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Transportable System for Monitoring Internal Radioactive Contamination in People

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Abstract

A transportable people monitoring system has been constructed and calibrated for use in an emergency where radioactive material could be inhaled or ingested by people. The system uses a hyper-pure germanium detector for either measurements of radioactive material in whole body or alternatively americium-241 (Am-241) in lung. Determination of whole body activity in people might be required following an accident at a nuclear power station where fission and activation products could be released. Am-241 in lung measurement may be required following an accident involving a nuclear weapon as these contain mixtures of plutonium radioisotopes and Am-241. The detection limit for caesium-137 (Cs-137) in the body of an adult at the 95% confidence level is 300 Bq, for a 10 minute counting time. The detection limit for Am-241 in lung for a 10 minute counting interval at the 95% confidence level varies from 60 to 250 Bq depending on the person's chest wall thickness. The capabilities of this system are compared with what might be required following a reactor or weapon accident. The system can be transported in a trailer which is pulled by an ordinary motor vehicle and so can be deployed to a Radiation Monitoring Unit which could be setup for monitoring members of the public.

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1 Introduction

In the event of an accident involving radioactive material there could potentially be a large number of people who require monitoring for internal contamination. If the release contains radionuclides which emit high energy gamma rays then the most suitable means of providing this monitoring is whole body counting. For incidents involving americium-241 (Am-241) or mixtures of Am-241 and plutonium isotopes, lung monitoring can provide a method of identifying people who require medical assessment. Some UK organisations have laboratories equipped with in vivo monitoring systems which are suitable for measurement of activity in whole body or Am-241 in the lung, but there are few of these and they may be located at some distance from an incident.

Following the accident at Chernobyl, Public Health England (PHE, then the National Radiological Protection Board) developed a well shielded transportable whole body monitor which is described in Youngman (2001). This transportable system was sensitive as it used thick lead shielding to reduce the influence of gamma-rays from surrounding naturally occurring radionuclides. This system used two HPGe detectors, one for measurements of whole body activity and one for measurements of iodine radionuclides in the thyroid. This system was shown to be very sensitive as it was capable of detecting internal contamination corresponding to an effective dose of much less than 1 mSv up to at least seven days following intake, for a wide range of fission and activation products which could be released following an accident at a nuclear reactor. The disadvantages of this system was that it was difficult to deploy as two trailers were required as the lead shielding used weighed approximately 400 kg, and the detectors required cooling with hazardous liquid nitrogen. The detector used was also insensitive to low energy gamma emitting radionuclides such as americium-241.

In addition to this transportable system, PHE has developed portable whole body monitoring equipment (Youngman, 2008) based on Detective radionuclide identifiers (Ortec, USA). Although these Detective based systems are much less sensitive (about a factor of 40 for measurements of caesium-137) they are capable of identifying people who have had intakes corresponding to a dose of much less than 1 mSv for a wide range of radionuclides which could be released following an accidental or deliberate release. However these systems could not be used in areas where there is environmental contamination because of the lack of of shielding.

The direct measurement of X-ray and low energy gamma-ray emitters in the body (such as from Am-241 and plutonium-239 (Pu-239)) is very much more difficult than higher energy emitters as most are absorbed by body tissues. Am-241 has been classified by the International Atomic Energy Agency (IAEA) as a radionuclide with a high security risk as it used in a variety of applications as high activity sources (Ferguson et al., 2003). As well as incidents involving dispersal of Am-241, there is the possibility of an accident involving a nuclear weapon. Such an accident could release isotopes of plutonium as well as Am-241. It is important to plan for such an accident as doses arising from internal contamination could be significant for the most exposed people because of the high radiotoxicity of Am-241 and isotopes of plutonium. None of the monitoring equipment described above is suitable for radionuclides which emit low energy gamma rays or X-rays. Where Am-241 is present together with plutonium isotopes it is common practice to infer the amount of plutonium by measuring the amount of Am-241 and using the activity ratios to calculate the amounts of plutonium present. This is because plutonium isotopes principally emit only very low energy X-rays (Scott, 2014). Am-241 and Pu-239 can also be quantified in the body by measurement of amounts excreted in urine and faecal samples. The collection and analysis of bioassay samples would increase the time required for completion of screening compared with direct measurements and also the use of an excretion model increases the uncertainty on calculated intakes and doses. The advantage of bioassay analysis is that capacity would be much greater than for direct measurements.

A transportable monitoring system for direct measurement of Am-241 in the lung is needed as potentially this offers the quickest method of identifying people who require medical assessment or additional measurements (Rojas-Palma et al., 2009).

This paper describes PHE’s revised transportable monitoring system which can be deployed close to the site of the accident. It will be capable of making measurements inside a Radiation Monitoring Unit (RMU, Thompson et al., 2011) which may be used by responders to carry out monitoring of external and internal contamination in people. This new system can be used to make measurements of fission and activation products in whole body and can also be used to measure Am-241 in the lung. The thickness of shielding has been reduced in order to allow easier deployment. In addition the detector has been replaced with one which is electrically cooled which has removed the requirement to transport liquid nitrogen. The detector unit includes all of the electronics required for signal analysis so that the detector can be connected to a laptop PC running spectrometry software with a Universal Serial Bus (USB) lead. The detector can be accurately positioned in both vertical and horizontal directions and the range of detector movement allows measurements of people of all ages and also positioning close to the centre of the chest to make measurements of Am-241 in lung.

