0.916 man-rem/MW(e)y in 1979 and 0.642 man-rem/MW(e)y in 1980. These figures indicate that our first NPS was in normal condition during the first two-years of commercial operation.

Ensuring that exposure to radiation on the job will be as low as reasonably achievable (ALARA) has long been the goal of TPC, both for individual workers and for station personnel. It has been accomplished through comprehensive plans, programs, and procedures administered by the Health Physics Division of TPC and its NPS. The licensing procedures adopted by our aec and the intensive training program given by the TPC have also contributed to the success of radiation control in our NPS.

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Direct Assessment of Plutonium in the Chest with Germanium Detectors

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FALK *et al.* (Fa79) and also Berger and Goans (Be81) have described arrays of high-purity planar germanium detectors, installed for the assessment of internal contamination. In both papers the authors discussed the possible application of these arrays in the assessment of plutonium in lungs through detection of uranium L_β and L_γ X-rays (energies 17.2–20.2 keV). The prospective advantages of such systems, compared with the "phoswich" detectors (i.e. dual scintillators) commonly used for this purpose, derive from their much better energy resolution. The consequent reduction in the energy interval over which spectral peaks need to be integrated offers the prospect of improved signal: background ratios. This applies both in connection with the detector's response to ambient background radiation, and also with the "subject background", i.e. the low-energy scattered photons from other sources of body radioactivity, whose intensity is determined by a subject's physique as well as by his contents of natural ^{40}K and any radioactive contamination other than plutonium. Moreover, there is a possibility that the total background (i.e. counter + subject) may be assessed reliably from the response observed in energy intervals adjacent to and/or between the L_β and L_γ X-ray regions.

The prospective user of the germanium detector must consider to what extent its other features may detract from the improvement in sensitivity promised by its good energy resolution. In particular, it has no inbuilt anti-coincidence potential which, in the phoswich detector, discriminates against ambient- and subject-background radiations; and the lack of availability of intrinsic germanium detectors, except in small sizes (maximum sensitive area ~ 50 mm diam.), means that arrays of counters, inevitably separated by insensitive regions, are required if larger areas of the chest are to be covered.

In this note we report the use of a planar germanium detector to record uranium L X-rays from a subject contaminated with ^{238}Pu, and use the results to assess the performance of an array of these counters. We then compare this performance with that deduced for an established system of 114-mm diam. phoswiches, also used in investigations on the contaminated subject.

The Subject and Assessment of His Lung Content

The subject was a man of average physique: weight 75 kg, height 1.74 m, chest circumference 0.98 m. His chest wall thickness (CWT) was investigated at LLNL by ultrasonic 'B' scanning methods (Ca79), and averaged 26 mm over the anterior surfaces of the upper thorax. The soft tissues of the chest wall contained about 30% adipose tissue.

The subject's contamination arose from an accidental intake of $^{238}PuO_2$ some years previously. It had been investigated periodically at AERE with a 200-mm-diam. phoswich detector viewing the anterior surfaces of the upper thorax, over the right and left lungs sequentially. On each occasion, the content was calculated from the combined response in the two positions which was attributable to ^{238}Pu, i.e. the observed count rate from uranium L X-rays, after subtraction of the counter- and subject-background response. This net count rate was translated into an estimate of ^{238}Pu activity by reference to previously recorded spectra of X-rays emitted by subjects whose lungs contained independently known quantities of ^{103}Pd (Ne78). In fact, other observations (including the detection of X-rays emitted from the skull) showed the additional presence of a systemic burden of ^{238}Pu, and it appeared that roughly 30% of the recorded X-ray emissions from the front of the chest could have originated in the ribs, rather than in the lungs. This proportion ought not to affect materially the superficial pattern of X-ray emissions from the chest; hence the comparisons we shall make should remain valid, in those situations where the activity is confined to the lungs.

Because of the interfering contributions from skeletal activity, the estimates of ^{238}Pu activity from these measurements with the phoswich will be referred to as "equivalent lung burdens", or ELBs. Each ELB represents an amount of ^{238}Pu which, if present exclusively in the lungs, would produce the same phoswich count-rate as that observed. From the serial investigations with the phoswich, AERE could estimate the contaminated subject's ELB of ^{238}Pu at the times when our two laboratories conducted the investigations to be described.

