

Estimation of Calibration Factors for Surface Contamination Monitoring Instruments for Different Surfaces

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Aim

The aim of this technical note is to clarify the interpretation of measurements using surface contamination instruments, in particular the use of the term 'P-factor'. Despite the simplicity of such measurements, a confusing array of terms is used in national and international standards and manufacturers' brochures. Misinterpretation of the terminology can lead to errors in reported measurements or the selection of an inappropriate instrument.

This note starts from first principles, identifies any assumptions made and uses this approach to show the differences between parameters used to describe instrument response. It goes on to provide a rigorous solution to the issue of calibrating and using instruments for assaying radionuclides with complex decay scheme.

Introduction

Surface contamination measurements are an important tool for radiation protection and for clearing potentially contaminated waste items. The regulatory limits for surface contamination are normally specified in terms of Becquerels per square centimetre (Bq cm^{-2}). However, it is not practicable to calibrate surface contamination monitoring instruments in terms of Bq cm^{-2} for every radionuclide that may be encountered for a number of reasons, including:

- the short half lives of many radionuclides;
- limited availability of suitable reference sources;
- differences between the calibration source and the monitored surface;
- difficulties in producing calibration sources with a known relationship between the activity and the surface emission rates.

The relationship between the instrument response and the activity on the surface is therefore more complex than might first appear. In the ideal world, each monitor would therefore have to be provided with radionuclide- and surface-specific calibration factors but the cost of this work would be prohibitive.

The pragmatic and economic approach that has been adopted in GPG14 [1], therefore, is to demonstrate that monitors are fit-for-purpose. This is achieved by determining the instrument response to a set of calibration sources that provide accurate and traceable alpha, beta and photon emissions over a reasonable energy range. These sources are defined in ISO8769 [2] and can be regarded as essentially mono-energetic emitters. Provided that the determined responses fall within $\pm 30\%$ of the Type Test values for these ISO8769 sources, the instruments can be regarded as fit for purpose. It is important to note that these sources are calibrated in terms of emissions emerging from the surface and **NOT** activity.

The calibrations using ISO8769 calibration sources allow the energy-dependent instrument response, in terms of response per emission, to be characterized over a wide energy range. This in turn allows responses to be interpolated for the various emissions associated with a particular radionuclide. If each of these emission responses is then modified by a factor which reflects the nature of the surface being monitored, they can be combined to provide a response factor for that radionuclide/surface combination in terms of response per Bq/cm².

In the next section, we look at the derivation of the modification factor using a simple mathematical model.

Radionuclides with single emission decay schemes

We assume that the radionuclide emits a single particle per decay (e.g. a pure beta-emitter that decays directly to the ground state of the daughter nuclide).

If we place an infinitely thin detector, with an effective probe area A_p , directly on the surface being monitored, the detector would only detect particles from the surface directly under the instrument (i.e. no edge effects). The probability of a particle emerging from the surface is given by ϵ_c and each particle hitting the instrument is detected with a probability, k , which is assumed to be independent of the particle energy.

To calibrate our ideal monitor, it is placed on a calibration source of known emission rate R_c and surface area S_c (larger in area than the detector window). Assuming zero background count rate, the observed count rate will be:

$$N_c = k \frac{R_c}{S_c} A_p$$

if the activity of the calibration source is A_c , we can see that $R_c = A_c \times \epsilon_c$ and the equation becomes

$$N_c = k \frac{A_c \epsilon_c}{S_c} A_p$$

If the instrument is now placed on a surface which is uniformly contaminated (larger in area than the detector) with the same radionuclide as the calibration source, the observed count rate is:

$$N' = k \frac{R'}{S'} A_p$$

where the primed terms relate to the contaminated surface

The emission rate per unit area of the contaminated surface is given by:

$$\frac{R'}{S'} = N' \left(\frac{A_c}{S_c} \right) \left(\frac{\epsilon_c}{N_c} \right)$$

Assuming that the activity on the contaminated surface is related to its measured emission rate by the relationship $R' = A' \times \epsilon'$ we find that

$$\frac{A'}{S'} = N' \frac{1}{\epsilon'} \left(\frac{A_c}{S_c} \right) \left(\frac{\epsilon_c}{N_c} \right)$$

It can be seen that the equations above comprise terms that describe the instrument (k and W) and that which describes the surface being monitored (ϵ): the latter term is related to the 'P-factor' (see next section).

The quantities in the above equations can be combined to give one parameter that describes the instrument, the instrument response factor, and one parameter that describes the surface being monitored. Instrument response factors have been defined in various ways over time and these are shown in the table below. All are equally valid although the first three are those which are in common use by accredited laboratories in the UK.

Three of the definitions are independent of the surface nature of the calibration source on condition that the response factors are determined using the stated emission rates of the ISO8769 calibration sources. However, the Instrument Response (Activity) is dependent on both the instrument characteristics and the nature of the surface (described by ϵ_c) of the calibration source.

Quantities that describe the instrument

Definition	Symbol	Formula	Description
Instrument Response (Emissions)	IR(E)	$IR(E) = kA_p = N_c \left(\frac{S_c}{R_c} \right)$	Detection probability times window area = observed count rate per surface emission rate per unit area
Instrument response (Activity)	IR(A)	$IR(A) = kA_p \epsilon_c = N_c \left(\frac{S_c}{A_c} \right) \epsilon_c$	Detection probability times window area times probability of a particle leaving the surface of source = observed count rate per Bq per unit area
2π efficiency	2π eff	$2\pi \text{ eff} = k = N_c \left(\frac{S_c}{R_c} \right) \left(\frac{1}{A_p} \right)$	Detection probability = observed count rate per surface emission rate under the detector window
Calibration factor (Emissions)	CF _E	$CF_E = \frac{1}{kA_p} = \frac{1}{N_c} \left(\frac{R_c}{S_c} \right)$	Reciprocal of detection probability times window area = surface emission rate per unit area from calibration source divided by observed count rate

Quantities that describe the surface

Quantity	Symbol	Description
Surface emission rate of calibration source	R_c	Surface emission rate (particles per second)
P-factor	$P \left(= \frac{1}{\epsilon} \right)$	Inverse of probability of particle emission

P-factor

The concept of the P-factor was introduced in the development of GPG14 [1]. This factor was designed to convert this measurement of emission rate from an ISO8769 [2] calibration source into a measure of activity. Because the calibration sources are single radionuclides with essentially a single emission which has a 100% emission probability, the P-factor could be used very simply to achieve this conversion. The P-factor is essentially just the reciprocal of ϵ . The original definition - "A P-factor is the ratio between the activity per unit area of a source and its surface emission rate per unit area" was correct - but only for the single emission ISO8769 calibration sources.

