Since the fraction of air kerma contributions from scattered photons relative to transmitted non-attenuated primary photons decreases, the values of the build-up factors decrease from Al 50 to Al 90. From Al 100 to Al 150 the scattered photon fraction starts to increase. This is due to the increasing amount of K-fluorescence photons arising from the photoelectric interactions of the increasing amount of photons in the primary beams with energies above the K-edge of lead.

Results at the same radiation quality were plotted against the lead thicknesses as shown in figure 12 for Al 90 and Al 150. It turned out that for all qualities it was possible to approximate the data by a linear fit as shown in figure 12 for Al 90 and Al 150. The obtained fit parameters for all the radiation qualities used are listed in table 6. Values calculated from the linear fits shown in table 7 agreed with measured data within about 1%.

Values of the attenuation factor with respect to the inverse broad beam condition were calculated as $F_{IB} = F_N / B$ using the $F_N$ values from table 4 and the $B$ values from table 7. The results are listed in table 8. Similar to the $F_N$ data, the obtained values of $F_{IB}$ were fitted by a second order
Figure 12. Linear fits to build-up factors $B$ measured at Al 90 and Al 150.

Table 6. Parameters $a$ and $b$ obtained from the linear fit $B(t) = a + bt$, $t$ is the lead thickness in units of $\mu$m.

| Quality code | $a$   | $b / \mu$m |
|--------------|-------|------------|
| Al 50        | 1.173 | $5.56 \times 10^{-4}$ |
| Al 60        | 1.176 | $3.48 \times 10^{-4}$ |
| Al 70        | 1.158 | $3.02 \times 10^{-4}$ |
| Al 80        | 1.144 | $2.63 \times 10^{-4}$ |
| Al 90        | 1.135 | $2.32 \times 10^{-4}$ |
| Al 100       | 1.134 | $2.97 \times 10^{-4}$ |
| Al 110       | 1.135 | $3.88 \times 10^{-4}$ |
| Al 120       | 1.133 | $4.76 \times 10^{-4}$ |
| Al 130       | 1.130 | $5.44 \times 10^{-4}$ |
| Al 140       | 1.127 | $5.86 \times 10^{-4}$ |
| Al 150       | 1.125 | $6.04 \times 10^{-4}$ |

Table 7. Build-up factors as a function of the radiation qualities and lead thicknesses.

| $t / \mu$m | Al 50 | Al 60 | Al 70 | Al 80 | Al 90 | Al 100 | Al 110 | Al 120 | Al 130 | Al 140 | Al 150 |
|------------|-------|-------|-------|-------|-------|--------|--------|--------|--------|--------|--------|
| 100        | 1.23  | 1.21  | 1.19  | 1.17  | 1.16  | 1.16   | 1.17   | 1.18   | 1.18   | 1.19   | 1.18   |
| 147        | 1.25  | 1.23  | 1.20  | 1.18  | 1.17  | 1.18   | 1.19   | 1.20   | 1.21   | 1.21   | 1.21   |
| 187        | 1.28  | 1.24  | 1.21  | 1.19  | 1.18  | 1.19   | 1.21   | 1.22   | 1.23   | 1.24   | 1.24   |
| 244        | 1.31  | 1.26  | 1.23  | 1.21  | 1.19  | 1.21   | 1.23   | 1.25   | 1.26   | 1.27   | 1.27   |
| 297        | 1.34  | 1.28  | 1.25  | 1.22  | 1.20  | 1.22   | 1.25   | 1.27   | 1.29   | 1.30   | 1.30   |
| 332        | 1.36  | 1.29  | 1.26  | 1.23  | 1.21  | 1.23   | 1.25   | 1.26   | 1.29   | 1.31   | 1.32   |
| 531        | 1.47  | 1.36  | 1.32  | 1.28  | 1.26  | 1.29   | 1.34   | 1.39   | 1.42   | 1.44   | 1.45   |
| 710        | 1.57  | 1.42  | 1.37  | 1.33  | 1.30  | 1.35   | 1.41   | 1.47   | 1.52   | 1.54   | 1.55   |
2016 JINST 11 T09002

Figure 13. Polynomial fit to the $\ln(F_{IB})$ values for the Al 90 radiation quality. Lead equivalent values $\delta_{IB}$ of a test object are obtained as shown in the figure.

