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Comparison of National Physical Laboratory and Public Health England Lead Equivalence Values determined for a Number of Vinyl Materials over a Range of X-ray Energies

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Comparison of National Physical Laboratory and Public Health England Lead Equivalence Values determined for a Number of Vinyl Materials over a Range of X-ray Energies

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ABSTRACT

This report details a comparison of the determination of lead equivalence and attenuation factor measurements carried out by Public Health England (previously by the Health Protection Agency) and the National Physical Laboratory on a variety of identical samples of differing thicknesses of vinyl materials. The comparison includes a joint analysis of results determined independently by each facility.

The measurements were performed over a range of X-ray excitation potentials from 60 to 120 kV as defined in BS EN 61331-1:2002. Due to physical constraints within the facilities, neither PHE (HPA) nor NPL are able to reproduce the exact measurement geometry as defined in this standard and there are also differences in the geometries between each facility. As a result, additional measurements were performed to determine if these differences produced any significant variation in results obtained.

The comparison also included a detailed analysis and review of the uncertainties associated with the determination of lead equivalence and attenuation factor, for both PHE (HPA) and NPL measurements.

A comparison was also made of the two sets of lead reference materials, of varying thicknesses, used by each of the facilities.

Crucially, an analysis was performed of the dependence of the results obtained on the techniques used for the interpolation of the measurement data.

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EXECUTIVE SUMMARY

The comparison exercise and associated investigations carried out by Public Health England and the National Physical Laboratory produced the following conclusions:

a The results of the testing performed by PHE and NPL indicate that there are no statistically significant differences between measurements made in the narrow and broad beam geometries. However, a standard uncertainty of 3% should be included to take account of the spread of results observed due to uncertainties in the generating potential and thickness of the copper filtration used

b There are no statistically significant differences in the results of the determination of attenuation ratio between those measured by PHE and NPL. Values of attenuation ratio, for all sample types and thickness, determined by PHE and NPL agree to within ± 3% for all X-ray excitation potentials

c There are no statistically significant differences in the results of the determination of lead equivalence between those measured by PHE and NPL. Values of lead equivalence, for all sample types and thickness, determined by the PHE and NPL agree to within ± 13% for all X-ray excitation potentials

d The newly derived uncertainty of +/- 13% (at the 95% confidence level, 2 σ) agrees with the standard uncertainty of +/- 7% (1 σ) contained in the draft revision of BS EN 61331-1

e The measurement geometry specified in the draft revision of BS EN 61331-1 more closely matches the irradiation geometry currently used by PHE

CONTENTS

1 INTRODUCTION

Determination of attenuation properties and lead equivalence values of materials is performed by Public Health England (previously by the Health Protection Agency) in the radiation metrology laboratories at Chilton. The lead equivalence of various sample materials and the associated attenuation factor can be determined for a range of X-radiation qualities generated with X-ray tube voltages between 20 and 300 kV. As a result of reported anomalies in some of the results obtained from this testing; an investigation was carried out with the National Physical Laboratory, Teddington, which involved repeat testing using the same samples. The purpose of this comparison was to determine whether there were differences in the values obtained by the two laboratories, and if so, to conduct further experimental work to determine the cause of any discrepancies.

2 METHOD

The method used for the determination of the attenuation ratio and lead equivalent of a protective material is defined in BS EN 61331-1:2002. Protective devices against diagnostic medical X-radiation. Determination of attenuation properties of materials. Due to physical constraints within the facilities, neither PHE nor NPL are able to fully comply with the requirements of this standard.

3 RADIATION QUALITIES

Measurements were performed at excitation potentials of 60 kV, 80 kV, 100 kV and 120 kV with the filtration detailed below. The 60 kV and 120 kV qualities are not listed in the standard. For these potentials the value of total filtration required was interpolated from the data for other qualities detailed in the standard.

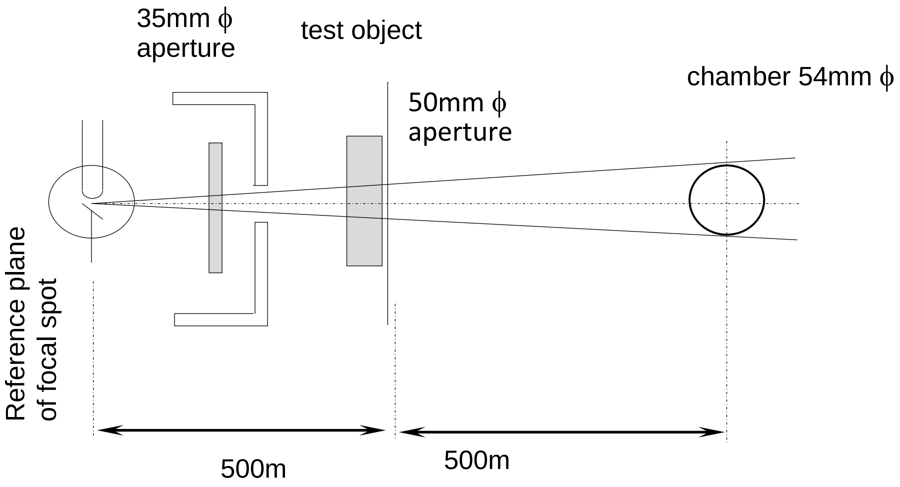
TABLE 1 Radiation qualities

X-ray tube voltage (kV)	Total filtration (mm of Cu) 61331-1:2002	Total filtration (mm of Cu) HPA	Total filtration (mm of Cu) NPL
60	--	0.072	0.075
80	0.15	0.15	0.15
100	0.25	0.25	0.25
120	--	0.43	0.41

4 PHYSICAL SET-UP

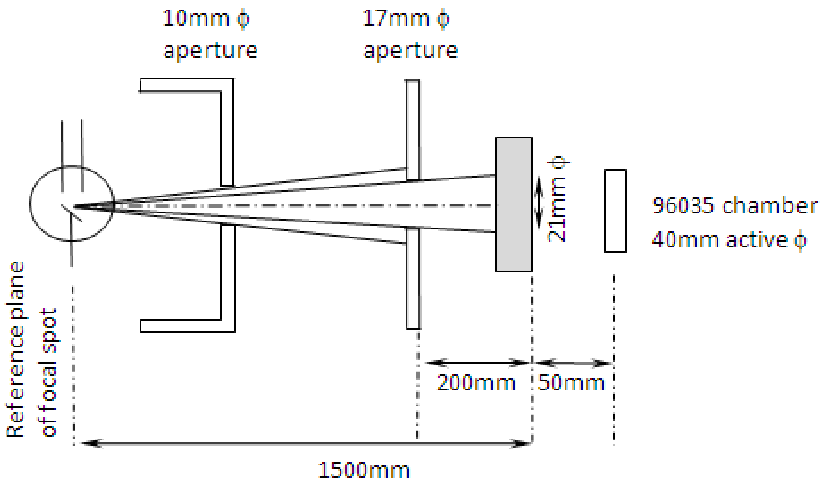
The measurement geometry, in terms of the distances and dimensions, used by PHE for these measurements, is shown in Figure 1. This geometry ensures that the entire sensitive volume of the secondary standard ionisation chamber is fully enveloped by the radiation beam. All other requirements of BS EN 61331-1:2002 narrow beam geometry were satisfied. This included the size of the sample, the energy response of the chamber and the distance between the reference point of the detector and any adjacent wall or object.