Investigations with the Germanium Detector

The counter was a high-purity planar germanium detector manufactured by Dektoren Technologie GMBH and on loan to AERE from PGT International. The quoted diameter and thickness of the sensitive region were 50 and 10 mm respectively. It was mounted inside a housing of overall diameter 77 mm, 5 mm behind a thin beryllium window of 57 mm diameter, which gave rise to negligible attenuation of low-energy photons. The energy resolution, which we measured both at 15.8 and at 122 keV, was ~800 eV (FWHM); the manufacturer had obtained a slightly better result (660 eV at 122 keV).

Photon-energy spectra were recorded with the detector viewing each of seven regions of the subject's chest. Six of the positions, on the anterior surfaces, are shown in Fig. 1. In each location, the detector was as close as was possible to the body, except that a 1-mm-thick beryllium plate was interposed in order to protect the fragile window; this introduced ~4% attenuation for uranium L X-rays. In positions 1 and 3, the detector housing (77-mm diameter) was roughly tangential to the relevant clavicle and lateral boundary of the sternum. In positions 2 and 4, the detector was displaced down the body from positions 1 and 3, by 57 mm (i.e. by one window diameter). Positions 5 and 6 were reached by lateral displacement from positions 3 and 4, again by 57 mm. In position 7, not shown in Fig. 1, the detector viewed the lateral surface of the thorax, from a location immediately below the right armpit.

Spectra recorded over 30 min, in each of the positions 1–4, showed discernible L_β and L_γ X-ray peaks. The sum of these four spectra, representing the response to be expected from an array of four such detectors occupying these positions, is shown in Fig. 2; an appropriate background spectrum, recorded with the detector viewing an inactive phantom, has been subtracted. The combined count rates for each position in the two energy ranges 16.2–18.1 keV (L_β) and 19.6–21.0 keV (L_γ) are given in Table 1. These count rates may be attributed wholly to ^{238}Pu; the estimated contributions from both the counter-and subject backgrounds have been subtracted, the latter assessed from a series of measurements with

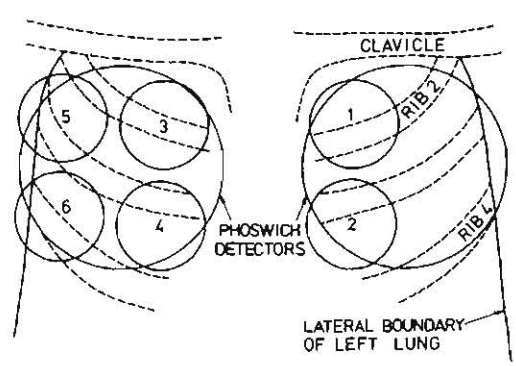

FIG. 1. Locations of detectors shown roughly in relation to anatomical features. The positions indicated are those occupied by the sensitive area of each detector window when in a horizontal plane, before re-orientation to achieve close contact with the body. Because of this re-orientation, the fields of view of the two phoswich detectors, and those of the germanium detector in positions 5 and 6, did not in practice overlap the lateral boundaries of the lungs, as appears in the figure.

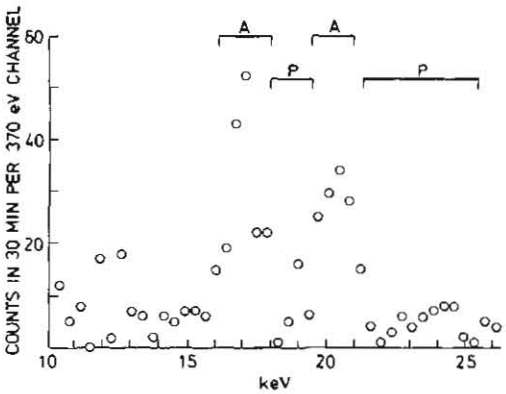

FIG. 2. Energy spectra of photons emitted from the chest of a subject contaminated with ^{238}Pu (sum of results in 30-min measurements with the planar germanium detector in each of the positions 1–4, Fig. 1, after subtraction of counter background). The energy intervals shown bracketed are those suggested for (A) assessment of a plutonium burden and (P) prediction of the subject background in the assessment bands.

