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Response characteristics of PADC track etch and NTA film neutron personal dosimeters for backscatter from standard calibration phantoms

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Abstract

The aim of this work was to provide information which could be used to improve the efficiency and cost effectiveness with which regular calibrations and checks of personal dosimeters are carried out. To this end simple factors have been determined relating the results of calibrations performed free-in-air to those for calibrations performed with the dosimeters mounted on the phantoms recommended by either the International Commission on Radiation Units and Measurements (ICRU) or the International Organization for Standardization (ISO). These factors were derived for the two most commonly used calibration sources, i.e. $^{241}\text{Am-Be}$ and ^{252}Cf , and for dosimeters from all the neutron dosimetry services presently approved in the UK.

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1. INTRODUCTION

The purpose of individual monitoring is to obtain, by some means, an estimate of the protection quantity effective dose equivalent. In the UK an estimation of this quantity is required by law for classified radiation workers. Where the estimate of effective dose equivalent is obtained by measurements with personal dosimeters, the quantity conventionally determined is the operational quantity, personal dose equivalent, defined by the International Commission on Radiation Units and Measurements, ICRU, in, for example, ICRU Report 51⁽¹⁾. This is considered acceptable as an estimate of effective dose equivalent in the majority of circumstances. Effective dose equivalent is defined in terms of a weighted mean of dose equivalents in various organs of an anthropomorphic phantom representing the human body and is therefore usually treated as a quantity which cannot be measured directly. In view of this, so called operational quantities were introduced by ICRU⁽²⁾ which were designed to be measurable and to be conservative estimates of effective dose equivalent.

A neutron dosimeter worn on the human body responds not only to directly incident radiation, but also, to a greater or lesser extent depending on the type of dosimeter, to neutrons backscattered from the body. These neutrons, on average, will have a lower energy. Similarly, if they are calibrated on-phantom, dosimeters respond to radiation backscattered from the calibration phantom. The extent of the response to backscatter is still uncertain.

In the UK, the neutron dosimeters issued by the presently approved dosimetry services use either PADC (poly-allyl diglycol carbonate, often known as CR-39) track-etch plastic or NTA film as the sensor element. The link between the readings of these dosimeters, which would be the number of pits in PADC track-etch plastic or tracks in NTA film, and the required quantity, personal dose equivalent, is established via a calibration of the dosimeters in a known neutron field. Throughout this report the term 'dosimeter' will be used to denote the complete assembly of neutron sensitive element, i.e. the track-etch plastic or film sensor, and the holder which may or may not include lead shields, boron-loaded shields, 'radiator' elements, or even sensors for other radiation types.

Phantoms play a fundamental role in defining and realising quantities in radiation protection⁽³⁾. They are central to the definitions of the dosimetric quantities. Personal dose equivalent, $H_p(d)$, is defined⁽¹⁾ as "the dose equivalent in soft tissue, at an appropriate depth, d , below a specified point on the body". Values for the appropriate depth depend on the type of radiation, but for neutrons, which are considered penetrating radiation, the depth is 10 mm. The definition on its own does not provide sufficient information to enable the quantity to be realised. Certain conventions and assumptions have been adopted over recent years to clarify matters, and it is assumed that they will eventually be incorporated into standards. The "specified point on the body" has been taken to mean the position where the individual dosimeter is worn. The impracticality of a human phantom in calibration situations led the ICRU, in Report 47⁽⁴⁾, to recommend that: "The quantity to be used for the calibration is, $H_p(d)$, in a phantom having the composition of ICRU tissue and the same shape and size as the calibration phantom". Practical considerations and common usage have narrowed the choice of calibration phantom for whole body irradiation down to a block measuring 30 x 30 x 15 cm, although different materials are used for the block. The International Organization for Standardization, ISO, has recommended⁽⁵⁾ a water phantom which is essentially a PMMA box, with walls 10 mm thick on all sides except the front face where the

thickness is 2.5 mm, filled with water. (PMMA is polymethyl methacrylate, $(C_5H_8O_2)_n$, commonly known as Lucite or Perspex.) In ICRU Report 47⁽⁴⁾, PMMA is recommended as the material for the complete phantom. Since this report was published in 1992, ideas have moved on, and ICRU recommendations may well change. PMMA is, however, still widely used as the material for phantoms, particularly in the USA. Throughout this document, the PMMA phantom is, for convenience, referred to as the ICRU phantom whilst the water phantom is referred to as the ISO phantom. The ISO phantom has backscatter characteristics which are more like those from ICRU tissue.

The present position in individual dosimetry is thus: a person wears, on the surface of his/her body, a dosimeter designed and calibrated to provide a measure of the dose equivalent at 10 mm below the surface of a 30 x 30 x 15 cm slab of ICRU tissue. For the types of personal dosimeters presently issued by Approved Dosimetry Services (ADSs) in the UK, the response of the dosimeter is due in the main to the sensor registering incident fast neutrons (with energies greater than about 100 keV for PADC track-etch elements and about 500 keV for NTA film). The sensors may also be sensitive to thermal and epi-thermal neutrons. NTA film has an inherent thermal neutron sensitivity, due to nitrogen present in the emulsion, and PADC plastic can be made sensitive to thermal neutrons by including a radiator element, for example nylon, which allows thermal neutrons to be detected via the (n,p) reaction with nitrogen, or by doping the PADC itself with a material such as ^{10}B which allows thermal neutrons to be detected via the (n, α) reaction. The thermal neutron sensitivity is not, however, expected to be an important issue in calibration situations with radionuclide neutron sources since the majority of the dose equivalent will be due to fast neutrons. Thus, although the phantom is essential for defining the quantity $H_p(10)$, its role and importance in the calibration process depends on the sensitivity of the dosimeter to backscattered radiation.

Calibrations on phantoms, rather than free-in-air, raise a number of practical problems. Phantoms have finite areas, thus limiting the number of dosimeters which can be calibrated at one time. The question of how close to the edge of a phantom dosimeters can be placed without influencing the calibration is an unresolved issue. The sensitivity of the dosimeter reading may also be a function of any gap between the phantom front face and the rear side of the dosimeter. Finally, because the phantoms used have a flat front face for attaching the dosimeters, these tend to be located at slightly different distances from the (essentially point) neutron source and the neutrons strike them at slightly different angles of incidence. All these effects introduce uncertainties into the calibration process.

The problems with phantoms, in particular the limited area available for affixing dosimeters, are of most concern when performing routine calibrations and regular checks. It is important that these are not an undue financial burden on the Dosimetry Services which issue the dosimeters, and hence on the customers. In the UK, the Health and Safety Executive, HSE, is moving towards routine performance testing of neutron personal dosimeters which will involve calibration checks being performed annually. One way of simplifying the procedure and maximising the number of dosimeters irradiated at one time, and thus performing regular checks in an efficient and cost effective way, would be to perform the irradiations free-in-air. This would be acceptable if simple factors were available to relate dose equivalent calibrations in free space to the results which would be obtained on phantom. These factors will depend to some extent on dosimeter type, methods of manufacturing the sensor element, sensitivity, approach to processing, etc., but, if the overall backscatter response is small, variations for different dosimeters may be negligible. This simplified approach would also

remove the uncertainties mentioned above which arise when phantoms are used and hence remove one potential source of differences between results reported by different ADSs.

Essentially, the aim of this project was to determine the response of PADC track etch and NTA film personal dosimeters to backscattered neutrons from calibration phantoms. With this information, allowances can be made for differences between calibration measurements on-phantom and free-in-air. Two approaches were adopted to determine the dosimeter response to backscattered radiation. The main approach was experimental, but this was backed up by a series of calculations which provided additional data and also valuable insight into the physical processes involved.

One of the main difficulties with an experimental approach arises from the relatively large uncertainties in dosimeter readings when compared to the size of the backscatter response under investigation. Previous investigations^(6-12,) have indicated that this backscatter effect is of the order of perhaps 10%. Most of the investigations have been for NTA film dosimeters. A variety of different phantoms, including ones made of paraffin, water, and tissue equivalent material, have been used. In addition, various different radionuclide neutron sources have been employed. The results are varied, ranging from 0% to 33%.

The calculational approach is hampered by lack of reliable knowledge of dosimeter characteristics. Some backscatter calculations have, nevertheless, been performed and the results published^(13,14).

The uncertainty on the reading of a single personal dosimeter depends on various factors, for example, background events in track-etch devices, gamma fogging in NTA film, subjectivity in counting pits or tracks, and the statistics of the number of pits/tracks formed. Statistical uncertainties can be reduced by increasing the dose equivalent delivered to a dosimeter, but excessively high dose equivalents introduce problems of overlapping pits or tracks. For PADC track etch dosimeters the optimum dose equivalent is of the order of 3 mSv, and for NTA film a little higher, possibly up to 10 mSv. Even under optimum conditions, the statistical standard deviation associated with the reading of an individual dosimeter is of the order of 10%. Measurement of a small on-phantom to free-in-air ratio thus requires a large number of dosimeters to be irradiated for each calibration field and each phantom so that the uncertainty of the mean response can be reduced to an acceptably low level.

The quantity used throughout this report to characterise the response characteristic of a dosimeter is the number of events in the sensor per unit neutron fluence, i.e., pits in the case of track-etch devices or tracks in the case of films, both per neutron per cm^2 . This removes the need for any fluence to dose equivalent conversion factors which would only represent an added complication.

Since the response to backscatter was expected to be small, it was possible that, even after irradiating a large number of dosimeters to the optimum dose equivalent level, the uncertainty in the measured response to backscattered neutrons would still be larger than the size of the effect. In such a case the detailed examination of even smaller effects, such as the reduction in the backscatter as the dosimeter is placed close to the edge of a phantom face, or the sensitivity to any gap between the phantom face and the dosimeter, would be of little value, both because the effect would be near impossible to measure, and also because it would be of no importance in practical dosimetry.

All UK ADSs use either PADC track-etch plastic or NTA film as the sensor in their dosimeters. Although there will be some variation between services because of differences in processing techniques, these differences are expected to be small, and once again they will be unimportant for this exercise if the backscatter effect itself is negligibly small. Thus, to avoid performing a huge series of measurements with dosimeters from all the different services, using different neutron sources, different phantoms, and measuring both edge and separation effects for all these dosimeters, it was decided to perform an initial set of measurements using track-etch dosimeters from a single ADS and also NTA film dosimeters from a single ADS. On the basis of the magnitude of the measured backscatter effects a decision would then be made on what further measurements needed to be performed to investigate dosimeters from other ADSs.