FIGURE 1 PHE narrow beam geometry



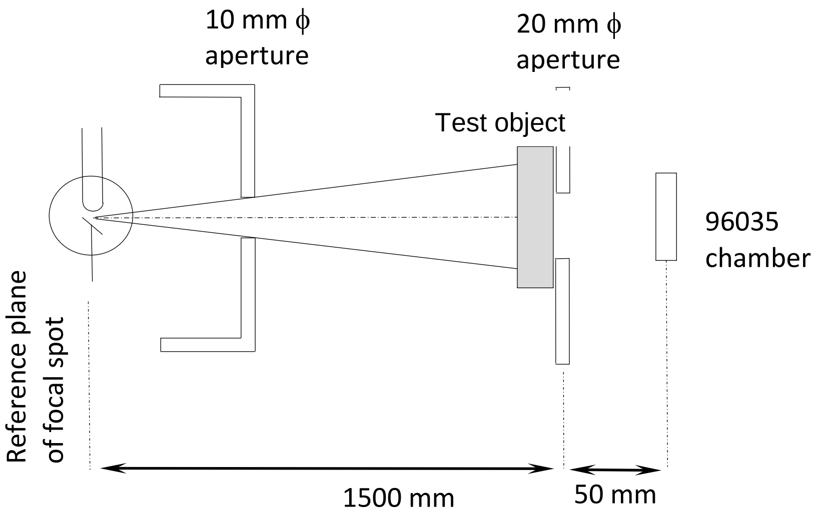
NPL performed measurements in a variety of experimental geometries, but were also unable to satisfy all the conditions associated with each, as defined in the standard. Narrow beam geometry resulted in the radiation detector not being fully enveloped by the radiation beam.

FIGURE 2 IEC 61331-1: narrow beam geometry as performed at NPL



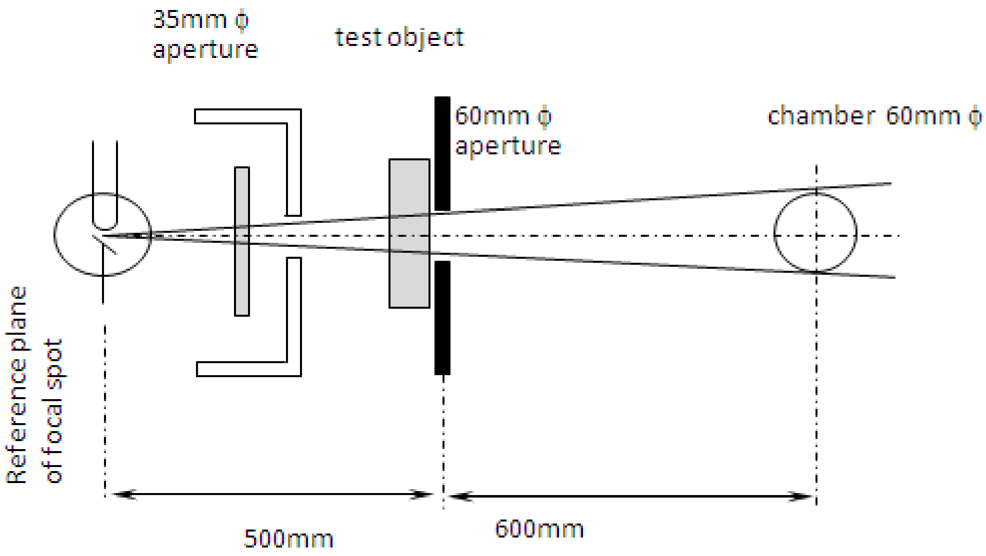
The NPL also conducted testing in a broad beam geometry, which allowed for the ionisation chamber to be fully enveloped by the radiation beam. However, the size of the samples tested needed to be 500 mm x 500 mm as opposed to 100 mm x 100 mm as were provided.

FIGURE 3 IEC 61331-1: broad beam geometry as performed at NPL



The NPL also conducted testing in the geometry as defined in the proposed replacement (draft) standard for BS EN 61331-1:2002. This fully enveloped the chamber and most closely represents the physical arrangement used by PHE.

FIGURE 4 NPL final geometry, as proposed in the replacement standard



5 RESULTS

5.1 Differences in irradiation geometry

NPL results obtained for attenuation ratios and lead equivalence values in narrow and broad beam geometries were compared and no statistically significant differences were observed between the results. The mean difference between the values obtained was less than 1%.

5.2 Attenuation ratio

The figures below show the attenuation ratios derived for four different types of material by PHE and NPL over a range of energies. The associated uncertainty of ± 5% is the initial (original) value estimated for the measurements, as reported on PHE and NPL certificates.

The attenuation ratio is defined as:

$$Attenuation\ ratio = 1 - \left(\frac{Air\ kerma\ rate\ in\ the\ attenuated\ beam}{Air\ kerma\ rate\ in\ the\ unattenuated\ beam}\right) \times 100\%$$

