Chapter I
Standard application in photon dosimetry

José Guilherme Pereira Peixoto
Maria da Penha Potiens

The characteristic ionizing radiation response is defined by the relationship between the stimulus and the correspondent response, which converge for many specifications that can be found using specific measurement instruments and that can be used for applications in Ionizing Radiation - IR. However, we looked for a response divided by the corresponding current or charge from the ionizing radiation stimulus; the sensitivity of these measurement instruments is related to their metrological property.

We found many response characteristic examples for measurement devices in different Ionization chambers, shapes and volumes and for solid-state dosimeters from thermo-luminescence or semiconductor materials. These results depended on the application: for use as therapy, protection or diagnostic measurement instrument.

The typical secondary standard device that is used for IR for X and gamma rays is the ionization chamber; its discrimination threshold is related not only to the sensitivity of the measuring instrument but also to its stable response overtime and ease of use, i.e., the largest change in a slowly and monotonically changing stimulus that produces no detectable change in the response of a measuring instrument.

Under these conditions, the dc ion chamber shows these characteristics because the charges or current is efficiently

collected, measuring its ion current and considering recombination to be negligible.

I.1 Proprieties

We could not obtain the measurement directly or invasively but rather non-invasively by looking at the gas cavity. The ionization chamber is the most widely used type of cavity for ionization measurements, is commercially available and has a wide variety of projects and designs for dosimetry applications.

The first view of one ionization chamber cavity is given by a gas volume in the presence of an electric field. The drift of the positive and negative, as represented by the ions and electrons, constitutes an electric current [1], and the rate of the ion pair that is formed is constant and directly proportional to the volume.

For any kind of gas volume, the rate of ion pairs is associated with the gas volume through recombination, diffusion or migration. However, the experimental difficulty of obtaining this ionization measurement generally requires the study of the charge-particle equilibrium.

For additional information and details, see *Radiation detection and measurement* [1], but figure I.1 illustrates the basic elements of a rudimentary ion chamber. A volume of gas is enclosed within a region in which an electric field can be created by the application of an external voltage.

At equilibrium, the current flowing into the external circuit is equal to the ionization current collected at the electrodes, and a sensitive ammeter in the external circuit can thus measure the ionization current. Usually, the electrometer that is connected to the chamber is used as a sensitive ammeter to measure the collected charge in real time.

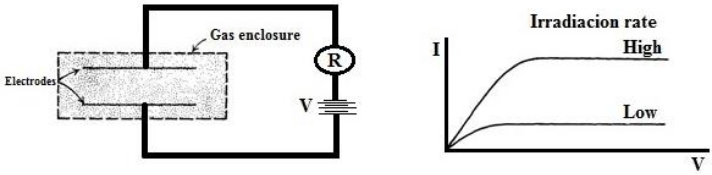

Figure I.1: The basic components of an ion chamber and the corresponding current-voltage characteristics [1].

An ionizing radiation chamber device should be connected to the measurement system, where the ionizing chamber serves as the sensor, connected to a power supply and an electrometer or a lower device counter, and at the end, displaying a device that is also connected to the air density measurement device.

I.2 Absolute dosimeter

The absolute dosimeter, similar to a free air chamber, as used to determine the photon X ray tube potential for diagnostic, protection and therapy applications has various special designs. However, it depends on this requirement to replace lost electrons [2] and has evolved into so many primary standard dosimetry laboratories in the countries.

We found that more traditional design is the plane-parallel geometry, as in figure I.2, where the plate system inside the box consists of three coplanar plates on one side of the beam and a parallel high-voltage plate opposite. The plates are all parallel to and equidistant from the X ray beam axis [2].

All types of free air ionization chambers are enclosed in a Pb-shielding box to exclude X rays scattering from elsewhere, and a tungsten-alloy diaphragm is at the front of the box and aligned with the X ray beam. Thus, the beam passes across of the section area in the plane of the axial point.

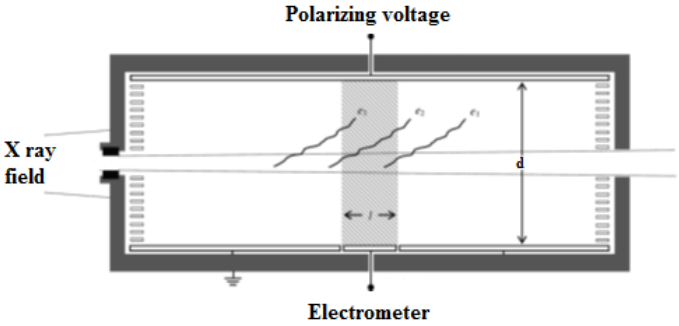

Figure I.2: Free-air chamber schematic diagram. Photons enter through an aperture of radius rap and interact with the air of the chamber to produce secondary electrons (e1, e2, and e3). If the electrode separation d is sufficiently large, the secondary electrons come to rest within the chamber. In the course of slowing down, charge is liberated and swept in the electric field between the electrodes. An isolated section of electrode creates an air region of length l (shaded) from which charge is collected and measured as ionization current [3].