To estimate the P-factor, the illustration (Figure 1) shows the various emission processes from a contaminated surface.

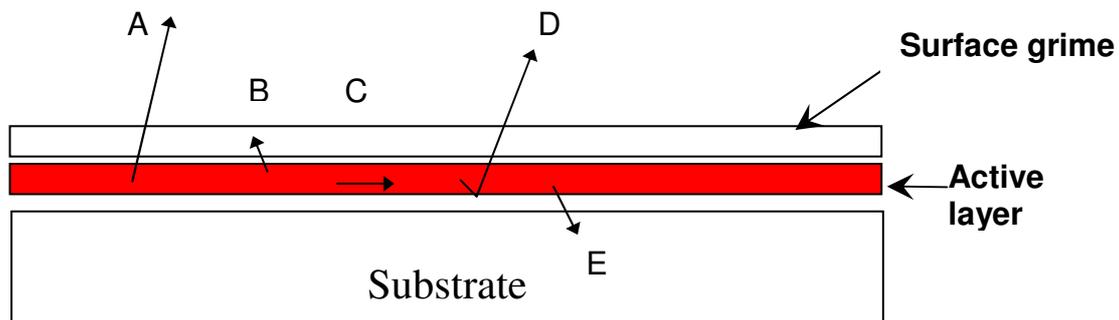


Figure 1. Schematic of emission processes from the surface of a source

- A: Particle/photon emitted from surface
- B: Particle/photon absorbed in surface grime (see Table 1)
- C: Particle/photon absorbed in active layer (see Table 1)
- D: Particle/photon back scattered from substrate (see Table 1)
- E: Particle/photon absorbed in substrate.

In the ideal situation, where the contamination is in an infinitely thin layer and not absorbed into the surface on which it lies, so that none of the emissions suffers attenuation emerging from the surface, and there are no scattering effects, exactly half of the emissions resulting from a radioactive disintegration will emerge and have the potential to enter the detector. For those cases where there is only one emission per decay, the P-factor has a value of 2 and the activity per unit area is twice the emission rate per unit area provided by the detector response. This is the situation which applies to the highest quality ISO8769 calibration sources.

The next section concentrates on calculating the P-factor for radionuclides with complex decay schemes.

P-factors for radionuclides with complex decay schemes

The majority of radionuclides do not exhibit simple decay schemes, and may have multiple branches from the parent ground state followed by the emission of photon(s), conversion electrons and secondary emissions such as X-rays and Auger electrons. For any single decay event, it is possible also that more than one emission may be produced, for example, a beta particle followed by a gamma ray.

The instrument may detect any or all of the emissions arising from a single decay but only one event is registered as the emissions occur at the same time. This is the key reason why interpreting readings from surface contamination instruments is complex, as it means that it is incorrect to sum the detection probabilities for all the emissions.

In estimating the appropriate calibration factor (in Bq/cm²) for a particular radionuclide, it is necessary to take into account the probabilities of the various emissions, the effect of the surface on each separate emission and the probability of detecting in coincidence any or all of the emissions from a single decay. The estimation of an appropriate instrument response factor for most radionuclides therefore is a complex issue because it is not possible to apply the same P-factor for each emission involved in the decay and indeed the simplistic definition of the P-factor is not appropriate here.

In practice, high uncertainties (tens of percent) in measurement can normally be tolerated as the measurements may be for screening or re-assurance purposes only. However, it is still necessary to understand the underlying physical processes and the estimation algorithms to check that gross errors are not being made. The following discussion is intended to provide a generic approach which puts these estimations on a sound footing.

Rather than seeking to re-define the P-factor which has come into general use, we shall introduce an additional factor (the 'emergence factor') which characterizes the ratio of the generation of individual emissions to the fraction of those emissions which emerge from the surface. Let us define this factor as $E_{i,e}$ for emission of type i (α , β or γ) with energy, e . We can then take each emission in turn, estimate the appropriate value for $E_{i,e}$, combine this with the emission probability per decay and then combine the effects of all emissions in the decay taking into account the potential for coincident detections.

Generic estimation of instrument response factor

Step 1: Determine the energy response of the monitor

The first step is to determine the inherent 2π efficiency [1] of the detector as a function of energy for the three emission types, namely alpha, beta and photon. Typical values are shown in Figures 2, 3 and 4.