FIGURE 5 Comparison of PHE (HPA) and NPL attenuation ratio for material A

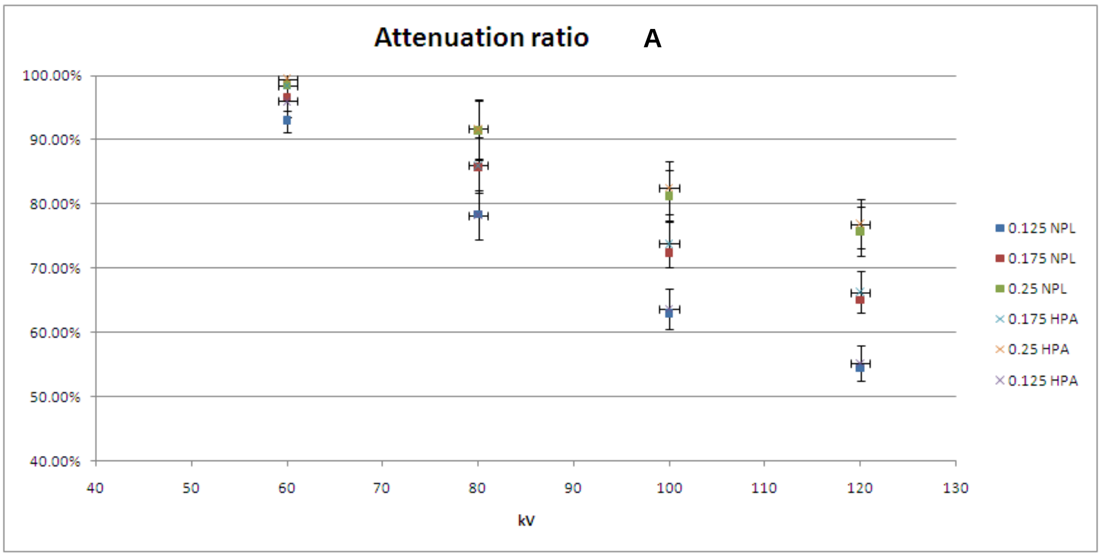


FIGURE 6 Comparison of PHE (HPA) and NPL attenuation ratio for material B

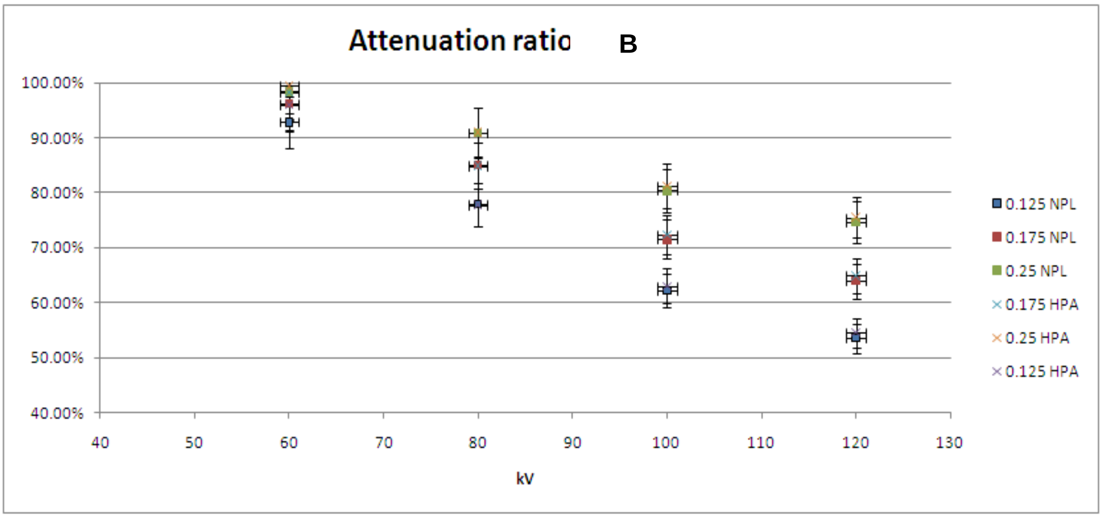


FIGURE 7 Comparison of PHE (HPA) and NPL attenuation ratio for material C

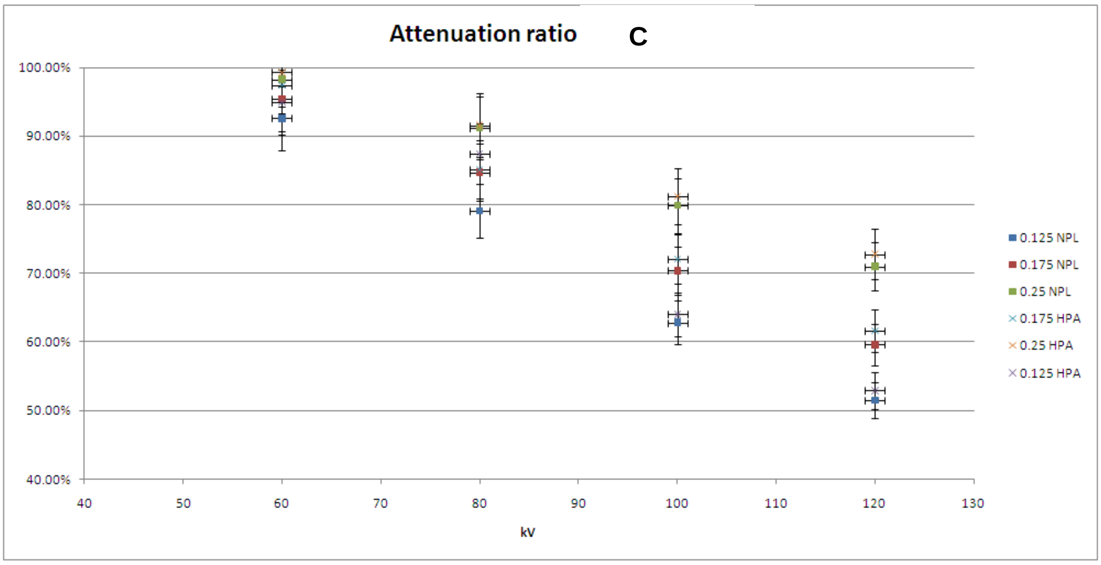
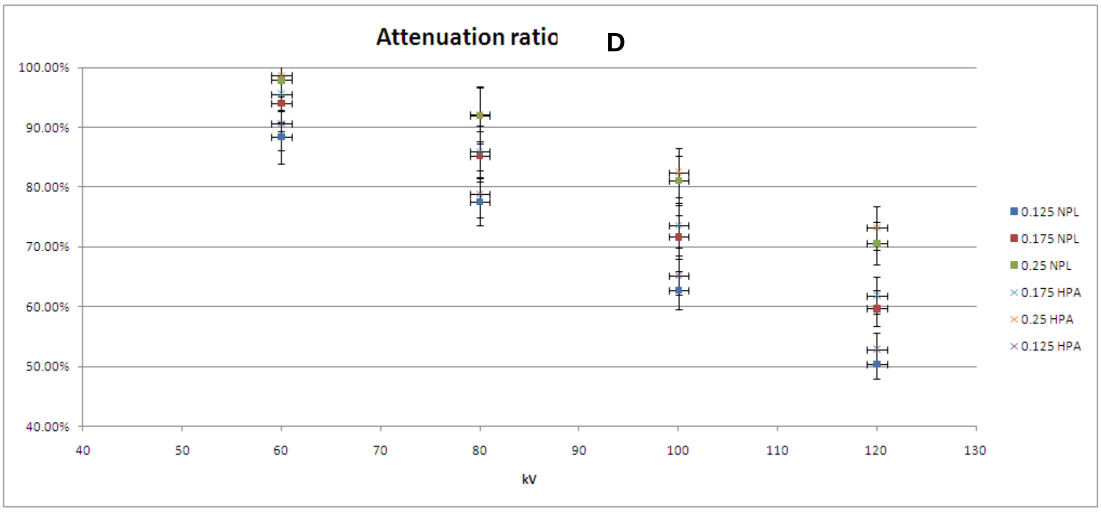


FIGURE 8 Comparison of PHE (HPA) and NPL attenuation ratio for material D



5.2.1 Uncertainties

A detailed uncertainty budget was derived for the calculation of the attenuation ratio. Factors considered included:

a Physical geometry

b Air kerma measurement

c Thickness of copper filtration

TABLE 2 Uncertainty budget for attenuation coefficient

Source of uncertainty	Value %	Probability distribution	Coverage factor	Standard uncertainty %
Operating potential	0.17	Rectangular	1.732	0.10
Thickness of Cu	2.00	Rectangular	1.732	1.15
Dosemaster calibration	1.00	Normal	2	0.50
Thermometer calibration	0.05	Normal	2	0.03
Barometer calibration	0.05	Normal	2	0.03
Air attenuation and scatter	0.05	Rectangular	1.732	0.03
Beam non-uniformity	2.00	Rectangular	1.732	1.15
Combined standard uncertainty				1.71
Expanded uncertainty				**3.42**

5.3 Lead equivalence

The figures below show the lead equivalence values derived for four different types of material by the PHE and NPL over a range of energies. The associated uncertainty of ± 5% is the initial (original) value estimated for the measurements, as reported on PHE and NPL certificates.