The requirement to use the transportable in vivo monitoring system to make measurements of iodine-131 in the thyroid has been removed, as these measurements can now be made with either the Detective based system or using shielded scintillation detectors (Youngman, 2014).

It will be possible to deploy the new system to any part of mainland Britain within 24 hours of a request for PHE’s assistance to monitor people. The detector supports, shielded chair and associated electronics are shown in figure 1.

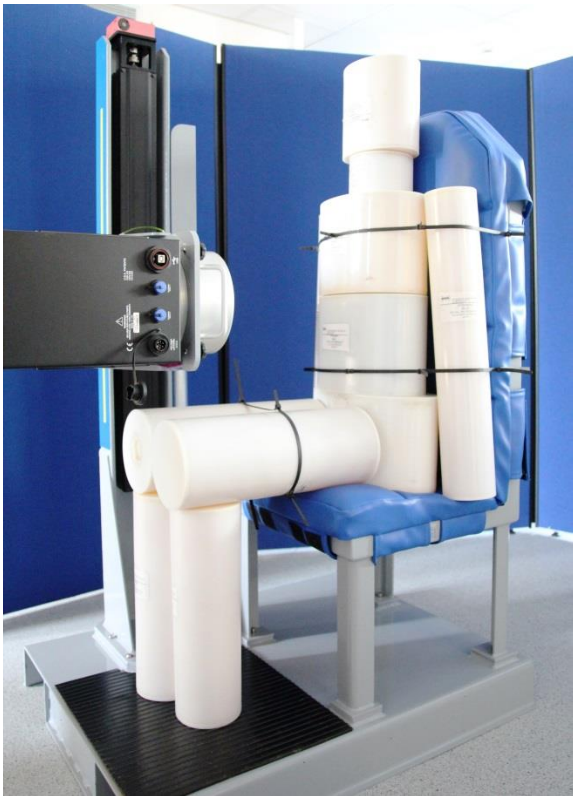

Figure 1 Transportable monitoring system in whole body measurement geometry showing BOMAB phantom

2 Detector

The detector used in this transportable monitoring system must be sensitive to higher energy gamma rays emitted by radionuclides such as caesium-137 and cobolt-60 so the crystal used must be large. In addition, to have sufficient sensitivity to Am-241, it must have a thin entrance window with a minimum of absorbing material in front of the sensitive part of the detector. The detector chosen for this application is an Interchangeable Detector Module (IDM) 200V (Ortec, USA). The crystal has a surface area of 57 cm^2 is 3 cm in length and it is electrically cooled using Sterling cycle technology. The end-cap window thickness is 1 mm aluminium, the front contact thickness is less than 10 microns and the detector has an internal 8mm thick tungsten back shield. This detector can be powered using batteries, so that it can be kept cold during transport and operated in locations where mains electricity is not available. The detector has internal signal processing electronics and so the only connections required are AC/DC power and USB. The detector is operated using GammaVision (Ortec, USA) Multi-Channel Analyser (MCA) emulator and gamma-ray spectrum analysis software.

The characteristics of this detector can be compared with that used on the previous transportable system (Youngman, 2001) which used a crystal which was of similar diameter but was 9 cm long, and had an end-cap thickness of 1.5 mm of magnesium alloy and a front contact thickness of 0.7 mm.

3 Shielding and Measurement Geometries

Figure 2 shows a side view of the transportable monitoring system and shows the detector in position for a measurement of whole body activity in an adult. The detector horizontal position can be adjusted so that the front face is from 10 to 70 cm from the chair, and the vertical position between 15 and 85 cm from the detector centre to the chair. This range of movement is greater than available on the previous system (Youngman, 2001).

The chair is shielded using 2.5 cm of low background lead and on the surfaces closest to the detector with a 3 mm layer of high purity tin and then a 1 mm layer of high purity copper. This 'graded lining' is intended to remove florescence X-rays produced in the lead which are of sufficient energy to interfere with measurements of Am-241. The chair has a padded cover positioned over the shielding.

A chair type measuring geometry has been utilised as it requires much less space than a bed geometry and is easier for the subjects to access. For measurements of activity in whole body, the detector is used at a fixed distance from the subject and the height adjusted so that the detector is over the centre of the torso. The range of vertical adjustment means that it should be possible to make measurements for people of all heights. For measurements of Am-241 in lung the detector is moved to 2 cm from the subject with the top edge of the detector in-line with the subject's clavicles.