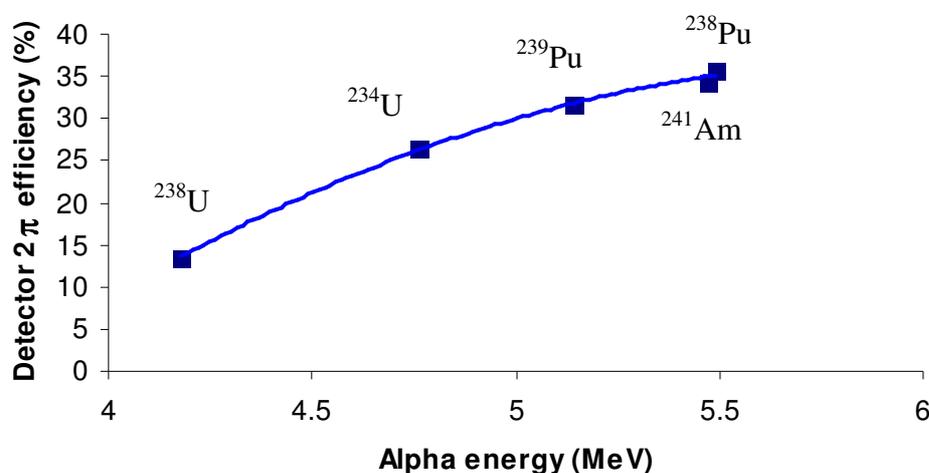


Figure 2. Alpha energy v Instrument response

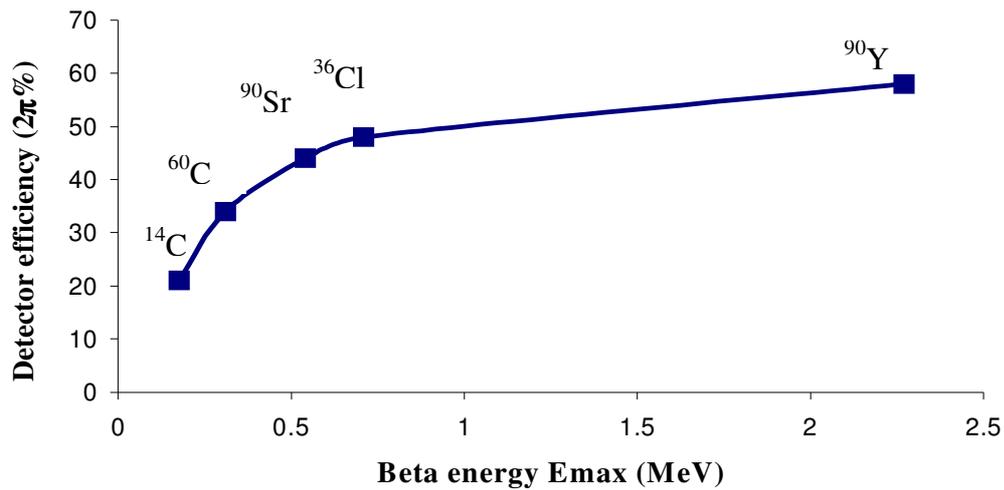


Figure 3. Beta energy v Instrument response

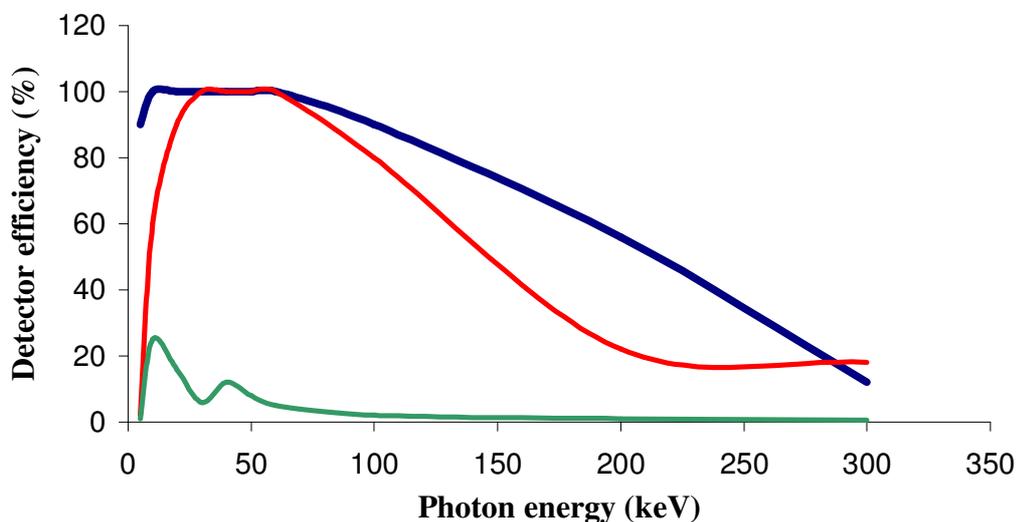


Figure 4. Photon energy v Instrument response

- - NaI detector 3 mm thick, Be window 47 mg cm⁻²
- - NaI detector 2 mm thick, Al window 14 mg cm⁻²
- - Xe gas detector 20 mm thick, Ti window 5 mg cm⁻².

Step 2: Model the decay paths of the radionuclide of interest

For each complete decay path, more than one emission may occur but these are normally emitted simultaneously (in cascade) and the detector only produces one pulse even though more than one of the emissions may have been detected. It is necessary to ensure in the calculations that double (or even multiple) counting is not included.

In this step, each decay path (cascade) of the radionuclide is therefore treated separately. For example, ⁶⁰Co has one cascade (beta decay followed by two gammas), whereas ¹³¹I has six beta branches with each of these branches being followed by the emission of various combinations of photons, conversion electrons, Auger electrons and X-rays. The latter case will produce tens of individual decay paths and, within each path, various values of E_{i,e} will need to be applied for the various emissions. However, given the

relatively coarse levels of accuracy required for radiation monitoring, the task can be simplified by judicious groupings and thresholds as will become evident below.

In general, the process to follow is:

- Identify each complete sequential decay path for the radionuclide and determine its abundance.
- Estimate the inherent detector efficiency for each emission (beta, gamma, etc) in that decay path
- Estimate the relevant E-factor for each emission from a knowledge of the nature of the contaminated surface
- Calculate the overall efficiency for each complete sequential decay path

For example, consider a typical decay scheme (Figure 5) which includes the complexity typical of many radionuclide decays. The initial decay shown here is beta decay but the method applies equally to those radionuclides where the initial decay from the parent ground state is by alpha particle emission or by electron capture.