FIGURE 9 Comparison of PHE (HPA) and NPL lead equivalence for material A

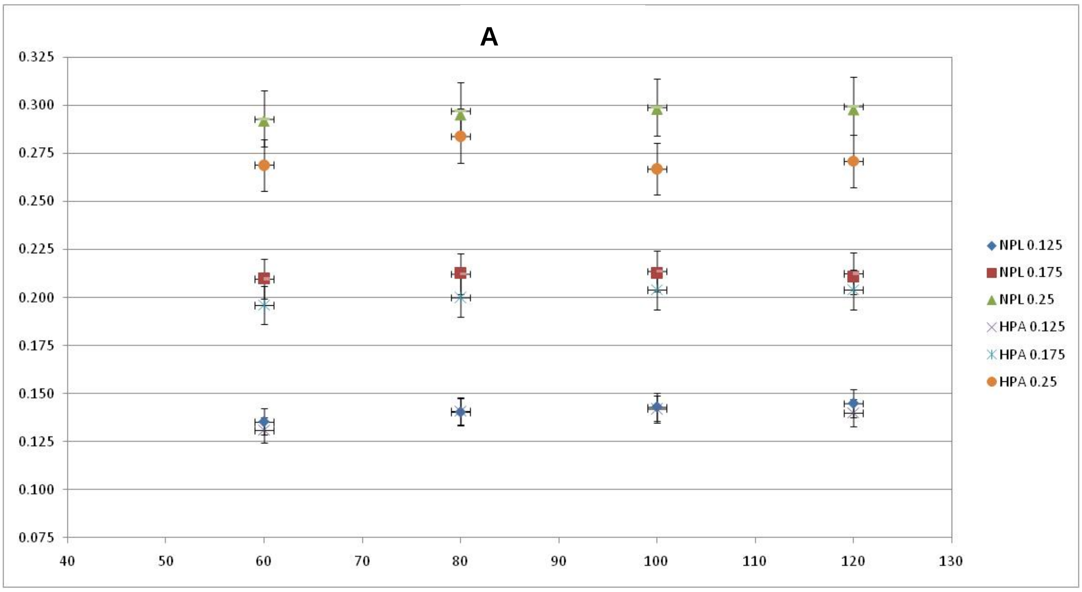


FIGURE 10 Comparison of PHE (HPA) and NPL lead equivalence for material B

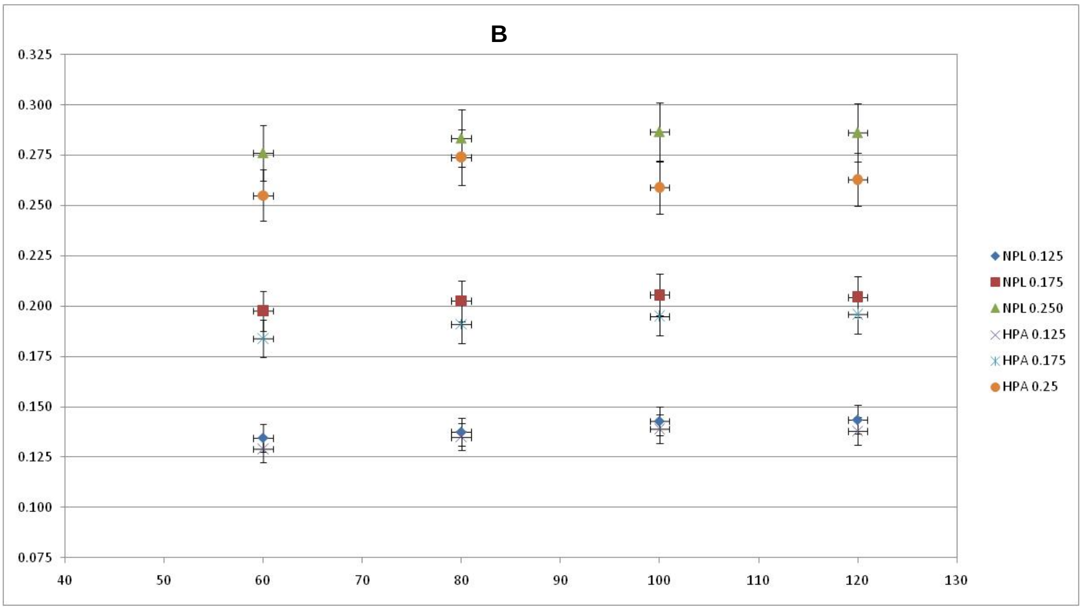


FIGURE 11 Comparison of PHE (HPA) and NPL lead equivalence for material C

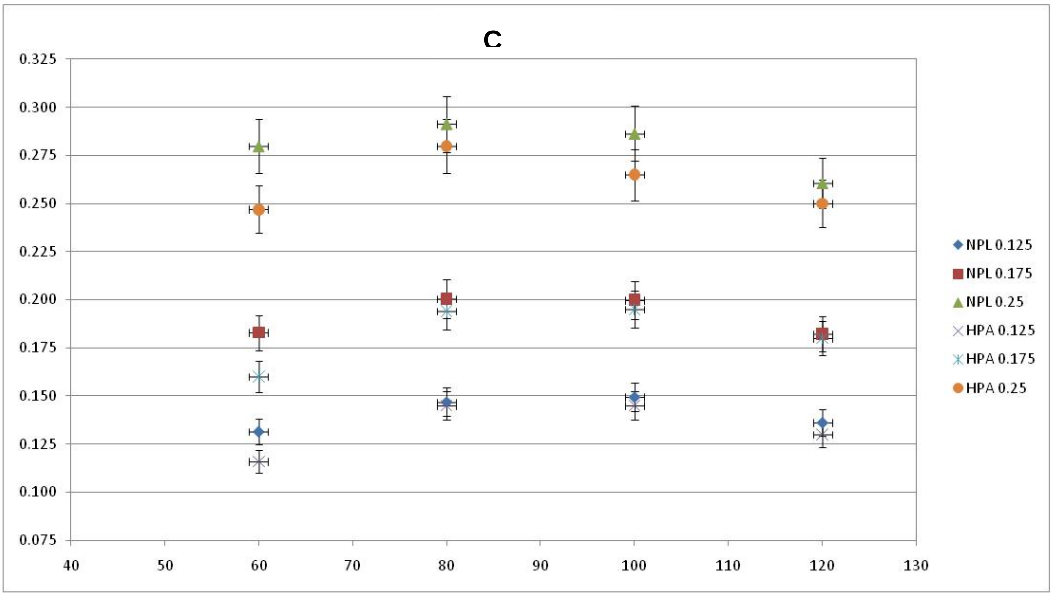
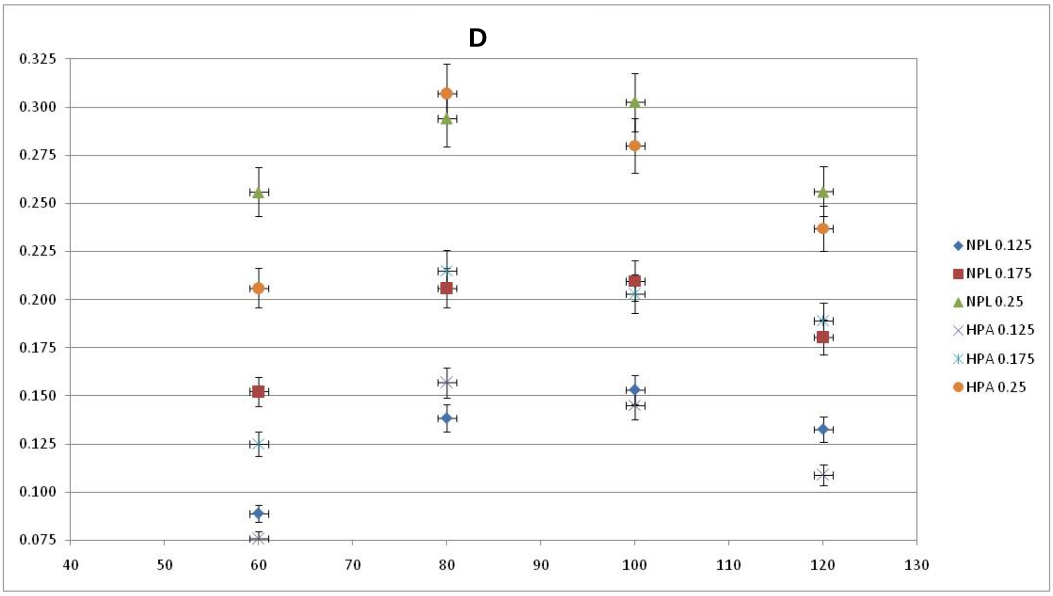


FIGURE 12 Comparison of PHE (HPA) and NPL lead equivalence for material D



5.3.1 Uncertainties

A detailed uncertainty budget was derived for the calculation of the determination of lead equivalence values.

Factors considered included:

a Physical geometry

b Thickness of lead samples

c Value of lead attenuation

d Air kerma measurement

e Thickness of copper filtration

f Interpretation of best fit

TABLE 3 Original uncertainty budget for lead equivalence

Source of uncertainty	Value %	Probability distribution	Coverage factor	Standard uncertainty %
Operating potential	0.17	Rectangular	1.732	0.10
Thickness of Cu	2.00	Rectangular	1.732	1.15
Dosemaster calibration	1.00	Normal	2	0.50
Thermometer calibration	0.05	Normal	2	0.03
Barometer calibration	0.05	Normal	2	0.03
Air attenuation and scatter	0.05	Rectangular	1.732	0.03
Beam non-uniformity	2.00	Rectangular	1.732	1.15
Thickness of Pb	2.00	Rectangular	1.732	1.15
Fit of best line	1.00	Rectangular	1.732	0.58
Combined standard uncertainty				2.14
Expanded uncertainty				**4.29**