Table 8. $F_{IB}$ values of the reference lead sheets for radiation qualities Al 50 to Al 150.

| $t/\mu m$ | Al 50 | Al 60 | Al 70 | Al 80 | Al 90 | Al 100 | Al 110 | Al 120 | Al 130 | Al 140 | Al 150 |
|----------|-------|-------|-------|-------|-------|--------|--------|--------|--------|--------|--------|
| 100      | 14.18 | 8.86  | 6.36  | 5.01  | 4.16  | 3.63   | 3.26   | 2.99   | 2.79   | 2.62   | 2.47   |
| 147      | 32.88 | 17.01 | 10.83 | 7.82  | 6.11  | 5.15   | 4.53   | 4.09   | 3.75   | 3.48   | 3.25   |
| 187      | 62.25 | 27.59 | 15.99 | 10.77 | 8.05  | 6.64   | 5.77   | 5.16   | 4.69   | 4.31   | 4.00   |
| 244      | 143.16| 51.28 | 26.14 | 16.09 | 11.35 | 9.13   | 7.83   | 6.93   | 6.24   | 5.68   | 5.21   |
| 297      | 294.30| 86.85 | 39.51 | 22.48 | 15.11 | 11.92  | 10.12  | 8.90   | 7.96   | 7.20   | 6.56   |
| 332      | 463.90| 120.72| 51.02 | 27.63 | 18.02 | 14.04  | 11.87  | 10.40  | 9.27   | 8.36   | 7.58   |
| 531      | 5074  | 638   | 186.41| 77.95 | 43.38 | 31.95  | 26.44  | 22.93  | 20.22  | 17.94  | 15.94  |
| 710      | 36944 | 2600  | 522.46| 176.53| 85.86 | 60.43  | 49.28  | 42.54  | 37.39  | 32.95  | 28.85  |

polynomial $y(x) = b_0 + b_1 x + b_2 x^2$, where $y = t_{Pb}$ is the thickness of lead and $x = \ln(F_{IB})$. An example of such a fit is shown in figure 13. Lead equivalent values $\delta_{IB}$ of materials under test are now easily obtained by a measurement of $F_{IB} = F_N/B$ and inserting $x = \ln(F_{IB})$ in the polynomial. This is shown graphically in figure 13. Note that curves as shown in figure 13 need to be measured for each reference radiation quality required for the test. Such curves are specific to the X-ray facility used and may differ for other facilities as already mentioned in section 2.1. Therefore, it is mandatory to use the same X-ray facility for the reference measurements with lead and for the material sheet under test. It is furthermore recommended to use the same radiation detectors and geometrical set-up for the reference measurements with the lead layers and the material under test. This method significantly reduces the uncertainties resulting from the energy dependence of the radiation detectors and the special set-up chosen for the measurements.
Table 9. Relative change of $\delta_N$ in % if $F_N$ changes by 1% estimated for three lead sheets of different thickness.

| Quality code | 244 $\mu$m % | 332 $\mu$m % | 531 $\mu$m % |
|--------------|--------------|--------------|--------------|
| AL50         | 0.3          | 0.2          | 0.2          |
| AL60         | 0.4          | 0.3          | 0.3          |
| AL70         | 0.5          | 0.4          | 0.4          |
| AL80         | 0.6          | 0.5          | 0.5          |
| AL90         | 0.7          | 0.6          | 0.5          |
| AL100        | 0.7          | 0.6          | 0.6          |
| AL110        | 0.7          | 0.6          | 0.6          |
| AL120        | 0.8          | 0.6          | 0.5          |
| AL130        | 0.8          | 0.6          | 0.5          |
| AL140        | 0.8          | 0.6          | 0.5          |
| AL150        | 0.8          | 0.7          | 0.5          |