2. EXPERIMENTAL METHOD

2.1 Experimental assemblies

All measurements, both on-phantom and free-in-air, were performed in NPL's low-scatter neutron irradiation facility. This is a shielded room 24 m long by 18 m wide and 18 m high. Irradiations are performed at a height of 6 m above the floor of the facility and approximately 6 m from the nearest wall.

All on-phantom irradiations were performed using two phantoms simultaneously, both at 75 cm from the source, but placed diametrically opposite each other. This doubled the number of dosimeters irradiated in a given time without measurably increasing the scatter component. The distance of 75 cm is the larger of the two calibration distances recommended by ISO⁽¹⁵⁾ (the other being 50 cm), and was chosen because both the variation of the fluence and the changes in the angle of incidence across the face of the phantom are smaller at this distance. The vertical positioning of the phantoms was set using an optical level by aligning the midpoint of each phantom to a set reference height. A similar procedure was used to set the height of the neutron source. Each phantom, was aligned rotationally by ensuring that its corners were equidistant from the centre of the source. Dosimeters were attached to the phantom using double-sided adhesive tape.

The free-in-air irradiations were performed using a jig consisting of a lightweight aluminium ring into which posts were set at fixed points. Each post supports a small rectangular piece of aluminium (63 mm long, 13 mm wide, and 1.6 mm thick) set with its long side vertical and with a flat side facing the source. The source to aluminium support distance is nominally 75 cm. Dosimeters are attached to the flat face using either double-sided adhesive tape or the dosimeter's own clip if appropriate. Up to 72 posts can be positioned at 5° intervals around the ring, and for small dosimeters more than one can be placed on each aluminium support.

The optical level was used to align the ring in the horizontal plane at the height of the neutron source, and when more than one dosimeter was attached to each aluminium flat, the height above or below the horizontal plane of the source was measured in order to derive distance corrections for use when calculating the incident fluence on each dosimeter. Owing to a slight asymmetry in the ring arrangement, there is a variation in the irradiation distance of roughly ± 5 mm around the ring. Consequently, it was necessary to measure the irradiation distance at each point used. Figure 1 shows a typical set of distance measurements, illustrating the asymmetry of the support ring arrangement.

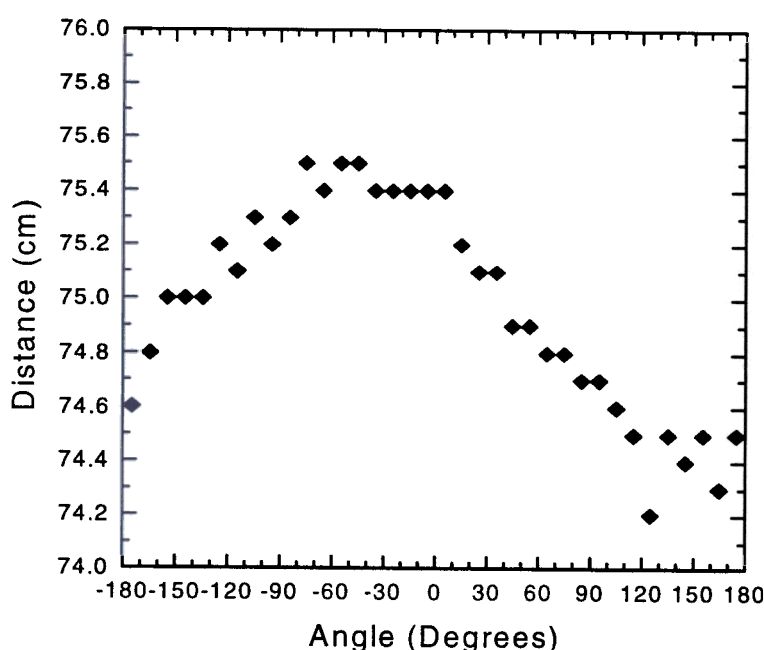


Figure 1. Dosimeter irradiation distances, as measured for the dosimeter ring.

dosimeters. The distance of the sensor within each dosimeter from the centre of the phantom face was measured in order to perform subsequent distance corrections during the calculation of the fluence.

2.2 Source positioning and irradiation time-keeping

Two radionuclide neutron sources were used in this work, one an $^{241}\text{Am-Be}(\alpha, n)$ source with a total emission rate of about $2 \times 10^7 \text{ s}^{-1}$, and the other a ^{252}Cf spontaneous fission source with an emission rate of about $9 \times 10^7 \text{ s}^{-1}$ at the time of the measurements. Their emission rates are traceable to national standards, i.e., to measurements in the NPL manganese sulphate bath. Both sources used were cylindrical, and were mounted in a small cup-shaped holder such that the dosimeters were irradiated by neutrons emitted from the curved surface of a source, i.e., at 90° to that source's cylindrical axis. The effective centre of the active material within the source capsule defined the height of the horizontal plane in which the dosimeters were positioned.

As personal dosimeters are passive devices, the mounting of the source and the timing of the irradiation had to be performed with extreme care. During the time while the personal dosimeters were being mounted on-phantom or on the support ring, and up until the time when the source was placed in position, a set of control dosimeters was kept at the irradiation position. These registered any background dose seen by the mounted dosimeters whilst the neutron source was brought into the irradiation area from the source storage location and prepared for mounting.

With the control dosimeters in position, the selected neutron source was brought into the low-scatter area in a heavily shielded transport keg and placed in a corner of the room, approximately 10 m from the experimental area. The source was then removed from the keg and placed behind a 20 cm thick wax shield, where it was mounted in a set of long-handled tongs. The control dosimeters were removed at this time and the source quickly carried to the source

To avoid dosimeter-to-phantom separation effects during the measurements of the basic backscatter response, the rear face of the dosimeter was attached directly to the phantom front face wherever possible.

Phantom edge effects were minimised by arranging all dosimeters within a $20 \times 20 \text{ cm}$ square at the centre of the phantom. A gap of at least 5 mm was included between all dosimeters to minimise scattering of neutrons between

holder, being held roughly 2 m above the plane of the irradiation. Once near enough to reach the holder, the source was lowered carefully but rapidly into position, ensuring that it was kept at least 75 cm away from any dosimeter at all times.

The timing of the irradiation was started once the source was within about 10 cm of the source holder to allow for the fact that the dosimeters would be recording events at all times while the source was exposed. Typically, the time taken to bring the source from the corner of the room to the experimental area and then mount the source was less than 30 seconds, a very short period in relation to the irradiation times, which were several hours. A similar procedure was adopted for the removal of the source. Exactly the same convention was adopted for both on-phantom and free-in-air irradiations so that any uncertainties in the timing tended to cancel-out when determining ratios of responses.

2.3 Data processing

After the irradiations were performed both the irradiated dosimeters and the associated set of control dosimeters were returned to the services for reading. The results were then reported to NPL where the analysis was performed. The reported reading for each irradiated dosimeter was corrected by subtracting the average reading of the control dosimeters. A response value was then calculated for each dosimeter by dividing the corrected reading by the neutron fluence incident on that dosimeter. In all cases the incident fluence was corrected, using the inverse square law dependence, for the small measured deviations of the source to dosimeter distance from the nominal value of 75 cm. This correction had a maximum value of 1.8% for on-phantom irradiations, and 2.1% for those performed free-in-air. Corrections were also made for the fact that on-phantom dosimeters positioned anywhere other than the centre of the phantom face see a very small reduction in the incident fluence because the dosimeter is not exactly perpendicular to the direction of the neutrons. The maximum value for this fluence reduction was 0.7%. The quantity finally derived was the ratio of the average on-phantom response to the average free-in-air response for a particular number of dosimeters.

For all the irradiations performed as part of this work, the fluence value used was that at the back surface of the dosimeter. For the majority of dosimeters this coincided with the position of the front surface of the phantom when the devices were mounted on-phantom. Two of the dosimeter types, however, had clips on the back surface so that the dosimeters were displaced from the phantom front surface when mounted on-phantom by 2 mm in one case and 7 mm in the other. Since the dosimeters are primarily fast-neutron detectors and the majority of the reading is due to the directly incident neutrons rather than those backscattered from a phantom, the use of the neutron fluence on the back surface of the dosimeter for all types of dosimeters was considered the most appropriate and consistent approach. No attempt was made to derive the fluence at the position of the sensor elements within the dosimeter which would have raised problems for multi-sensor dosimeters, particularly those where the sensors were not all in one plane.

3. PRELIMINARY BACKSCATTER MEASUREMENTS

3.1 Initial considerations

As a first step to determining the response to backscatter a series of measurements were performed with a number of PADC track-etch dosimeters from a single ADS, denoted as dosimeter type P1, and a similar number of NTA film dosimeters, again from a single

service, denoted as dosimeter type N1. Measurements were performed with both $^{241}\text{Am-Be}$ and ^{252}Cf radionuclide neutron sources, and for both ICRU and ISO recommended phantoms. Both types of dosimeter contained just one sensor element.

Since the statistical uncertainty on the reading of a single dosimeter is relatively large, being about 10%, a significant number of dosimeters needed to be irradiated and read in order to reduce the uncertainty to an acceptably low level if the response to backscatter was small. The important quantity to be measured is the ratio of on-phantom to free-in-air responses, which means that a similar number of dosimeters needed to be irradiated under both conditions. A figure of 36 was chosen for the number of dosimeters irradiated in each case. There were a number of practical reasons for this choice including the numbers which can be placed on the face of a phantom during an irradiation, 9 or 18, depending on dosimeter type, and also the fact that the free-in-air irradiation jig is capable of supporting 36 dosimeters at 10° intervals. This arrangement keeps the dosimeters sufficiently far apart to make scatter between dosimeters negligible. With a statistical uncertainty of $\pm 10\%$ for a single dosimeter, using 36 reduces the overall statistical uncertainty for a particular irradiation condition to about 1 to 2% and gives the required statistical uncertainty of about 2 to 3% for the on-phantom to free-in-air ratio. In most cases, this is the dominant uncertainty since that in the irradiation timing is small, and uncertainties in source output and anisotropy cancel out when taking ratios of responses.