A cylindrical chamber, such as a variable volume of free air ionization chamber, was proposed by Attix [2, 4].

These new free-air ionization chambers are made by two telescopic cylinders, where the air can move independently, and the variable air volume, which is maintained at the same longitudinal axis, opens and closes the chamber volume, as shown in figure I.3. The polarizing potential is applied to a pair of telescoping cylinders [5, 6].

The collecting electrode is an off-axis rod that extends the entire length of the cylinders; this arrangement has a non-uniform electric field but does not interfere with the operating principle of the chamber [7].

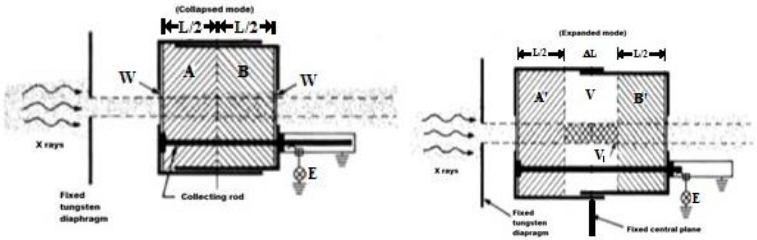

Figure I.3: Design of the cylinder free-air ionization chamber with variable volume [2,4].

These chambers show differences between the plane parallel; as in geometry and operations, knowing the charge-particle equilibrium and electronic loss, electric field uniformity and better air mass definition are not needed because the electrode collector length uncertainty is eliminated.

The point (P) at the border of the diaphragm is the reference point at the cavity chamber to be compared with the free air chamber when centered. The diaphragm is positioned such that the beam axis coincides with the plate or concentric cylinders axis center. The diameter of the cylinders is subject to the same dimensional constraints as the electrode separation d in parallel-plate chambers, namely electron-loss considerations.

The quantity is obtained by the direct measurement for the plane-parallel and that for the concentric variable cylinder is determined differentially by measuring the ionization current charge in open and closed cylinders.

The cylinders are equipped with precision movement such that the distance from the fixed diaphragm to the center of the collecting region remains constant. The charge that is collected for the collapsed position arises from photon interactions in regions A and B in figure I.3. The charge that is collected for the

expanded position by the increased volume V creates regions A´, B´ and V. The photon interactions in the A´ region will be greater than those for the collapsed measurement in region A because it is closer to the diaphragm. However, this difference will be compensated for by a good approximation and by reduced photon interactions in the B´ region. The secondary electrons that are generated in the V region will stop within the chamber and do not depend on the homogeneity of the electric field.

The main advantage of the concentric cylindrical chamber is that the difference in the measurement by the first cylinder expanded and by the second one collapsed. When the first cylinder collapsed and the second expended, we could determine the air mass effect directly related to the cylinder movement, figure I.4 shows into the Victoreen model 480 [4] implemented as a primary standard dosimetry for medium X Ray energy.

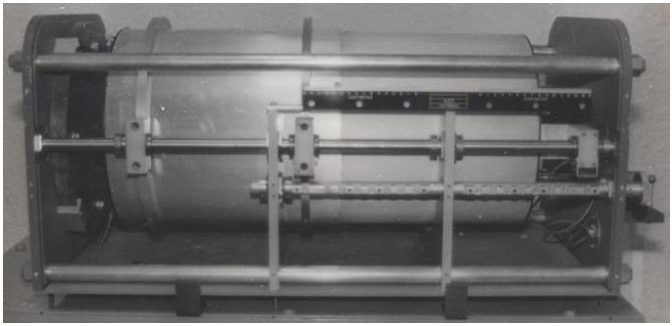

Figure I.4: Victoreen Free air ionization chamber, model 480, implemented as a primary standard dosimetry for medium X ray energy [4].