4 Uncertainty of lead equivalent determination

4.1 Narrow beam conditions

In order to obtain an estimation of the uncertainty of the lead equivalent value $\delta_N$ of a material under test, the single steps of the procedure as described above in sections 2 and 3 are analysed. Usually, the nominal lead equivalent thickness of a material sheet under test is known. To ensure that all the PTB testing equipment is still in the same condition as when the attenuation measurements of the lead reference sheets were taken which led to the polynomial fits as shown in figure 10, the following is undertaken. First, a reference lead sheet of a known thickness close to the nominal lead equivalent value of the material sheet under test is used to perform a constancy check of all the equipment and the procedure. This is done by actually measuring $F_N$ of the reference lead sheet and by determining its lead equivalent value according to the method shown in figure 10 at all radiation qualities needed for the measurements with the material under test. From several repeated measurements of this kind at the PTB testing facility at different dates, it was observed that the expected $\delta_N$, which is of course the known lead thickness in this case, is always obtained with a relative deviation of less than 0.5%.

The next step is to measure $F_N$ of the material sheet under test and to determine its $\delta_N$ according to the method shown in figure 10. As long as $F_N$ is not significantly larger than about 1000, its value can be measured with a relative standard uncertainty of less than 0.54%. This uncertainty is not dominated by the type A uncertainty in the charge measurements in the attenuated and non-attenuated beams which is estimated at 0.2% but by the energy dependence of the air kerma response of the radiation detector shown in figure 6 which is estimated at 0.5% if it is not possible to correct for it. To evaluate the uncertainty of $\delta_N$ due to the uncertainty of $F_N$ the sensitivity coefficient of the procedure shown in figure 10 was estimated. Results are shown in table 9 where the percentage change of $\delta_N$ is given if the attenuation factor $F_N$ changes by 1%. It is obvious that the sensitivity depends on the thickness of the material and the radiation quality. However, $\delta_N$ never changes by more than 0.8%. According to these estimates, a relative standard uncertainty $u(\delta_N)$ of $\delta_N$ of about 1.7% is estimated. The component uncertainties are listed in table 10.
Table 10. Uncertainty budget of $\delta_N$ in %.

| Source of uncertainty                                           | Type A | Type B |
|-----------------------------------------------------------------|--------|--------|
| Thickness of the reference lead samples (table 3)               | 1.5    |        |
| Repeated measurements to determine $\delta_N$ of lead reference samples | 0.5    |        |
| Measured attenuation ratio $F_N$ of the sample                  | 0.2    | 0.5    |
| $\delta_N$                                                      | 1.6    | 0.5    |

Table 11. Relative change of $\delta_{IB}$ in % if $F_{IB}$ changes by 1% estimated for three lead sheets of different thickness.

| Quality code | 244 $\mu$m | 332 $\mu$m | 531 $\mu$m |
|--------------|------------|------------|------------|
| AL50         | 0.3        | 0.2        | 0.2        |
| AL60         | 0.4        | 0.3        | 0.2        |
| AL70         | 0.5        | 0.4        | 0.3        |
| AL80         | 0.6        | 0.5        | 0.4        |
| AL90         | 0.7        | 0.6        | 0.5        |
| AL100        | 0.8        | 0.7        | 0.5        |
| AL110        | 0.8        | 0.7        | 0.5        |
| AL120        | 0.8        | 0.7        | 0.5        |
| AL130        | 0.9        | 0.7        | 0.5        |
| AL140        | 0.9        | 0.7        | 0.5        |
| AL150        | 0.9        | 0.7        | 0.6        |

4.2 Inverse broad beam conditions

Similar estimates to those described in 4.1 also apply in the case of the $\delta_{IB}$ determination under inverse broad beam conditions according to the method shown in figure 13. In the case of repeated measurements with reference lead sheets at different dates, the maximum deviation of $\delta_{IB}$ from the expected value was always less than 0.5%. However, the uncertainty which must be assumed for the measurement of $F_{IB}$ of the material under test may be larger now. This is again not caused by the charge measurements which can be conducted with high precision (within a type A uncertainty of 0.2%) but by the determination of $F_{IB}$ from the quotient $F_N/B$. As already pointed out in the previous section, the relative uncertainty of $F_N$ is estimated at 1.7%. To evaluate the uncertainty of $\delta_{IB}$ due to the uncertainty of $F_{IB}$, the sensitivity coefficient of the procedure shown in figure 13 was estimated. Results are shown in table 11 where the percentage change of $\delta_{IB}$ is given if the attenuation factor $F_{IB}$ changes by 1%. From table 11 it is obvious that the maximum change in $\delta_{IB}$ due to a 1% change in $F_{IB}$ is 0.9%.

