



DEPARTMENT OF COMMUNITY SERVICES AND HEALTH

Australian Radiation Laboratory



Participation of the Australian Radiation Laboratory
in International Intercomparisons of the Measurement of
External Environmental Radiation Using Thermoluminescence Dosimeters

by

Joseph G. Young, John F. Boas and Neville J. Hargrave

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ABSTRACT

The Australian Radiation Laboratory has participated in two International Intercomparisons of the measurement of external environmental radiation levels using thermoluminescence dosimeters. More than 130 organisations from 30 countries participated in these intercomparisons.

The first intercomparison in which ARL participated was held in 1984 with the field exposures being performed at a former nuclear weapons testing ground in Nevada, USA. This was the seventh in a series of International Intercomparisons of Environmental Dosimeters sponsored by the United States Department of Energy. Except for a standard exposure to a ^{137}Cs source, the results obtained by ARL agreed well with the delivered exposures, and compared favourably with the average exposure measured by the other participants. In the case of the ^{137}Cs exposure, ARL over-estimated the delivered exposure by approximately 18%.

The Eighth International Intercomparison was held during the northern hemisphere's 1985/86 winter. Two sites were used in this intercomparison; one was 58km west from New York City in a predominantly rural area while the other site was on the coast 30km south of the city. The environmental radiation levels for this intercomparison were a factor of approximately 5 lower than those measured in the previous intercomparison. In each case the agreement between ARL's reported exposures and the delivered exposures was only fair.

In all eight intercomparisons it was observed that those participants who used ^{137}Cs as their calibration source underestimated the delivered exposure by approximately 6% when compared with those participants who used a ^{60}Co calibration source. This was investigated further in a mini-intercomparison by those organisations (including ARL) able to calibrate dosimeters with both ^{137}Cs and ^{60}Co . A separate investigation undertaken at ARL also observed a 6% difference. The difference in response of thermoluminescence materials to ^{137}Cs and ^{60}Co remains unexplained.

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INTRODUCTION*

The Australian Radiation Laboratory (ARL) has participated in two International Intercomparisons of Environmental Dosimeters since 1984. The reasons for taking part in these intercomparisons were;

- (i) to assess the validity of the techniques employed at ARL for measuring very low environmental radiation levels,
- (ii) to compare ARL's performance with that of other organisations, and
- (iii) to test independently the accuracy and reliability of the ARL thermoluminescence dosimeter.

The two major intercomparisons in which the Laboratory took part were the seventh and eighth in a series sponsored by the United States Department of Energy. Interested groups representing more than 130 organisations from 30 countries participated in these intercomparisons. The organisations included dosimeter manufacturers, private consulting firms, nuclear utilities, government research laboratories and universities. Although film, radiophotoluminescence and thermally stimulated exo-electron dosimeters were submitted for evaluation, the most common type of dosimeter submitted incorporated thermoluminescence materials.

Thermoluminescence dosimeters are particularly well suited to low level external environmental radiation monitoring because of their small physical size, reliability and the long term stability of the thermoluminescence (TL) signal. In addition, they are relatively inexpensive, which is an important consideration when large scale environmental monitoring programs are being considered.

Thermoluminescence dosimetry (TLD) has been used routinely in the fields of medical and personal dosimetry since the late 1940s.⁽¹⁾ However, it was not until the mid 1960s that the technique was extended to the measurement of environmental radiation levels. Early researchers however, found that the use of thermoluminescence dosimeters for environmental monitoring was not straightforward and put demands on TLD not previously

* Non S.I. units employed for consistency with much published data;
1 mR = 0.258×10^{-6} C Kg⁻¹; 1 Ci = 37 GBq.

encountered in medical and personal dosimetry. Adverse environmental conditions such as rain, humidity and extremes of temperature, coupled with the requirement to measure very low radiation levels, made reliable and accurate measurements difficult. Despite these difficulties, environmental radiation monitoring using TLD has matured over the past 30 years into a well accepted practice. (2-8)

In 1974, the first of a series of International Intercomparisons of Environmental Dosemeters sponsored by the United States Department of Energy was commenced in an attempt to compare the techniques employed by different organisations. To date there have been eight International Intercomparisons of Environmental Dosemeters. These intercomparisons have proved extremely popular, with the number of participants increasing each time. The results of each intercomparison have been reported in a series of papers presented at the triennial International Conference on Solid State Dosimetry. (9) ARL has participated in the last two, namely the Seventh, held in 1984 and the Eighth, in 1985-86.