The results for the lead equivalence values did not show the same level of agreement, within ± 5%, as was observed for the attenuation values. The addition of measurements involving standard lead reference samples was the only condition to have changed between the measurement of attenuation ratio and lead equivalence. In order to investigate this change, various aspects of the standard lead samples, such as the physical thickness and methodology of interpretation of the measurements, were investigated.

5.4 Investigation of lead

5.4.1 Lead sample thickness

The thickness of each sample used in the determination of the lead equivalence thickness was measured a total of ten times by NPL using a calibrated micrometer. Table 4 contains the standard deviation associated with each thickness. It can be seen that the previous estimate of 2% contained in the previous uncertainty budget is unreasonably low.

TABLE 4 Mean of ten physical measurements of lead sample thickness

Pb reference	NPL Pb 13	NPL Pb 14	NPL Pb 15	PHE 0.25	PHE 0.056	PHE 0.012
Mean	0.1139	0.1087	0.1143	0.2498	0.0529	0.1294
Standard deviation	0.0051	0.0061	0.0056	0.0039	0.0014	0.0063
% standard deviation	4.48	5.63	4.92	1.56	2.74	4.87

5.4.2 Interpolation of lead equivalence value

The value of lead equivalence is determined by the derivation of the line of best fit for the measured lead samples and the value of lead thickness that corresponds to the associated value of $\ln(I/I_0)$ of that function. PHE use a polynomial relationship that crosses through the origin with no lead in the beam for the interpolation of lead attenuation values, whilst NPL use a linear fit that does not go through the origin.

