Gamage, K. A.A., Crompton, A. J., Jenkins, A., Bell, S. and Trivedi, D. (2020)
Performance characteristics of a tungsten collimator and UVTRON flame sensor in the
detection of alpha-induced radioluminescence. *Radiation Physics and Chemistry*, 177,
109197.

(doi: [10.1016/j.radphyschem.2020.109197](https://doi.org/10.1016/j.radphyschem.2020.109197))

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Deposited on: 25 September 2020

Performance characteristics of a tungsten collimator and UVTRON flame sensor in the detection of alpha-induced radioluminescence

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Abstract: It has been established that the UVTRON flame sensor (Hamamatsu) can detect alpha-induced radioluminescence, but that the presence of gamma and beta radiation both interfere with this detection. A UVTRON was placed inside a tungsten collimator and exposed to a range of radioisotopes, ²¹⁰Po, ²⁴¹Am, ¹³⁷Cs, ⁹⁰Sr and ⁶⁰Co, to investigate the effect of shielding the UVTRON. The collimator is a cylinder with a hole in the curved wall to allow light and particles to access the interior, without providing a direct shine path to the UVTRON sensor. Ultraviolet C (wavelength 180-280 nm) radioluminescence is reflected onto the UVTRON sensor using a UVC reflecting mirror. It was found that the collimator does not affect the low background count of the UVTRON, but that it does greatly reduce the UVC signal reaching the UVTRON from an alpha source. For example, the collimator reduced the signal by 94 % at 60 mm, and 78 % at 120 mm, where the signals were still far greater than the background (88 and 84 times background respectively). Beta particles entering the collimator, although not directly impacting on the UVTRON, do increase the count, likely due to bremsstrahlung radiation. The collimator attenuates gamma radiation dependent on the gamma energy, but as expected, does not block it. When using more than one source, the count is cumulative and therefore it may be possible to determine the presence of UVC radioluminescence through subtraction of the gamma and beta element of the signal. The results and findings of the experiments carried out are presented herewithin.

Keywords: UVTRON flame detector; alpha detection; radioluminescence; gamma radiation; beta radiation; nuclear decommissioning.

1. Introduction

The detection of alpha radiation is difficult and time consuming due to the short travel of alpha particles, around 50 mm in air depending on their energy. For example, researchers found the range of alpha particles with energy of 5.1 MeV to be 38 mm in air, with the area of highest intensity of radioluminescence scintillation within a radius of 10 mm from the source [1]. This means that detectors which require the direct impact of the alpha particle on a probe or sensor window must be within that range, and it is time consuming for large areas or complex geometries, for example where pipes or equipment are present. It may also present a hazard to operators, both from accidental alpha contamination and from other radiation sources which may be present [2]. Hence a stand-off alpha detector has long been sought.

As alpha particles travel, they ionise the air, causing the production of ultraviolet (UV) photons, known as radioluminescence. These photons travel in the order of kilometres and so provide a potential means to detect alpha radiation from a distance. The majority of the UV is produced in the

UVA and UVB wavelength ranges (280 – 400 nm). However, there is a significant background of natural and artificial light in this wavelength range, making identification of the radioluminescence difficult. In 2011 Ivanov et al. [3] used an off-the-shelf, solar-blind, UV camera to locate alpha contamination in daylight conditions through air radioluminescence. They had estimated in 2009 [4] that they would be able to detect alpha radiation of 5 MeV energy with an activity between 40 and 100 Bq cm⁻² with a corresponding integration time of 600 s to 3600 s from a separation of 3 m between detector and source. The camera they used (DayCor SuperB UV, Ofil Ltd., Lawrenceville, GA, USA) is designed to show the corona and arcing of high voltage equipment for fault diagnosis [3]. It is 'blind' to UVA and UVB (400–315 nm and 315–280 nm wavelengths respectively), and only detects UV light of less than 290 nm (UVC). This removes the interference of the stronger background light, allowing detection of the much weaker air radioluminescence in daylight conditions.