*Table 1. Response (combined energy ranges 16.2–18.1 and 19.6–21.0 keV) of germanium detector to a subject containing ^{238}Pu**

Detector position (Fig 1)	Counts/minute ± 1σ†
1	1.5 ± 0.3
2	1.0 ± 0.2
3	1.8 ± 0.4
4	3.2 ± 0.4
5	0.3 ± 0.3
6	0.3 ± 0.3
7	0.6 ± 0.3

*Counter- and estimated subject backgrounds have been subtracted, and the results have been corrected for the 4% X-ray attenuation occurring in an additional thickness of beryllium interposed between the subject and the detector.

†σ : statistical standard error

uncontaminated subjects. The low count rates for positions 5 and 6, relative to those in positions 3 and 4, must be at least partly due to the subject's larger chest wall thicknesses at greater lateral distances from the mid-line; they may also of course reflect a non-uniform distribution of activity in the lungs. Position 2, on the left side of the chest, gave a lower response than position 4, the corresponding location over the right lung, presumably because the detector viewed a portion of the heart at the expense of lung tissue.

The summed response for positions 1–4 was 7.5 ± 0.7 counts/min (cpm). At the time of these investigations, the subject's ELB of ^{238}Pu, assessed from measurements with AERE's 200-mm-diam. phoswich detector, was 140 nCi. Good agreement between estimates (to be given below) made by AERE and LLNL 15 months earlier, when the ELB was slightly higher, supports the essential validity of this assessment. Hence we estimate that, in a subject of this chest-wall thickness (26 mm), with the same distribution of activity in the lungs and the same relative quantity of skeletal activity, the calibration factor for a four-detector array viewing these regions would be 7.5/140, or 0.054 cpm/nCi.

Sensitivity of Four Germanium Detectors Viewing the Central Regions of the Chest

Knowing the calibration factor for this arrangement, we may now calculate the statistical uncertainty attached to an estimate of zero nCi ^{238}Pu in a subject of 26-mm CWT, initially with the following assumptions:

(i) The subject's spectrum is recorded, over a period of 4000 sec, with an array of four detectors occupying positions 1–4 (Fig 1).

(ii) The counter background is assessed in an additional measurement, also of 4000 sec.

(iii) A reliable relationship can be established, from investigations of uncontaminated subjects or phantoms, between the subject background in the L_β and L_γ X-ray energy regions chosen for integration (i.e., the "assessment bands"), and the response in some neighbouring spectral region or regions (which we may call "prediction bands"). This relationship enables the subject background in the assessment bands to be calculated for a contaminated person, free of uncertainty except that imposed by counting statistics.

We chose as prediction bands the ranges 18.1–19.6 and 21.4–25.2 keV; for assessment bands the ranges 16.2–18.1 and 19.6–21.0 keV were used, as indicated in Fig. 2. In both cases, the count rates in the two ranges were combined. From measure-

ments of a whole-body phantom containing 2.5 kg KCl in solution, we found

$$\frac{\text{Cpm in assessment bands}}{\text{Cpm in prediction bands}} = 0.64 \pm 0.06 \quad \text{(statistical standard error)}$$

and, for our present purposes, we assume that this ratio of 0.64 is applicable, without error, in all uncontaminated subjects.

The calculation of ^{238}Pu in a subject returning a zero net count rate in the plutonium bands would appear typically as shown below; the counter backgrounds and subject responses assumed were based on measurements of an inactive phantom and of subjects with no likelihood of internal contamination. The uncertainties reflect counting statistics only.