An expanded perspective of the air ionization chamber variable volume pieces is given by Victoreen model 481, figure I.5. In detail, these pieces are the "diaphragm" (1), the "large cylinder" (2) and the "lower cylinder" (3) and are fundamental in obtaining the interest volume and the air

attenuation correction factor, depending on the cylinder positioning, figure I.6 shows into the Victoreen model 481, implemented as a primary standard dosimetry for low X ray energy [8].

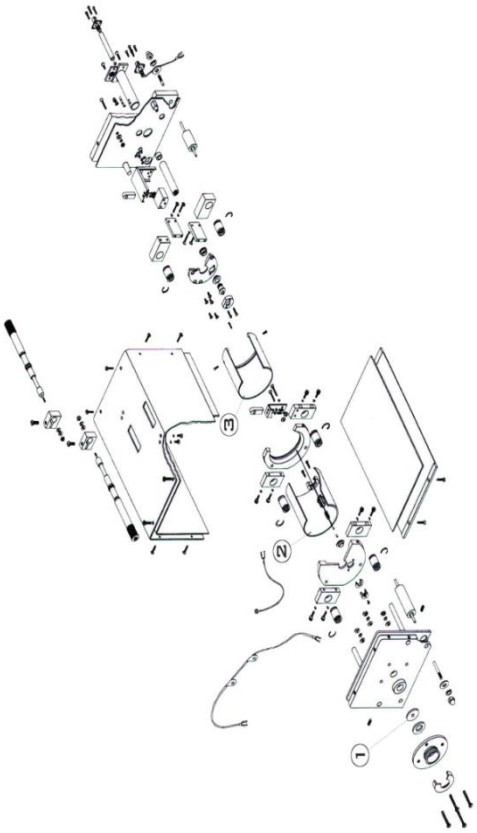

Figure I.5: Expanded perspective of the air ionization chamber variable volume pieces set in Victoreen model 481. In detail, these pieces are the "diaphragm" (1), the "large cylinder" (2) and the "lower cylinder" (3) and are fundamental parts in obtaining the interest volume and the air attenuation correction factor, depending on the cylinder positioning [8].

Figure I.6: Victoreen Free air ionization chamber, model 481[8].

The concentric cylinder free air ionization chamber has been implemented as the primary standard for medium-energy X rays in Italy [9] and in Taiwan [10] and for mammography X rays in the USA [8, 9] and Brazil [5, 10, 11].

I.3 traceable dosimeter

We found many geometry varieties of the cavity ionization chamber, but all basically consist of a solid envelope, such as spherical, plane parallel and cylindrical, surrounding a gas-filled cavity, as seen at table I.1, and an electric field is established to collect the ions that are produced by radiation. If the sensitive gas enters the atmosphere, it is considered the vented type [12–14].

We could determine this type by the chamber shape in each area; in particular, the spherical designs were used more in the isotropic irradiations. Conventionally such ‘thimble’ chambers, as they are sometimes called, are irradiated at mono-directional beams and at therapy beams.

The chambers can be designed as very compact or larger as needed for applications for therapy, diagnosis or protection,

including whether mono- or multi-directional radiation fields are used.

Observing the specific application of the ionization chambers, low to high energy beams and different dose measurements for photons or electrons ensure that the solid wall material is necessary for the range of the secondary electrons.

Ionization chambers are technical devices that are defined specifically with metrological characteristics applied to make ionization radiation measurements. Applications in X ray diagnostics include fluoroscopy, interventional radiology, mammography, CT and dental. Applications in X and Gamma rays include protection and therapy.

The ionizing standard chambers are calibrated in order to ensure traceability of their measurement, known as secondary standards, which have advantages in working with dosimeters with calibrations that are traceable in the laboratory. Thus, before ordering the calibration of the secondary standard, it should be established that the Primary Standard Dosimetry Laboratory – PSDL – that should be employed for the task is capable of providing traceability, i.e., in the energy region considered, the free-air chamber or the calorimeter (water or graphite) could be a primary standard for realizing the air kerma or absorbed dose (water or graphite) quantities. When the ion-collecting gas volume is precisely known, the chamber is an absolute dosimeter [2].

Now, the Secondary Standard Dosimetry Laboratory – SSDL– is traceable to stated references. This traceability chain should make it possible to trace the calibration results back to PSDL, which is acceptable for the customer. This secondary standard must reflect the traceability of the standard to the workshop level or user.

I.4 Secondary standard dosimeters and their characterization

An SSDL must have at least one secondary standard dosimeter that has been calibrated at the BIPM or at a PSDL. This dosimeter should conform to the specifications that are given in IEC 60731 [18] for reference class instruments. For each category of measurements, the SSDL should have two reference class ionization chambers.