In general, the overall performance of environmental dosemeters in these intercomparisons has been very satisfactory, with good agreement between the delivered exposures and the mean of the exposures measured by the participants. However, since the inception of these intercomparisons a discrepancy has been observed between the results of those participants who calibrate their dosemeters with ^{60}Co and those who calibrate with ^{137}Cs . The results have shown that participants using a ^{60}Co calibration source report exposures which are in good agreement with the measured value while those using ^{137}Cs as their calibrating source report exposures which are, in general, 6% lower than the measured value.

A mini-intercomparison was undertaken in 1987 to try and resolve this anomaly. Because ARL has the ability to calibrate dosemeters with both ^{137}Cs and ^{60}Co the Laboratory was one of 60 organisations invited to participate.

This technical report describes the performance of the ARL TLD badge in the Seventh and Eighth International Intercomparisons. The results of the Mini-intercomparison are also discussed.

INTERCOMPARISON PROTOCOL

(i) Seventh and Eighth International Intercomparison

The intercomparison protocol has been described in detail by Gesell et. al. (9a) All exposures were performed in the United States of America by the Intercomparison organisers, namely the Environmental Measurement Laboratory (EML) or the National Institute of Standards and Technology (NIST, previously known as the National Bureau of Standards). Participants were requested to send one set of dosimeters for each type submitted for evaluation. Each set consisted of (i) field, (ii) laboratory and (iii) control dosimeters. Both laboratory and field exposures were performed in a similar manner to those of the previous six intercomparisons.

For each Intercomparison, a total of 8 dosimeters were submitted for evaluation. Six were used for "laboratory" or "field" exposures and two were used as "controls". On receipt in the USA, all dosimeters were stored in a room with a known low background radiation level. The "field" dosimeters were then removed and placed at the "field" sites for the specified time, after which they were returned to the low background area. The "laboratory" dosimeters were kept in the low background area until their exposure to ^{137}Cs or ^{60}Co after which they were also returned to the low background area. After completion of the exposures, all dosimeters were returned to the participants for evaluation. The radiation exposure during the time of storage, the number of days the dosimeters were in the "field" and the dates of the laboratory exposures were all supplied to the participants.

In addition to the eight dosimeters sent to the USA, eleven dosimeters were given a single exposure to ^{137}Cs and retained at ARL with their corresponding controls. The exposure was performed at ARL on the same date as the intercomparison dosimeters were sent to the USA. Although this was not part of the protocol specified by the organisers, these dosimeters were used to provide an estimate of the fading of the TL signal during the period of the intercomparison.

Field exposures were delivered under a variety of climatic conditions ranging from the high temperatures experienced in the Nevada desert during summer (Seventh International) to the cold, sub-zero conditions of mid-

winter in New Jersey (Eighth International). At each field site ionisation chambers were used to provide an accurate measurement of the background radiation level. Both TLD and ionisation detectors were placed 1m above the ground.

For the Seventh Intercomparison the laboratory exposures were delivered using a panoramic exposure stand with point sources of ^{137}Cs and ^{60}Co and a source to detector distance of 1m. In the case of the Eighth Intercomparison, dosimeters were exposed at a distance of 4m from a collimated ^{137}Cs source. The "control" dosimeters sent to the USA were used to estimate the transit exposure. Full details of the field and laboratory exposures are given in Table 1.

(ii) Mini-intercomparison

In an attempt to resolve the apparent 6% discrepancy referred to above selected participants were asked to send 20 dosimeters to EML in New York for exposure. Twelve dosimeters were exposed to collimated ^{137}Cs and ^{60}Co beams at NIST and to collimated ^{137}Cs beams at EML, while the remaining eight dosimeters were used as controls to assess the transit exposure between ARL and EML, as well as the exposure received during transport of the dosimeters between EML and NIST.

When the exposed dosimeters were returned for readout and assessment, the participants were given instructions as to which calibration factors (i.e. for ^{60}Co or ^{137}Cs) should be used to convert each dosimeter readout to exposure.

THE ARL TLD DOSEMETER AND PROCEDURES

(i) Choice of TL Phosphor

The measurement of external environmental radiation levels using TLDs is not straightforward and its success depends on several factors. The most important factor in making accurate and reliable low level radiation measurements is the choice of TL phosphor. A TL phosphor should exhibit the following characteristics;

- (a) a stable main dosimetry peak that does not fade appreciably at high ambient temperature (~50°C),

- (b) a linear response to integrated exposure, independent of exposure rate,
- (c) be unaffected by humidity and dust,
- (d) a uniform energy response,
- (e) a simple anneal treatment,
- (f) a simple readout cycle,
- (g) a minimum detectable exposure of less than 0.5 mR, and
- (h) a reproducible response.