The uncertainty in the measurement of $B$ of the sample material is mainly caused by the unknown photon fluence spectra of the attenuated beam at the entrance window of the flat ionization chamber (see figure 3, lower part) because usually the material composition is not known. The vast majority of commercial shielding garments are nowadays made of lead-reduced or lead-free composites which may contain bismuth ($Z=83$) and/or large amounts of elements with atomic numbers close to $Z=50$ such as Cd, In, Sn, Sb, Cs, Ba or Ce. Bismuth is very close to lead ($Z=82$) and will not cause additional uncertainties in the measurement of $B$. This may not be true for the
Table 12. Ratio $R_1/R_2$ of the PTW 34060 chamber response if the 0.5 mm Sn sheet is close ($R_1$) or far away ($R_2$) from the entrance window of the detector D shown in the lower (IB-AT) and upper (IB-AP) part of figure 3, respectively.

| Quality code | $R_1/R_2$ |
|--------------|-----------|
| AL50         | 0.997     |
| AL60         | 0.995     |
| AL70         | 0.980     |
| AL80         | 0.973     |
| AL90         | 0.971     |
| AL100        | 0.972     |
| AL110        | 0.972     |
| AL120        | 0.974     |
| AL130        | 0.976     |
| AL140        | 0.977     |
| AL150        | 0.978     |

Table 13. Uncertainty budget of $u(\delta_{IB})$ in %.

| Source of uncertainty                                      | Type A | Type B |
|------------------------------------------------------------|--------|--------|
| Thickness of the reference lead samples                    | 1.5    |        |
| Repeated measurements to determine $\delta_{IB}$ of lead reference samples | 0.5    |        |
| Measured attenuation ratio $F_N$ of the sample             | 0.2    | 0.5    |
| Measured build-up factor $B$ of the sample                 | 0.2    | 3      |
| $u(\delta_{IB})$                                           | 1.61   | 3.04   |

other elements. Sn (Z=50) is a good candidate test material to estimate the uncertainty which is connected with the measurement of $B$ for the other materials. In order to estimate the difference in the mean air kerma response of the radiation detector used (see figure 6, PTW 34060 in IBG) if the Sn sheet is close to or far away from the entrance window, the corresponding transmission spectra were calculated by the flurznrc user code [7] of the EGSnrc Monte Carlo system [8].

Examples of such spectra at Al 50 and Al 150 are shown in figure 14. The mean air kerma response of the radiation detector was estimated for transmission spectra of this kind for the reference qualities ranging from Al 50 to Al 150. The essential number needed to correct the measurement of $B$ is the ratio $R_1/R_2$ of the mean responses of the radiation detector if the Sn sheet is close to ($R_1$) or far away ($R_2$) from the entrance window. Results are listed in table 12. From table 12 it is obvious that $R_1$ and $R_2$ deviate by no more than about 3% at maximum which is therefore taken as the estimated maximum relative type B uncertainty of $B$. According to these estimates, a relative standard uncertainty $u(\delta_{IB})$ of 3.44% is estimated. The component uncertainties are listed in table 13. The expanded uncertainty (coverage factor $k = 2$) is 6.88% and thus complies with the statement in clause 5.5.3 of the standard IEC 61331-1 which reads: “A relative standard uncertainty of 7% in the determination of the lead equivalent shall be taken into account in the decision of conformity.”
Figure 14. Normalized photon fluence spectra $\phi_E/\phi$ of the radiation qualities Al 50 (top chart) and Al 150 (lower chart) with additional 0.5 mm of tin. $\phi_E/\phi$ is the number of photons contained in energy bin $E$ normalized to the total number of photons contained in the spectrum. The red spectrum contains only transmitted primary photons expected at the entrance window of the air kerma detector D in the IB-AP set-up shown in the upper part of figure 3. The green spectrum contains both the transmitted primary photons and the scattered photons expected at the entrance window of the air kerma detector D in the IB-AT set-up shown in the lower part of figure 3. The peaks between 25 keV and 30 keV are the K-fluorescence photons of tin.
5 Short guide for testing laboratories