The emissions in the UVC wavelength range (180-280 nm) are much fewer in number, but there is no competition from other lighting sources. The UVC in sunlight is absorbed by the ozone layer, and bulbs used for general artificial lighting do not routinely emit UVC. Although special UVC emitting bulbs are available they are not used for indoor lighting as the human eye can not see in the UVC wavelength range and it can be damaging to the eye.

A solar-blind flame detector, the UVTRON (Hamamatsu, Japan) has proven capable of detecting the UVC emission from a ²¹⁰Po source [5]. It is designed to detect the UVC from flames in fire detection systems and has excellent background light rejection capabilities. However, it is susceptible to interference from beta and gamma sources [6]. Hence a collimator has been designed to attenuate gamma and beta radiation and to block any shine path to the UVTRON. A UVC mirror is used to reflect the UVC onto the UVTRON within the body of the collimator.

A set of experiments were carried out at the National Physical Laboratory (NPL) in Teddington, UK, to assess the efficacy of the collimated system prior to field trials. Sources were selected for their prevalence in industrial nuclear applications and provided a range of alpha, beta and gamma emitters of different energies. Po-210 was selected as one of the only sole alpha emitters. The results of these experiments, conclusions and recommendations are laid out in this document.

2. Materials and Methods

2.1. UVTRON

The UVTRON (Hamamatsu, Japan) is a UVC detector designed to detect UVC from flames for commercial applications. The R9533 model selected for this application is sensitive to light in the 180 – 260 nm wavelength range [7]. It uses the photoelectric effect and gas multiplier effect to generate an output pulse when a UVC photon is incident on its Ni cathode. This pulse can be channeled into a bespoke driving circuit (C10805, Hamamatsu, Japan) which processes the signal and outputs a 5 V square wave. In the configuration used within the collimator, this signal is outputted to an Arduino Uno which counts the pulses for each second and outputs this value to a computer. Due to the 25 ms quenching time of the driver circuit the UVTRON's maximum output is a theoretical 40 cps. However, in practice the value reaches no greater than 38 cps.

2.2 Collimator

The collimator is a bespoke design for this application. It is made of a tungsten alloy (Wolfmet HA190) which has good radiation shielding properties due to the density of the material. It is 90% tungsten with a nickel and copper binder [8]. It provides a 15 mm shield wall around the UVTRON and associated electronics. Its geometry is cylindrical, enclosed at both ends, with a 15 mm diameter hole in the side wall through which the UVC enters the collimator (see Figure 1). The UVTRON is mounted vertically inside the cylinder. A UVC reflecting mirror is located at 45 degrees to the hole and to the UVTRON, positioned to reflect any UVC entering the collimator onto the cathode of the UVTRON (see Figure 1 a & b). Modelling of the effect of the mirror angle showed that this is the

optimum angle (see Figure 2), as well as being convenient for limiting the space required inside the collimator. The UVTRON is positioned to prevent a shine path from the hole to the sensor, ensuring that no particle entering the hole can impact directly on the UVTRON.

Figure 1. Tungsten collimator: (a) & (b) Internal electronics showing placement of UVC reflecting mirror; (c) External geometry (front view); (d) External geometry (top view). Collimator consists with a 15 mm diameter hole in the side wall which the UVC enters the collimator.

Figure 2. Modelling of different mirror angles (45°, 60° and 70°) using FRED32 raytracing software [9]; a), b) and c) show the rays passing through the collimator hole and reflecting from the mirror onto the UVTRON cathode; d), e) and f), show the rays incident on the UVTRON cathode. Using a limited number of rays, it is possible to see the decrease in incident rays with increase in angle, from 55 at 45°, to 48 at 60°, to 32 at 70°. At 70° not all rays impact on the mirror, i.e. there are less dots on e and f than there are on d.