At present, no TL phosphor completely fulfils all of these requirements. However, the phosphor calcium sulphate doped with dysprosium at a level of approximately 0.4% ($\text{CaSO}_4:\text{Dy}$), satisfies all but one of the above criteria, namely (d) and when incorporated in a badge case with suitable filtration, the resultant monitor becomes a nearly ideal environmental dosimeter.

(ii) ARL TLD Dosimeter

The ARL dosimeter was designed for use in uranium mines in the Northern Territory of Australia.⁽¹⁰⁾ It has been in use for the past decade and has performed reliably under harsh environmental conditions encountered in the field.

The dosimeter consists of two $\text{CaSO}_4:\text{Dy}$ teflon discs; one shielded by 2.4 mm of copper and 1.4 mm of plastic, and the other shielded only by the plastic case. The overall response of the disc shielded by the copper filter and the plastic badge case is nearly uniform over the energy range 60 keV to 1.17 MeV.⁽¹⁰⁾

(iii) ARL Procedures

For the first intercomparison (the seventh) sixty $\text{CaSO}_4:\text{Dy}$ impregnated teflon discs manufactured by Teledyne Isotopes were selected at random from a batch of 80,000. The discs were washed in distilled water, rinsed with ethanol, allowed to dry at room temperature and then numbered using a graphite pencil.

The sixty discs were annealed for 2 hours at 260°C on stainless steel trays, shock cooled between two copper blocks and then exposed to gamma rays from a collimated ^{137}Cs source.⁽¹¹⁾ After 2 days the discs were read

out using a Pitman 654 TOLEDO TLD reader and their individual relative sensitivities calculated. The readout cycle used a preheat stage of 30s at 135°C and a readout stage of 30s at 275°C. This procedure was repeated three times.

From the relative sensitivities of each disc, twenty four discs whose sensitivities varied between 97% and 103% of the mean were selected to be used in the intercomparison.

The intercomparison discs were annealed and loaded into 12 ARL TLD badge cases (2 discs per badge case). Each disc/badge combination was then calibrated as a unit to ^{137}Cs collimated gamma rays. During the course of all three intercomparisons the sixty discs were kept together as a single batch and all discs were subjected to the same anneal treatments.

For the intercomparison, 8 badges and their corresponding discs were selected from the above 12 dosimeters. The discs were then annealed, loaded into their corresponding ARL badge case, packaged according to the organisers' instructions and air-mailed to the USA. When the dosimeters were returned to ARL they were assessed immediately and then re-calibrated to ^{137}Cs gamma rays. This repeat calibration was to ensure that there had been no significant change in the individual dosimeter calibration factors.

(iv) Exposure Calculations

The total exposure to ionising radiation X_T as measured by the TL output emitted by a dosimeter, comprises six components. For a given disc/filter combination, this may be written as;

$$X_T = X_i + X_{si} + X_{sa} + X_{sus} + X_t + X$$

where	X_i	=	inherent background,
	X_{si}	=	self irradiation exposure,
	X_{sa}	=	storage exposure in Australia,
	X_{sus}	=	storage exposure in USA,
	X_t	=	transit exposure, and
	X	=	delivered laboratory or field exposure.

The contribution to the total exposure from the inherent background

was determined prior to the commencement of each intercomparison by reading out all of the discs immediately after annealing. For the discs used in this series of intercomparisons the inherent background was found to be 1.2 ± 0.1 mR. The contribution due to self irradiation was considered to be part of the TL signal emitted by the control dosimeters and was therefore accounted for in the final calculation.

Since the dosimeters were sent by airmail to the intercomparison organisers on the same day as they were annealed, and were read out the same day as they were returned to ARL, no correction for storage at ARL was necessary. The magnitude of the exposure received by the TLDs during storage in the USA was supplied by the organisers since the control dosimeters were stored in an area whose background radiation level was known.

All ARL results were calculated using the individual calibration factors for each disc/badge combination. The methods of estimating the field and laboratory exposures differ slightly and are outlined below.

(a) Field exposures

The field exposure is defined as the average exposure recorded by the field dosimeters minus the average exposure recorded by the control dosimeters, after the subtraction from the latter of the average exposure received by the control dosimeters during storage in the USA. This must then be corrected for fading if appropriate.

(b) Laboratory exposures

The laboratory exposures were calculated by subtracting the total exposure recorded by the control dosimeters from the total exposure recorded by the laboratory dosimeters. As the period of time the laboratory dosimeters were separated from the control dosimeters was less than 24 hours, the intercomparison organisers advised participants to ignore the small difference in background exposure. The laboratory exposure calculated as above must then be corrected for fading if appropriate.