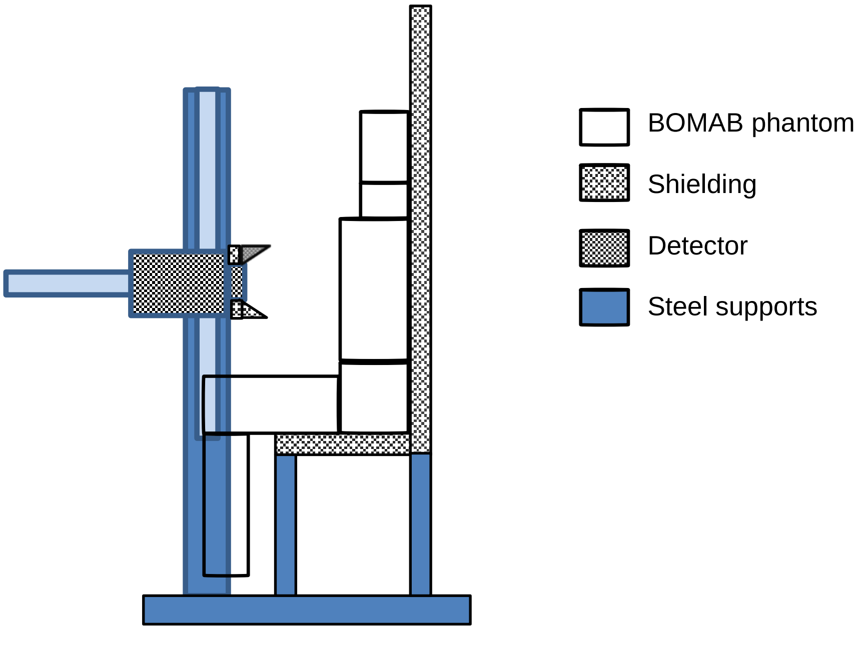

Figure 2 Cross section of the transportable monitoring system

As the system is designed to be readily transported it is not possible to use the massive shielding often used for fixed whole body counters. Instead a shadow shield arrangement has been used which places the shielding where it is most effective ie close to the detector. A result of using lead shielding around the detector is to increase the load on the detector support and positioning arrangement and so a safety device is fitted to prevent the detector and shielding falling rapidly following a mechanical failure of the positioning mechanism.

The effectiveness of the lead shielding at reducing natural background radiation is shown in figure 3, and table 1 gives attenuation factors at various energy intervals. Table 1 shows that the chair shielding is not reducing the natural background significantly but the detector shield is more effective. The principal reason for using shielding is to reduce the effect of possible environmental contamination on measurements of people. The thickness of lead used for this system gives approximately 95% attenuation for 661 keV photons.

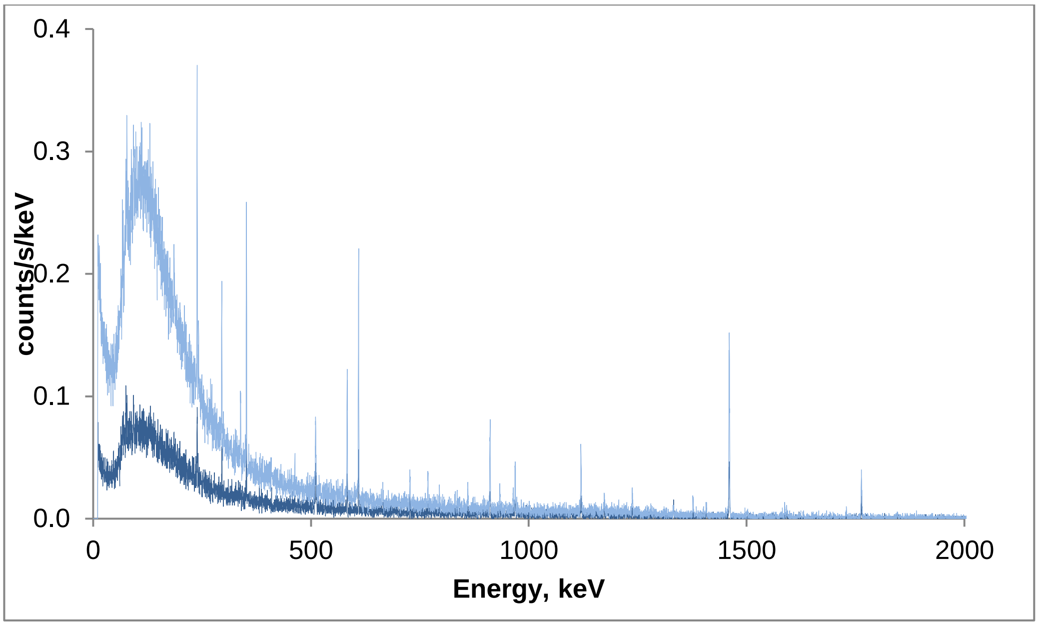

Figure 3 Background spectra for system used for whole body measurements (top spectrum shows background without shielding and lower spectrum with shielding)