The collimator system was tested as a ‘black-box’ with the output to stimuli recorded without reference to any internal processes. The performance of the system as a whole is presented in this document, with some discussion of the cause of certain results and some suggestion for further work.

2.3 Sources

Five sources were used for the experiments. A table is provided of the sources and their relevant characteristics (see Table 1). The sources were used in isolation or in combination as required, as stated in the results section.

Table 1. Sources

Source	Activity MBq	Main emissions and energies [10]	Notes
²¹⁰ Po	180	Alpha 5304 keV (100%)	Disc source with thin window allowing alpha emission
²⁴¹ Am	73	Gamma 60 keV (36%), 18 keV (18%), 14 keV (13%)	Sealed source with no alpha emission
¹³⁷ Cs	4.5	Beta 512 keV (95%) Gamma 662 keV (85%)	Sealed source with beta and gamma emissions
⁹⁰ Sr	32	Beta 546 keV (100%), 2284 keV (100%)	Sealed source with beta emissions
⁶⁰ Co	8.1	Beta 318 keV (100%) Gamma 1173 keV (100%), 1333 keV (100%)	Sealed source with beta and gamma emissions

2.4 Set up

The collimated UVTRON was placed at a horizontal distance from the source, as can be seen in Figure 3. **Figure 3.** Set up of the collimator, uncollimated UVTRON and source – showing the distances.

The uncollimated UVTRON was placed at a vertical distance from the source.

Figure 3. Set up of the collimator, uncollimated UVTRON and source – showing the distances.

3. Results

3.1 Background

A background count was taken in the laboratory under normal lighting conditions without the presence of a source. Counts per second were recorded over a period of approximately 17 hours. The collimated UVTRON recorded 92 counts in 62,591 seconds, giving an average cps of $1.47 \times 10^{-3} \pm 0.153 \times 10^{-3}$. The uncollimated UVTRON recorded 88 counts in 62,542 seconds, giving an average cps of $1.41 \times 10^{-3} \pm 0.150 \times 10^{-3}$. These are in line with earlier background counts taken in the same laboratory at NPL [5, 11]. The overlap in confidence intervals for the collimated and uncollimated results indicate that the background count is unaffected by the collimator. This supports the assertion that the background count is not related to ambient light, but is a function of the UVTRON system itself.

Comparisons to background in this document utilise the recorded background count relevant to the UVTRON system used for that particular set of results (collimated or uncollimated).

3.2 UVC / alpha response

When the 180 MBq ^{210}Po source was placed before the sensor, the count increased to 56 times background at a distance of 25 mm, 88 times at a distance of 60 mm, and 84 times at a distance of 120 mm. When a black-out cloth was placed over the collimator to attenuate radioluminescence, the signal reduced from 56 to 1.5 times the background signal. In line with earlier research [5, 11] this confirms the collimated UVTRON was detecting UVC from the ^{210}Po source. It has already been shown through earlier experimentation that the UVTRON can detect UVC from ^{210}Po [5, 11]. However, this is the first time that collimated UVC, reflected onto the UVTRON using a UVC mirror has been detected. It confirms that the collimator design will admit and reflect UVC onto the UVTRON sensor.

By taking measurements with an uncollimated UVTRON at the same distances, the effect of the collimator was investigated. The collimator reduced the signal by 94 % at 60 mm, and 78 % at 120 mm, see Table 2. The signals were still far greater than background, 88 and 84 times background respectively. The untypical signal drop off, discussed in the following paragraph, may account for the large difference in collimator effect between the 60 mm and 120 mm results.

Table 2. The comparison between the signal between the collimated and uncollimated UVTRON when exposed to ^{210}Po , and the recorded background.