(c) Transit exposure

The transit exposure was calculated from the total exposure received by the control dosimeters minus the exposure received by the control dosimeters during storage in the USA. The transit exposure was not corrected for fading.

RESULTS

(i) Seventh Intercomparison, 1984

The ARL results for the field and laboratory exposures are compared in Table 2 with the delivered exposures and the average exposures as determined by the participants in the intercomparison. The uncertainties stated in Table 2 are one standard deviation.

The transit exposure to and from the USA was found to be $8.5 \pm 0.7\text{mR}$. The exposure received by the control dosimeters during the time they were separated from the field dosimeters was $6.5 \pm 0.3\text{mR}$.

An experiment was undertaken at ARL to determine how much a TL signal would fade during the course of the intercomparison. For this experiment 11 ARL TLD badges, each containing 2 discs from the remainder of the original 60, were given a single exposure to ^{137}Cs gamma rays on the same day as the intercomparison dosimeters were sent to the USA. A further 10 badges containing the remaining 20 discs were used as controls and were stored together with the 11 exposed badges in a low background area at ARL. Exposed and control dosimeters were then read out at various times during the course of the intercomparison. Figure 1 shows that after 65 days approximately 77% of the initial TL signal remained.

The method of Burke and Gesell⁽¹²⁾ was used to determine the appropriate fading factor for the field exposures. This fading correction factor applies to cases where the dosimeter is exposed continuously over a long period of time and takes into account the fact that exposures registered early in the period fade more than the exposures registered late in the period. The fraction of the actual exposure which gives the TL response is

$$f = (1 - e^{-\lambda t}) / \lambda t \quad (1)$$

where

- $\lambda = b e^{-E/kT}$,
- b - a frequency factor,
- E - the trap depth,
- T - the absolute temperature,
- k - the Boltzmann constant, and
- t - the length of the measurement period.

The fraction of the TL signal which remains at a time, t , after a single exposure is given by

$$F = e^{-\lambda t}. \quad (2)$$

From the results of the laboratory fading experiment conducted at ARL equation (2) was used to calculate λ . This value of λ was then substituted in equation (1) and yielded a value of 0.85 for f for the period of time the dosimeters were in the field.

(ii) Eighth Intercomparison, 1985-86.

In contrast to the Seventh Intercomparison, the Eighth Intercomparison involved two field exposures and only one laboratory exposure. The results from this intercomparison are shown in Table 3.

The transit exposure was again estimated from the control dosimeters and the exposure received by the control dosimeters during storage in the USA. For this intercomparison the exposure received during storage in the USA was 3.0 ± 0.2 mR and the transit exposure was found to be 11.6 ± 2.5 mR.

A fading experiment was again conducted at ARL in conjunction with the intercomparison measurements. In contrast to the Seventh Intercomparison no detectable fading was observed. Since this contradicted previous studies conducted at ARL, it was decided to apply the same correction factor as used for the 7th Intercomparison. In hindsight however, this appears to have been an incorrect decision.

(iii) Mini-Intercomparison, 1987.

All dosimeters were calibrated individually at ARL by use of

collimated beams of ^{137}Cs and ^{60}Co gamma rays prior to the intercomparison. The ARL results shown in Table 4 were calculated using the average of the before and after calibration factors for each disc/badge combination. The average variation in the individual calibration factor of each disc/badge combination was less than $\pm 4\%$ with the maximum deviation being approximately -8% . Also shown in Table 4 are the sources used, the organisation which performed the exposures, the delivered exposure and the average exposure reported by the participants.

As can be seen, in all cases except one, the agreement between the exposure measured by ARL and the delivered exposure is excellent and shows no difference between the ^{137}Cs and ^{60}Co calibration factors for the dosimeters. However, this result conflicts with exhaustive measurements performed at ARL with collimated ^{137}Cs and collimated ^{60}Co sources (see Appendix) in which a 6% difference was observed.

DISCUSSION

(i) Seventh Intercomparison

From the results shown in Table 2 excellent agreement was obtained between the field and ^{60}Co exposures reported by ARL and the delivered exposures. However, the result reported for the ^{137}Cs exposure overestimated the actual exposure by approximately 18% . This result gave rise to some concern and a re-assessment of the ARL results was undertaken.

A new measurement of the output from the 1 Curie ^{137}Cs source used to calibrate the dosimeters was made. This showed that the original output of the source had been overestimated by approximately 4% . Applying this correction gave the following results;

field measurement = 73.8 mR,
LAB ^{60}Co = 79.9 mR, and
LAB ^{137}CS = 84.1 mR.