Response in prediction bands	cpm($\pm 1\sigma$)
A Observed with subject in 4000 sec	5.00 ± 0.27
B Detector background, 4000 sec	3.16 ± 0.22
C Net from subject A–B	1.84 ± 0.35
Response in assessment bands	**cpm($\pm 1\sigma$)**
D Observed with subject in 4000 sec	3.50 ± 0.23
E Detector background, 4000 sec	2.32 ± 0.19
F Predicted subject background (0.64C)	1.18 ± 0.22
G Net attributable to Pu D–E–F	0 ± 0.37
Estimate of ^{238}Pu	
H G/0.054 = 0 ± 6.9 nCi	

This uncertainty (± 6.9 nCi) was not reduced by the use of narrower or wider assessment bands.

If we make the further assumption that the relative count rates in the prediction and assessment bands are similar for the subject- and counter- background components, then the total background in the assessment band can be assessed from the prediction-band response in the subject's *gross* spectrum, eliminating the need for measurement of the detector background. The burden would then be calculated from D—0.64A, which would carry a statistical uncertainty of ± 0.29 cpm, i.e. the uncertainty in the estimate of ^{238}Pu would be reduced to 5.4 nCi.

Investigations with 114-mm-dia. Phoswich Detectors

Lung burdens of plutonium are estimated on a routine basis at LLNL by a procedure employing two 114-mm-dia. phoswich detectors; very similar equipment is used in many other laboratories in the USA and elsewhere. Four assessments of the subject's ELB were made with these counters during a 2-day period.

In this standardised procedure, the detectors are positioned in contact with the anterior surfaces of the supine thorax, one viewing each lung, with the periphery of each roughly tangential to the sternum and clavicle (Fig 1). The analytical method which LLNL uses to derive an estimate of plutonium in lungs is essentially as follows:

(i) Subtract detector background (recorded in the presence of an inactive phantom) from spectrum obtained with subject present.
(ii) Subtract the estimated subject background in the assessment band (13–24 keV) from the net count rate after (i) above. This subject background is estimated from the subject's net count rate in the prediction band (80–100 keV), and for average physiques amounts typically to 23% of that count rate.
(iii) Convert the residual assessment-band response into an estimate of lung contamination by reference to calibration data appropriate to a subject's CWT, derived from measurements of a phantom (Gr79) with plutonium-loaded lungs.

In operational practice, the analysis is often modified to allow for the possible presence of ^{241}Am, emitting 60-keV γ-rays and Np L X-rays. With the proportions of ^{241}Am normally found, this modification does not greatly affect the statistical precision of assessments of plutonium from the U L X-ray emissions, and for the present, comparative purposes we may ignore this complication.

For our subject contaminated with ^{238}Pu, the mean of the four estimates of count rate attributable to plutonium, from step (ii) in the procedure above, was 38.3 cpm, with an observed standard deviation of 1.7 cpm. The corresponding burden of ^{238}Pu in a subject of this size, derived from step (iii), was 206 nCi. The contemporary ELB of 181 nCi, from measurements with AERE's 200-mm-dia. phoswich, was in close agreement; a major discrepancy was not to be expected, in view of previous consistency in calibration factors independently derived by the methods of AERE and LLNL (Ca81; Ne81). To ensure consistency with assumptions made for the germanium detector, we shall employ the lower (AERE) estimate which, if correct, would imply that the calibration factor for this subject was 38.3/181 or 0.21 cpm/nCi ^{238}Pu.

Sensitivity of the 114-mm-dia. Phoswich Detectors

As a measure of the sensitivity of LLNL's equipment and procedures, we may use the standard deviation about zero of calculated ^{238}Pu contents in a group of subjects with no likely exposure to risks of contamination. In 27 such subjects of close-to-average physique, the observed standard deviation of the residual count-rate (i.e. the count-rate with subject present, less counter background, less predicted subject background) was ± 0.77 cpm. Of this, a standard deviation of ± 0.48 cpm can be attributed to counting statistics:

	$\pm 1\sigma$(cpm)
Uncertainty in assessment-band response (typically 9.0 cpm) during 4000-sec measurement with subject present	0.37
Uncertainty in response (typically 4.5 cpm) during 4000-sec measurement with inactive phantom	0.26
Uncertainty in predicted subject background (typically 4.5 cpm), associated with counting statistics in the prediction band	0.16
Total uncertainty from counting statistics	0.48

From this it appears that other sources of variance are responsible for a contribution of $\pm\sqrt{0.77^2-0.48^2}$, or ± 0.60 cpm, to the observed standard deviation. This is assumed to result from errors in the prediction of the subject background (estimated from the net count-rate in the prediction band) which in an individual subject are systematic and related to his physique.