3.2 Measurements for PADC track-etch plastic dosimeters type P1

The PADC track-etch plastic used for neutron dosimetry is obtained as large sheets from which a fixed number of sensor elements are cut. In view of the large number of dosimeters needed for this exercise, four separate sheets of plastic had to be used. Different sheets may not be completely identical in terms of their sensitivity or the number of ‘background’ events inherent in the un-irradiated plastic. Services usually have quality assurance procedures to test sheets and reject any which do not conform to their quality criteria. Even with these checks some differences between sheets can still occur which could mask the phantom backscatter effects if different sheets are used for on-phantom and free-in-air irradiations. To avoid this potential problem, measurements for each source and phantom combination were performed with dosimeters from each sheet and the ratios for different sheets derived separately. Thus, for example, responses to ^{252}Cf neutrons were determined (i) free-in-air, (ii) on the ICRU PMMA phantom, and (iii) on the ISO water phantom, using 9 dosimeters from each of the four sheets making 36 for each irradiation condition, and 108 in total. Similarly, 108 dosimeters were irradiated with $^{241}\text{Am-Be}$ neutrons.

The results for the PADC track-etch plastic dosimeter set P1 are presented in Figure 2 which is divided into four parts to show the results for the two sources and the two phantoms separately. The quantity plotted is the ratio of the on-phantom to free-in-air fluence responses, and values are given separately for the four sheets of PADC plastic from which the sensor elements were cut. Table 1 lists the actual values for the ratios. Uncertainties for particular sheets of plastic, under particular irradiation conditions, were derived simply from the spread of the results. The standard errors for the on-phantom data and the free-in-air data were derived separately and the uncertainty in the ratio obtained by combining these in quadrature. When calculating mean values for several sheets, for a particular irradiation condition, the uncertainty was derived in the same way, i.e., uncertainties for the average of all the on-phantom and for the average of all the free-in-air responses were calculated and then combined in quadrature to give the uncertainty on the ratio. All uncertainties quoted in this

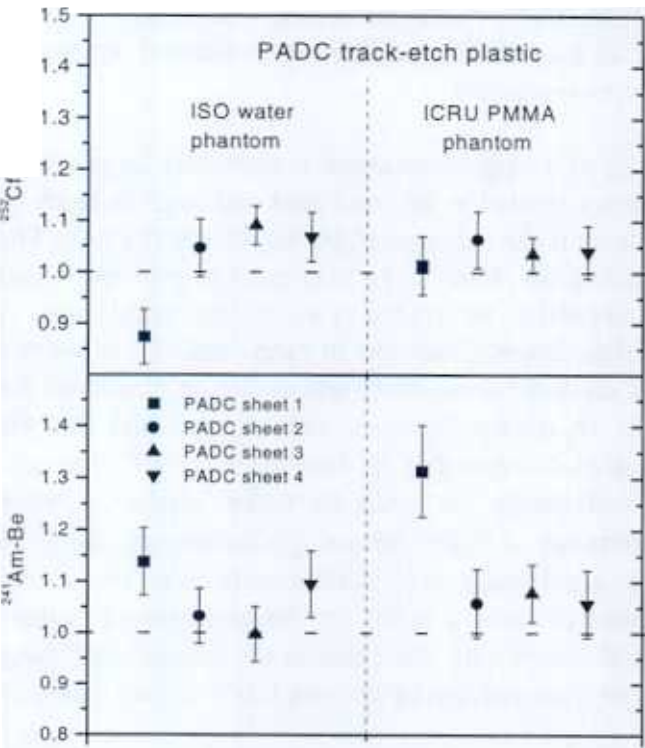


Figure 2. On-phantom to free-in-air response ratios for irradiation of PADC track-etch plastic personal dosimeter set P1 on an ISO water phantom or an ICRU PMMA phantom with either ²⁴¹Am-Be or ²⁵²Cf neutrons.

report are estimates of ‘standard (1σ) uncertainties’ representing a confidence level of approximately 67%.

From Figure 2 it can be seen that, within the uncertainties, the ratios for sheets 2, 3, and 4 are in excellent agreement and the increased response due to backscatter appears to be of the order of 5 to 6% on average for both sources and both phantoms. The results for sheet 1 are rather variable. For ²⁵²Cf neutrons and the ISO phantom the on-phantom response is almost 13% less than the free-in-air response, while for ²⁴¹Am-Be neutrons and the ICRU phantom the response to backscatter for sheet 1 is almost 4σ greater than that for the other three sheets. From the table it can be seen that the average ratio for both sources and both phantoms, when all four sheets are used, is almost identical to the value obtained if only sheets 2, 3, and 4 are used.

Nevertheless, after consultation with the dosimetry service, it was decided that the results for sheet 1 were questionable and they were therefore excluded from the final results.

Table 1. On-phantom to free-in-air ratios for PADC track-etch plastic dosimeters of type P1

PADC plastic sheet number	Neutron Source			
	²⁵² Cf		²⁴¹ Am-Be	
	Phantom		Phantom	
	ISO	ICRU	ISO	ICRU
1	0.874 ± 0.054	1.014 ± 0.057	1.138 ± 0.065	1.313 ± 0.088
2	1.047 ± 0.056	1.064 ± 0.055	1.033 ± 0.054	1.058 ± 0.067
3	1.091 ± 0.038	1.035 ± 0.034	0.997 ± 0.054	1.078 ± 0.056
4	1.068 ± 0.048	1.040 ± 0.051	1.095 ± 0.064	1.057 ± 0.066
Means from all four sheets	1.020 ± 0.029	1.038 ± 0.024	1.064 ± 0.030	1.124 ± 0.037
	1.029 ± 0.027		1.094 ± 0.033	
	1.062 ± 0.018			
Means from sheets 2, 3, and 4	1.069 ± 0.027	1.046 ± 0.027	1.041 ± 0.033	1.065 ± 0.036
	1.057 ± 0.026		1.053 ± 0.036	
	1.055 ± 0.019			

3.3 Measurements for NTA film dosimeters type N1

NTA film dosimeters suffer from fogging by X and γ rays which make it difficult to see small neutron induced tracks. For this reason a thin sheet of lead is usually incorporated in the dosimeter to shield the film. In most cases, however, the lead is placed at the front of the dosimeter, shielding the sensor from any directly incident photons, but not from any radiation incident from the back, e.g. photons backscattered from an individual wearing the dosimeter or from a phantom. The photon dose equivalent rate from a ^{252}Cf source is only about 10% of that from the neutrons, but $^{241}\text{Am-Be}$ sources produce a photon dose equivalent rate comparable to the neutron value. When comparing responses on-phantom to free-in-air the dosimeters are all subject to the same incident photon irradiation, but in the case of the on-phantom dosimeters they are also subjected to backscattered photon radiation, which may induce additional fogging, which could in theory mask some small tracks. To investigate this possibility all the NTA film measurements with an $^{241}\text{Am-Be}$ source were performed once with the source unshielded, and once with a 2 mm thick lead shield over the source capsule and the results compared.

NTA film neutron dosimeters are read manually by many UK dosimetry services with the reader counting tracks in a well defined area on the sensor. This introduces an element of subjectivity into the results, and in an attempt to quantify this all the films from dosimeter type N1 were read by two different readers and the on-phantom to free-in-air ratios reported separately.

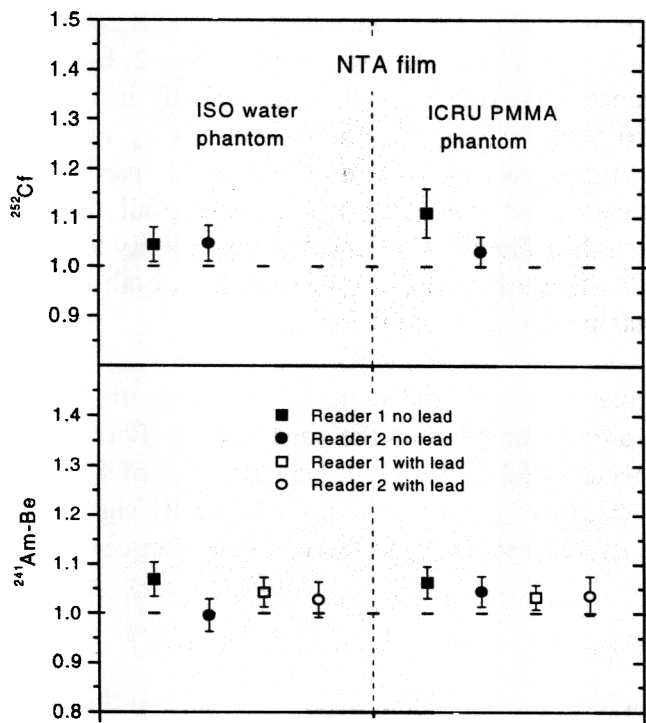


Figure 3. On-phantom to free-in-air response ratios for irradiation of NTA film personal dosimeters set N1 on an ISO water phantom or an ICRU PMMA phantom with either $^{241}\text{Am-Be}$ or ^{252}Cf neutrons.

All the results for NTA film type N1 are plotted in Figure 3, where once again the figure is divided into four parts to show the results for different sources and phantoms separately. Results for the different readers are also plotted separately as are those with and without the lead shield around the $^{241}\text{Am-Be}$ source. The measured values and uncertainties for the ratios are presented in Table 2.

Comparing first the results for $^{241}\text{Am-Be}$ neutrons with and without the lead shield: the ratios measured are, within the uncertainties, the same in both cases. In fact, the ratio measured without lead is slightly larger than with lead, although the difference is not statistically significant. This result is counter to what would be expected if

fogging due to photons backscattered from the phantom was masking small neutron tracks. It would thus appear that this effect is unimportant, at least for the two readers concerned. It could, however, become more significant for dosimeters closer to the source, or for higher dose levels.