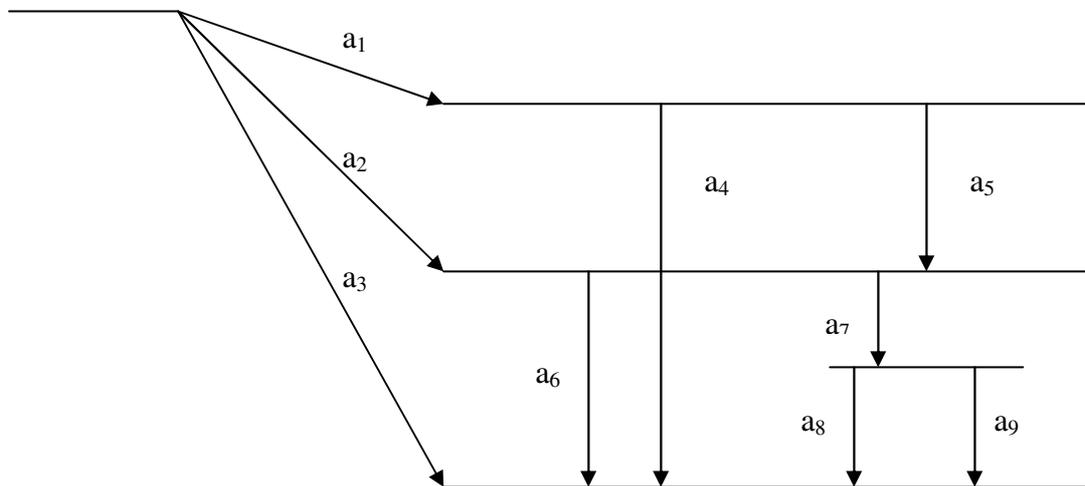


Figure 5. Typical decay scheme

If, for the relevant emission, i which has an energy e , we define, ϵ_i and $E_{i,e}$ as the inherent detector 2π efficiency and the appropriate Emergence factor, respectively, we can summarise the decay scheme in tabular form as shown, where the decay path abundance is the fraction of decays from a particular state::

Decay path abundance	Nature of decay	Inherent 2π efficiency	Emergence factor, E
a_1	Low energy beta	ϵ_1	$E_{\beta 1,e}$
a_2	Medium energy beta	ϵ_2	$E_{\beta 2,e}$
a_3	High energy beta	ϵ_3	$E_{\beta 3,e}$
a_4	High energy gamma	ϵ_4	$E_{\gamma 4,e}$
a_5	Medium energy gamma	ϵ_5	$E_{\gamma 5,e}$
a_6	Medium energy gamma	ϵ_6	$E_{\gamma 6,e}$
a_7	Internal conversion	ϵ_7	$E_{\beta 7,e}$
a_8	K-Xray	ϵ_8	$E_{\gamma 8,e}$
a_9	L, M,N...X-rays and K,L,M,N...Augers	ϵ_9	$E_{\beta 9,e}$

There are 8 complete paths to the ground state and if we define each complete path abundance as k_i these are:

Decay path abundance	Components of path
k_1	$a_1 \cdot a_4$
k_2	$a_1 \cdot a_5 \cdot a_6$
k_3	$a_1 \cdot a_5 \cdot a_7 \cdot a_8$
k_4	$a_1 \cdot a_5 \cdot a_7 \cdot a_9$
k_5	$a_2 \cdot a_6$
k_6	$a_2 \cdot a_7 \cdot a_8$
k_7	$a_2 \cdot a_7 \cdot a_9$
k_8	a_3

It will be seen that:

$$\sum k_i = 1$$

Consider just two of these paths, k_8 and k_4 .

For path k_8 , the calibration factor in respect of activity is given by:

$$IR(A) = \frac{a_3 \cdot \epsilon_3 \cdot A_p}{E_{\beta 3,e}} \quad \text{Units: } s^{-1}/(s^{-1} \text{ cm}^{-2}) \text{ or } s^{-1}/(\text{Bq cm}^{-2})$$

where A_p is the probe area.

This is analogous to the situation with a pure beta emitter (e.g. ^{14}C). In that case, assuming no attenuation of the source, $a_3 = 1$ and $E_{\beta 3,e} = 2$ and the equation simplifies to:

$$IR(A)_{C14} = \frac{\epsilon_3 \cdot A_p}{2}$$

For path k_4 , the situation is more complicated. The $IR(A)$ for each part of the path may be expressed in the same way as above but we are now looking at a cascade effect. If any one of the four different emissions is detected, a pulse will be registered (the instrument may detect other emissions in the cascade as well, but only one pulse is registered). The detection efficiency is therefore given by one minus the probability of not detecting any of the emissions, which is the same as the product of the probabilities of not detecting each individual emission. The relevant E-factors must also be included and the probability of registering a pulse for that path may be expressed as:

$$1 - \left(1 - \frac{\epsilon_1}{E_{\beta 1,e}}\right) \cdot \left(1 - \frac{\epsilon_5}{E_{\gamma 5,e}}\right) \cdot \left(1 - \frac{\epsilon_7}{E_{\beta 7,e}}\right) \cdot \left(1 - \frac{\epsilon_9}{E_{\beta 9,e}}\right)$$

In most practical cases, the above equation may be simplified by taking one of the terms (corresponding to the emission in the cascade with the highest detection probability). This will underestimate the detection efficiency, resulting in an over-estimate of the activity on the surface but for radiation protection/clearance purposes this errs on the side of caution.

Step 3: Determine the overall instrument response

For the whole radionuclide decay we then add the probabilities of detecting at least one emission from each complete path and combine these with the complete path abundances. The activity calibration factor can then be expressed generally as:

$$IR(A) = Ap \cdot \sum_{j=1}^n k_j \left\{ 1 - \prod \left(1 - \frac{\epsilon_i}{E_{i,e}} \right) \right\}$$

Where j represents the different complete path abundances and i represents the individual emissions in each complete path.

