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*Direct Penetrating
Radiation Monitoring Systems:
Technical Evaluation for Use at Area G,
Los Alamos National Laboratory*

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**DIRECT PENETRATING RADIATION MONITORING SYSTEMS:
TECHNICAL EVALUATION FOR USE AT AREA G,
LOS ALAMOS NATIONAL LABORATORY**

by

D. Kraig, W. A. Treadaway, and R. J. Wechsler

ABSTRACT

Recent advances and commercialization of electret-ion-chamber (EIC) technology for photon measurements prompted us to consider EICs as a replacement for our TLD system. After laboratory tests indicated that both systems gave adequate results for controlled exposures, throughout 1998 we conducted field tests with paired TLDs and EICs, in LANL technical areas and in public areas. We had approximately 30 paired sampling sites at Area G. At each sampling site, we deployed three TLDs and three EICs. The EICs were contained in air-tight jars, each of which was placed in a Tyvek envelope and hung about 1 m above the ground. The dosimeters were read (and, if necessary, replaced) every three months. At the sites outside Area G, the TLD readings for the first two quarters were statistically significantly higher than those of the EICs: group average exposures were 38 and 36, compared with 33 mR (both quarters) for the EICs; during quarter 3, the EIC average (40 mR) was higher than the TLD average (34 mR); and during quarter 4, the two systems were statistically the same: EIC = 42, TLD = 41 with a *p*-value of 0.61. We are still evaluating these differences and performing additional laboratory studies to determine causes. At the Area G sites, we noticed that several of the TLDs gave much higher readings than their co-located EICs; we believe that the TLDs were over-responding by ~50% to the low-energy (60-keV) gamma radiation associated with ²⁴¹Am, whereas the EICs were responding accurately. We conclude that EICs are more accurate at a wide range of gamma energies and are preferable to TLDs in environments where a significant fraction of the photons are low energy.

INTRODUCTION

Los Alamos National Laboratory (LANL) has been using thermoluminescent dosimeters (TLDs) to monitor environmental direct penetrating radiation (DPR). The TLDs have been in use at Area G, a radioactive waste storage and disposal facility for many years. Although this system has provided reasonably consistent data, the program has traditionally been expensive to operate; in addition, a number of issues have arisen that led us to explore whether viable alternatives existed.

Recent advances and commercialization of electret technology for photon measurements (Kotrappa et al., 1992) prompted us to consider this technology as a potential replacement for the TLD system. Among the primary advantages advertised by Rad Elec Inc. company literature are the following: low cost per measurement, nondestructive readings, consistent measurements in extreme environmental conditions, no fading, consistent intra-batch calibration, tissue-equivalent response, excellent response to low-energy emitters, and a sensitivity of 5 mR with less than 10% error. Additionally, the system is advertised to have a flatter energy response than most measurement systems: a maximum over-response of only 18% between 250 and 350 keV.

Although the electret technology appears to offer some important advantages over TLDs, we felt that available testing results were inadequate to justify an immediate transition. We therefore evaluated the systems in laboratory and field environments over time and under a variety of conditions to assess their suitability for LANL's environmental DPR monitoring program and for monitoring of the wide range of radiation energy at Area G. This report describes our evaluations and findings.

DESCRIPTION OF CURRENT MONITORING SYSTEM (TLDs)

For many years, LANL has used TLDs to monitor environmental photon radiation levels. Although system specifications have changed over time, the current system (and the one that was evaluated in this study) comprises an acetate plastic holder, which contains five 1/8" x 1/8" x 0.035", 25-mg lithium fluoride (LiF):Mg,Ti elements (also called chips). These chips have a natural abundance of the isotopes ^6Li (7.4%) and ^7Li (92.6%) and are trade-named TLD-100s.

Field deployment and collection of TLDs is simply a matter of recording the dosimeter identification number and time/date of deployment or collection. Calculating a dose from the dosimeter involves heating the individual chips and registering the amount of light produced, then calculating the exposure/dose associated with that amount of light. We use a Harshaw 5500 reader. The process of reading, annealing before subsequent deployment, and calculating dose involves a number of calibration and correction factors and is time-intensive in the laboratory. The TLD reading process is destructive in that, if an error occurs, it is not possible to reread the chips.