Distance (mm)	60 (*)	120 (*)
Collimated (cps)	$0.125 \pm 1.414 \times 10^{-3}$ (88)	$0.118 \pm 1.374 \times 10^{-3}$ (84)
Uncollimated (cps)	$2.013 \pm 5.675 \times 10^{-3}$ (1340)	$0.543 \pm 2.947 \times 10^{-3}$ (369)
Collimated/ uncollimated	0.06	0.22

* It shows each collimated (cps) and uncollimated (cps) as how many times larger compared to the corresponding background, i.e. collimated cps at 60 mm is 88 times background.

The effect of the collimator on signal drop off was further investigated using a UVC bulb to represent the source. The body of the collimator was removed to provide the uncollimated result for comparison (see Figures 1 a & b). At 15 cm distance, the uncollimated UVTRON saturated (38 cps) at all angles (up to 90° with respect to the source was tested) and so the UVTRON itself was shielded, with the mirror reflecting UVC onto the UVTRON sensor. It was found that at 15 cm distance and a 0° angle, the UVTRON saturated both with and without the collimator cylinder in place (see Figure 4). However, the drop off in signal was much greater when the collimator was turned at an angle to the source with the body in place (collimated) than without (uncollimated). At 15 cm distance the collimated signal reduced by half over each 5 degrees turned between 5° and 20° . The uncollimated signal remained saturated until 30° was reached, and then reduced by just under a half over the next 10° . With the light source at 2 m the collimator had a greater effect on the drop in signal caused by angle, with a drop to 72 % in the first 5° , but a drop to less than 3% of the 0° count at 10° . Without the collimator, the signal dropped by only 10% in the first 20° . It can therefore be seen that the reduction in signal produced by the collimator during the experiments with the radioactive sources is due to the reduced field of view caused by the entrance hole diameter. There is also a reduction caused by the reflection of the signal in the UVC mirror, which reflects 85% of UVC, as was demonstrated by the saturation at all angles when the UVTRON was directly exposed to the UVC bulb at 15 cm. The length of travel inside the collimator is also likely to cause a reduction in signal due to the widening of the collimated light over distance (see Figure 2). Modification to the geometry of the collimator and the addition of optics could increase the UVC reaching the UVTRON.

Figure 4. Graph showing the response of the UVTRON when within the collimator and with the collimator body removed, at a distance between the bulb and the collimator of 2 m and 15 cm.

The increase in signal from the ^{210}Po source between 25 mm to 60 mm distance when a reduction would be expected, is likely due to two factors; the collimator being within range of the alpha particles and the geometry of the collimator. Any slight variation in alignment of the aperture may also affect the count. An estimate of the average distance of travel of the alpha particles emitted by the ^{210}Po can be calculated using the empirical equation [12];

$$R_{air} = (0.005E + 0.285)E^{1.5} \quad (1)$$

where R_{air} is the travel of the alpha particle in cm, and E is the energy of the alpha particle in MeV. The alpha particles emitted by the ^{210}Po , which are of energy 5.304 MeV, would travel approximately 38 mm. Therefore, some of the particles would impact on the collimator at 25 mm, reducing the path length along which the radioluminescence photons are produced. As the Bragg peak shows, the main energy loss of alpha particles is close to the end of their travel path and so impact on the collimator wall would reduce the total radioluminescence caused by alpha ionisation of the air. The collimator was tested as a 'black-box', but the internal geometry extends the travel path of the radioluminescence photons and the mirror attenuates the signal, meaning that the $1/r^2$ drop off in signal which would be expected may be affected by the collimator design.

The uncollimated UVTRON showed a more expected response to distance, with the signal varying less than 10% from the expected signal at 60 mm and 120 mm distance distances. To determine the expected cps at each distance equation 2 was used to calculate the $1/r^2$ relationship in the drop off in signal;

$$S_2 = S_1 \left(\frac{R_1^2}{R_2^2} \right) \quad (2)$$

where S_2 is the expected signal, S_1 is the recorded signal, R_2 is the distance at which S_2 is expected, and R_1 is the distance at which S_1 was recorded. This was applied to the data and the results for both

the collimated and uncollimated UVTRONs are shown in Table 3. The table shows the actual cps at each distance, and the expected cps at different distances. Assuming the actual cps is the true value and the $1/r^2$ relationship will be observed, the expected cps is the counts that would be measured at a different distance. For example, at 25 mm the reading was $0.0784 \pm 1.120 \times 10^{-3}$ cps. The expected cps at 60 mm would therefore be 0.0136 cps (using equation 2). As the actual count at 60 mm was 0.1245 this is $9.14 \times$ the expected count.