Some typical radionuclides have been examined and, for each, two different surface scenarios are considered. The detailed analyses are shown in Appendix 2.

Conclusion

It will be seen from the discussions above and the examples given in Appendix 2 that the use of a P-factor as originally defined is not applicable for radionuclides which have complex decay schemes. Attempting to redefine the factor would only cause confusion and the discussions here have sought to resolve the problem by showing how to determine instrument response factors from fundamental principles.

In this technical note, we have derived formulae to enable the count rate observed on a surface contamination monitor to be converted from counts per second to Bq/cm², assuming the identity of the radionuclide on the surface is known, the energy response of the monitor can be estimated and there is some knowledge of the nature of the surface and the depth distribution of the radionuclide.

Surface contamination measurements are subject to high uncertainties and are probably best regarded as qualitative rather than quantitative. The formulae in this note should enable the reader to check whether measurements are fit-for-purpose.

References

- [1] National Physical Laboratory, Measurement Good Practice Guide No.14, *The Examination, Testing & Calibration of Portable Radiation Protection Instruments*, NPL, 1999 (*currently in revision*).
- [2] International Organisation for Standardisation, *Reference Sources for the Calibration of Contamination Monitors*, BS ISO 8769 (*currently in revision, to be published 2010*)

Appendix 1

Effect	P Factor component	Particle type affected	Magnitude of effect
Backscatter	D	High energy β s	Increases surface emission by 10-20% for high energy β particles on high atomic number backings (e.g. steel)
Self absorption	C	Alphas	Decreases surface emission by a factor 2 or more
		Low energy β s (0.15-0.4 MeV)	Even very thin deposits will produce a considerable reduction in surface emission rates
		High energy β s	Surface emission unaffected for thin deposits ($< 1 \text{ mg cm}^{-2}$)
Surface coatings	B (see Table 2)	Alphas	Layer 5 mg cm^{-2} thick totally absorbs α radiation
		Low energy β s	Layer 5 mg cm^{-2} thick: decreases surface emission by a factor of 2 or more
		High energy β s	Layer 5 mg cm^{-2} thick: decreases surface emission by 30%
Interfering radiation			Some γ interference possible, effect normally small (typically 1% for ^{137}Cs / ^{60}Co)

Table 1. Variation of attenuation effects with emission type and energy (illustrative only)

Surface coating	Mass per unit area (mg cm^{-2})	Typical Nuclide and Radiation Type				
		^{238}Pu Alpha	^{14}C Soft beta	^{36}Cl Medium beta	$^{90}\text{Sr} + ^{90}\text{Y}$ Medium + hard beta	^{55}Fe 5.9 keV photon
Car paint	2.6	10	50	90	95	30
Anti rust paint	4.0	0	30	90	95	35
Lacquer	2.4	10	50	90	95	50
Wood varnish	1.4	30	60	95	100	70
Furniture polish	0.1	90	95	100	100	95
Oil as applied	1.3	30	70	95	100	70
Oil wiped off	0.14	90	95	100	100	95
Grease as applied	1.8	20	60	95	100	60

Table 2. Percentage transmission factors for surface coatings (illustrative only)

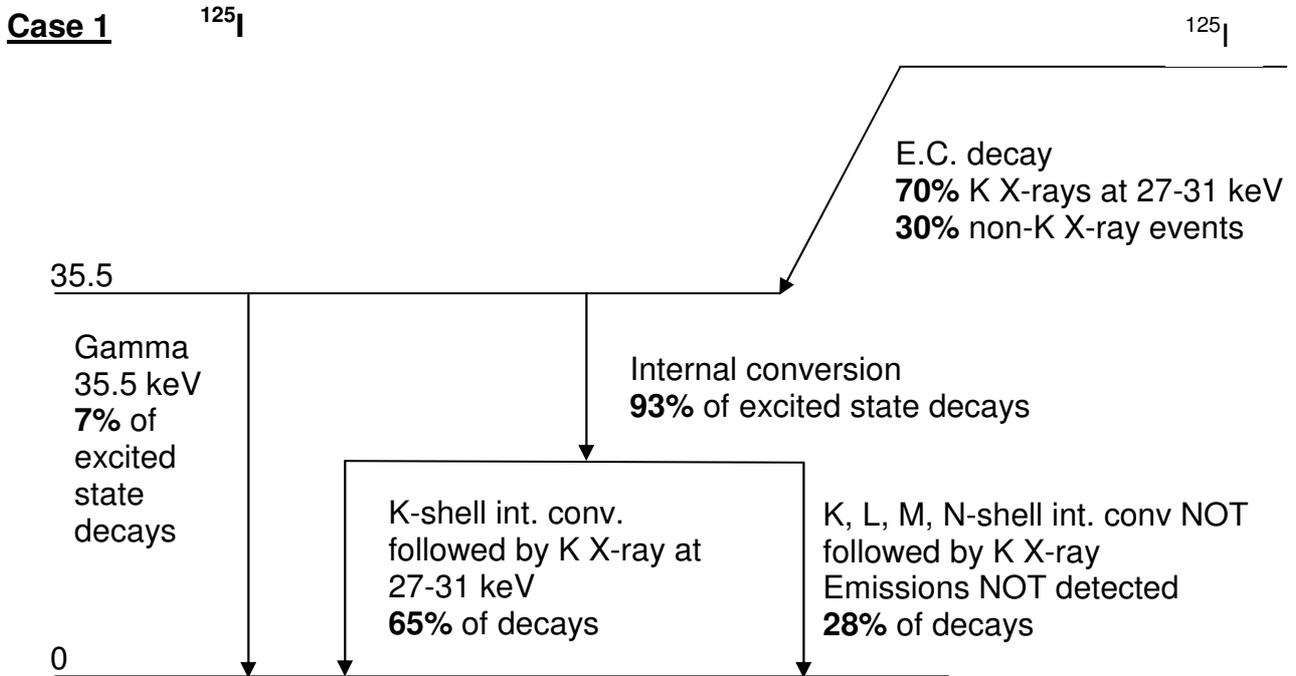
Note: The paints are one coat only. The polish is two coats. All are applied according to the manufacturers' instructions.