FIGURE 13 PHE (HPA) and NPL lead attenuation 60 kV – polynomial and linear

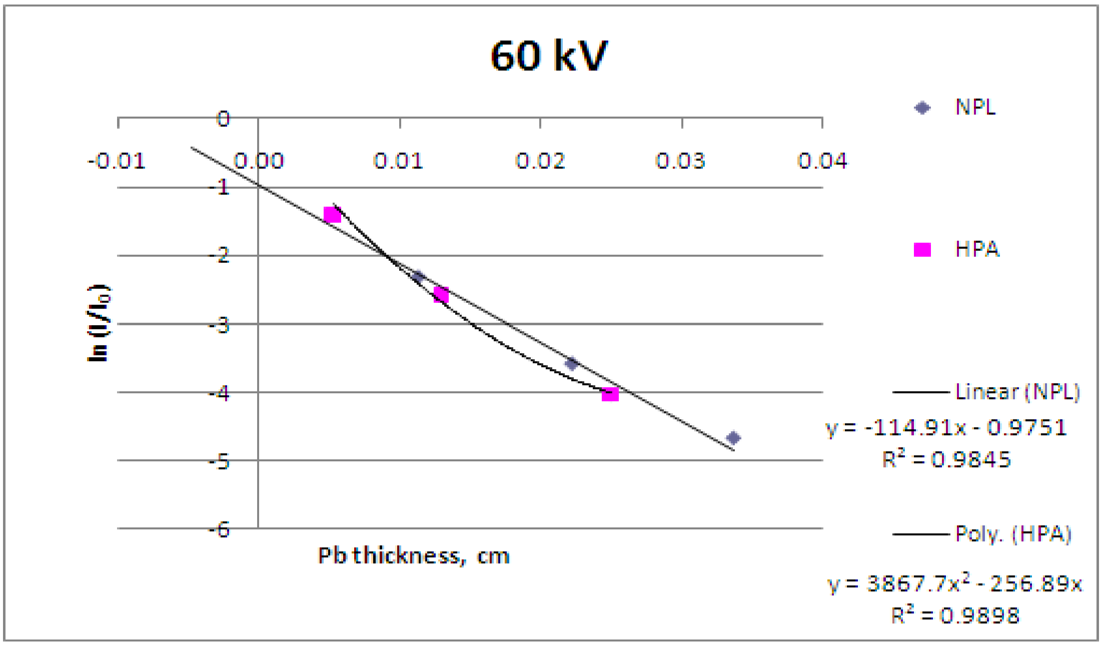


FIGURE 14 PHE (HPA) and NPL lead attenuation 80 kV – polynomial and linear

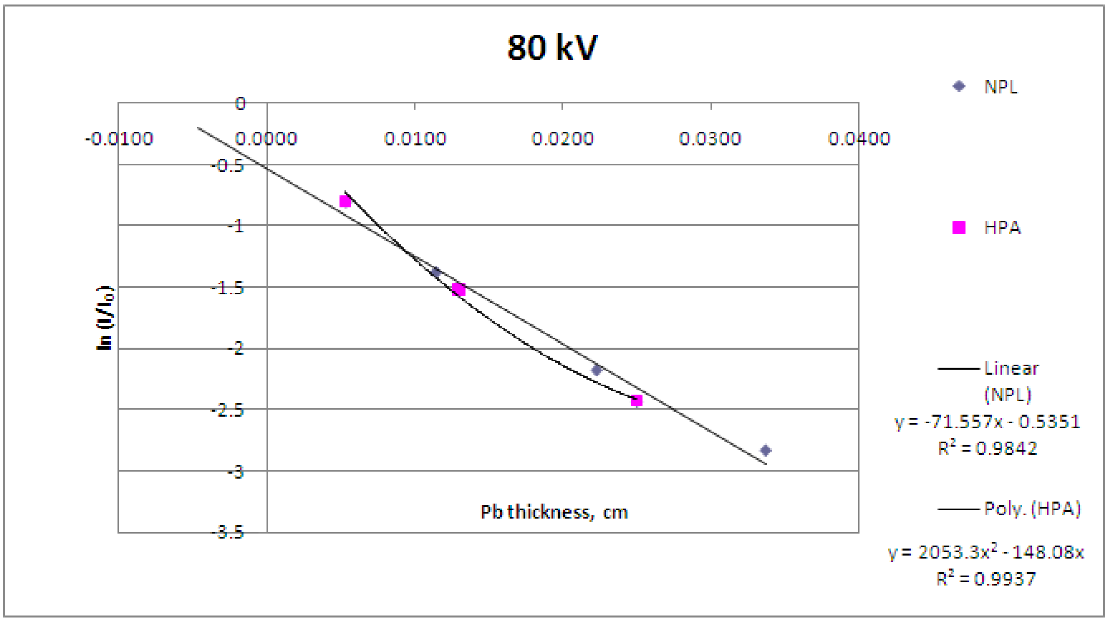


FIGURE 15 PHE (HPA) and NPL lead attenuation 100 kV – polynomial and linear

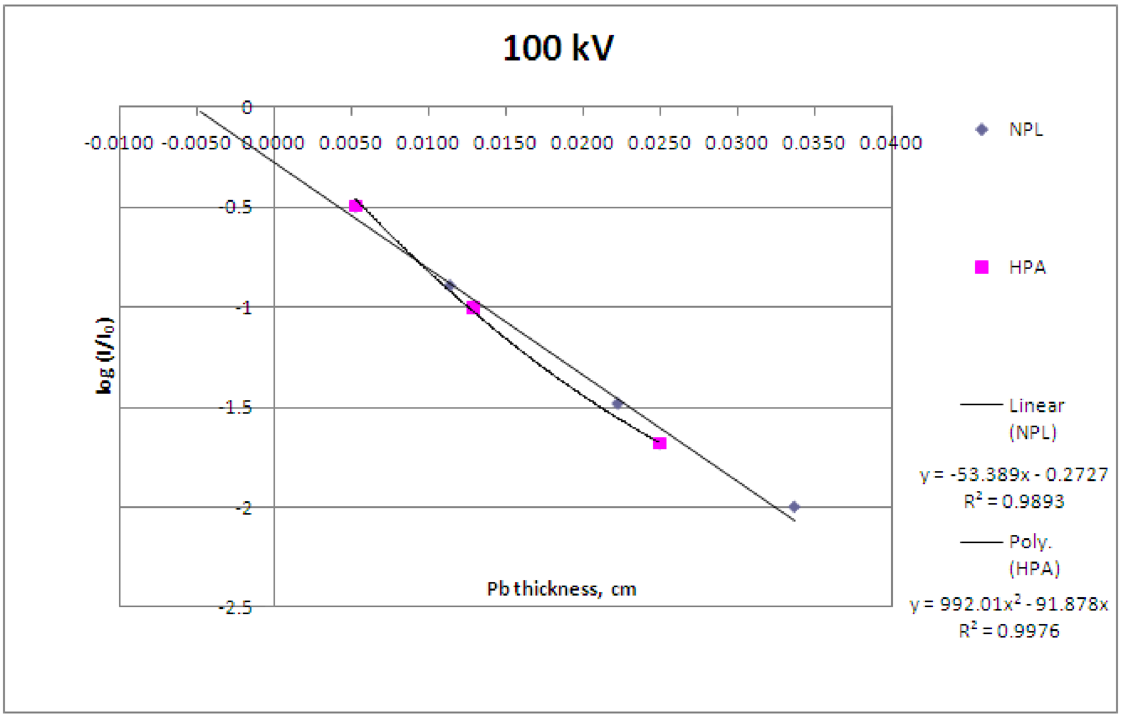
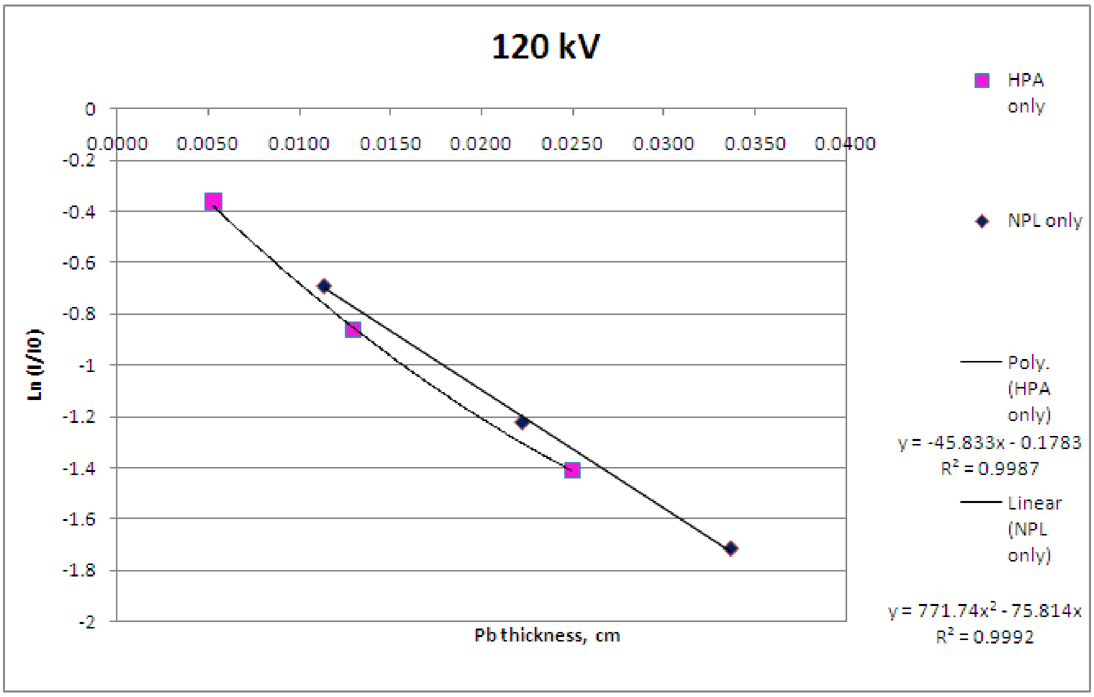