Each reference chamber (or set of reference chambers) should provide a useful operating range of radiation qualities applicable to all qualities of sets that have been approved for that category. Some specifics characteristics for diagnostic radiology instruments performance are recommended by IEC 61674 [19]. It is recommended that the secondary standard be recalibrated at intervals of approximately three years, although this period can depend on its demonstrated long-term stability and might therefore differ between instruments [20–22].

The secondary standard can be used either directly for the routine calibration of user instruments or periodically to calibrate one or more working standard instruments or to determine the air kerma or absorbed dose rate for subsequent use in calibration. The overall calibration uncertainty that is attributed to the user instrument might be slightly less when calibrated against the secondary standard rather than a working standard, but the difference should be small and must be balanced against the increased damage risk of a calibration coefficient change of the secondary standard if used regularly.

The SSDL dosimetry depends on the secondary standard stability is preserved with the maximum care and is stored in a safe place under stable environmental conditions that minimize the possibility of calibration coefficient change.

The secondary standard dosimeter ionization chamber must have a high degree of long-term stability and low energy dependence and must be vented and have sealed chambers that are generally less stable in the long term. For the measurement of air kerma, suitable buildup caps might be necessary for Co^{60} and Cs^{137} sources. If the water phantom chamber is used, a waterproof sleeve must be available unless the ionization chamber is designed to be inserted directly into water.

The measuring assembly, usually an electrometer, measures the charge or current from the ionization chamber and often also provides the polarizing potential. The measuring assembly can either be calibrated together with the ionization chamber, or the recommended methods are calibrated separately. In the latter case, the measuring assembly calibration in terms of electric current or charge must be traceable to electrical standards. Special high insulation coaxial cables are necessary to connect the ionization chamber to the measuring assembly [23–25].

Electrometers measure currents equal to or less than 10^{-9} A with a high gain, negative feedback, and operational amplifier with resistor or capacitor standard in the feedback path to measure the current or charge that is collected over a fixed time interval, as shown schematically in figure I.7 [26].

I.4.a Ionization chamber properties

Ionization chambers come in various shapes and sizes depending on the specific requirements, but they generally all have the following properties [26]:

These chambers are basically gas-filled cavities surrounded by a conductive outer wall and with a central collecting electrode, as shown in figure I.8. The wall and the collecting electrode are

separated with a high-quality insulator to reduce the leakage current when a polarizing voltage is applied to the chamber.

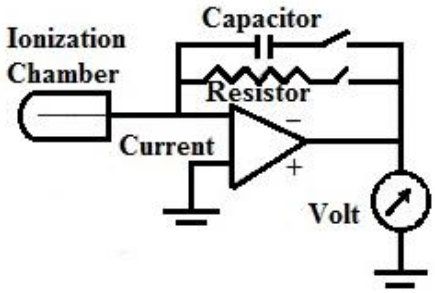

Figure I.7. Electrometer in feedback mode of operation. Using *rate mode* is $V = R.I$, and using *integrate mode* is $V = (I.t)C$, where V is in voltage, R is in ohm, I is in ampère, t is in second and C is in farad units.

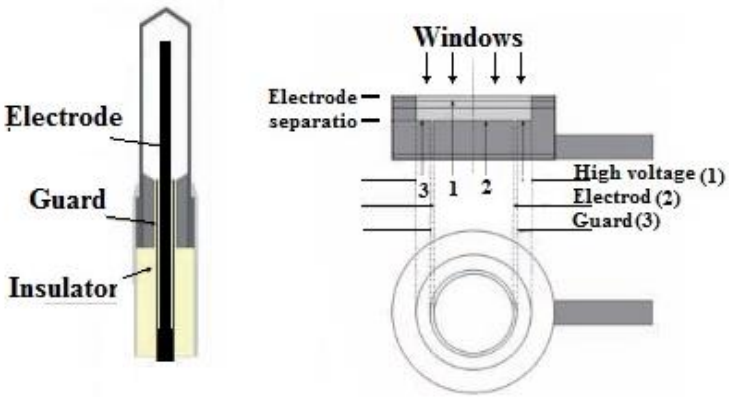

Figure I.8. Schematic diagram of cylindrical (left) and plane parallel (right) ionization chambers. That could see the electrode, guard, insulator and electrode separation of the air cavity.

A guard electrode is usually provided in the chamber to further reduce chamber leakage. The guard electrode intercepts

the leakage current and allows it to flow to the ground, by passing the collecting electrode. This guard also ensures improved field uniformity in the active or sensitive volume of the chamber, with resulting advantages in charge collection.