With the assumed calibration factor of 0.21 cpm/nCi ^{238}Pu for a subject of 26-mm CWT, the observed standard deviation (0.77 cpm) implies an uncertainty of ± 3.7 nCi in the calculated ^{238}Pu content.

Discussion

We have chosen to compare the sensitivity of the germanium-detector array with that of the 114-mm-dia. phoswich detectors at LLNL, rather than with that of the larger phoswich at AERE. This was because LLNL's detectors, and their arrangement relative to subjects referred for routine assessments of plutonium in the lungs, are much more typical of those employed by laboratories generally, especially in the USA, than are AERE's equipment and techniques. The validity of this comparison does of course depend on the two laboratories possessing equally effective shielding. We believe this to be the case. Expressed as counts per minute per cm^2 surface area of NaI(Tl) in their respective phoswich detectors, the counter backgrounds were 0.022 (LLNL) and 0.019 (AERE), for 13–24 keV.

We have estimated that if the envisaged array of four germanium detectors were used to assess small lung burdens of ^{238}Pu in male subjects of 26 mm CWT, the results would carry uncertainties (1σ) of 5.4 or 6.9 nCi, depending on what assumptions were permissible in deriving the values. In both cases, however, sources of variance other than counting statistics were assumed not to exist. The uncertainty which we have derived for an established method using phoswich counters (all sources of variance considered) is 3.7 nCi. The X-ray emissions from isotopically pure ^{239}Pu are some 2.5 times less abundant than from ^{238}Pu, and each of these uncertainties would be correspondingly increased for ^{239}Pu.

Certain aspects of the germanium detector's design must have impaired its efficiency for recording X-rays from distributed sources. The 50-mm-dia. sensitive surface was recessed inside the detector housing by 5 mm (the minimum distance practicable, according to the manufacturer), and the presence of this housing, and of internal structures supporting the crystal and the beryllium window, would restrict the detector's field of view. If a modified design were possible, substantially reducing the effective collimation, the sensitivity of an array of such counters might become comparable with that of the twin phoswich detectors.

Without such a change of design, or the development of a practical anti-coincidence technique to reduce the background substantially, it is difficult to foresee any major improvement in the sensitivity of germanium detectors of the sizes currently available. There may be scope for reducing the counter background of detectors like

the one we tested, by careful examination of all materials and components for radioactivity prior to manufacture or assembly; this one had not been made with our requirements specifically in mind. However, even if, hypothetically, the detector background could be reduced to zero, and the only relevant counting statistics were those associated with the subject background, the four-detector array simulated in our experiments would be only marginally more sensitive than Livermore's present phoswich detectors. Some decrease in both the counter- and subject backgrounds could result from reducing the sensitive thickness (10 mm) of the germanium detector, at the expense of its efficiency for detecting photons of higher energies. The scope for reductions in thickness to below 5 mm is apparently limited, if acceptable energy resolution is to be maintained. On the other hand, a substantial *improvement* in the resolution of these detectors, if it could be achieved, might not materially improve their sensitivity, owing to the spectral complexity of the X-ray emissions and the line-broadening effect of scatter by the body.

We note that our views on the potential of planar germanium detectors, vis-à-vis phoswich detectors in this context, are the reverse of those reached in an earlier comparison, by Berger and Goans (Be81). A contributory source of the discrepancy may be that Berger and Goans compared the performance of a germanium-detector array positioned over the right lung with that of a single phoswich detector viewing the left lung, from which, to judge from our Table 1 and other data (Ru73; Ne78), fewer X-rays would be emitted.