FIGURE 16 PHE (HPA) and NPL lead attenuation 120 kV – polynomial and linear



It can be seen that the variation of the derived lead equivalence thickness changes with the operating voltage of the X-ray set, the apparent lead equivalent thickness, and the form of the function used to determine the best fit.

PHE use a polynomial fit since the incident radiation consists of a broad spectrum of energies rather than mono-energetic photons. This gives rise to a hardening of the beam with increased values of lead thickness and hence the attenuation coefficient will change. For all cases where there is no lead in the beam there will be no attenuation and hence the line of best fit should go through the origin.

NPL use a straight-line fit as described by the Lambert law. This states that the measured intensity (I_x) transmitted through a layer of material with thickness x, is related to the incident intensity (I_0) according to the inverse exponential power law:

$$\therefore \frac{I_x}{I_O} = \exp(-\mu x)$$

where x denotes the path length. The attenuation coefficient (or linear attenuation coefficient) is µ.

The difference in the determination of lead equivalence thickness values, when calculated using either a polynomial or straight line fit, ranges from 0 to 20%. Therefore the value of 1% contained within the original uncertainty budget is also unrealistic and should be increased to ± 10%. Using this value the uncertainty associated with the determination of lead equivalent thickness was recalculated.

TABLE 5 Re-evaluated uncertainty budget for lead equivalence

Source of uncertainty	Value %	Probability distribution	Coverage factor	Standard uncertainty %
Operating potential	0.17	Rectangular	1.732	0.10
Thickness of Cu	2.00	Rectangular	1.732	1.15
Dosemaster calibration	1.00	Normal	2	0.50
Thermometer calibration	0.05	Normal	2	0.03
Barometer calibration	0.05	Normal	2	0.03
Air attenuation and scatter	0.05	Rectangular	1.732	0.03
Beam non-uniformity	2.00	Rectangular	1.732	1.15
Thickness of Pb	4.00	Rectangular	1.732	2.31
Fit of best line	10.00	Rectangular	1.732	5.77
Combined standard uncertainty				6.45
Expanded uncertainty				**12.90**

Since the expanded uncertainty is expressed at the 95% confidence level, or 2 σ, the uncertainty derived above is almost identical to the standard uncertainty of 7%, which is expressed at 1 σ, contained in the draft revision of BS EN 61331-1.

The figures below show the lead equivalence values derived for four different types of material by the PHE and NPL over a range of energies. The associated uncertainty of ± 13% is the value derived from the re-evaluated uncertainty budget.