Table 3. The expected and actual results of exposure to ^{210}Po .

Source to detector distance	Actual cps	Expected cps (*)		
Collimated	Actual cps	Expected at 25 mm	Expected at 60 mm	Expected at 120 mm
25 mm	$0.0784 \pm 1.120 \times 10^{-3}$		0.0136 (9.14 x)	0.0034 (34.7 x)
60 mm	$0.1245 \pm 1.411 \times 10^{-3}$	0.7170 (0.11 x)		0.0311 (3.80 x)
120 mm	$0.1182 \pm 1.375 \times 10^{-3}$	2.7227 (0.03 x)	0.4727 (0.26 x)	
Uncollimated	Actual cps	Expected at 25 mm	Expected at 60 mm	Expected at 120 mm
60 mm	$2.0132 \pm 5.675 \times 10^{-3}$	0.8041 (0.71 x)		0.5040 (1.08 x)
95 mm	$0.5721 \pm 3.025 \times 10^{-3}$		1.4843 (1.41 x)	1.2634 (0.42 x)
120 mm	$0.5425 \pm 2.946 \times 10^{-3}$	0.8656 (0.66 x)	2.1699 (0.93 x)	

*The numbers in brackets are how many times greater / less the predicated cps are than the actual cps.

It can be seen from the table that the actual signal was 93 % of the expected signal at 60 mm and 108 % at 120 mm for the uncollimated UVTRON, meaning the actual and expected values are a close match. Whereas for the collimated UVTRON it was 26% at 60 mm and 380 % at 120 mm, which shows a marked variation from what would be the expected count. This is likely due to the collimator internal design which will affect the distance of travel of the UVC photons.

When the result at 25 mm is considered as S_1 , the count at 60 mm was 914 % of expected and 3472 % at 120 mm. This is likely due to the close proximity of the source to the collimator, within the alpha travel for the R_1 value. As noted earlier, this is likely due to the alpha particles impacting on the collimator before reaching their maximum energy transfer point, and the source being a sphere of radioluminescence with radius equal to the travel of the alpha particles and not a point source.

3.3 Beta response

It has already been shown that the UVTRON is susceptible to interference from beta radiation and gamma radiation [6], which the collimator seeks to reduce or remove. The collimated UVTRON was exposed to the ^{90}Sr source with the following results (see Table 4);

Table 4. Results of exposure of collimated and uncollimated UVTRONs to ^{90}Sr source

Distance mm	Av cps	Comparison to background (%)	Uncollimated cps (150/300/450 mm)	^{210}Po cps (25/120 mm)
35	$1.803 \pm 5.371 \times 10^{-3}$	1281.23		$0.0784 \pm 1.120 \times 10^{-3}$
140	$0.105 \pm 1.296 \times 10^{-3}$	74.8	$2.131 \pm 5.839 \times 10^{-3}$	$0.1182 \pm 1.375 \times 10^{-3}$
240	$0.047 \pm 0.867 \times 10^{-3}$	33.64	$0.8003 \pm 3.578 \times 10^{-3}$	
600	$0.007 \pm 0.334 \times 10^{-3}$	4.88		

It can be seen from the results shown in Table 4 that up to at least 600 mm distance the signal generated by the beta emissions can be distinguished from background by the collimated UVTRON system. Comparisons of recorded cps with the anticipated cps at different distances shows that the drop off in signal follows an approximate $1/r^2$ reduction.