If the pattern of deposition within our subject's lungs is typical, then the data in Table 1 suggest that the 114-mm-dia. phoswich detectors may be of larger than optimum size, since their field of view evidently included regions from which few X-rays were emitted. Phoswich detectors of square, rather than circular, section have been produced experimentally (Um78), and twin counters of rectangular section, whose field of view was restricted essentially to regions 1–4 in Fig 1, could offer a worthwhile improvement in sensitivity. We believe that such an arrangement is potentially more sensitive than the array of germanium detectors, notwithstanding possible improvements in their mechanical design.

We must conclude by stressing that our inferences and remarks apply solely to the assessment of plutonium in lungs through detection of its L X-ray emissions. We accept that a germanium-detector array could prove to be useful in assessing contamination with ^{241}Am through its 60-keV photons, and in using the ^{241}Am as a tracer to estimate the amount of associated plutonium, where this is held to be valid.

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Beta Dosimetry using Laser Heating of Hot-pressed TLDs

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RECENT publications concerning the use of lasers as a heating source for thermoluminsescent dosimeters have prompted the consideration of this technique as an aid to beta dosimetry (Br81; Ga81. Suppose for the moment a suitable TLD material in the form of a hot-pressed chip is exposed to a beta source in such a way that only one surface, the front, can directly receive the incident betas. If this material is a few millimeters in thickness there will be a gradient of trapped electrons within the material due to the attenuation and absorption of the incident betas. If a γ-field is also present a uniform distribution of trapped electrons will be superimposed on the beta caused gradient.

Reading of this TL material in the conventional manner will result in the depopulation of the TL traps regardless of physical location due to the slow heating rate and the relatively high thermal conductivity of the material. If the material is heated with a pulsed laser as demonstrated by Braunlich *et al.* (Br81) the traps near the irradiated surface will depopulate first followed by deeper layers. It would appear that this technique or some modification of it may allow selective readout of TL traps depth by following the time history of the emitted TL. Various problems are immediately apparent as well as some inherent advantages. The brief discussion below touches on only a few.

The heating vs depth caused by a brief laser pulse will be directly related to the total energy content of the incident pulse, i.e. its peak power and width in time. Manipulation of these parameters could be used, for example, to allow only the first millimeter or fraction of a millimeter to be raised to a temperature high enough to allow trap depopulation. A second pulse or pulses could then be made having a much larger energy content which would allow all remaining traps to be depopulated. Problems due to surface damage would limit the maximum heating rate possible, but the signal-to-noise ratio improves as the heating rate increases due to the shorter time needed to receive the TL signal and hence the proportionately smaller noise signal. Thus a high heating rate limited only by material properties produces a better signal to noise ratio and if delivered in a short time can allow only near surface TL traps to be depopulated.

Figure 1 (adapted from Davis (Da63), illustrates the calculated time history of temperature rise due to a rectangular laser pulse having an absorbed irradiance of 340 W cm^{-2} and a width of 100 mec in a hotpressed LiF chip. Time zero starts at the beginning of the pulse. The maximum surface temperature occurs at the end of the pulse at time = 0.1 sec. The maximum temperature at depth depends upon the thermal diffusivity of the material and is illustrated by the dashed line. As an example 150°C is reached at a depth of 0.05 cm for the given laser output. These conditions are ideal for beta detection since a tenth value thickness for ^{85}Kr betas for example is about 0.05 cm in LiF. Other pulse shapes have been investigated, i.e. gaussian and triangular, and may be more suitable or easier to obtain than the rectangular pulse.

A detector that totally absorbs an incident spectrum of particles produces an output proportional to the particle fluence rather than absorbed dose. Clearly if the spectrum is known, the absorbed dose can be calculated from the fluence. The detector discussed here is intended to be totally absorbing (or nearly so) and thus will measure fluence. Based upon work done in this laboratory several years ago, it may be possible to unfold the TL vs depth data to yield crude incident specctral shapes. The process employed required an input "guess" and provides an output spectral shape which is one of a a family of possible shapes. Fortunately this method may not be needed at all since the ratio between beta fluence rate and absorbed dose rate is approximately constant (±10–15%) from 0.3 to 10 MeV. Hence a fluence measurement can be converted to an absorbed dose determination via a constant multiplier.