5.1 Testing equipment

5.1.1 X-ray facility and reference radiation qualities

Testing laboratories need a suitable X-ray facility for the attenuation measurements. Using medical diagnostic X-ray devices for this purpose is not recommended. Instead, industrial constant potential X-ray facilities as described in section 2 shall be used. As described in the standard IEC 61331-1, the X-ray tube voltage shall not differ from the nominal values by more than 2% or 2 kV, whatever is less. This can, for instance, be verified by a non-invasive metering of the tube high voltage. The aluminium filter shall be of 99.9% purity or higher and have a density of 2.70 g/cm$^3$. The thickness of the aluminium filter shall not differ from the nominal value by more than 0.1 mm. The first Al half-value layers shall be measured and compared with those given in table 1 of part 1 of the standard. These values should not deviate significantly (less than 5%) from the values given in table 1. For example, the PTB X-ray facility described in 2.1 operates with a tube characterized by a W-anode angle of 30˚ and yields Al half-value layers which are different from those given in table 1 of the standard by up to 4% (see table 1 of this report). Note that the values given in table 1 of the standard were measured at a facility with a tube characterized by an anode angle of 21˚. Both facilities are suited for the purpose discussed here but it is important that all measurements for the whole procedure are consistently carried out at one characterized facility (see 5.2).

5.1.2 Reference lead sheets

Lead equivalent values of a test material can be obtained by interpolation from measured attenuation ratios of high-purity (at least 99.94%) lead sheets of different thicknesses covering the range of interest. It is recommended to use at least four different thicknesses but preferentially more to obtain reliable fits according to those shown in figures 10, 12 and 13 of this report. The mean thickness of a sheet shall be known with a relative standard uncertainty of about 2% or less. The homogeneity of the lead sheets across the area which is used in the measurements shall be of the order of 2% of the mean thickness. One possibility to check the homogeneity is to measure its thickness at different points over its area with a micrometer. Determining the mean area density of the sheet by measuring its area and weight is recommended. The density of pure lead is usually 11.4 g/cm$^3$ which shall compare well with the density determined for the sheet using the measured volume and weight. If a testing laboratory has the equipment for photon spectrometry (not mandatory), it is possible to measure the photon fluence spectra of the different radiation qualities. Calculated attenuation ratios using the linear mass-attenuation coefficients of lead and its known mean thickness can be compared with measured ones by use of the narrow beam conditions. Figure 9 of this report shows such results obtained at PTB. If measured and calculated attenuation ratios agree within about 1% this is an indirect experimental verification of the correctness of the assumed mean thickness and area density of the lead sheets.

5.1.3 Radiation detectors

One detector is needed for the attenuation measurements using the narrow beam conditions according to the descriptions in 2.2.1 and 2.3.1. The relative air kerma response of this detector in its
usual usage shall be known in the energy range from about 10 keV to 150 keV. For this purpose, the detector shall be calibrated at narrow-spectrum X-ray qualities as shown in figure 2 of this report. The air kerma response in the photon-energy range between about 30 keV and 150 keV should not vary by more than 5%. Usually, reference ionization chambers used for applications in dosimetry in diagnostic radiology fulfill this requirement.