Table 1 Background reduction factors by various shielding components of the system

energy interval (keV)	chair shield only	detector shield only	all shielding
100-300	1.2	2.1	3.1
300-500	1.2	1.9	2.6
500-700	1.2	1.8	2.3
700-900	1.1	1.7	2.0
900-1100	1.1	1.7	2.1
1100-1300	1.1	1.7	2.2
1300-1500	1.1	1.7	2.2
1500-1700	1.1	1.7	2.0
1700-1900	1.0	1.8	1.9

The background reduction factors are similar to those achieved for a scintillation detector whole body counter described by Lahham and Fulop (1997) .This work gives experimentally determined Detection Limits values for Cs-137 at various levels of Cs-137 ground contamination. The Detection Limits was shown to increase by a factor of 3 at 100 kBq m-2 and by a factor of 6 at 1000 kBq m^{-2} it is likely that similar factors can be applied to this system and therefore the system will still be able to measure significant whole body activities in the presence of ground contamination.

For measurements of whole body activity, the front of the detector is fitted with a collimator which is made from the same materials and thicknesses as the chair shielding. The outside edge of the cylindrical diameter extends away from the detector front face to give an angle between the inside and outside collimator edges of 45 degrees. The detector shield has the effect of reducing sensitivity to the person’s extremities. In the standard position for whole body measurements, for a count of a BOMAB phantom containing Cs-137, the pelvis and chest sections (see figure 4 labelled C and E) contribute approximately 80% of the total count from the phantom. The standard counting position for activity in whole body is to have the detector 60 cm from the back of the chair and positioned vertically to be central over the torso. The effect of detector positioning error was investigated using a BOMAB phantom containing Cs-137. It was found that a 20 cm variation in detector height has very little effect on counting efficiency. However it is likely that vertical detector position will be more important for measurements of children. It was also shown that having the detector 10 cm closer or 10 cm further away from the person has little effect on counting efficiency, however it would be expected that greater distances will decrease the effectiveness of the shadow shield arrangement and at closer distances any inhomogeneity of activity in whole body would have a greater effect on measured activity; for example if activity is concentrated in the lungs.

For measurements of Am-241 in lung the detector is placed 2 cm from the subject over the lungs which maximises counting efficiency and reduces background. The detector is placed centrally over the chest to simplify the detector supports system. A sleeve collimator is used of the same construction as the chair shielding and the end of the collimator is level with the detector endcap.

The effect of detector positioning error for Am-241 measurements was investigated using the Lawrence Livermore phantom (LLP), (Griffith et al., 1986). It was shown that the central position was more efficient than placing the detector over the LLPs left lung (by 20%) but less efficient (by 24%) than placing the detector over the right lung. The central position has the effect of counteracting differences in activity deposited in the left and right lungs. The variation of count rate with position across the chest shows that an error of 2 cm would not significantly affect the measurement efficiency. The standard distance between the person and detector is 2 cm, measurements with the LLP show that doubling this distance decreases the measurement efficiency by 17%. Varying the vertical position of the detector has shown that a 2 cm positioning error does not significantly affect the measurement efficiency.

4 Transport

The mass of the major system components are shown in table 2. For transportation the equipment is loaded into a trailer which can be towed by a normal car. The heavy equipment items are loaded and unloaded using a pallet truck and transported to the building to be used as an RMU. The facilities which buildings must have to be suitable for use as an RMU are described in Thompson at al. (2011) Installing the system inside a building takes 1 to 2 hours.

Table 2, Masses of major system components

Component	Mass (kg)
detector collimator (sleeve)	12
detector collimator (angled)	15
chair shielding	150
detector support assembly	180
detector (including internal tungsten back-shield)	23
pallet truck	80
loading ramps	65
Total	525

5 Calibration

5.1 Reactor Accidents

The system was efficiency calibrated for whole body activity in the energy range 560 keV to 1460 keV using solutions of radionuclides uniformly distributed in a Bottle Mannikin Absorption phantom (BOMAB, figure 4), (ICRU,1992).The radionuclide standards used to prepare these BOMABs are traceable to National Laboratory standards, The standard BOMAB phantom is approximately the same size and weight as ICRP Reference Man (ICRP, 1975). Figure 5 shows the calibration factors determined with this system and compares them with calibration factors determined using the previous system which used a large (90% relative efficiency) p type coaxial detector. It can be seen that efficiencies achieved with the older system were higher, particularly at higher gamma-ray energies; this can be accounted for as the 90% detector is much thicker. At lower energies the efficiencies are closer together which would be expected as the IDM-200 has a thinner end-window.