Table 2. On-phantom to free-in-air ratios for NTA film dosimeters of type N1

Reader, and whether lead shield was used	Neutron Source			
	²⁵² Cf		²⁴¹ Am-Be	
	Phantom		Phantom	
	ISO	ICRU	ISO	ICRU
Reader 1 no lead	1.044 ± 0.032	1.109 ± 0.034	1.069 ± 0.034	1.063 ± 0.031
Reader 2 no lead	1.047 ± 0.029	1.030 ± 0.029	0.996 ± 0.030	1.045 ± 0.028
Reader 1 with lead			1.043 ± 0.028	1.032 ± 0.025
Reader 2 with lead			1.028 ± 0.029	1.036 ± 0.034
Mean values	1.045 ± 0.021	1.070 ± 0.022	1.034 ± 0.015	1.044 ± 0.014
	1.058 ± 0.018		1.039 ± 0.013	
	1.046 ± 0.011			

Considering next the ratios as determined by the two readers: taking results for both sources and both phantoms the mean ratio was 1.060 for reader 1 and 1.030 for reader 2. These values are slightly more than one standard uncertainty from the mean reflecting the possibility of some slight differences in the way small tracks are interpreted - backscattered tracks are likely to be on average shorter. Certainly reader 1 always saw more tracks than reader 2, by about 10% on average, but because this difference was roughly the same for all irradiation conditions, the ratios determined by the two readers agree reasonably well, being only 3% different. The subjectivity introduced by manual evaluation of the tracks is all part of the dosimeter reading process, and the final mean ratios given in Table 2 include all the data from both readers. The uncertainties in these ratios therefore reflect this subjectivity to some extent. For the service in question, when a dosimeter records a significant dose, both readers are required to read the dosimeter so that systematic effects are removed.

Looking finally at the mean values for particular phantoms and sources: the mean ratio for the two sources are shown in Table 2, and these are identical within the uncertainties. For the two phantoms the mean ratios were: 1.038 (ISO) and 1.052 (ICRU) with uncertainties of 1 to 2%. Thus, as with the PADC track-etch dosimeters, there appear to be no statistically significant differences for NTA film between the backscatter responses for either of the sources or the phantoms.

3.4 Summary for dosimeter types P1 and N1

Taking a mean of all the measured ratios (including only PADC sheets 2, 3, and 4) the value for the on-phantom to free-in-air ratio was measured to be (1.050 ± 0.006), i.e., the backscatter adds on average 5% to the reading. Any real differences between the different dosimeter types, the different neutron sources, and the different phantoms are masked by the uncertainties.

4. MEASUREMENTS OF SEPARATION AND EDGE EFFECTS

4.1 Initial considerations

The measurements with dosimeter types P1 and N1 involved a total of 540 dosimeters and associated controls. The net result was a measurement of a value of 5% for the increase in dosimeter response when on-phantom, with a 12% uncertainty in the value for this percentage increase. Any experimental attempt to measure the decrease in this value as a function of separation distance between the dosimeter and the phantom face, or as a function of the proximity to the edge of the front face would involve irradiating and processing an enormous number of dosimeters and, in view of the uncertainties in individual dosimeter readings, would be of little practical value. Because of these considerations, measurements of separation and edge effects were limited to an attempt to see if these effects were significant in 'worst case' scenarios.

When dosimeters are mounted on a phantom, the mounting method may introduce a small gap between the dosimeter and the phantom face. There is no reason, however, why the gap cannot very easily be kept below about 10 mm. Measurements to investigate the sensitivity to dosimeter-phantom separation were therefore performed at a single distance of 11 mm - the exact distance was determined by the particular mounting arrangements employed. If no reduction in the backscatter response can be detected at this distance, then the effects due to the small gaps which occur in normal mounting arrangements are unimportant.

Adopting a similar approach for edge effects, a series of measurements was made for dosimeters with one edge flush with the edge of the phantom front face, and also for dosimeters positioned at the corners. These were compared to the readings for dosimeters at the centre of the phantom face.

4.2 Separation effects

Measurements of separation effects were made with the same, type P1, PADC track-etch dosimeters as used for the initial set of backscatter response measurements. Three irradiations were performed in all, each one using the arrangement of two ISO water phantoms mounted facing each other with the source between them. One of the phantoms was arranged with its front face 75 cm from the source, and the dosimeters were attached directly to this face. The second phantom had small lightweight brackets attached to the front face and dosimeters were hung from these with their rear surfaces 11 mm from the phantom face. The distance for this phantom was set so that the rear plane of the dosimeter array was 75 cm from the source, i.e. both sets of dosimeters were subjected to the same incident neutron fluence from the source, but for one set the phantom surface was set back by 11 mm. For both phantoms the dosimeters were arranged in a 4 row by 3 column array contained within an area of 10 x 10 cm at the centre of the phantom face. For each irradiation 12 dosimeters were thus irradiated flush with the phantom face and 12 separated by 11 mm making a total of 36 flush and 36 separated if the three irradiations are aggregated.

As for the previously described measurements, the irradiations were performed in the low-scatter area, the dosimeters returned to the service for processing and reading, and the readings sent to NPL. Fluence responses were calculated for each dosimeter, correcting the fluence values for the variation introduced by the fact that the dosimeters are distributed in a plane, and average values were derived for the ratio of the response of the dosimeters

mounted flush to the phantom surface to that for those separated by 11 mm. If the backscatter fluence falls off rapidly with separation distance between the dosimeter and the phantom face, then this ratio should be greater than one.

The results are presented in Table 3. The uncertainties quoted have been derived solely from the spread of the results. For an individual irradiation, this involved a quadratic combination of uncertainties obtained from the spread of the 12 flush mounted dosimeters and from the spread of the 12 separated ones. Similarly, for the final mean value, the uncertainties added in quadrature were derived from the spreads of the two sets of 36 data values.

Table 3. Ratios of responses for type P1 dosimeters mounted flush to the ISO phantom surface to responses when mounted with an 11 mm separation between phantom face and dosimeters

Irradiation	Flush to separated ratio
1	1.048 ± 0.037
2	0.986 ± 0.029
3	0.953 ± 0.055
Mean	0.995 ± 0.024

The ratios from the three irradiations are consistent with each other, within the uncertainties, and the mean value of 0.995 ± 0.024 is consistent with the ratio being unity. This implies that the backscatter response is the same with the dosimeters 11 mm from the phantom face as when the dosimeters are attached directly. It would thus appear that small gaps between the dosimeters and the phantom face are not significant.

It is important to note that in the above measurements the distance which was the same for both the flush and separated arrangements was that between the source and the rear plane of the dosimeter arrays, and not between the source and the front face of the phantom. In the terminology of current ISO standards⁽⁵⁾ the *reference point of the dosimeter*, which should be placed at the *point of test* in the field where the calibration quantity, fluence or dose equivalent, is known, was taken as being on the rear surface of the dosimeter. For flush mounting of the dosimeter on the phantom this, of course, coincides with a point on the phantom front face.

The above convention represents a practical approach for these types of dosimeters, for which the majority of the reading is due to the incident neutron fluence from the source, in calibration situations where a point source is used, for which the fluence varies as the square of the distance. It is perhaps a surprising convention to define the point at which the fluence is calculated in terms of the source-to-dosimeter distance in view of the fact that a personal dosimeter should in principle measure the dose equivalent at 10 mm below the surface of a phantom. It is, however, a reflection of the problems that arise because the quantity personal dose equivalent is defined in terms of a plane parallel beam striking the phantom, whereas the calibration situation involves a divergent beam from a point source.

4.3 Edge effects

Measurements of edge effects were made with the same type P1 PADC track-etch dosimeters. The 'worst case' scenario for edge effects is that the dosimeters are positioned at the corners of the front face of the phantom. At these locations the dosimeters would be expected, just from simple geometrical considerations, to receive up to 75% less backscatter radiation than a dosimeter at the centre of the phantom face. Only four dosimeters can, of course, be irradiated at the corners during a single irradiation with a single phantom.

Dosimeters can be placed around the edge of the phantom face at places other than the corners, and for the present measurements a dosimeter was also placed at the mid point of each edge. Again from simple geometrical considerations, these would be expected to receive up to 50% less backscattered radiation than a dosimeter at the centre of the phantom.

Two irradiations were performed, using two ISO phantoms in both cases. Six dosimeters were positioned near the centre of a phantom face in an approximately 12 x 9 cm rectangular arrangement, and eight other dosimeters were arranged around the outside of the face, one at each corner, and one at the centre point along each edge. These dosimeters were mounted flush to the edge but still entirely on the phantom surface, i.e. they did not overhang the edges. Source to centre of phantom face distances were set to 75 cm.

As in the separation effect measurements, the dosimeters were returned to the services to be read and the readings, in terms of pits per unit area, were sent to NPL. From this information the fluence responses of all the irradiated dosimeters were derived. In all cases the fluence was corrected for the increased source to dosimeter distance for those dosimeters positioned away from the centre of the phantom face, and also for the reduced area presented by these dosimeters because they are not orientated exactly normal to the direction of the neutrons incident from the source. For dosimeters at the corners the final quantity calculated was the ratio of the average response for these dosimeters to the average response for dosimeters at the centre. A similar ratio was calculated for the dosimeters at the mid points of the edges. The ratios for the two phantoms and two irradiations were consistent within the uncertainties and the final overall average results were: corners (0.935 ± 0.049), and mid point of edges (0.962 ± 0.039).

The measurements and the results highlight the difficulties of determining small effects with dosimeters which exhibit uncertainties of about 10%. For the ratio involving the mid points of the edges the result is compatible, within the uncertainties, with the value of 0.975 which would be expected for a 50% reduction in the backscattered radiation and taking the response to backscatter to be 5%. Because of the size of the uncertainty in the average ratio, however, the result is also compatible with the backscatter response at the edges being anywhere between 0% and 8% at the 67% confidence level. For the corner to middle ratio the value is smaller at 0.935, indicating that there is probably some reduction in the reading for dosimeters in this position compared to those at the middle. Whether this is due to reduced backscatter radiation, or angular effects in the dosimeter response not allowed for by the correction of the fluence for the non-normal area presented by the dosimeter, is not clear.

It is difficult to draw any hard and fast conclusions from the present edge-effect measurements, however, it would appear wise to adhere to the general rule-of-thumb which has been adopted in several calibration laboratories not to place dosimeters within 5 cm of the edge of the phantom front face.