A plane parallel ionization chamber of a suitable size is needed for the attenuation measurements under inverse broad beam conditions according to the descriptions in 2.2.2 and 2.3.2. Suitable chambers for this purpose are those otherwise used as reference ionization chambers in dosimetry for diagnostic radiology. It is recommended to measure the relative air kerma response of those chambers in the inverse broad beam geometry at the energy range from about 10 keV to 150 keV. Examples are shown in figures 6 and 7. Unfortunately, there are currently no such chambers available on the market which reflect a flat energy response at inverse broad beam conditions. However, using a chamber with a relative energy response similar to that shown in figure 6 is acceptable as discussed in section 4.2 of this report.

5.2 Calibration of the testing facility

Calibration of the testing facility means measuring the lead attenuation curves as described in 3.1 and 3.2 and producing polynomial fits to the measured data as shown in figures 10 and 13 for each radiation quality needed for the characterization of a test object.

5.3 Procedure for lead equivalent determination

The area density of the test object shall be measured by determining its area and weight. The attenuation ratios of the test object shall be measured at the calibrated testing facility for all radiation qualities needed for the characterization according to part 3 of standard IEC 61331. Note that \( F_N \) and \( B \) must be determined according to the descriptions in 2.3.1 and 2.3.2. The lead equivalent value of the test object can then be determined according to the methods described in figures 10 and 13. Determining both the lead equivalent values at narrow beam and inverse broad beam conditions is recommended. The additional knowledge of the lead equivalent value under narrow beam conditions supports the physical interpretation of the lead equivalent value under inverse broad beam conditions. Note that if a test material contains lead (or other elements with Z numbers close to that of lead) as the major attenuating material, both values will be close, otherwise larger differences may occur. It is furthermore recommended to determine by new measurements the lead equivalent value of one of the reference lead sheets which is closest to the nominal lead equivalent value of the test object at the calibrated testing facility. The thus determined lead equivalent thickness should agree with the known mean thickness of the sheet within less than 1%. This latter procedure is a good constancy check of all the testing equipment and the procedure.

5.4 Evaluation of uncertainties

The aforementioned procedures and recommendations should be followed and documented in a short report. If a testing laboratory follows the recommendations described in this report, its standard uncertainties of the determined lead equivalent values of a test object can be expected to be less than 1.7% and 3.5% for narrow beam and inverse broad beam conditions, respectively.
5.5 test certificate: recommended contents

The usual general information found on a test certificate shall, of course, be included and is not mentioned here. Including the following specific contents and information in a test certificate of a sample material is recommended:

C.1 Scope

E.g.: “Determination of the lead equivalent class for a specified range of radiation qualities according to IEC 61331-1 clause 5.5. The range of qualities is specified as 50 kV, 70 kV, 90 kV and 110 kV according to IEC 61331-3 clause 5.3.”

C.2 Description of the samples

Report material type, nominal lead equivalent, identification (e.g. lot #), area density indicated (in units of kg/m$^2$), area density measured (in units of kg/m$^2$).

C.3 Results

C.3.1 Assignment of lead equivalent class

Could be a table like this:

| Material type | Nominal lead equivalent / mm | Lead equivalent class 50 kV — 110 kV according to 5.5 of EN 61331-1 |
|---------------|-----------------------------|---------------------------------------------------------------|
| LR-0.25mmPb   | 0.25                        | Passed                                                        |
| LR-0.35mmPb   | 0.35                        | Passed                                                        |
| LR-0.50mmPb   | 0.50                        | Passed                                                        |

C.3.2 Statement of compliance

Could be a table like this:

| Material type | Statement of compliance |
|---------------|-------------------------|
| LR-0.25mmPb   | Lead equivalent 0.25 mm Pb: inverse broad beam 50–110 kV EN 61331-1:2014 |
| LR-0.35mmPb   | Lead equivalent 0.35 mm Pb: inverse broad beam 50–110 kV EN 61331-1:2014 |
| LR-0.50mmPb   | Lead equivalent 0.50 mm Pb: inverse broad beam 50–110 kV EN 61331-1:2014 |

C.4 Single results of attenuation ratios and lead equivalent values

C.4.1 Narrow beam conditions according to EN 61331-1 clause 4.2

Report attenuation factors $F_N$ and corresponding lead equivalent values $\delta_N$ at each radiation quality of the materials under test.