FIGURE 17 Comparison of PHE (HPA) and NPL lead equivalence for material A

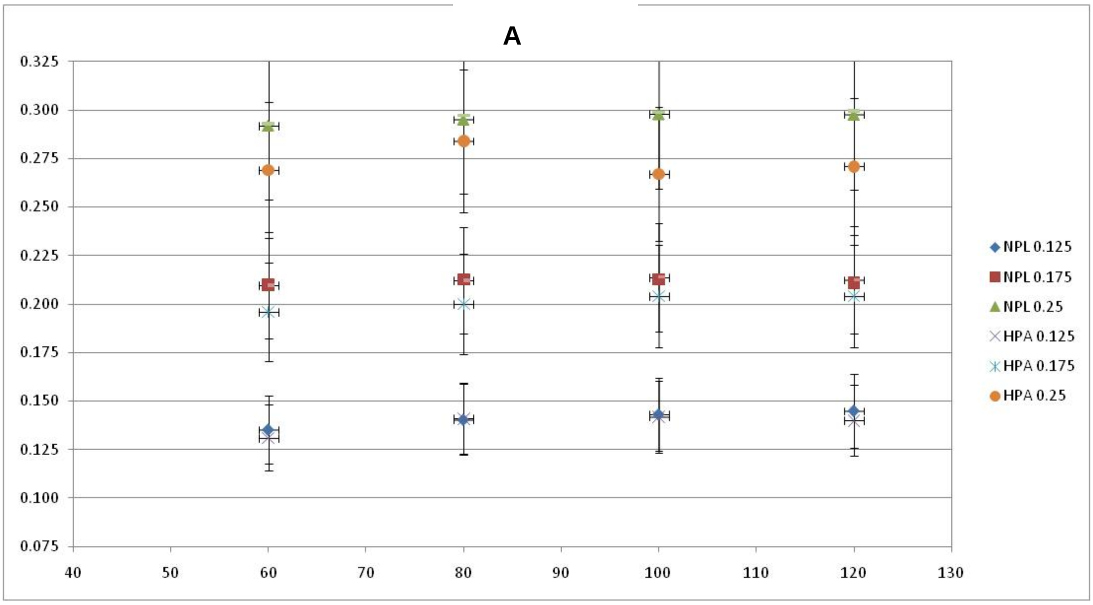


FIGURE 18 Comparison of PHE (HPA) and NPL lead equivalence for material B

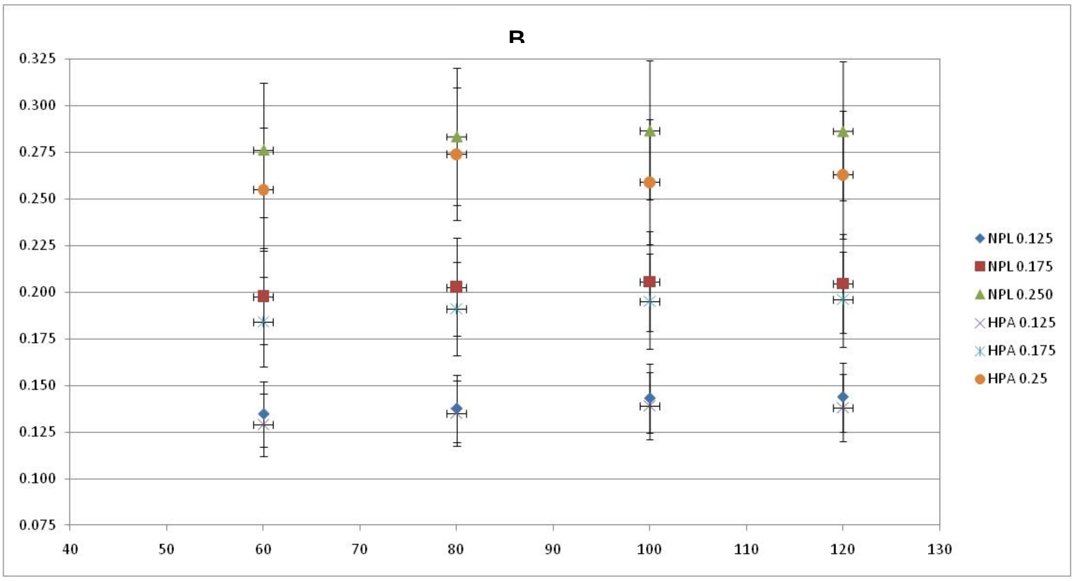


FIGURE 19 Comparison of PHE (HPA) and NPL lead equivalence for material C

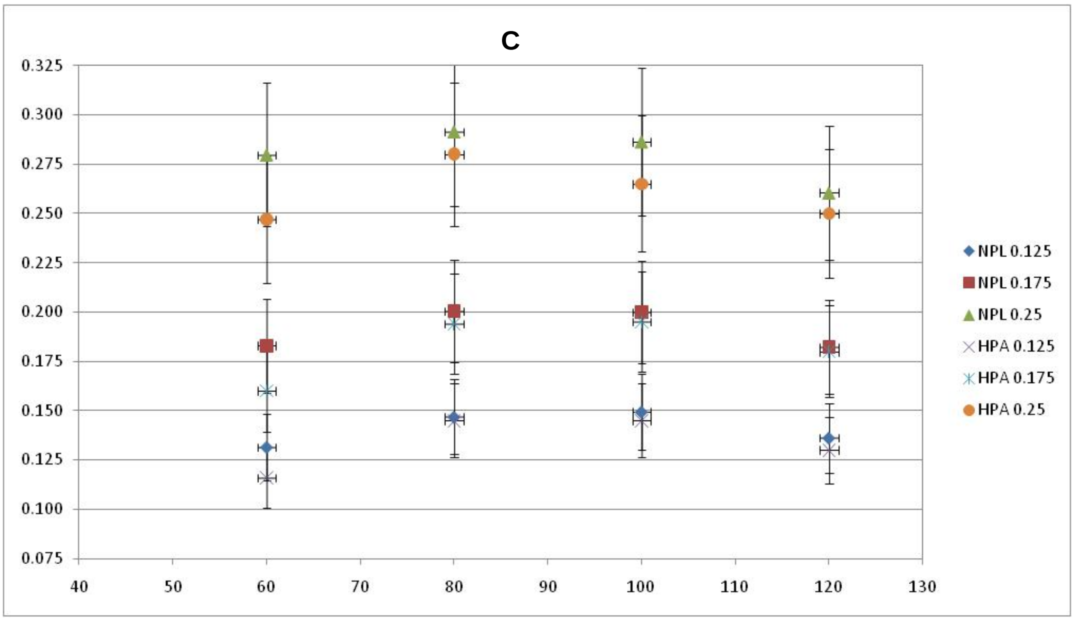
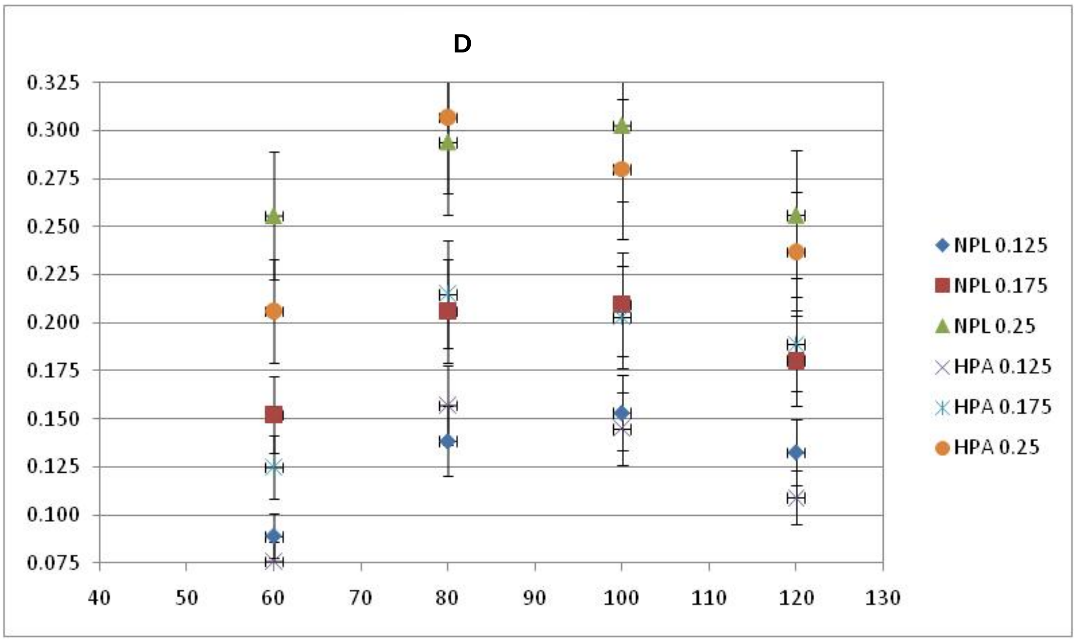


FIGURE 20 Comparison of PHE (HPA) and NPL lead equivalence for material D



6 CONCLUSION

6.1 Differences in irradiation geometry

There are no statistically significant differences observed between results obtained in the narrow or broad beam geometry, however a standard uncertainty of ± 3% should be included to take account of the spread of results observed due to uncertainty in the X-ray generating potential and copper filtration thickness.

6.2 Attenuation ratio

There are no results that are statistically different between those determined by PHE and NPL. Values of attenuation ratio, for all sample types and thickness, determined by PHE and NPL, agree to within ± 3% for all X-ray excitation potentials.

6.3 Lead equivalence

There are no results that are statistically different between those determined by PHE and NPL. Values of lead equivalence, for all sample types and thickness, determined by PHE and NPL, agree to within ± 13% for all X-ray excitation potentials.