5. MEASUREMENTS FOR A RANGE OF DOSIMETRY SERVICES

5.1 Initial considerations

The preliminary measurements with dosimeter types P1 and N1 showed that, within the experimental uncertainties, the response of both types of dosimeters was the same for both ²⁴¹Am-Be and ²⁵²Cf radionuclide sources and for ISO and ICRU phantoms. In view of this, the measurements with other dosimeter types from the remaining UK dosimetry services were all performed with just one type of neutron source, ²⁵²Cf, and one type of phantom, that recommended by ISO. The choice of source was made to minimise the irradiation times since the largest ²⁵²Cf source available has a higher neutron output than the largest ²⁴¹Am-Be source - even so each irradiation was of the order of three hours or more. The ISO phantom was chosen because it is expected that, since it has almost ideal backscatter characteristics when used for photons, it will be designated the standard phantom for both neutron and photon calibrations in future.

Measurements were made for five different types of dosimeters, and these were provided from three different services. (Two services operate two different PADC track-etch dosimeters.) Four of the five different types were based on PADC plastic, these are designated P2 to P5, and one, designated N2, was based on NTA film.

5.2 Experimental measurements

The procedures for the irradiations, the reading of the dosimeters, and the analysis of the data were the same as those described earlier for dosimeter types P1 and N1.

Three of the dosimeter types had clips on their rear surfaces which are used for attaching the dosimeter to the clothing of the wearer. One of these was a small metal clip whose presence

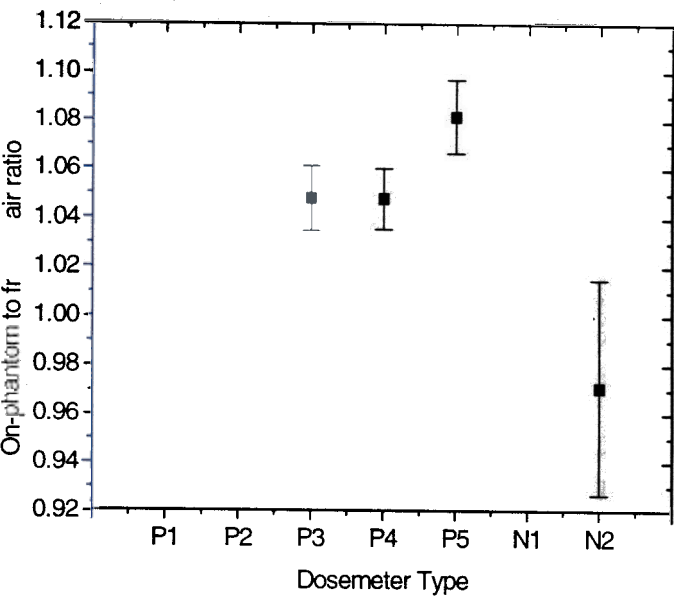


Figure 4. On-phantom (ISO water) to free-in-air ratios for dosimeters from the various services for neutrons from a ²⁵²Cf source.

meant that the rear face of the dosimeter was separated from the phantom face by 7 mm. For both free-in-air and on-phantom irradiations the fluence was calculated at the rear surface of this dosimeter, cf., the discussion of the earlier measurements of sensitivity to the separation between the dosimeter and the phantom face. The other two had plastic clips. One of these only introduced a 2 mm gap between phantom and dosimeter, but again the fluences were calculated for the rear surface of the dosimeters. The clip on the third device was an integral part of the dosimeter itself in that the sensor was located in the clip and so for

this device all fluences were calculated for the rear surface of the clip where it touches the phantom face.

Two of the track-etch dosimeter types used sensor elements cut from different sheets of PADC plastic. The results for individual sheets were kept separate in the calculation of on-phantom to free-in-air ratios to investigate any possible inter-sheet differences. These were, however, averaged when quoting the final results.

All the results are presented in Table 4 and plotted in Figure 4. The uncertainty quoted for each type of dosimeter was calculated by combining in quadrature, the standard error of the mean of all the free-in-air responses, with the standard error of the mean of all the on-phantom responses. Data for Types P1 and N1 are also included for completeness, and some details are provided about the way in which the various types of dosimeters are processed. Brief summaries are given below of the experimental arrangements for the various dosimeter types.

Table 4. Results for all types of fast neutron dosimeters available from UK dosimetry services for ²⁵²Cf neutrons and the ISO water phantom.

Dosimeter types	PADC track-etch plastic					NTA film	
	P1	P2	P3	P4	P5	N1	N2
Total no. irradiated	72	100	100	76	38	72	72
Processing details	Chemical pre-etch, electro-chemical etch, automated counting	Chemical etch, no pre-etch, manual counting	Chemical etch, no pre-etch, manual counting	Two stage chemical etch, automated counting	Two stage chemical etch, automated counting	Several areas on film read manually using a microscope	Several areas on film read manually using a microscope
On-phantom to free-in-air ratio	1.069 ± 0.027	1.028 ± 0.020	1.048 ± 0.013	1.048 ± 0.012	1.082 ± 0.015	1.045 ± 0.021	0.971 ± 0.044

5.2.1 Type P2 dosimeters

Altogether, 50 dosimeters were irradiated free-in-air and 50 on-phantom with 12 or 13 dosimeters per phantom. Two irradiations were performed to obtain the on-phantom data with two phantoms per irradiation. Each dosimeter contained just one sensor element. No information was provided to identify the sheet of plastic from which particular elements had been cut since the service believes that inter-sheet differences are not significant for the plastic they use. The final uncertainty in the on-phantom to free-in-air ratio was about 2%.

5.2.2 Type P3 dosimeters

Exactly the same arrangement for numbers of dosimeters irradiated was employed as for the Type P2 dosimeters. Again there was one sensor element per dosimeter, and no information was given on the sheets from which the sensors had been obtained. The calculated statistical uncertainty was a little smaller at 1.3%.

5.2.3 Type P4 dosemeters

These dosemeters were physically somewhat larger than the previous two types and so only 9 could be mounted on-phantom at one time while keeping the dosemeters within a 10 x 10 cm square at the centre of the phantom face and still retaining a reasonable gap between them. A total of 40 dosemeters were irradiated free-in-air and 36 on-phantom. Each dosemeter, however, contained two sensor elements, both of which were read. All the sensor elements were taken from just two sheets of PADC plastic (half from each sheet), and the data for the two sheets were kept separate until the final stages of the analysis. The values for the two sheets, however, agreed well and the value shown in Table 4 is the average of the two.

5.2.4 Type P5 dosemeters

Only 38 dosemeters of this type were used, 20 free-in-air, and 18 on-phantom with 9 on each of the two phantoms used. This type of dosemeter, however, contains three sensor elements, all three of which were read, which helped reduce statistical uncertainties. Again the sensors were taken from two different sheets of PADC plastic and the data for the sheets kept separate. There was a difference of about 7% between the results for the two sheets with statistical uncertainties of the order of 2% on the results for individual sheets. Since this was a little outside the expected variation, some effort was expended in examining possible causes for the difference. The dosemeter readings were re-examined and the irradiation arrangements reviewed. No explanation could be found for the differences. All the dosemeters irradiated free-in-air were exposed in a single irradiation. Likewise for the on-phantom irradiation, where the dosemeters from the two sheets were evenly divided between the two phantoms. Thus the dose delivery arrangements were identical for dosemeters from both sheets. It is possible that the discrepancy is due to genuine differences between the two sheets. The final value quoted in Table 4 is a mean of the data from the two sheets.

5.2.5 Type N2 dosemeters

These dosemeters were identical in appearance to type N1. They consisted of a single sample of NTA film within a holder which contained a thin layer of lead to provide some photon shielding for the front face of the film. A total of 36 dosemeters were irradiated free-in-air, and 36 on-phantom during two irradiations, with 9 dosemeters on each of the two phantoms used. Data for the two on-phantom irradiations and the two different phantoms were kept separate when determining on-phantom to free-in-air ratios to investigate any possible systematic effects, but all the results were consistent within the uncertainties. The final overall result is, however, a ratio which is less than one, although the uncertainty, at just over 4%, is somewhat larger than for the other dosemeter types. Careful re-checking of the data and irradiation arrangements failed to reveal any errors in the results.

5.3 Review of the results

The on-phantom to free-in-air ratios presented in Table 4 represent a reasonably consistent set of results. Taking a simple unweighted mean and the standard error on that mean, gives an average ratio of (1.042 ± 0.013) . The standard error for a single reading is 0.036, which is a little greater than the uncertainties for most of the results. The individual uncertainties are, however, rather different in size, the largest being about four times the smallest, and so a better estimate of the backscatter effect is probably obtained by taking a weighted mean. This approach gives an average value of (1.051 ± 0.008) , i.e. a $(5.1 \pm 0.8\%)$ effect.

Two of the results, the smallest and the largest, warrant closer scrutiny.

The smallest measured ratio, that for dosimeter type N2, is (0.971 ± 0.044) . Any attempt to measure an effect as small as the added response in a personal dosimeter due to phantom backscatter, which is of the order of 4 to 5%, with uncertainties on measurements for particular types of dosimeters which range from about 1% to over 4%, is likely, simply from statistical considerations, to throw up one or more results which 'go the wrong way', i.e. where the measured effect is negative. Thus, although the result for type N2 dosimeters is a little surprising, it is by no means completely outside the bounds of statistical variations.

The largest result, a value of 1.082 for dosimeter type P5, is not as far from the mean as the smallest result, but still warrants some discussion because the dosimeter type is a little different to all the others. Each dosimeter of type P5 contains three sensor elements. These are not orientated parallel to the flat rear surface of the dosimeter, and hence the elements are not parallel to the face of the phantom. Much of the backscattered radiation from a phantom is emitted at acute angles relative to the phantom face and hence strikes the sensor elements in most dosimeters at acute angles. At such angles the sensitivity of the sensor is much reduced. Since this is not the case for type P5 dosimeters some enhancement of the response to backscatter might be expected.

6. CALCULATIONS

6.1 Modelling the PADC dosimeter response to backscattered neutrons

In order to model the response of a personal dosimeter in a multi-energy and multi-directional radiation field, such as that at the surface of a phantom, it is necessary to know the angular response of that dosimeter to radiations of all energies. Unfortunately, deriving this information is not straight forward. The best way to determine the angular response of any dosimeter is to measure it. However, even at a single energy this would require a great number of dosimeters to be irradiated to cover the required range of angles and to get reasonable statistics. Furthermore, measurements would need to be performed over the full range of neutron energies for which the dosimeters respond. All this would be both time consuming and expensive. The alternative to measuring the angular response is to calculate it. However, given the complexity of the processes involved in pit formation, the subjectivity in the reading of pits, and all the other uncertain elements, this is not at present feasible.