Measurements with open-air ionization chambers require air density correction to account for the change in the mass of air in the chamber volume, which changes with the ambient temperature and pressure. The ionization current was standardized using 20 °C and 101.325 kPa as reference conditions. Using the ideal gas law for the air density correction inside the chamber, volume sensitive measurement and the relative humidity were maintained between 40 and 70 %, as shown in equation I.1.

$$k_{TP} = \frac{(273.15 + T)}{(273.15 + 20)} \cdot \frac{101.325}{P} \qquad \text{I.1}$$

I.4.b Ionization chambers (shape and volume)

Ionization chambers are technical devices that are defined specifically with metrological characteristics applied for ionization radiation measurements. Protection, therapy and X ray diagnostic applications include fluoroscopy, interventional radiology, mammography, CT and dental uses.

An ionizing radiation chamber device should be connected to the measurement system, where the ionizing chamber serves as the sensor, with a power supply and an electrometer or a lower device counter, and at the end, should display a device that also connects to the air density measurement device.

The ionizing radiation measuring system has different measuring instrument data processors and auxiliary devises, which are assembled in the laboratory with environmental

controlled conditions and linked together to carry out specified measurements.

The Primary Standard Dosimetry Laboratory – PSDL – is capable of providing traceability, i.e., in the energy region considered, the free-air chamber or the calorimeter (water or graphite) could be a primary standard for determining the air kerma or absorbed dose (water or graphite) quantities. The ionizing standard chambers are calibrated in order to ensure the traceability of their measurements, known as secondary standards.

Now, the Secondary Standard Dosimetry Laboratory – SSDL – is traceable to stated references. This traceability chain should make possible tracing the calibration results back to PSDL.

The more common ionization chambers that are used for these purposes should be of the vented type, i.e., their sensitive gas volume should communicate with the atmosphere, independent of their shape or volume design.

The codes of practice TRS 398 [27] and TRS 457 [28] and standards IEC61267 [29] and ISO4037 [18–21] generally follow ICRU 74 [34] on patient dosimetry for X and Gamma rays used for medical or protection purposes. The dosimetry quantities are divided into basic and application-specific quantities. Basic quantities are fundamental quantities as defined in ICRP 60 [23, 24, 35 and 36].

I.4.b.i Cylindrical or spherical ionization chamber

The response of cylindrical or spherical chambers is very symmetrical with respect to the axis. These chambers are usually oriented with the cylindrical or spherical axis of the chamber perpendicular to the X or gamma ray beam and are measured from all directions; back scattering is included [37].

I.4.b.ii Plane parallel ionization chamber.

Plane parallel ionization chambers use two parallel, flat electrodes that are separated by a few millimeters. These chambers are calibrated with their plate oriented perpendicular to the beam axis, which is also the orientation in which they should be used. Some of these chambers have different windows for entrance and exit, in which case it is important that the entrance window faces the beam focal point and that they measure only from one direction.

Different ionization chamber shapes for X and Gamma ray applications for measuring air kerma or absorbed dose (water or graphite) quantities are found in the market.

I.5 Calibration method

The measurement conditions cannot be kept perfectly constant, as by air density imperfections or same cavity effect and electric field, causing random changes in the indications that are obtained by an ionizing measuring system. Thus, it is necessary to repeat the measurement an appropriate number of times under repeatable conditions in order to minimize the random influences, and a calibration method will be more accurate for the capability of a measuring instrument. Independent of the calibration method that is used, the repeatability is shown by the arithmetic mean and standard deviation of the stability result indications.

I.5.a Substitute method

For the reference point at this calibration, each chamber is placed successively at the measurement point. Note that the reference point of a cylindrical or thimble ionization chamber is located on the chamber axis at a distance from the tip either as stated by the manufacturer or as indicated on the instrument.

For a plane-parallel chamber, the reference point is normally taken to be at the center of the inner surface of the front window (for the thin-window chambers that are used for low-energy X rays, the outer surface is taken) [38]. X ray calibration by substitution normally requires extra control equipment, such as an X ray tube current or monitor chamber.

I.5.bTip-to-tip method

The two ionization chambers are placed coaxially with the ends of the chambers close to each other and irradiated simultaneously. If either sensitive volume has a length much greater than its diameter or if measurements are being carried out in a phantom, it might be better to place the chambers side by side with the chamber axes parallel (still referred to as tip-to-tip calibration).