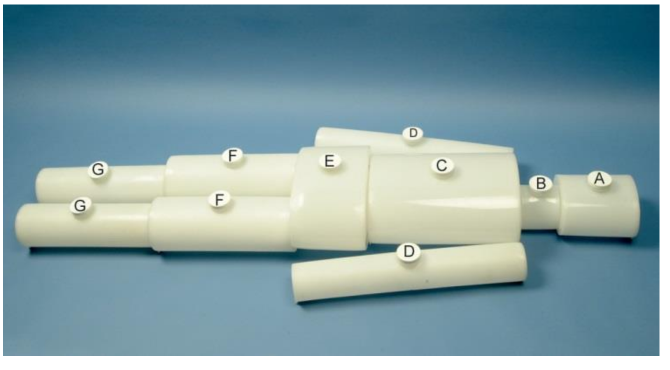

Figure 4 Bottle Mannikin Absorption Phantom (BOMAB)

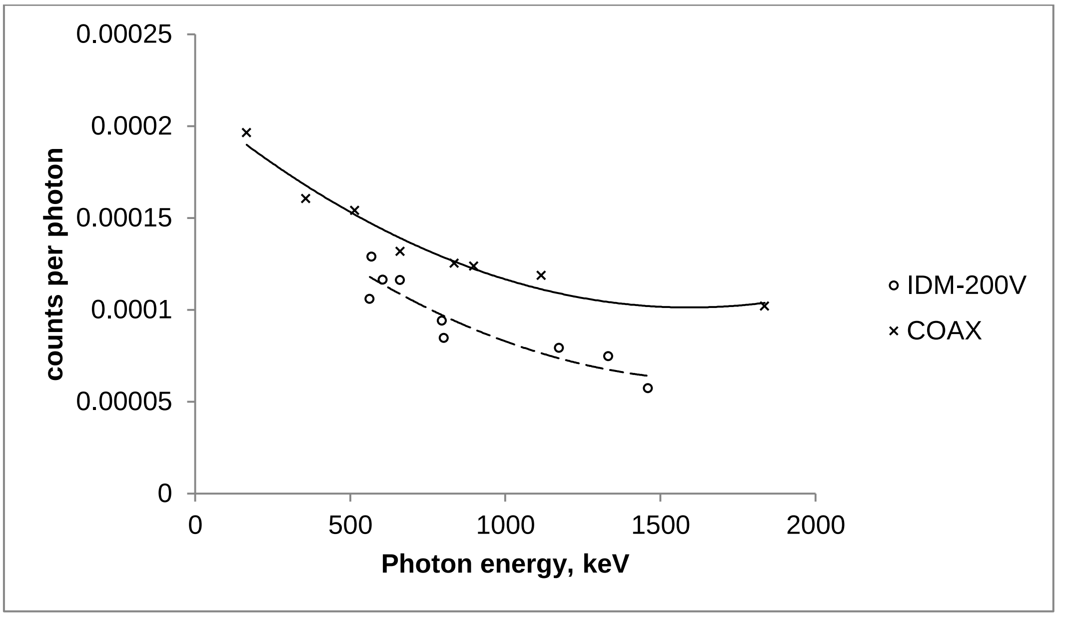

Figure 5 Efficiency for measurements of radionuclides in whole body for this study (IDM-200V) and for an earlier study (COAX, Youngman, 2001)

Efficiencies for measurements of children will be higher and an earlier study (Youngman, 2001) indicates that for children < 1 year old that the counting efficiency would be 2-3 times higher than for adults.

Table 3 gives Detection Limits (DLs) for measurements of activity in whole body for a 10 minute count for radionuclides which could be released following a reactor accident. DLs were calculated using the method described by Currie (Currie, 1968). DLs for ruthenium-106 (Ru-106) and barium-140 (Ba-140) are higher because relative few gamma-rays are emitted per decay for these radionuclides. The value for cerium-141 (Ce-141) is noticeably higher because of the low gamma-ray emission probability combined with higher background at lower energies (see figure 3).

Table 3 Detection Limits (95% confidence) for whole body measurements of an adult for a 10 minute count time

Nuclide	Energy of principal emission , keV	Detection Limit, Bq
Zirconium-95 (Zr-95)	757	640
Niobium-95 (Nb-95)	766	230
Ruthenium-106 (Ru-106)	622	1500
Tellerium-132 (Te-132)	228	390
Caesium-134 (Cs-134)	604	340
Caesium-136 (Cs-136)	819	180
Caesium-137 (Cs-137)	662	280
Barium-140 (Ba-140)	537	1200
Lanthium-140 (La-140)	1596	320
Cerium-141 (Cs-141)	145	2900

5.2 Americium-241 in lung

Lung calibrations were done using a Lawrence Livermore realistic thoracic phantom (LL phantom), (Griffith et al, 1986). This phantom has been used as the *de facto* standard for calibration of lung counting systems for measurements of Caucasians. The phantom represents a 1.77 m tall male weighing 76 kg and consists of a torso shell of muscle equivalent material with an embedded rib cage and the anterior thickness of the shell is 1.6 cm. The LL phantom can be loaded with lungs uniformly labelled with Am-241 or blank lungs. It is possible to add overlays to the torso plate to simulate people of different morphologies. These plates are 0.7, 1.3, 1.7 and 2.5 cm thick and the ones used in this study represent 50% muscle and 50% adipose tissue. The overlays are designed to be used singly, however for the purpose of achieving an estimated calibration for people of larger stature it was decided to carry out an extra measurement using the two thickest overlays together. The Lawrence Livermore phantom is shown in figure 6.