Nevertheless, some information is available at the NRPB where an energy-angle response for a PADC dosimeter has been derived at four angles and sixteen energies using a combination of calculation and experiment⁽¹⁶⁾, enabling calculations of phantom backscatter responses to be attempted. It is known, however, that these responses are not perfect and any calculations performed using them will have to be interpreted accordingly.

The Monte Carlo neutron transport code MCNP version 4A⁽¹⁷⁾ was used to model a 30 x 30 x 15 cm PMMA phantom (density 1.19 g cm^{-3} , composition $\text{C}_5\text{H}_8\text{O}_2$), irradiated by a point (infinitesimally small) ^{252}Cf neutron source, placed 75 cm away from the centre of the front face in vacuum. A 'point detector' was placed 1 mm above the centre of the front face of the phantom (i.e. 74.9 cm from the source), which automatically tallied the total and uncollided fluences.

In the parlance of MCNP, a point detector provides a deterministic estimate, derived from the current event point, of the fluence at a point in space. Contributions are made at all source or

collision events throughout the random walk of a neutron. The point detector approach basically provides a measure of the probability of any event producing a neutron travelling in the direction of the point detector, and of that neutron NOT colliding before reaching this point. This type of estimator is particularly useful for places where the fluence may be changing rapidly in which case an average fluence over a volume may not be representative of that at a particular point in that volume.

In order to ascertain the angular distribution, the phantom was nominally divided into a set of coaxial conic annuli with 10° angles, all meeting at the centre of the front face. These were then 'tagged' in the model so that MCNP recorded the fluence contributions from each conic section to the total at the centre of the front face.

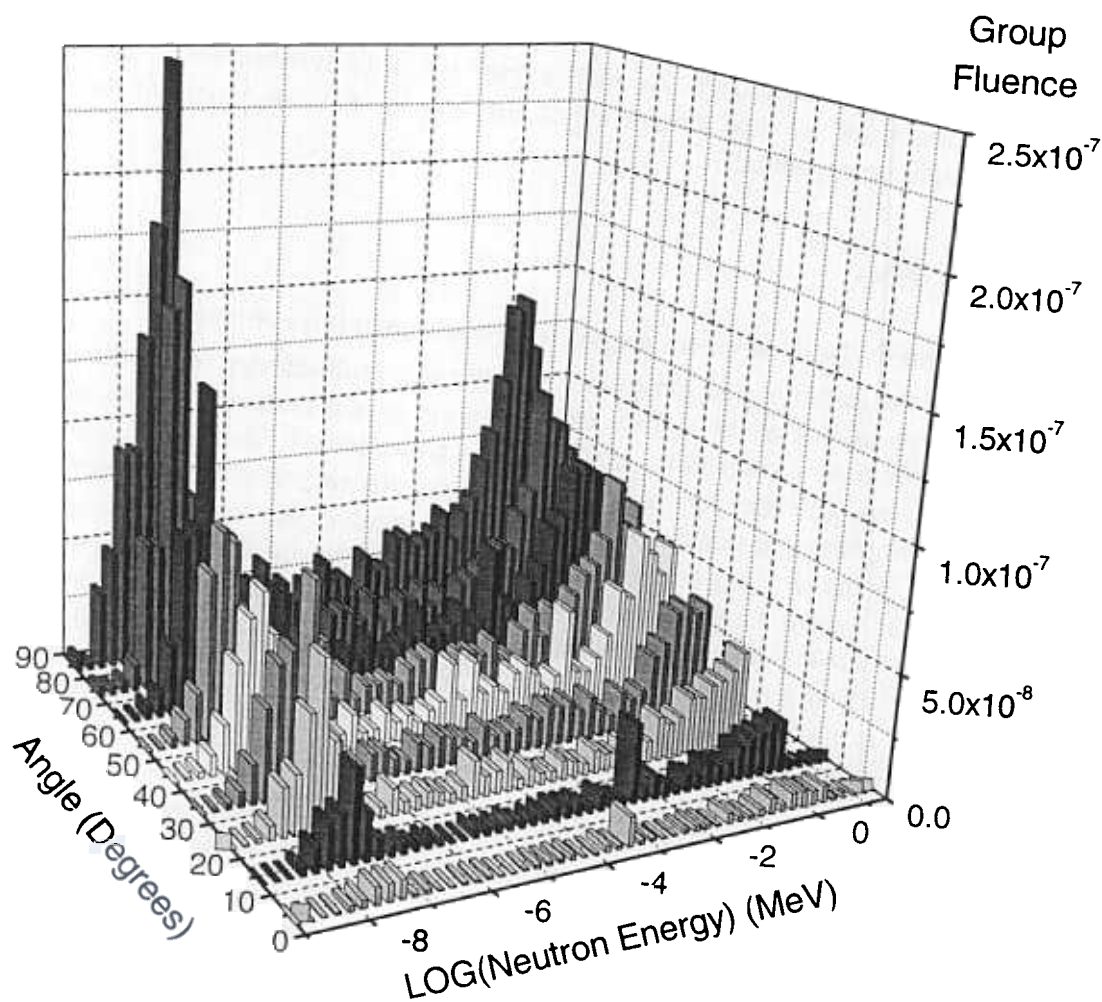


Figure 5. Energy and angle distribution of backscattered fluences from a PMMA phantom irradiated by ^{252}Cf neutrons.

The resulting fluence distribution is shown in terms of energy and angle in Figure 5. It shows that the phantom backscatter fluence contribution increases with increasing angle, which simply reflects the larger solid angle subtended. The energy distribution of the fluence shows a substantial thermal component and a significant number of intermediate energy neutrons. The

total / direct fluence ratio was found to be (1.72 ± 0.02) . The uncertainty is purely statistical from the Monte Carlo simulation.

In order to get values for the dosimeter response, R , at the energies and angles used in the model to tally the fluence, the angular data provided by NRPB was fitted using the expression:

$$R = A + B \cos \theta.$$

Values at intermediate energies were ascertained using logarithmic interpolation.

The contribution to the PADC dosimeter response in terms of energy and angle can be seen in Figure 6. This demonstrates that virtually the entire response is caused by neutrons of energies greater than 100 keV, and that the most important angles are between 30° and 60° .

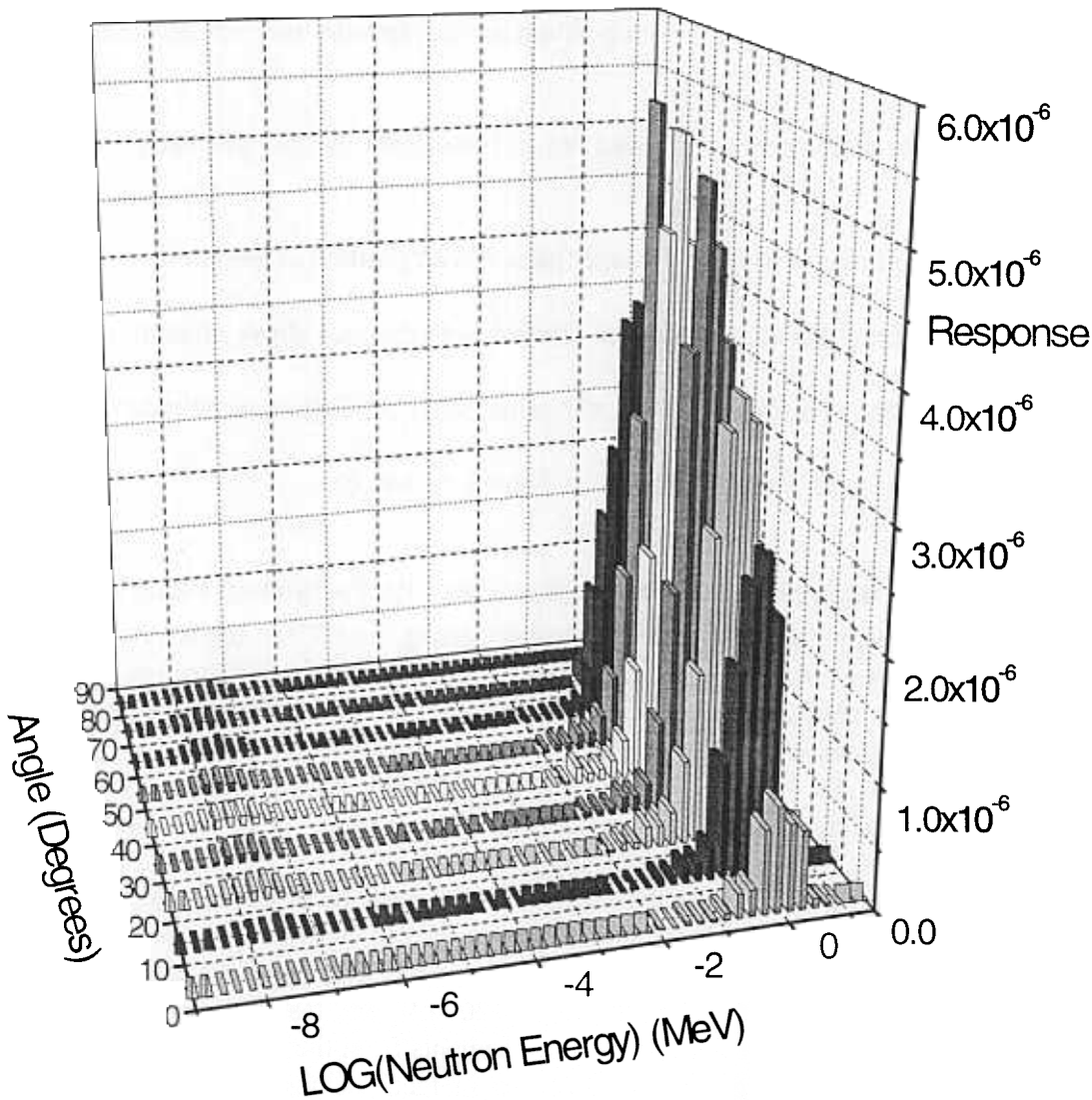


Figure 6. Plot of backscatter contribution to the PADC dosimeter response from a PMMA phantom irradiated by ^{252}Cf neutrons.