Although the field exposure and the ^{60}Co laboratory exposure are still in excellent agreement with the delivered exposure, the ARL recalculated ^{137}Cs exposure still overestimates the actual exposure by approximately 12% . The reason for this discrepancy remains unexplained.

(ii) Eighth Intercomparison

The results reported by ARL overestimated the delivered exposure for the laboratory and field exposures. Since no fading of the TL signal had been observed during the laboratory fading experiment and a fading correction factor had been applied to the results sent to the intercomparison organisers, it was decided to re-assess the exposures without taking fading into account. The re-calculated results are;

laboratory ^{137}Cs exposure = 17.8 mR,
field exposure number 1 = 30.9 mR and
field exposure number 2 = 10.7 mR.

As can be seen the results shown above are in excellent agreement with the delivered exposures shown in Table 3. It is apparent from these results that a more detailed investigation of the fading of the TL signal should be undertaken if accurate estimates of environmental radiation levels are required.

(iii) Mini-intercomparison

As can be seen by the results shown in Table 4 the agreement between the exposures as measured by ARL and the mean value of all the participants is satisfactory. However, the ARL measurements are not in such good agreement when compared with the delivered exposures, particularly when collimated ^{137}Cs sources were used. During the course of the mini-intercomparison a fading experiment was conducted at ARL and, as in the case of the Eighth Intercomparison, no fading was observed. The ARL results shown in Table 4 have therefore not been corrected for fading.

(iv) Sources of Uncertainty

The measurement of environmental radiation levels is fraught with difficulty and accurate measurements are hindered by several sources of uncertainty. Estimates of those uncertainties which can be quantified are listed in Table 5.

Sources of uncertainty which are difficult to quantify, but can be reduced significantly are;

- (i) the uneven cooling of discs during the anneal stage which affects the sensitivity of individual discs,
- (ii) uneven heating of the discs during readout,
- (iii) the change in light transmission of a disc due to the accumulation of grime on its surface,
- (iv) the stability of the TLD reader,
- (v) spurious readings from dust on the surface of the disc and
- (vi) the effect of UV-visible light on the TL signal.

The estimated overall uncertainty in the ARL measured exposures is approximately 10%, expressed as one standard deviation.

CONCLUSIONS

The intercomparison results described in this report indicate that the techniques employed at ARL for environmental radiation monitoring are acceptable, that the accuracy and reliability of the ARL TLD dosimeter is satisfactory and that ARL's performance in the intercomparisons compares well with that of other participants.

The number of organisations using TLD for environmental monitoring is growing throughout the world and it appears from the results of the intercomparisons that a high degree of precision has been attained. It is also apparent from the ARL results that the accuracy of environmental monitoring could be improved if more accurate correction factors for fading were available.

No difference was observed between the calibration factors for ^{137}Cs and ^{60}Co in the mini-intercomparison from the results obtained by ARL. However, the mean of the results of the participants showed a difference of 6%. The additional studies performed at ARL and described in the Appendix showed a difference of 6%. This difference in response of the TLD materials to ^{137}Cs and ^{60}Co cannot be explained at the present time.

More studies to improve ARL's procedures so that the reliability and accuracy of the calculated exposures are improved may not be justified when it is considered that there was no significant difference between the results obtained by those participants who made their best effort and the others.

It is noted that all three intercomparisons gave a different transit exposure. This may not be significant as the TLDs were probably stored in different places and were transported to different parts of the USA.