DESCRIPTION OF ELECTRET ION CHAMBERS

The electret ion chamber (EIC) is an integrating ionization chamber comprising a charged Teflon disk, referred to as the electret, mounted within a small chamber composed of conductive plastic (Kotrappa et al., 1992). The electret serves both as a source of electrostatic field and as a sensor. Recently, Rad Elec Inc. has been marketing EICs as environmental gamma monitors. The EIC offers a number of options for monitoring of gamma radiation over a wide range of exposure rates and total exposures. The configuration we tested used a short-term (ST) electret with an "L" chamber. This configuration is advertised to provide an exposure range of approximately 300 mR and a sensitivity of approximately 5 mR, with less than 10% error.

Electrets come with a full charge of approximately 750V and are not recommended for use when the potential falls below about 150V. The electrets discharge at approximately 2V per mR exposure; thus, the usable potential range of about 600V yields an integrated usable exposure of about 300 mR. Electrets are read by unscrewing them either from their protective cap (for the initial reading) or from the exposure chamber itself and placing them on a small, portable, battery-operated reading device. Readings can be performed quickly in the field. For field measurements, we used both SPER I and SPER II readers. The SPER II reader has the capacity to store data and utilizes a bar-code reader to identify and catalogue the readings. Although the SPER II reader has the capability to perform dose calculations, we found the process of using the data manipulation or dose-calculating capabilities to be cumbersome and not well matched to our office personal computers. Because of these limitations and because we found the SPER I to be more dependable and easy to use in the field, we discontinued using the SPER II after a trial of approximately one year. All readings of electrets are nondestructive, a very nice feature that greatly reduces the potential of losing data through accidents during reading or processing. For example, if a technician returns to the lab after reading electrets in the field and discovers a suspect reading, the technician can return to the field and reread the electret.

The chamber of the EIC screws down onto the plastic base that contains the electret such that the entire enclosure remains conductive. However, the assembly is not sealed and radon gas must be prevented from entering the enclosure or calculated exposures will not accurately represent photon exposure rates. Several methods are available to minimize the effects of ambient radon. For our field work we enclosed three EICs within a polystyrene jar having a volume of approximately 1 liter. The jar was sealed with a spring-loaded cap and rubber washer. A silicone bead was placed on the side of the rubber washer to attach it to the top. Within each jar we also placed a small cotton bag containing about 50 g of activated charcoal (the charcoal would be heated and reused at the end of the three-month field cycle). The jar was then enclosed inside a Tyvek bag so that we could suspend it about 1 m above the ground.

TESTING OF EICS AND TLDS

Assessment of EICs and TLDs comprised laboratory exposures, field exposures, and a series of follow-up evaluations. We also compared the overall EIC and TLD systems for ease of field deployment and reading, robustness of the system in the field, ease of data downloads and manipulations, and time requirements outside of the field.

Laboratory Tests

Phase I Exposures

An exposure facility operated by the Environmental Safety and Health 4 (ESH-4) group at LANL was used to expose EICs and TLDs under controlled conditions. The purpose of the first set of exposures (Phase I) was to compare the systems at an energy normally encountered in natural settings. Cesium-137 was chosen for this "average" test because the 662-keV energy associated with its decay is in the middle of the range of energies that cause the greater part of the dose from natural background radiation. The exposure area is configured with an 85-GBq (2.3-Ci) ^{137}Cs source, which provides a low-scatter, panoramic radiation field with an exposure rate of approximately 0.2 mR s^{-1} at 1 m.

Twenty EICs and twenty TLDs (each dosimeter contains five TLD chips) were arranged along a semi-circular arc, 1 m from, and on the same horizontal plane as, the source. The positions of the TLDs and EICs were alternated and the instruments were oriented such that their active volumes should receive as close to the same exposure as possible. Three 30-mR exposures were performed. This exposure level was chosen because it represents an average quarterly field exposure in this area, and we were interested in testing the instruments at likely

field exposures. The same EICs and TLDs were used in each run, but their positions on the arc were selected at random.

Phase I Results: EICs

The EIC system performed well in general (Table 1). Individual EIC averages were generally very close to the expected value, and the standard deviation of all EICs that were exposed together was generally quite low. Some high (>10%) standard deviations are discussed below. The variation from exposure to exposure among the 20 EICs was also quite low; their averages differed by a maximum of 2% from the expected exposure. With the exception of one exposure (which indicated a *p*-value slightly below 0.05), the EICs' average was statistically indistinguishable from the desired value. The "Grand Mean" and "Grand Standard Deviation" indicate that over the 60 measurements, the EICs were a very reliable measuring system, with an approximately 5% overall standard deviation.