The total backscattered response amounts to roughly 9% of the direct response, i.e., a backscatter to direct response ratio of 1.09. This is somewhat higher than the experimental value, but given the uncertainties in both the calculational and experimental approaches, it is fair agreement. It may imply that the angular response of the dosimeter is somewhat different to that used, or that, for some parts of the energy range, the response is lower than assumed.

Similar calculations performed for a ^{241}Am -Be source instead of a ^{252}Cf source resulted in a slightly larger backscatter factor of 1.11.

In order to achieve a closer match between calculation and experiment, it would be necessary to characterise the response of the personal dosimeters in terms of energy and angle in considerably more detail.

Although the agreement between calculation and experiment is fair at best, this does not preclude calculations from providing worthwhile information, especially for the investigation of the variation in fluence components with position on the phantom face and separation from this face.

Further calculations were therefore carried out to investigate various geometric effects. These were:

- the variation in backscatter fluence fraction with position on phantom,
- the variation in backscatter fluence fraction with distance above phantom,
- the variation in backscatter fluence fraction with composition of phantom,
- the effect of a second phantom 75 cm behind the source.

6.2 The Variation in Backscatter Fluence Fraction with Position on Phantom

This effect was investigated for a PMMA phantom using an MCNP model that used a point source of ^{252}Cf neutrons at the origin of the co-ordinate system (0, 0, 0) to irradiate a PMMA phantom with the centre of its front face set to (75, 0, 0). Point detectors were located just above the front face of the phantom at the following positions: (74.9, 0, 0), (74.9, 5, 0), (74.9, 10, 0), (74.9, 12, 0), (74.9, 13, 0), (74.9, 14, 0), (74.9, 5, 5), (74.9, 10, 10), (74.9, 12, 12), (74.9, 13, 13) and (74.9, 14, 14). The results are shown in Table 5.

The backscatter fluence falls by roughly 7% from 0 to 10 cm, then falls by a similar amount in the next 2 cm, but falls away more rapidly beyond this point. This can be seen more clearly in Figure 7, which shows the breakpoint to be between 10 and 12 cm. However, if the fluence spectra at these points are broken into slow ($E_n < 126$ keV) and fast ($E_n > 126$ keV) regions, it can be seen that the variation in fluence for displacements from the centre of less than 10 cm is caused entirely by the slow component and that, in fact, the fast component is essentially constant for displacements up to 12 cm. This is significant in terms of the responses of both PADC and NTA based personal dosimeter, which have higher sensitivities at higher neutron energies, as explained in section 1. The backscatter contribution at (74.9, 14, 0) is approximately half that at the centre, and at (74.9, 14, 14) is roughly one quarter. This is consistent with the amount of scattering material in the vicinity of the detector.

Table 5. Variation in backscatter fraction with position on phantom surface.

Detector Position	Total Fluence (cm ⁻²)	Direct Fluence* (cm ⁻²)	Ratio Total/Direct
(74.9, 0, 0)	2.454x10 ⁻⁵ (±1.7%)	1.418x10 ⁻⁵	1.731 ± 0.029
(74.9, 5, 0)	2.353x10 ⁻⁵ (±1.0%)	1.412x10 ⁻⁵	1.666 ± 0.017
(74.9, 10, 0)	2.256x10 ⁻⁵ (±1.4%)	1.394x10 ⁻⁵	1.618 ± 0.023
(74.9, 12, 0)	2.108x10 ⁻⁵ (±1.3%)	1.383x10 ⁻⁵	1.524 ± 0.020
(74.9, 13, 0)	1.978x10 ⁻⁵ (±0.9%)	1.377x10 ⁻⁵	1.436 ± 0.013
(74.9, 14, 0)	1.863x10 ⁻⁵ (±1.8%)	1.371x10 ⁻⁵	1.359 ± 0.024
(74.9, 5, 5)	2.379x10 ⁻⁵ (±1.2%)	1.406x10 ⁻⁵	1.692 ± 0.020
(74.9, 10, 10)	2.132x10 ⁻⁵ (±1.6%)	1.370x10 ⁻⁵	1.556 ± 0.025
(74.9, 12, 12)	1.879x10 ⁻⁵ (±0.8%)	1.349x10 ⁻⁵	1.393 ± 0.011
(74.9, 13, 13)	1.769x10 ⁻⁵ (±0.8%)	1.338x10 ⁻⁵	1.322 ± 0.011
(74.9, 14, 14)	1.618x10 ⁻⁵ (±1.5%)	1.326x10 ⁻⁵	1.220 ± 0.018

- The direct fluence is calculated simply from $(4\pi r^2)^{-1}$ where r is the source to point detector distance. It is assumed to have zero uncertainty.

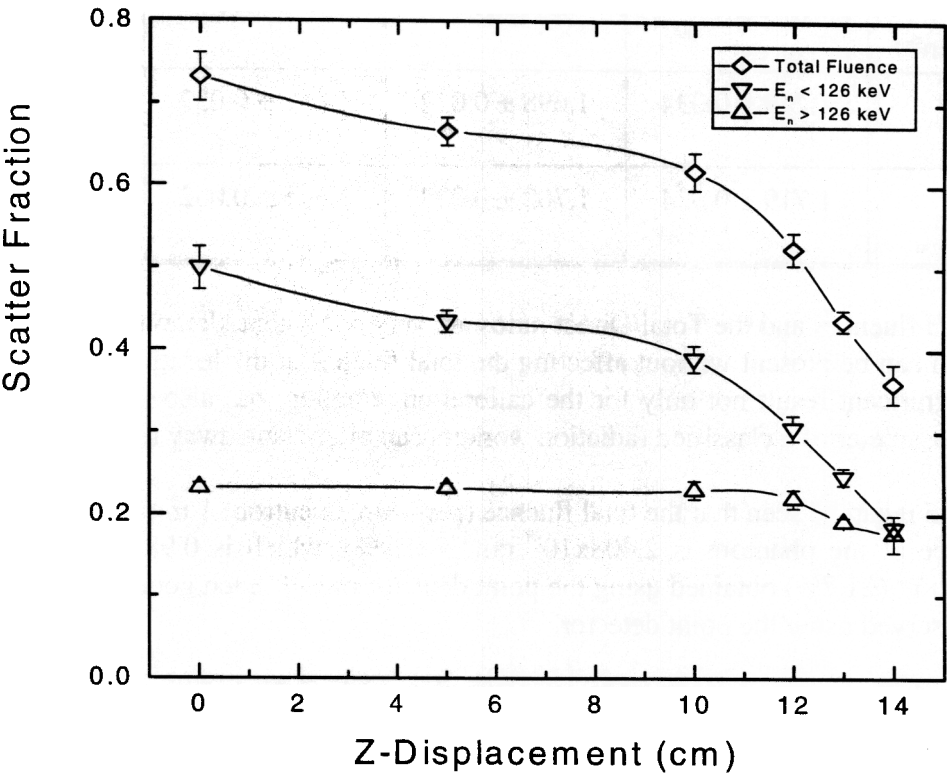


Figure 7. Variation in fractional scatter fluence with Z-Displacement for irradiation of a PMMA phantom with ²⁵²Cf neutrons at a source to phantom distance of 75 cm.

The 73% fluence backscatter calculated at the centre of the phantom's front face was thought, initially to be unreasonably large. This was checked against the more robust, but less efficient, surface detector to tally the fluence. The results are presented below in the section describing the effect of having a gap between the phantom and the dosimeter.

6.3 The Variation in Backscatter Fluence Fraction with Distance Above Phantom

This effect was investigated for two reasons: firstly, it is not always possible to mount certain designs of personal dosimeter flush against a phantom and secondly, the dosimeters of classified workers can hang away from the body during use.

A ‘surface detector’ was used in this part of the investigation. This provides an estimate of the fluence at a surface. Although a surface estimator, it can be thought of as the limiting case of the cell fluence (track length estimator) when the cell becomes infinitely thin.

Surface detectors of 2 cm diameter were positioned at the centre of the front face of the PMMA phantom and at 1 mm, 5 mm, and 10 mm above the same point. The results are shown in Table 6 below:

Table 6. Variation in backscatter fraction with displacement from phantom surface.

Height above Phantom	0 mm	1 mm	5 mm	10 mm
Total Fluence (cm ⁻²)	2.431x10 ⁻⁵ (±2.0%)	2.408x10 ⁻⁵ (±1.9%)	2.426x10 ⁻⁵ (±1.9%)	2.440x10 ⁻⁵ (±1.8%)
Direct Fluence (4πr ²) ⁻¹ (cm ⁻²)	1.415x10 ⁻⁵	1.418x10 ⁻⁵	1.434x10 ⁻⁵	1.453x10 ⁻⁵
Total / Direct	1.719 ± 0.034	1.698 ± 0.032	1.692 ± 0.032	1.679 ± 0.030
Total / Direct _{75cm}	1.719 ± 0.034	1.702 ± 0.032	1.715 ± 0.032	1.725 ± 0.031

Both the total fluences and the Total/Direct ratios are very consistent, demonstrating that gaps of up to 10 mm can be present without affecting the total fluence at the location of the dosimeter. This is a significant result not only for the calibration situation, but also for the practical one where the dosimeter of a classified radiation workers can often hang away from the body.

From Table 6 it can be seen that the total fluence (per source neutron) 1 mm above the centre of the front face of the phantom is 2.408x10⁻⁵ cm⁻² (±1.9%), which is 0.98 times the value of 2.454x10⁻⁵ cm⁻² (±1.7%) obtained using the point detector model. Such good agreement verifies the value observed using the point detector.

6.4 The Variation in Backscatter Fluence Fraction with Composition of Phantom

The difference in composition between the ISO phantom and the ICRU phantom is sufficiently large that there may be differences in their backscattered fluences. To investigate this, a new model was created. This simply consisted of the ISO water phantom, a point detector 1 mm

above the centre of the front face and a point ^{252}Cf source 74.9 cm from the point detector. This yielded a total fluence of $2.266 \times 10^{-5} \text{ cm}^{-2}$ ($\pm 1.4\%$), which is 0.92 times the value from the equivalent PMMA model. However, this represents a difference in backscattered fluences of 0.83. When this is broken down into $<126 \text{ keV}$ and $>126 \text{ keV}$ sections, this factor remains approximately constant. Above 126 keV : 0.77 ± 0.04 ; below 126 keV : 0.86 ± 0.04 .