In comparison with uncollimated results at similar distances, the collimator greatly attenuates the beta signal, by up to 94 %. However, at a similar distance the collimated beta signal and alpha signal recorded are of a similar magnitude, $0.105 \pm 1.296 \times 10^{-3}$ and $0.1182 \pm 1.375 \times 10^{-3}$ cps respectively, though the alpha source has a much greater activity level. The pulse shape is the same for any stimulus which causes the UVTRON to emit a pulse, as verified using an oscilloscope connected directly to the UVTRON. Therefore, it is not possible to distinguish with this collimated system between an unknown beta and an unknown alpha source. The results of exposing the collimated UVTRON to mixed sources are presented in section 3.5 *Mixed radiation response*.

When a sheet of fused silica, thickness 2 mm (Spectrosil[®], > 90% UVC transmittance [13]), was placed over the entrance to the collimator [14], the signal reduced from $0.1053 \pm 1.297 \times 10^{-3}$ cps to $0.008 \pm 0.357 \times 10^{-3}$ cps, a reduction of 93% compared to the signal without the fused silica. As it requires 5 mm of glass to fully attenuate beta particles emitted by ⁹⁰Sr, some ingress of beta particles to the collimator is to be expected, and the cps with the fused silica was found to be 5 times background which would support this. When the collimator entrance was turned to 90° relative to the source, the signal dropped from $1.8028 \pm 5.370 \times 10^{-3}$ cps to $0.005 \pm 0.707 \times 10^{-3}$ cps, a more than 99 % reduction, indicating that it is the ingress of beta particles to the collimator which is generating the signal.

Although the geometry of the collimator prevents beta particles impacting directly on the UVTRON, it is possible that bremsstrahlung radiation is being created within the collimator, affecting the UVTRON and causing the response. The collimator was tested as a 'black-box' in these experiments and any internal processes were not investigated at this stage. However, as the fused silica glass used in these experiments has a transmittance of over 90 % at up to 10 mm thickness, it is likely that the inclusion of a fused silica window in excess of 5 mm thickness would have negated the collimated UVTRON response to beta radiation from the ⁹⁰Sr source.

The distance travelled by beta particles from ⁹⁰Sr is approximately 10 meters in air. However, assuming a $1/r^2$ reduction the signal would be equal to background in approximately 1.3 m for this source. In the field where the activity of any source is likely to be unknown, although the isotope in question and therefore energy of beta particles may be known, it is unlikely that the distance calculation can be made. Hence the travel of the beta particles will determine the minimum distance required to ensure the prevention of beta particles entering the collimator. This further supports the necessity for a fused silica window if beta particle interference is to be eliminated from any alpha detection count.

The collimated UVTRON was also exposed to a ⁶⁰Co source, with and without the fused silica window being present. The thickness of the fused silica window (2 mm) is sufficient to block the low energy beta particles from the ⁶⁰Co, which are stopped by as little as 0.4 mm of glass. The gamma radiation emitted from ⁶⁰Co requires 46 mm of lead to reduce the signal by 1/10 and is unlikely to be attenuated by the fused silica to any discernible amount in this instance. By a comparison with and without the fused silica it was determined that approximately 5% of the signal could be attributed to beta radiation at 35 mm distance. This was supported by the results when the collimator was turned through 180° where a 4% difference was found between comparisons with and without the fused silica window (see Table 5).

3.4 Gamma response

The collimated UVTRON was also exposed to sources of gamma radiation, ²⁴¹Am, ⁶⁰Co and ¹³⁷Cs. The ²⁴¹Am was a sealed source which prevented the emission of alpha particles. ⁶⁰Co and ¹³⁷Cs also emit beta radiation, though of a low energy which is easily shielded. The results are presented in Table 5.