C.4.2 Inverse broad beam conditions according to EN 61331-1 clause 4.4

Report attenuation factors $F_{IB}$ and corresponding lead equivalent values $\delta_{IB}$ at each radiation quality of the materials under test.
C.5 Materials and methods used for testing

C.5.1 X-ray facility and radiation qualities

C.5.2 Set-up for narrow beam conditions

Could be a sketch of the set-up with a short description.

C.5.3 Set-up for inverse broad beam conditions

Could be a sketch of the set-up with a short description.

C.5.4 Radiation detector used at narrow beam condition to measure \( F_N \)

Include the relative energy response (e.g. a curve as shown in figure 6).

C.5.5 Radiation detector used at inverse broad beam conditions to measure \( B \)

Include the relative energy response (e.g. a curve as shown in figure 6).

C.5.6 Reference lead sheets used for testing

Purity, thickness, uncertainty in thickness.

C.5.7 Results of the attenuation factor \( F_N \) for the reference lead sheets

Present a table of the results and describe how they compare with the values of IEC 61331 table A.1.

C.5.8 Determination of lead equivalent thicknesses \( \delta_N \) for the test material

Describe briefly how the lead equivalent values were determined. Add a statement of uncertainty.

C.5.9 Results of the attenuation factor \( F_{\text{IB}} \) for the reference lead sheets.

Present a table of the results.

C.5.10 Determination of lead equivalent thicknesses \( \delta_{\text{IB}} \) for the test material

Describe briefly how the lead equivalent values were determined. Add a statement of uncertainty.

6 Conclusions

Materials used for the production of protective devices against diagnostic medical X-radiation described in IEC 61331-3:2014 need to be specified in terms of their lead equivalent attenuation properties according to the methods described in IEC 61331-1:2014. Usually, national notified bodies or other authorities rely on test results of testing laboratories which offer such services. To the knowledge of the author of this technical report, those testing laboratories are not accredited with special emphasis on such material specifications. This technical report describes in detail how such attenuation measurements and lead equivalent determinations can be performed in compliance with the standard. This report and the guidelines are intended to support testing laboratories in establishing such a service. The recommended contents and information that should be contained in a test certificate of this kind will improve the possibility of verifying the results. Furthermore, if testing laboratories follow the guidelines of this report, it is hoped that the test results of different
testing laboratories in different countries worldwide will reflect an acceptable agreement which will improve the confidence in those certificates issued by different testing laboratories.

References

[1] IEC 61331-1:2014, Protective devices against diagnostic medical X-radiation — Part 1: Determination of attenuation properties of materials, (2014).
[2] IEC 61331-2:2014, Protective devices against diagnostic medical X-radiation — Part 2: Translucent protective plates, (2014).
[3] IEC 61331-3:2014, Protective devices against diagnostic medical X-radiation — Part 3: Protective clothing, eyewear and protective patient shields, (2014).
[4] D.T. Burns, C. Kessler and L. Büermann, Key comparison BIPM.RI(I)-K3 of the air-kerma standards of the PTB, Germany and the BIPM in medium-energy X-rays, Metrologia 51 (2014) 06016.
[5] D.T. Burns and L. Büermann, Free-air ionization chambers, Metrologia 46 (2009) S9.
[6] International Organization for Standardization, X and γ reference radiation for calibrating dose meters and dose rate meters and for determining their response as a function of photon energy — Part 1: radiation characteristics and production methods, International Standard ISO 4037-1 (1997).
[7] D.W.O. Rogers et al., NRC user codes for EGSnrc, NRCC Report PIRS-702 rev B (2005).
[8] I. Kawrakow et al., The EGSnrc code system: Monte Carlo simulation of electron and photon transport, Technical report, National Research Council Canada, NRC report PIRS-701 (2010).
[9] J.H. Hubbell and S.M. Seltzer, Tables of X-ray mass attenuation coefficients and mass energy-absorption coefficients (version 1.4), National Institute of Standards and Technology, Gaithersburg, U.S.A. (2004), available online http://physics.nist.gov/xaamdi, originally published as NISTIR 5632.