Reference for tables 1 and 2:

P H Burgess, *Handbook on measurement methods and strategies at very low levels and activities*, European Commission Report EUR 17624, 1998.

Appendix 2

Case Studies



Assumptions made:

Conversions electrons (~ 30 keV) and non K X-rays are absorbed by the source and/or the detector window and are not detected.

2π efficiencies for the gamma and the K X-rays are approximately the same, ϵ_{30}

E-factors for the gamma and the K X-rays are approximately the same, E_{30}

Components of paths	Decay path abundance	Product, k_i
ec K X-ray, gamma	0.7×0.07	0.049
Ec K X-ray, Int.Conv. K X-ray	$0.7 \times 0.93 \times 0.7$	0.456
EC K X-ray, Int.Conv non K X-ray	$0.7 \times 0.93 \times 0.3$	0.195
Ec non K X-ray, gamma	0.3×0.07	0.021
Ec non K X-ray, Int.Conv. K X-ray	$0.3 \times 0.93 \times 0.7$	0.195
Ec non K X-ray, Int.Conv. non K X-ray	$0.3 \times 0.93 \times 0.3$	0.084 (no detections)

It should be noted that for the last path (ec non K X-ray, Int.Conv. non K X-ray) the detection efficiency is zero i.e. none of the emissions is detected.

Therefore $IR(A)_{^{125}\text{I}} = A_p \times \text{probability of registering a detection}$

$$\begin{aligned}
&= A_p \bullet \left[0.049 \left\{ 1 - \left(1 - \frac{\epsilon_{30}}{E_{\gamma,30}} \right)^2 \right\} + 0.456 \left\{ 1 - \left(1 - \frac{\epsilon_{30}}{E_{\gamma,30}} \right)^2 \right\} + 0.195 \left\{ 1 - \left(1 - \frac{\epsilon_{30}}{E_{\gamma,30}} \right) \right\} \right. \\
&\quad \left. + 0.021 \left\{ 1 - \left(1 - \frac{\epsilon_{30}}{E_{\gamma,30}} \right) \right\} + 0.195 \left\{ 1 - \left(1 - \frac{\epsilon_{30}}{E_{\gamma,30}} \right) \right\} \right] \\
&= A_p \bullet \left[0.505 \left\{ 1 - \left(1 - \frac{\epsilon_{30}}{E_{\gamma,30}} \right)^2 \right\} + 0.411 \left\{ 1 - \left(1 - \frac{\epsilon_{30}}{E_{\gamma,30}} \right) \right\} \right]
\end{aligned}$$

Consider a NaI detector 2 mm thick, Al window 14 mg cm⁻² where $\epsilon_{30}=1$

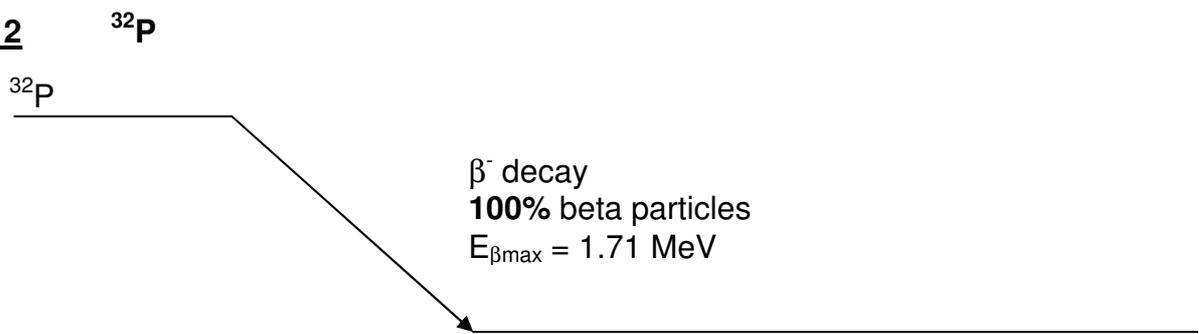
For an ideal source i.e. no absorption or attenuation, $E_{\gamma,30} = 2$,

$$\text{giving } IR(A)_{I125} = 0.58 \times A_p$$

For a greasy, porous surface, we might estimate that only 70% of the 30 keV photons are transmitted through the surface layer so that $E_{30} \approx 3$,

$$\text{giving } IR(A)_{I125} = 0.38 \times A_p$$

Case 2



In this case there is just a single decay branch and no cascade emissions. The activity calibration figure is therefore:

$$IR(A)_{P32} = A_p \cdot \frac{\epsilon_{1710}}{E_{\beta,1710}}$$

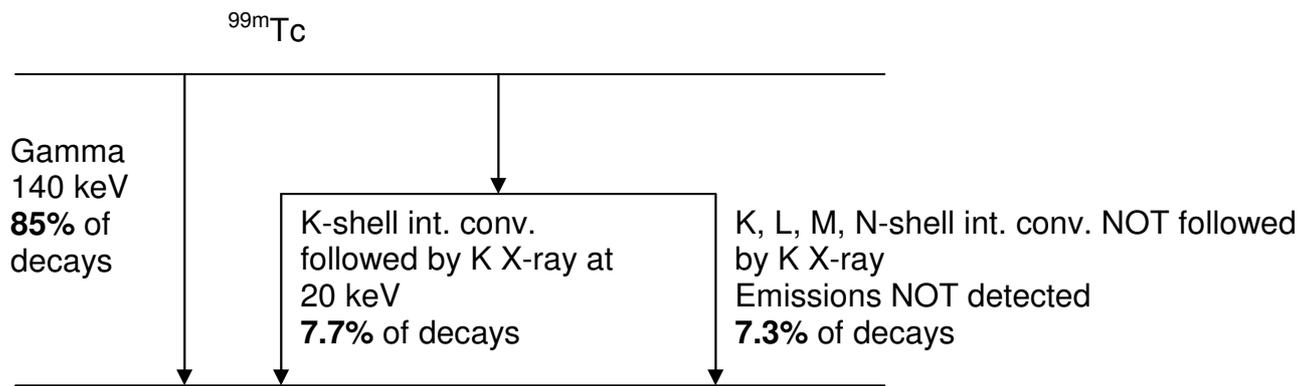
Using the data in Figure 3, the 2π efficiency at 1.71 MeV is 0.545.

For most surfaces, there is almost no absorption and the E-factor may be taken as 2, giving:

$$IR(A)_{P32} = \frac{0.545 \cdot A_p}{2} = 0.27 \cdot A_p$$

Case 3

^{99m}Tc



^{99m}Tc decays by isomeric transition with the emission of a 140 keV photon or the emission of conversion electrons, X-rays and Augers following the internal conversion process. It is assumed that the conversion electrons, Auger electrons and the L, M, N, etc X-rays are of sufficiently low energy that they are not detected.

There are no cascade emissions to be taken into account. Therefore the activity calibration factor is given by:

$$IR(A)_{Tc99m} = A_p \cdot \left[0.85 \left\{ 1 - \left(1 - \frac{\epsilon_{140}}{E_{\gamma,140}} \right) \right\} + 0.077 \left\{ 1 - \left(1 - \frac{\epsilon_{20}}{E_{\gamma,20}} \right) \right\} \right]$$

Consider a NaI detector 2 mm thick, Al window 14 mg cm⁻² where $\epsilon_{20}=1$ and $\epsilon_{140}=0.5$

For an ideal source i.e. no absorption or attenuation, $E_{\gamma,20} = E_{\gamma,140} = 2$,

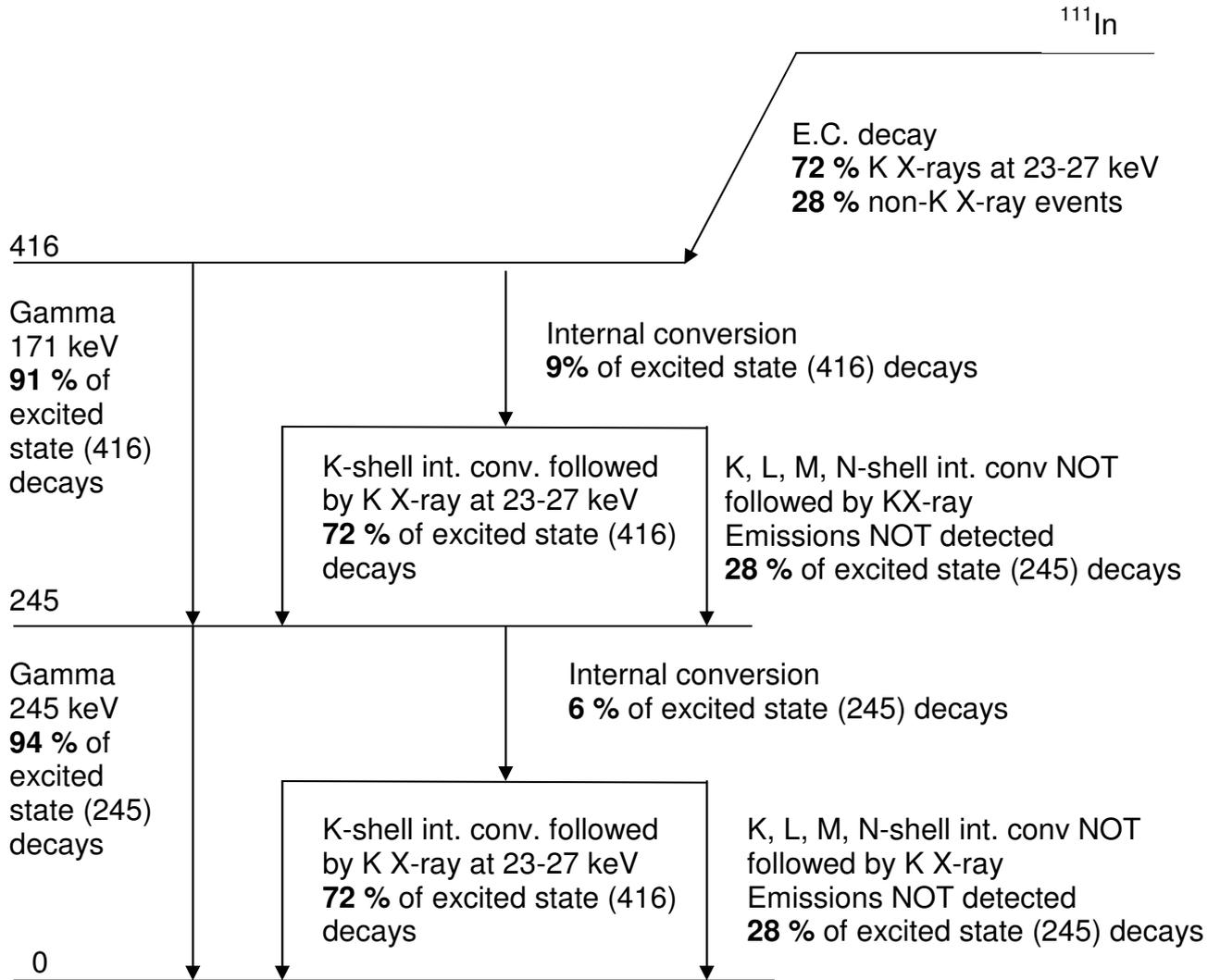
giving $IR(A)_{Tc99m} = 0.24 \times A_p$

For a greasy, porous surface, we might estimate that only 70% of the 20 keV photons are transmitted through the surface layer whilst the 140 keV photons have a transmission efficiency of 90% so that $E_{\gamma,20} \approx 3$ and $E_{\gamma,140} \approx 2.2$,

giving $IR(A)_{Tc99m} = 0.22 \times A_p$

Case 4

¹¹¹In



Assumptions made:

All X-rays other than K-shell X-rays are absorbed by the source and/or the detector window and are not detected.