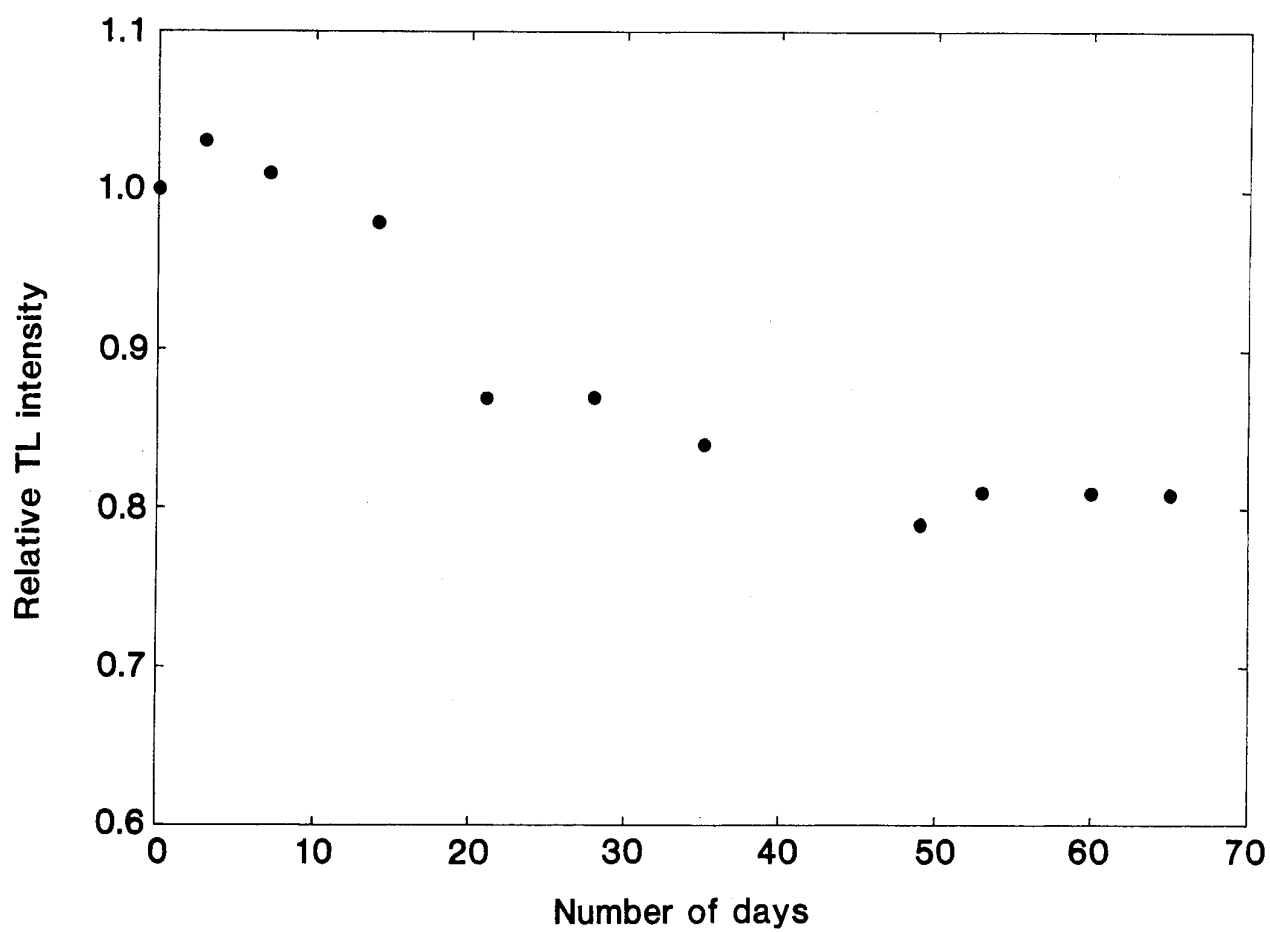


Figure 1: Variation of the thermoluminescence signal with time for discs given a single exposure to ^{137}Cs gamma rays, stored in a low background area and subsequently read out.

Table 1: Exposure details for the Seventh and the Eighth International Intercomparisons.

INTERCOMPARISON	EXPOSURE DETAILS
<p>SEVENTH April to July 1984</p>	<p>FIELD SITE: Nevada, USA. Mixed radiation field from natural sources and fallout at a nuclear weapons test site; major man made sources ^{137}Cs, ^{102}Rh and ^{60}Co.</p> <p>LABORATORY: Point sources of ^{137}CS and ^{60}Co</p>
<p>EIGHTH December 1985 to March 1986</p>	<p>FIELD SITE: (1) Chester (58km inland), NEW JERSEY, USA. Radiation comprised 75% natural background and 25% cosmic radiation.</p> <p>FIELD SITE: (2) Sandy Hook (on the coast), NEW JERSEY, USA. Radiation comprised 80% cosmic radiation and 20% natural background radiation.</p> <p>LABORATORY: Collimated ^{137}Cs source</p>

Table 2: Summary of the results of the Seventh International Intercomparison of Environmental Dosimeters.

EXPOSURE TYPE	DELIVERED EXPOSURE (mR)	PARTICIPANTS AVERAGE EXPOSURE (mR)	ARL MEASURED EXPOSURE (mR)
FIELD	75.8 ± 6.0	75.1 ± 7.5	76.0 ± 3.5
LAB - ^{60}Co	79.9 ± 4.0	77.9 ± 6.9	80.5 ± 8.7
LAB - ^{137}Cs	75.0 ± 3.8	73.0 ± 5.5	88.2 ± 4.0

Table 3: Summary of the results of the Eighth International Intercomparison of Environmental Dosemeters.