Figure 6 The Lawrence Livermore torso phantom used for Am-241 in lung calibrations

Vickers (1996) has produced equations which can be used to determine an appropriate chest wall thickness (CWT) for a particular person using their sex, height and weight. ICRP have published average values for height and weight for people of different ages (ICRP, 2002). The average height and weight data has been used with the equations taken from Vickers to determine approximate average CWTs for people of different ages (see table 4). Equations to determine CWT are available for males and females but are not intended application to children. For this work, the equation for female adults was used to predict CWT for children. For children aged 10 years and younger the Vicker's equation predicts a CWT lower than that which can be achieved using the LL phantoms and so it is proposed to use the calibration factor for a CWT of 1.6 cm (the minimum possible) which will ensure that that activity in lung is not underestimated. For children aged older than 10 and for all females the calibration factor for a CWT of 2.3 cm will be used and for adult males the calibration factor for a CWT of 2.9 cm. Calibration factors and DLs are shown in table 5 for a number of CWTs determined using the LL phantom and a photograph of the lung counting geometry is shown in figure 7. If Am-241 is identified in the lung then for adults the persons CWT should be calculated using their individual height (in centimetres) and weight (in kilograms) using the equations below (Vickers, 1996). These equations were developed using ultrasound measurements of people in a sitting position which is appropriate for the system described here. The uncertainty (95% confidence interval) on the calculated CWTs is about 0.5 cm. The majority of publications giving equations to calculate CWT are for people in a supine position and these are 0.3 cm to 0.5 cm higher than for people in a sitting position (Kramer et al, 2001).

CWT (cm) = [4.19 (W/H) + 0.82] (male, Vickers,1996)

CWT (cm) = [5.35 (W/H) + 0.17] (female, Vickers,1996)

Figure 7 Lung counting geometry shown with Lawrence Livermore Phantom

Table 4 Predicted Average Chest Wall Thicknesses

Age	Male/Female	Average Height, cm[1]	Average Weight, kg[1]	Predicted chest wall thickness, cm
1	-	76	10	0.9[2]
5	-	109	19	1.1[2]
10	-	138	32	1.4[2]
15	-	164	55	2.0[2]
20-30	Female	170	55	1.9
20-30	Male	170	70	2.5
>30	Female	170	60	2.1
>30	Male	170	80	2.8

Notes
1. Data taken from ICRP (2002)
2. Calculated using the equation for females (Vickers, 1996)

Table 5 Calibration factors for measurements of Am-241 in lung and corresponding Detection Limits (95% confidence)

Chest wall thickness, cm	Calibration factor, counts per second/ gamma per second	Detection Limits for 600 second count, Bq
1.6	0.0034	58
2.3	0.0026	76
2.9	0.0022	90
3.3	0.0018	110
4.1	0.0016	120
5.8	0.00078	250

6 Performance

6.1 Reactor Accidents

The TMT Handbook (Rojas Palma, et al., 2009) has proposed the use of Action Levels to facilitate decisions about actions following intakes of radionuclides. An upper Action Level is associated with urgent actions (such as medical assessment) and a lower action level associated with actions which are less urgent, such as inclusion in any programme of long-term follow-up monitoring. The lower Action Level should be considered as a variable quantity, between a committed effective dose of 1 mSv and 20 mSv. For children (below 16 years of age) the TMT Handbook recommends that Action Levels determined for adults should be reduced by a factor of 10 to provide an adequate degree of conservatism in the initial stages of a response. Table 6 shows doses corresponding to a measurement equal to the Detection Limit assuming measurement is made 7 days after intake (Detection Limits are taken from table 3). It can be seen that this system is sensitive enough to detect activities corresponding to committed effective doses of 1 mSv in adults.

For measurements of children, if the advice given in the TMT Handbook (Rojas Palma, et al., 2009) is followed then for some radionuclides with low gamma-ray emission probabilities (ie Ru-106, Ba-140, La-140, Ce-141) the system would not be sufficiently sensitive to detect activity in children that exceeds the lower Action Level (ie 0.1 mSv). However these radionuclides would be released with larger quantities of radionuclides which are more readily detected, such as Cs-137, and so these radionuclides could be used as a ‘tracer’ for the presence of radionuclides which are more difficult to detect. It is worth noting that the National Council on Radiation Protection and Measurements (NCRP) recommends that dose criteria for adults are reduced by a factor of five for children (NCRP, 2008).

Table 6 Dose corresponding to a whole body measurement equal to the Detection Limit

	Dose corresponding to a measurement equal to the Detection Limit made 7 days after intake, mSv	
Nuclide	**Age 1 year**	**Adult**
Zr-95	0.07	0.03
Nb-95	0.01	0.004
Ru-106	0.7	0.3
Te-132	0.07	0.009
Cs-134	0.005	0.008
Cs-136	0.003	0.001
Cs-137	0.003	0.004
Ba-140	0.2	0.1
La-140	0.4	0.1
Ce-141	0.2	0.1

IAEA (IAEA, 2011) have published guidance that if the dose that has been received exceeds 100 mSv (effective dose in the first month following intake) that longer term medical actions should be taken to detect and to effectively treat radiation induced health effects. IAEA does not give separate dose reference levels for children, but instead states that if the dose criteria are applied that all members of the public will achieve a level of protection that meets international standards. The monitoring system would be sensitive enough to detect intakes that correspond to this dose.