Table 5. Results of exposure of collimated UVTRON to gamma sources

Source	Distance mm	Shielding / angle	Average cps	Times background
⁶⁰ Co	35		1.601±5.061x10 ⁻³	1138
	35	Fused silica	1.528±4.944x10 ⁻³	1086
	35	180°	1.423±4.771x10 ⁻³	1011
	60	180° & 50 mm lead	0.059±0.971x10 ⁻³	41.8
²⁴¹ Am	60		0.027±0.657x10 ⁻³	19.5
	80		0.025±0.632x10 ⁻³	17.8
	140		0.012±0.438x10 ⁻³	8.7
¹³⁷ Cs	35		0.105±1.296x10 ⁻³	74.4
	35	Fused silica	0.076±1.102x10 ⁻³	53.9
	140		0.029±0.681x10 ⁻³	20.8
	600		0.005±0.282x10 ⁻³	3.5

The beta element of the ⁶⁰Co signal is approximately 5% (see section 3.3 *Beta response*). When the collimator was orientated at 180° to the source (i.e. the collimator entrance was turned away from the source), the signal reduced to 89% of the unshielded signal and 93% of the signal measured whilst the fused silica was in place. This suggested that the gamma radiation is attenuated, but not blocked by the collimator. To verify that the signal was caused by gamma entering the collimator interior through the walls, the distance between the source and collimator was increased to 60 mm to allow a 50 mm thickness of lead block be inserted between the two. The collimator entrance remained at 180° to the source. In this configuration the signal dropped significantly, to only 4% of the signal without the lead. This is still 42 times background as some of the gamma may still pass through the lead and the collimator wall. The drop upon turning the collimator indicates that only a small percentage of the signal, up to 7%, is due to gamma entering through the hole. The largest part must be entering through the collimator wall.

In comparison with the collimated UVTRON, the uncollimated UVTRON recorded an average 2.345±6.125x10⁻³ cps, 40 times the collimated cps. The collimator reduces the gamma signal produced by ⁶⁰Co significantly, but this still exceeds the UVC signal recorded from the ²¹⁰Po. In comparison with the largest ²¹⁰Po signal (at 60mm) the ⁶⁰Co signal was still 13 times that of the ²¹⁰Po.

The gamma radiation from ²⁴¹Am is attenuated to 1/10 of the signal by less than 1 mm of lead, compared to 46 mm for ⁶⁰Co. The collimated average cps both at 60 mm and 120 mm were approximately 200 times smaller than the uncollimated results at those distances, showing that the collimator was able to greatly attenuate the gamma from the ²⁴¹Am source. The average cps from the ²¹⁰Po source were 4.5 and 9.7 times that from the ²⁴¹Am, indicating that it may be possible to distinguish between the two, see section 3.5 *Mixed radiation response*.

3.5 Mixed radiation response

The collimator was exposed to combinations of alpha, beta and gamma radiation using ²¹⁰Po, ²⁴¹Am and ¹³⁷Cs sources. The results are presented in Table 6. The individual cps for each of the sources at 60 mm and 120 mm distance were recorded. Due to the geometry of the sources, the ²⁴¹Am and ¹³⁷Cs were at an approximately 20 mm greater distance than the ²¹⁰Po when the sources were tested in combination.

Table 6. Results of mixed radiation field.

Distance	60 mm	120 mm
Source	Recorded average cps	
²¹⁰ Po	0.1245±1.411×10 ⁻³	0.1182±1.375×10 ⁻³
²⁴¹ Am	0.0250±0.632×10 ⁻³	0.0122±0.441×10 ⁻³
¹³⁷ Cs		0.0292±0.683×10 ⁻³
(²¹⁰ Po & ²⁴¹ Am)	0.2202±1.877×10 ⁻³	0.1293±1.438×10 ⁻³
(²¹⁰ Po & ²⁴¹ Am & ¹³⁷ Cs)		0.1501±1.549×10 ⁻³
Addition of cps (percentage of recorded average cps)		
²¹⁰ Po + ²⁴¹ Am	0.1495±0.707×10 ⁻³ (68 %)	0.1304±1.444×10 ⁻³ (100.8 %)
(²¹⁰ Po & ²⁴¹ Am) + ¹³⁷ Cs		0.1585±1.592×10 ⁻³ (105.6 %)
²¹⁰ Po + ²⁴¹ Am + ¹³⁷ Cs		0.1596±1.597×10 ⁻³ (106.3 %)

Note: The “&” shows that the two (or three) sources were present during the experiment. The “+” shows that the cps are the additions of the results of the sources when tested individually.