EXPOSURE TYPE	DELIVERED EXPOSURE (mR)	PARTICIPANTS AVERAGE EXPOSURE (mR)	ARL MEASURED* EXPOSURE (mR)
LAB - ^{137}Cs	17.2 ± 0.9	16.2 ± 1.7	21.3 ± 4.5
FIELD 1	29.7 ± 1.5	28.9 ± 3.1	38.1 ± 3.6
FIELD 2	10.4 ± 0.5	10.1 ± 2.3	14.8 ± 2.7

* These results were corrected for fading as described in the text.

Table 4: Summary of the results of the Mini-Intercomparison.

ORGANISATION & EXPOSURE TYPE	SOURCE USED BY ARL	DELIVERED EXPOSURE	PARTICIPANTS AVERAGE EXP	ARL MEASURED EXPOSURE
EML coll ^{137}Cs	coll ^{60}Co	60.9	59.9 ± 8.0	57.6 ± 0.7
NIST coll ^{137}Cs	coll ^{60}Co	59.0	60.4 ± 7.9	59.4 ± 0.5
NIST coll ^{60}Co	coll ^{60}Co	59.9	58.4 ± 6.4	59.7 ± 0.5
EML coll ^{137}Cs	coll ^{137}Cs	57.1	54.1 ± 5.8	53.5 ± 0.4
NIST coll ^{137}Cs	coll ^{137}Cs	61.1	59.5 ± 5.8	59.3 ± 0.5
NIST coll ^{60}Co	coll ^{137}Cs	61.9	56.9 ± 7.3	60.1 ± 0.4

N.B. (1) All exposures listed above have the units mR.

(2) "coll" in columns 1 and 2 is used as an abbreviation for "collimated".

TABLE 5 : Sources of uncertainty which can be quantified in exposures of 80 and 20 mR.

Source of Uncertainty	Uncertainty	
	80 mR	20 mR
Calibration source output	1.5%	1.5%
Distance source to detector	0.2%	0.2%
Exposure time	0.01%	0.01%
Variation in TLD reader sensitivity	0.1%	0.1%
Uncertainty in inherent background *	0.1%	0.5%
Uncertainty in transit exposure*	1.9%	7.5%
Uncertainty in storage exposure*	0.8%	3.0%
Uncertainty in the fading correction factor	9.0%	9.0%
Quadratic sum of the squares	9.3%	12.1%

(* these uncertainties are statistically based and the other values have been estimated)

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APPENDIX

Comparison of the Response of the ARL TLD Badge to ^{137}Cs and ^{60}Co Gamma Rays

An investigation was undertaken at ARL to compare the response of the ARL TLD badge, incorporating $\text{CaSO}_4:\text{Dy}$ impregnated in teflon discs, to ^{60}Co and ^{137}Cs gamma rays. Sixty new $\text{CaSO}_4:\text{Dy}$ teflon discs were selected at random from a batch of 9500 discs purchased from Teledyne Isotopes (New Jersey, New York). The discs were washed in distilled water, rinsed in research grade ethanol and then allowed to dry naturally on paper tissues. The discs were subjected to the standard anneal cycle of 2 hours at 260°C followed immediately by a 15 minute shock cool, sandwiched between two copper blocks. Within minutes of the completion of the shock cool the discs were read out on a Vinten 654 TOLEDO TLD reader. The mean inherent background of the freshly annealed discs was 3.1 ± 1.0 counts which was equivalent to 0.3 ± 0.1 mR.

Four anneal, exposure and readout cycles were carried out to determine the mean relative sensitivity of each disc. The 30 discs with the most reproducible relative sensitivities were used in the experiments. The relative sensitivities of these discs ranged from a minimum of 0.84 to a maximum of 1.10 with each disc having a typical coefficient of variation of approximately $\pm 3\%$.

Fifteen ARL TLD badges were numbered, each of the 30 discs was allocated to a particular badge and to either the shielded or unshielded positions in the badge. The discs and their corresponding TLD badge were kept together for the duration of the experiments. Badges 1 to 10 were used in the comparison study while badges 11 to 15 were exposed to ^{137}Cs gamma rays and used to track the variation in the mean sensitivity of the discs after repeated anneal, exposure and readout cycles.

All 30 discs were maintained as a single batch and were given identical heat treatments. To ensure the experiment was completely unbiased, badges 1 to 10 were used in a Latin Squares series of experiments as shown in Table A1.

One complete Latin Square sequence involves the following: badges 1 to 5 were exposed to either ^{137}Cs or ^{60}Co depending on the toss of a coin.

Badges 6 to 10 were exposed to the other source (see Table A1). After 24 hours the discs were read out. To complete the Latin Square, the discs were then annealed and the sequence of exposures reversed.