The only significant anomalies appeared to occur where an individual EIC read high during one of the three exposures (indicating that this was not simply an out-of-range electret). These high values are outside the manufacturer's stated accuracy of $\pm 10\%$. In response to our questions about the cause of these outliers, Rad Elec Inc. suggested we had not read carefully enough. We performed a series of tests to evaluate how sensitive the process is to reader's errors and found the system to be quite robust, i.e., different readers and different orientations and positions of the electret on the reader appeared to have no effect on the readings.

One potential cause of the high readings is dust or something else coming into contact with the teflon surface. The presence of dust causes a discharge of the teflon disc, and this additional discharge is then factored into the exposure calculation, resulting in an erroneously high calculated exposure. Throughout our tests, anomalous readings were always high (i.e., when multiple EICs were exposed and one EIC showed a reading different from the others, the reading was always higher). A representative of Rad Elec Inc. suggested that, if readings are taken from three EICs and one reading is quite high, it would be reasonable to remove that reading from the data set. However, we felt that removal of "high" EIC readings might give the public the perception that we were trying to remove high but real values. Therefore, we have implemented the following data verification and reporting policy. If the standard deviation among the three EICs at a site is greater than 10, then the three values are checked to see whether any two of the EICs are in close agreement. If two are in close agreement, then the datum from the third EIC is considered to be an outlier and is not included in the calculated average from that station. If no two are alike, the data from all three are rejected and no station average is computed for that quarter. This process effectively removes EIC readings affected by inadvertent charge depletion but should not cause the perception that we are biasing data toward the low values.

Phase I Results: TLDs

The TLDs did not perform as accurately or with as high precision as the EICs (Table 1). Variability among exposures as well as variability among these dosimeters for each exposure was higher than for the EICs. The "Grand Mean" was a good representation of the average desired exposure, but individual exposure averages differed from the desired exposure by as much as 8%. The "Grand Standard Deviation" was approximately double that of the EICs. Unlike the EICs, there didn't appear to be any pattern for those TLDs that differed significantly from the expected value. We conclude that there is simply more variability inherent to the TLD system.

Electret Ion Chambers (EICs)					
	1st Exposure ¹ (mR)	2nd Exposure ² (mR)	3rd Exposure ³ (mR)	Mean	Std Dev
	29.1	32.7	29.3	30.4	2.1
	28.4	29.4	29.2	29.0	0.5
	29.1	30.1	29.9	29.7	0.5
	28.5	30.8	28.0	29.1	1.5
	29.8	30.1	28.6	29.5	0.8
	31.2	31.0	29.5	30.5	0.9
	30.4	30.1	29.3	29.9	0.6
	29.8	30.8	30.6	30.4	0.5
	29.8	30.1	33.3	31.0	1.9
	29.1	28.8	35.2	31.0	3.6
	30.4	31.5	29.3	30.4	1.1
	27.8	29.4	28.6	28.6	0.8
	30.4	32.8	30.6	31.3	1.3
	29.1	32.8	29.3	30.4	2.1
	29.8	30.9	34.0	31.6	2.2
	30.5	32.2	31.3	31.3	0.8
	28.4	29.4	31.9	29.9	1.8
	28.5	30.1	30.6	29.7	1.1
	35.6	30.2	30.7	32.1	3.0
	31.1	30.1	29.9	30.4	0.6
Mean	29.8	30.7	30.5	30.3	1.6
Std Dev	1.7	1.2	1.9	Grand Mean	Grand Std Dev
Thermoluminescent Dosimeters (TLDs)					
	1st Exposure ¹ (mR)	2nd Exposure ² (mR)	3rd Exposure ³ (mR)	Mean	Std Dev
	29.2	28.9	27.3	28.5	1.0
	29.4	31.8	28.5	29.9	1.7
	30.9	31.0	27.3	29.7	2.1
	30.4	32.3	27.3	30.0	2.5
	31.8	36.1	30.7	32.9	2.9
	32.6	33.1	30.6	32.1	1.3
	33.5	32.9	28.0	31.5	3.0
	32.5	31.4	24.9	29.6	4.1
	35.3	32.1	26.5	31.3	4.5
	31.0	31.8	28.3	30.4	1.8
	36.0	32.2	26.4	31.5	4.8
	42.8	35.0	28.8	35.5	7.0
	32.7	32.4	27.1	30.7	3.2
	29.8	31.8	28.5	30.0	1.7
	29.3	30.4	26.9	28.8	1.8
	36.4	32.1	25.3	31.3	5.6
	30.4	30.8	28.3	29.8	1.4
	31.0	31.9	29.2	30.7	1.3
	32.0	30.8	25.1	29.3	3.7
	31.1	30.7	25.7	29.2	3.0
Mean	32.4	32.0	27.5	30.6	3.2
Std Dev	3.2	1.6	1.6	Grand Mean	Grand Std Dev