In both cases, the reference points of the two chambers should be positioned symmetrically with respect to the beam axis and at the same distance from the radiation source [38].

Conventional X ray tubes usually have reflection targets (in contrast to the transmission targets that are used with accelerators, for example). As a result, there can be significant variation in the output rate and photon energy along the cross section of the beam parallel to the anode–cathode direction of the X ray tube (the heel effect). For tip-to-tip calibration in X rays, therefore, the reference points of the two chambers should be positioned on a line that is perpendicular to the anode–cathode direction.

To compensate for any residual radial non uniformity of the beam, the measurement should be repeated with the chambers interchanged in position, and if time allows, the positions should be interchanged several times. The mean of the calibration coefficients that are obtained with the chamber in the two positions should be used as the best estimate [38].

In tip-to-tip calibration, each chamber receives scattered radiation from the other. The error that is introduced by this effect is minimized when the two chambers are similar in design. Tip-to-tip calibration might be considered the method of choice in X ray beams if there is no monitor chamber or if it has become unreliable [38].

I.5.c Known radiation field or Dosimetry method

For the dosimetry reference point at this calibration, the reference chamber is placed at the measurement point for all of the dosimetry measurements that are needed for the radiation conditions set.

The chambers or dosimeter to be calibrated should be stated at the same point and measured. The time measurement should be used. Note that the reference point of a cylindrical or thimble ionization chamber is located on the chamber axis at a distance from the tip either as stated by the manufacturer or as indicated on the instrument.

For a plane-parallel chamber, the reference point is normally taken to be at the center of the inner surface of the front window (for the thin-window chambers that are used for low-energy X rays, the outer surface is taken).

I.6 Calibration Results

From the definition of accuracy of a measuring instrument, it follows that the quantitative expression for the measuring the instrumental capability to provide reliable indications would be the difference between its indication and the true value of the corresponding input quantity.

This difference is called the error (of indication) of a measuring instrument. However, upon recognizing the fact that a

true value cannot be determined, a conventional true value is used instead. In most cases, the reference value provides a suitable measurement standard. The error of a measuring instrument is estimated through instrument calibration.

Therefore, the measurement conditions cannot be kept perfectly constant, as by air density imperfections or same cavity effect, causing random changes in the indications that are obtained by an ionizing measuring system. Thus, it is necessary to repeat the measurement an appropriate number of times under repeatable conditions in order to minimize the random influences.

At the end of this repeat, we use the arithmetic mean and standard deviation of the indications as the result and type A uncertainty, respectively. The difference between the value thus obtained and the measured yields a reference value of a systematic error estimative of the indication of a measuring instrument. In addition to random variation in the charge or current, this result depends to some extern on the measurement conditions, and the uncertainty should be determined [39].

The accredited National Metrology Institute – NMI – or SSDL provides result traceability to measure the standard following the ISO/IEC 17025 [40], ensuring appropriateness and relevance. Once the air kerma or absorbed dose of a beam is established, the reference class ionization chamber is calibrated using the substitution method. If the customers do not find a suitable accredited SSDL, the employed laboratory may be able to provide traceability to the ionizing chamber, but the customer should ensure that the calibration is carried out using an appropriately documented calibration method.

Each calibration carried out by the SSDL must be reported accurately, clearly and objectively on a calibration certificate. The most important information on a calibration certificate is a

list of calibration coefficients with their uncertainties, which must be clearly indicated and determined using the ISO and IAEA recommendations; however, additional information is necessary for the correct interpretation and subsequent use of the calibration results. The information contained in a calibration certificate is specified in the international standard ISO/IEC 17025 [40]. The following list of items is an interpretation of these general requirements for the calibration of dosimeters:

(a) A title (e.g., Calibration Certificate).
(b) Name and address of the calibrating laboratory.
(c) A unique certificate number, printed on every page.
(d) Date of issue of the certificate.
(e) Page number on every page, in the form "Page x of y".
(f) Name and address of the user.
(g) Unique identification of the instrument(s).
(h) Date of calibration measurements and staff performing the calibration.
(i) Results of the calibration (preferably in tabular form):
Beam quality specified (HVL, gamma ray source);
Calibration coefficients, stating quantity and unit;
Uncertainty of measurement and coverage factor.
(j) Reference conditions.
(k) Calibration conditions.
(l) Instrument operation.
(n) Results of additional measurements.
(o) Information about the beams.
Miscellaneous information:
(i) Calibration traceability.
(ii) Name, position and signature of the responsible person.