It can be seen from the percentage of recorded average cps that at 120 mm the combination of sources resulted in a very similar result to the addition of the individual measurements, being only around 6 % greater.

4 Conclusions and discussion

It can be seen from the results of the experiments, that the collimator provides protection for the UVTRON from beta and gamma radiation to some extent, whilst still allowing for the detection of alpha radiation through UVC radioluminescence. The internal configuration shields the UVTRON from the direct path of beta particles and gamma rays, with the UVC mirror successfully reflecting the UVC onto the UVTRON cathode. However, the collimator also greatly reduces the UVC signal, by approximately 80%, compared to the uncollimated UVTRON, although this is dependent on the distance from and the angle to the source as shown by the UVC bulb experiments. Further work on the configuration of a collimator, possibly with the inclusion of optics, may increase the field of view of the UVTRON without compromising the shielding. As the portion of alpha-induced radioluminescence is small in the UVC wavelength range, an increase in the field of view would be beneficial to increase the sensitivity of the system. It would also improve the signal to noise ratio by increasing the signal strength. It may also be beneficial in further work to investigate the drop off in signal with distance, as the effect of the collimator may change with distance and this should be characterised.

The collimator highly attenuates the low energy gamma emissions from ²⁴¹Am, but is insufficient to block higher energy gamma radiation, for example from ⁶⁰Co. Although the half thickness of the tungsten used is 7.5 mm, a 15 mm thickness was unable to sufficiently attenuate the ⁶⁰Co in this instance. Dependent on the specific radionuclides which the collimated UVTRON will encounter in field conditions, further shielding may be required to remove the interference from gamma radiation when attempting to detect alpha radiation. It may be useful to determine if there is direct impact on the UVTRON or a secondary phenomenon, such as Compton scattering or x-ray production, is causing the signal. This would determine the type of shielding required.

As the addition of the signals caused by different radioisotopes is in line with exposure to a combined of the sources, it may be possible to subtract the gamma part of the signal from the overall signal by shielding against UVC and beta ingress to the collimator. This would required further investigation, but the results of this work suggest that this may be a possible route to using the

collimator in a mixed radiation field. Some modification to the collimator would be required to implement a UVC and beta shield in the field.

Although not directly incident on the UVTRON, beta particles which enter the collimator do cause a signal, likely through bremsstrahlung radiation. The collimator provides sufficient shielding against beta radiation, which is only able to enter through the hole. A sheet of fused silica of sufficient thickness across the entrance hole should prevent any interference from beta radiation.

The effectiveness of this collimated UVTRON system in the field will depend on the radioisotopes to which it is exposed. Activity levels and energy levels of any source will impact on the response of the system. In an environment high in alpha particles with low energy gamma emissions it may be possible in its current configuration to detect alpha-induced radioluminescence. Field trials and further experimentation are warranted based on the results of this work.

Additional to the testing of the collimator, the research has also determined that the background count is a function of the system and not reliant on ambient lighting conditions. Measurement of the output pulse directly from the UVTRON using an oscilloscope has shown that the pulse characteristics do not vary depending on the stimulus [15]. The pulse shape, amplitude and duration remained the same for all pulses observed from the UVTRON. It is therefore not possible to determine the source from the output pulse.

Acknowledgement

This research was funded by Sellafield Limited, UK and the Nuclear Decommissioning Authority, UK.

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