Conversion electrons are absorbed by the source and detector window.

If we use the following abbreviations for the individual paths

ecK – electron capture event resulting in a K X-ray

ecL – electron capture event NOT resulting in a K X-ray

g171 – 171 keV photon

g245 – 245 keV photon

ic171K – internal conversion from the 416 keV excited state resulting in a K X-ray

ic171L – internal conversion from the 416 keV excited state NOT resulting in a K X-ray

ic245K – internal conversion from the 245 keV excited state resulting in a K X-ray

ic245L – internal conversion from the 245 keV excited state NOT resulting in a K X-ray

There are then 18 separate pathways to consider:

Components of paths	Decay path abundance	Product
ecK, g171, g245	0.72 x 0.91 x 0.94	0.62
ecK, g171, ic245K	0.72 x 0.91 x 0.06 x 0.72	0.03
ecK, g171, ic245L	0.72 x 0.91 x 0.06 x 0.28	0.01
ecK, ic171K, g245	0.72 x 0.09 x 0.72 x 0.94	0.04
ecK, ic171K, ic245K	0.72 x 0.09 x 0.72 x 0.06 x 0.72	0.002
ecK, ic171K, ic245L	0.72 x 0.09 x 0.72 x 0.06 x 0.28	0.001
ecK, ic171L, g245	0.72 x 0.09 x 0.28 x 0.94	0.02
ecK, ic171L, ic245K	0.72 x 0.09 x 0.28 x 0.06 x 0.72	0.001
ecK, ic171L, ic245L	0.72 x 0.09 x 0.28 x 0.06 x 0.28	0.001
ecL, g171, g245	0.28 x 0.91 x 0.94	0.24
ecL, g171, ic245K	0.28 x 0.91 x 0.06 x 0.72	0.01
ecL, g171, ic245L	0.28 x 0.91 x 0.06 x 0.28	0.004
ecL, ic171K, g245	0.28 x 0.09 x 0.72 x 0.94	0.02
ecL, ic171K, ic245K	0.28 x 0.09 x 0.72 x 0.06 x 0.72	0.001
ecL, ic171K, ic245L	0.28 x 0.09 x 0.72 x 0.06 x 0.28	0.0003
ecL, ic171L, g245	0.28 x 0.09 x 0.28 x 0.94	0.007
ecL, ic171L, ic245K	0.28 x 0.09 x 0.28 x 0.06 x 0.72	0.0003
ecL, ic171L, ic245L	0.28 x 0.09 x 0.28 x 0.06 x 0.28	0.0001 (no detections)

It should be noted that for the last path (electron capture and internal conversions all with no K X-rays) the detection efficiency is zero i.e. none of the emissions is detected. The total expression for the activity calibration factor is propagated in the same way as for the ¹²⁵I example. For reasons of space, the total propagation is not given here but two pathway examples are shown below for illustration.

For the (ecK, g171, g245) pathway, the relevant term is:

$$A_p \bullet 0.62 \left\{ 1 - \left(1 - \frac{\epsilon_{25}}{E_{\gamma,25}} \right) \left(1 - \frac{\epsilon_{171}}{E_{\gamma,171}} \right) \left(1 - \frac{\epsilon_{245}}{E_{\gamma,245}} \right) \right\}$$

and for the (ecL, ic171K, g245) pathway, the relevant term is:

$$A_p \bullet 0.004 \left\{ 1 - \left(1 - \frac{\epsilon_{25}}{E_{\gamma,25}} \right) \left(1 - \frac{\epsilon_{245}}{E_{\gamma,245}} \right) \right\} \text{ (there is no efficiency term for ecL as it is not detected)}$$

If we let

$$a = \left(1 - \frac{\epsilon_{25}}{E_{\gamma,25}} \right)$$

$$b = \left(1 - \frac{\epsilon_{171}}{E_{\gamma,171}} \right)$$

$$c = \left(1 - \frac{\epsilon_{245}}{E_{\gamma,245}} \right)$$

The total expression for the nuclide activity calibration factor reduces to:

$$IR(A)_{In111} = A_p \bullet \left[\begin{array}{l} 0.62(1 - a.b.c) + 0.03(1 - a^2.b) + 0.04(1 - a^2.c) + 0.003(1 - a^2) + \\ 0.002(1 - a^3) + 0.02(1 - a.b) + 0.04(1 - a.c) + 0.24(1 - b.c) + \\ 0.001(1 - a) + 0.004(1 - b) + 0.007(1 - c) \end{array} \right]$$

Consider a NaI detector 2 mm thick, Al window 14 mg cm⁻² where:

$$\epsilon_{25} = 0.9, \epsilon_{171} = 0.4, \epsilon_{245} = 0.15$$

For an ideal source i.e. no absorption or attenuation, $E_{\gamma,25} = E_{\gamma,171} = E_{\gamma,245} = 2$,

$$\text{giving } IR(A)_{In111} = 0.50 \times A_p$$

For a greasy, porous surface, we might estimate that $E_{\gamma,25} \approx 4$, $E_{\gamma,171} \approx 2$, $E_{\gamma,245} \approx 2$

$$\text{giving } IR(A)_{In111} = 0.39 \times A_p$$