A series of four complete Latin Squares were performed. The mean sensitivity of the 10 discs in each group (i.e. badges 1 to 5, badges 6 to 10 and badges 11 to 15) in terms of counts/mR are shown in Table A2. Since badges 11 to 15 were exposed only to ^{137}Cs the variation in the mean sensitivity of these discs can be related to the anneal cycle and exposure history. The source used to expose each disc/badge combination is shown in brackets beside each mean sensitivity.

The typical coefficient of variation for the mean sensitivities shown in Table A2 is approximately 6%. The data in column 4 clearly shows how the mean sensitivity of the discs decreases with repeated anneal treatments and/or exposure history. In order to determine whether or not there is a change in response of the discs to ^{60}Co and ^{137}Cs , the effect of the repeated annealing on the disc sensitivity must be taken into account.

Normalising the data in column number 4 to 6.416 (the initial mean sensitivity) gives the correction factors to be applied to the data in columns 2 and 3. Table A3 shows the data after the correction factors have been applied.

From the normalised data shown in Table A3, the ratios of ^{137}Cs to ^{60}Co i.e. (SET 1/SET 2), (SET 3/SET 4), (SET 6/SET 5), (SET 7/SET 8) for columns 2 and 3 were obtained. The mean ratios for Cs/Co is 1.070 ± 0.013 for badges 1 to 5 (column 2) and 1.047 ± 0.026 for badges 6 to 10 (column 3). The overall mean ratio of ^{137}Cs to ^{60}Co for all discs was found to be 1.058 ± 0.023 for the normalised mean sensitivities.

It should be noted that a similar series of measurements was also undertaken for $\text{CaSO}_4:\text{Dy}$ in powder form and a similar difference in the response to both sources was observed. A ratio of 1.060 ± 0.031 was found.

A similar series of measurements were undertaken using $\text{LiF}:\text{Mg,Ti}$ impregnated teflon discs. However, due to the non-reproducibility of the sensitivity of the discs used it was not possible to draw any conclusions from the results.

The secondary calibration facility used in these experiments has been described in detail in reference 10. Both the ^{137}Cs and the ^{60}Co sources were used in the same source housing and identical source holders, hence the exposure geometry in both cases was the same. The output from both sources was measured with three different ionisation chambers which had been compared with the Australian primary standard of exposure. These results agreed to better than 1%. It should be noted that the ionisation chambers used had been calibrated using the gamma rays from ^{60}Co and it was assumed that the same calibration factor applied for the gamma rays from ^{137}Cs .

TABLE A1: Sequence of exposures based on Latin Squares.

BADGES	SOURCE	
1 - 5	^{60}Co	^{137}Cs
6 - 10	^{137}Cs	^{60}Co

(a) tails

BADGES	SOURCE	
1 - 5	^{137}Cs	^{60}Co
6 - 10	^{60}Co	^{137}Cs

(b) heads

TABLE A2: Mean sensitivities for the disc/badge combinations.

DATA SET	BADGES		
	1 to 5	6 to 10	11 to 15
SET 1	6.608 (Cs)	6.058 (Co)	6.416 (Cs)
SET 2	6.054 (Co)	6.300 (Cs)	6.192 (Cs)
SET 3	5.937 (Cs)	5.711 (Co)	5.945 (Cs)
SET 4	5.443 (Co)	5.787 (Cs)	5.914 (Cs)
SET 5	5.331 (Co)	5.692 (Cs)	5.749 (Cs)
SET 6	5.800 (Cs)	5.496 (Co)	5.869 (Cs)
SET 7	4.928 (Cs)	5.014 (Co)	5.429 (Cs)
SET 8	4.591 (Co)	5.184 (Cs)	5.432 (Cs)

N.B. The data above have the units counts/mR.

TABLE A3: Normalised mean sensitivities for the disc/badge combinations.

DATA SET	BADGES		
	1 to 5	6 to 10	11 to 15
SET 1	6.608 (Cs)	6.058 (Co)	1.000 (Cs)
SET 2	6.272 (Co)	6.527 (Cs)	1.036 (Cs)
SET 3	6.406 (Cs)	6.162 (Co)	1.079 (Cs)
SET 4	5.906 (Co)	6.279 (Cs)	1.085 (Cs)
SET 5	5.949 (Co)	6.352 (Cs)	1.116 (Cs)
SET 6	6.339 (Cs)	6.007 (Co)	1.093 (Cs)
SET 7	5.825 (Cs)	5.927 (Co)	1.182 (Cs)
SET 8	5.422 (Co)	6.122 (Cs)	1.181 (Cs)

N.B. The data in columns 2 and 3 have the units counts/mR and have been normalised for the relative sensitivities in column 4.