However, in terms of the difference in the response of dosimeters on different phantoms, the factor of 0.83 in the backscattered fluence becomes 0.83×0.05 , equal to 0.04, i.e., a difference of only 0.01 between the two, which would not be expected to be seen in the experiments given their statistical uncertainties.

6.5 The Effect of a Second Phantom 75 cm Behind the Source

Given that the on-phantom measurements were performed using two phantoms simultaneously, it was important to assess what effect the presence of a second phantom would have on the results. This was investigated using a model which had a second PMMA phantom 75 cm behind the source (i.e. 150 cm between phantoms). This second phantom was 'tagged' in MCNP so that a separate tally was kept of its contribution to the fluence at the centre of the front face of the first phantom. The results showed that the contribution from the 'tagged' phantom was $5.433 \times 10^{-8} \text{ cm}^{-2}$ ($\pm 3.0\%$), i.e. a mere 0.2% of the fluence recorded at the centre of the front face of the single-phantom model used earlier. The presence of a second phantom was therefore considered to have a negligible effect.

7. SUMMARY AND CONCLUSIONS

The main conclusion of the work is that the increase in fast-neutron personal dosimeter response due to backscattered neutrons from a calibration phantom is about 5%. Within the uncertainties of the various measurements, the increase is the same for both types of dosimeter studied, PADC and NTA, for both types of sources used, ^{252}Cf and $^{241}\text{Am-Be}$, and for both phantoms, PMMA and water (ICRU and ISO).

The difference between the backscatter fluence value calculated in the present work, of about 70%, and the measured increase of about 5% in personal dosimeter response on-phantom is large. The explanation for this difference can be outlined quantitatively. A test point close to the phantom surface sees a relatively small fraction of the total fluence incident on the phantom surface. This surface acts as a plane source of backscatter neutrons. Since the test point is close to this surface, and the majority of the backscatter fluence travels at small angles relative to the phantom face, the test point sees a substantial backscattered fluence. Because of the lower average energy of this fluence, and the angular dependence of its incidence on a dosimeter placed parallel to the surface, the size of the dosimeter's backscatter response is substantially less than the magnitude of the backscatter fluence.

As a simple test of the present calculations the 'fate' of all neutrons entering the phantom was tallied to ensure no extra neutrons were being produced and that account was being taken of all neutrons. For a ^{252}Cf source 75 cm from an ISO water phantom the calculation indicated that 30% of the neutrons entering the slab escaped from the front face, 42% through the sides, 12% through the back, and 16% were captured. The difference between the figure of 30% escaping from the front face and a backscatter fluence of 70% of the incident fluence for a

small device close to the surface is explained by the angular dependence of the fluence as described earlier.

Prior to this work, little has been reported in the open literature for backscatter from the phantoms used during personal dosimeters calibration. In one of the earliest investigations Cheka⁽¹²⁾, in 1954, performed measurements using $^{210}\text{Po-B}$ and $^{210}\text{Po-Be}$ neutron sources to irradiate NTA film dosimeters with and without a 16 cm diameter cylindrical paraffin phantom. For normal incidence on the dosimeters he reported backscatter responses of about 30% ($\pm 7\%$), even when the dosimeters were separated from the phantom by 1.5 cm. This value cannot easily be reconciled with the present experimental figure of about 5%. The sources used by Cheka were different, although $^{210}\text{Po-Be}$ has a similar spectrum to $^{241}\text{Am-Be}$. Paraffin is a hydrocarbon and as such should not be too different in terms of backscatter properties to PMMA. In view of the fact that no differences were detected in the present measurements for the two different sources and types of phantom, it is unlikely that the disagreement with the result of Cheka is due to the different sources or phantoms. It thus remains unexplained at present.

Further data for NTA film can be found in references 7 to 12. The last of these references, reporting experimental work by Bartlett et al. in 1976, includes the most extensive set of measurements for NTA film up to that date, and also provides a useful summary of the previous results. As was the case for Cheka's measurements, none of the phantoms used in references 7 to 12 were identical to those in the present work, and a variety of different sources were used. The backscatter responses varied from about 2% to 33%. There was some indication that $^{210}\text{Po-Be}$ sources gave the highest backscatter, although there is no obvious reason for this, and the backscatter from paraffin appears higher than that from a water phantom.

The results of Bartlett et al. were for both $^{241}\text{Am-Be}$ and ^{252}Cf sources, but the phantom was either a slab of paraffin or a cylindrical container of water. Nevertheless, the data, which gave backscatter percentages of between 2 and 10% depending on the experimental conditions, are in good agreement with the present results for dosimeter type N1.

Measurements by Naismith and Thomas⁽⁶⁾ of dosimeter performance involved mainly free-in-air irradiation although a small number were made on-phantom. A comparison of the on-phantom results to those free-in-air failed to show up any difference, mainly because the number of dosimeters was small and the uncertainties large, but indicated that the response to backscatter was most probably less than 10%.

The observation that the backscatter response was the same for all the irradiation situations was unexpected. PMMA has a higher density than water and might thus be expected to give more backscatter; PADC has a lower low-energy detection threshold for neutrons than NTA and so might be expected to see more backscatter; $^{241}\text{Am-Be}$ neutrons have a higher mean energy than ^{252}Cf and so one might expect more of the scattered radiation to have energies above the detection threshold. All these effects were probably present to some extent, but were too small to detect.

Very few calculations of backscatter from phantoms have been reported in the literature. Siebert et al.⁽¹³⁾ at the German National Standards Laboratory, PTB, performed an extensive set of calculations of fluences at 10 mm depth and on the surface of various phantoms using

an in-house Monte Carlo neutron transport code. The results are given for a number of point neutron energies ranging from thermal to 5 MeV. Most of the results are quoted for the 30 cm ICRU tissue sphere phantom, however, factors are also given to allow conversion of these data into results for an ICRU tissue or polyethylene slab phantom.

Direct comparison with the present work is not possible, but, taking the data for an ICRU tissue slab, which is the phantom most similar to the one used in the present work, the total percentage backscatter fluence values for incident neutron energies in the same energy region as those from a ^{252}Cf source range from about 30% for 0.5 MeV, to 15% for 5 MeV - the maximum value of about 40% occurs at 1 MeV where resonances in the oxygen cross section enhance the backscatter. These values are significantly smaller than the present backscatter calculation, and it is not easy to reconcile the results. The calculations of Siebert were reported in 1990, but there is no reason to believe that basic Monte Carlo techniques or the cross section data used will have changed significantly over this period. The different results warrant further investigation to resolve the discrepancy, and this would best be undertaken in collaboration with the PTB group.

An attempt by Hollnagel et al.⁽¹⁴⁾ to calculate the influence of phantoms on the response of track-etch dosimeters was hampered to a large extent by poor knowledge of the energy and angular response of the dosimeter. Their extensive set of calculations was performed for both the 30 cm ICRU tissue sphere phantom and the MIRD anthropomorphic phantom, and for three different neutron sources, including ^{252}Cf . The results for the calibration situation, i.e., normal incidence on the dosimeter, depend strongly on the angular dependence assumed for the dosimeter response, and also to a lesser extent on the phantom and the energy dependence of the dosimeter response. Values calculated for the increased response due to the phantom ranged between 3% and 14% although the larger values corresponded to the assumption of an isotropic dosimeter response, and are hence the least applicable. The results are thus in reasonable agreement with the present measurements and calculations.

Variations in the backscatter from different types of calibration phantoms have been investigated by McDonald et al.⁽¹⁸⁾. In a set of calculations using the MCNP code they calculated the kerma on the phantom surface, including both direct and backscatter components, and converted this into a dose equivalent quantity using neutron quality factors. This quantity is thus not personal dose equivalent, but is what a small instrument, with an isotropic response to this particular dose equivalent quantity, would register on the surface of the phantom. Calculations were performed for two different size PMMA phantoms, 30 x 30 x 15 cm and 40 x 40 x 15 cm, and the calculated dose equivalent was the same at the centre of the phantom face in both cases.

Calculations were also performed for 30 x 30 x 15 cm PMMA and water phantoms and these were compared with the results for the ICRU tissue phantom for which the quantity personal dose equivalent is defined. They showed that, for the dose equivalent quantity calculated, the backscatter was the same for the water and ICRU tissue phantoms, but that for PMMA it was 5% higher. This can be compared to the approximately 8% higher fluence calculated in this work for PMMA (see section 6.4). Neither the fluence nor the dose equivalent quantity of McDonald et al.⁽¹⁸⁾ is, however, the same as the quantity measured in this work, i.e. the response of a neutron personal dosimeter. It is assumed therefore that the phantom composition effect on the dosimeter response is either masked by the experimental

uncertainties, or that different angular dependencies of the backscatter fluence result in their being negligible difference.

Quantitatively the agreement between the present measured backscatter response of 5% and calculated value of about 9% is not particularly good, but it is believed to be due mainly to poor knowledge of the energy and in particular the angular dependence of the dosimeter response. Data on the energy response of dosimeters for normal incidence are often available although they are usually not completely comprehensive, but data on the angular dependence are much rarer. This information needs to be measured if differences between measurements and calculations are to be resolved. These data are also needed for evaluation of dosimeter performance in real workplace fields.

One of the underlying reasons for performing this work was to investigate whether a single factor could be derived for backscatter responses which could be used to correct free-in-air measurements. Knowledge of this factor would simplify the performance of regular calibrations and checks of personal dosimeters which could be performed free-in-air rather than on-phantom with the appropriate correction factor applied. From the experimental results there appears to be a single universal correction factor for the dosimeters tested and this is about 5%.

The best-estimate value of $(5.1 \pm 0.8)\%$ quoted earlier was derived by taking a weighted mean of all the data. This approach assumes all dosimeter types have the same backscatter factor. This is probably an oversimplification and genuine, but small, differences do exist between different types. A more realistic uncertainty to use when applying the correction factor which would cover differences between different dosimeter types would be $\pm 2\%$.

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