The TMT Handbook upper Action Level is set at 200 mSv (Rojas Palma et al., 2009) and the monitoring system described here would be capable of identifying people who exceed this criterion for reactor accidents.

6.2 Americium-241 and mixtures of americium-241 and plutonium isotopes

In order to be valuable following an incident where Am-241 or mixtures of Am-241 and plutonium isotopes are released to the environment a monitoring system needs to be able to detect activity in the body which correspond to levels where deterministic effects are likely or correspond to unacceptably high stochastic risk. The stochastic risk can be judged by the calculated effective dose over 50 years for adults and to age 70 years for children and avoidance of deterministic effects can be judged by the relative biological effectiveness (RBE) weighted absorbed dose (IAEA, 2005).

The TMT Handbook (Rojas-Palma et al., 2009) has defined an upper Action Level of 200 mSv (committed effective dose) and if doses exceed this level than urgent medical assessment is needed.

The RBE-weighted averaged absorbed dose in the organ or tissue is defined as a product of averaged absorbed dose and the relative biological effectiveness (RBE). For internal contamination, IAEA has set a RBE weighted absorbed dose of 30 Gy-Eq for the lung and 0.2 Gy-Eq for exposure of the red bone marrow to actinides, integrated over 30 days following intake (IAEA, 2005). If these dose criteria are exceeded then IAEA recommends actions which include immediate medical examination and immediate decorporation (if applicable).

NCRP (NCRP, 2008) have also recommended numerical values for doses when considering the need for medical treatment of internally deposited radionuclides or as a screening level for a more detailed investigation as follows. For consideration of deterministic effects to bone, NCRP have set a RBE weighted absorbed dose of 0.25 Gq-Eq and 1 Gy-Eq for consideration of deterministic effects to the lungs, integrated over 30 days.

NCRP (NCRP, 2008) have recommended numerical values for consideration of stochastic risk for adults as 250 mSv (effective dose integrated over 50 years) when considering the need for medical treatment or as a screening level for more detailed investigation. For children (0 to 18 years) numerical values were set by NCRP to one-fifth of the adult values.

Considering the above, it was decided the detection limit of the lung monitoring system should be compared with activity in lung corresponding to a committed effective dose of 200 mSv (integrated over 50 years for adults and to age 70 for children), (Rojas-Palma et al., 2009) and the IAEA RBE weighted absorbed dose of 30 Gy-Eq for the lung and 0.2 Gy-Eq for exposure of the red bone marrow (RBM) to actinides, integrated over 30 days. The IAEA RBE-weighted absorbed dose criteria were used as these are specific to intakes of actinides. According to

IAEA (IAEA, 2011), the proposed values do not need to be adjusted to take account of any particular members of the population (eg children or pregnant women).

6.2.1 Americium-241 only

Table 7 shows activity in lung corresponding to RBE-weighted dose criteria where immediate medical examination is required for intake by inhalation of Am-241.

Table 7 Activity in Thoracic Lung Corresponding to the Absorbed Dose Criteria for Intakes of Am-241

		Activity in Thoracic Lung, Bq[a]			
Target Organ	**Age, years**	**Delay between intake and measurement, days**			
		1	10	20	30
Lung	20	1.62E+06	1.38E+06	1.15E+06	1.15E+06
	5	3.57E+05	2.86E+05	2.86E+05	2.14E+05
	0.25	7.50E+04	7.50E+04	5.00E+04	5.00E+04
Red Bone Marrow	20	1.89E+06	1.62E+06	1.35E+06	1.35E+06
	5	1.82E+05	1.45E+05	1.45E+05	1.09E+05
	0.25	2.00E+04	2.00E+04	1.33E+04	1.33E+04

(a) Activity in thoracic lung corresponding to an RBE weighted dose of 0.2 Gy-Eq to RBM or 30 Gy-Eq to lung for intake of Am-241 only, integration period is 30 days (IAEA, 2011). Assuming Absorption Type M, Activity Mean Aerodynamic Diameter of 5µm and f1 = 0.0005

Table 8 gives activity in lung corresponding to a committed effective dose where immediate medical examination is required (Rojas-Palma, 2009).

Table 8 Activity in Thoracic lung corresponding to a Committed Effective Dose of 200 mSv for Intakes of Am-241

	Activity in Thoracic Lung, Bq[a]			
Age, years	**Delay between intake and measurement, days**			
	1	10	20	30
20	3.33E+02	2.86E+02	2.38E+02	2.38E+02
5	1.96E+02	1.57E+02	1.57E+02	1.18E+02
0.25	8.22E+01	8.22E+01	5.48E+01	5.48E+01

(a) Activity in thoracic lung corresponding to a committed effective dose of 200 mSv for adults and children. Dose coefficients were taken from ICRP publication 119 (ICRP, 2012). Assuming Absorption Type M, Activity Mean Aerodynamic Diameter of 5 µm and f1 = 0.0005. Dose integrated over 50 years for adults and to age 70 for children.

Comparison of the activities corresponding to dose criteria from table 7 and 8 with the detection limits from table 5, show that this system is generally capable of identifying people where urgent action is required. The exception is the committed effective dose criteria for children if the advice given by the TMT Handbook to divide action levels determined for adults by a factor of ten.

6.2.2 Plutonium-239 and Americium-241

Table 9 shows activity in lung corresponding to RBE-weighted dose criteria where immediate medical examination is required for intake by inhalation of mixtures of Pu-239 and Am-241.

Table 9 Activity in thoracic lung of americium-241 corresponding to absorbed dose criteria for intakes of a mixture of plutonium-239 and americium-241

		Activity in thoracic lung, Bq[(a)]			
Target Organ	Age, years	Delay between intake and measurement, days			
		1	10	20	30
Lung	20	9.42E+04	8.07E+04	6.73E+04	6.73E+04
	5	2.05E+04	1.64E+04	1.64E+04	1.23E+04
	0.25	4.35E+03	4.35E+03	2.90E+03	2.90E+03
Red Bone Marrow	20	1.41E+06	1.21E+06	1.01E+06	1.01E+06
	5	1.52E+05	1.21E+05	1.21E+05	9.10E+04
	0.25	1.72E+04	1.72E+04	1.14E+04	1.14E+04

(a) Activity od Am-241 in thoracic lung corresponding to an RBE weighted dose of 0.2 Gy-Eq to RBM or 30 Gy-Eq to lung for intakes of Pu-239 and Am-241, integration period is 30 days (IAEA, 2011).

Assuming Pu-239:Am-241 activity ratio is 15:1.

For Am-241, assumes absorption Type M, Activity Mean Aerodynamic Diameter of 5 µm and f1 = 0.0005

For Pu-239, assumes absorption Type S, Activity Mean Aerodynamic Diameter of 5 µm and f1 = 0.00001

Table 10 gives activity in lung of Am-241 corresponding to a committed effective dose where immediate medical examination is required for a mixture of Pu-239 and Am-241(Rojas-Palma, 2009).

Table 10 Activity in Thoracic lung of americium-241 corresponding to a committed effective dose of 200 mSv for intakes of a mixture of plutonium-239 and americium-241

	Activity in thoracic lung, Bq[(a)]			
Age, years	Delay between intake and measurement, days			
	1	10	20	30
20	4.96E+01	4.26E+01	3.55E+01	3.55E+01

5	2.19E+01	1.75E+01	1.75E+01	1.32E+01
0.25	8.36E+00	8.36E+00	5.57E+00	5.57E+00

(a) Activity in thoracic lung corresponding to a committed effective dose of 200 mSv for adults and children.
Pu-239:Am-241 activity ratio 15:1. Dose integrated over 50 years for adults and to age 70 for children.
For Am-241, assumes absorption Type M, Activity Mean Aerodynamic Diameter of 5 µm and f1 = 0.0005
For Pu-239, assumes absorption Type S, Activity Mean Aerodynamic Diameter of 5 µm and f1 = 0.00001

Comparison of the detection limits from table 5 with the activities in tables 9 show that the system would be capable of identifying people who exceed the IAEA absorbed dose criteria. Comparison of detection limits with effective dose criteria in table 10 show that the monitoring system would not be sufficiently sensitive to identify people who exceed an effective dose of 200 mSv.

7 Conclusions

A transportable combined whole body and Am-241 in lung monitoring system has been described. This system can be deployed to the site of an accident in the UK within 24-hours.

Following a release from a nuclear reactor the monitoring system described here would be capable of detecting people who have received intakes corresponding to doses of much less than a committed effective dose of 1 mSv, for a wide range of fission and activation products.

Following a release of Am-241 or a mixture of Am-241 and Pu-239 to the environment it would be necessary to identify anyone who requires medical assessment. Such a release could result from a deliberate release, an accident involving a nuclear weapon or at a nuclear site. The best means of identifying these people is direct measurement of Am-241 in the lungs of potentially exposed people. This monitoring should happen as soon as possible after the intake and so is best provided by deploying monitoring equipment to the vicinity of the incident.

For intakes of Am-241 only, it has been shown that the transportable lung monitoring system described here would be able to detect activity in lung which corresponds to the IAEA absorbed dose criteria for people of all ages. The system is also capable of identifying adults who exceed the TMT Handbook's upper Action Level which is used to indicate urgent medical assessment is required. However the system is not capable of detecting activity in lung corresponding to the upper Action Level for children if the TMT advice is taken to divide Action Levels by a factor of 10 for application to children.

For intakes of Am-241:Pu-239 mixtures, it has been shown that the system would be capable of detecting activity in lung which correspond to the IAEA absorbed dose criteria. However the system would not be capable of detecting people who will receive a committed effective dose of 200 mSv.

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