¹ The first exposure was 30.07 mR with a lab-reported uncertainty of $\pm 2\%$

² The second exposure was 29.95 mR with a lab-reported uncertainty of $\pm 2\%$

³ The third exposure was 29.81 mR with a lab-reported uncertainty of $\pm 2\%$

Table 1. Results of three Phase I Laboratory Exposures (30 mR of 662-keV Source).
The shaded exposure values are those that are outside the mean by more than 10%; such values are more numerous for the TLDs, showing the greater variability of the TLD measurements. In addition, the TLD variations ranged statistically about the mean, whereas the few EICs that varied from the mean by more than 10% were all above the mean. The high EIC values were probably erroneous, caused by electrical discharge from dust on the electret surface.

Phase II Exposures

Our ongoing evaluation of field data at Area G and at our broader monitoring network had indicated some fundamental differences between the responses of TLDs and of EICs under field conditions. The most glaring discrepancy had been seen at Area G, where TLD readings at several sites were consistently much higher than EIC readings at the same location. Our preliminary conclusion had been that the TLDs and the EICs were responding differently to ^{241}Am in transuranic (TRU) waste. The TRU waste had been exhumed from storage in underground berms to be inspected, characterized, and repackaged so that it would be acceptable for delivery to the Waste Isolation Pilot Plant (WIPP).

To verify this conclusion, we ran a series of laboratory exposures of TLDs and EICs to a monoenergetic, 58.8-keV x-ray source (similar to the 60-keV photon energy associated with ^{241}Am decay). During some of these exposures, we were evaluating other issues. Specifically, we wanted to measure attenuation through the polystyrene jars that contain the EICs. We were also interested in verifying that scatter from the apparatus used to support the TLDs and EICs during the early 58.8-keV exposures had not created a significant exposure difference between the EICs and the TLDs. All exposures were run at 30 mR to simulate an average quarter's field exposure.

In the first exposures, eight EICs and eight TLDs were exposed to 30 mR of 58.8-keV x-rays. Three exposures were performed, because the usable beam was too narrow to expose all 16 TLDs and EICs at once. The dosimeters were mounted on a metal jackstand, which could be positioned such that the active volume of the dosimeters was aligned vertically with the beam centerline. Because of variations in the degree of exposure and the somewhat crude method of ensuring consistent distance from the exposure source, the precision of these exposures is estimated to be about 5%. The exposures were done with the dosimeters inside a polystyrene jar like those we have been using in the field. The second set of exposures were done to evaluate attenuation through the jar and were similar to the first except that they were done with the dosimeters not enclosed in a polystyrene jar. Finally, we exposed eight TLDs suspended from a wire (rather than mounted on a metal stand) to verify that backscatter from the stand had not affected the TLD results significantly.

Phase II Results

The results from the three sets of exposures were very similar, indicating that the polystyrene jar and the metal jackstand did not affect exposure values significantly (the jackstand may have caused a small—less than 10%—increase in exposures for the TLDs; a similar increase was not seen for the EICs, because their active exposure volume is larger and farther from the stand). Therefore, all exposure results have been combined for simplicity. The mean exposure calculated for the EICs was 31 (2s = 2.8) mR, which agrees very well with the expected exposure of 30 mR. The calculated TLD mean exposure of 47 (3.3) mR is more than 50% higher than the expected value. The TLD result from dosimeter #207 was an outlier and was not included in the calculation of the mean and two standard deviations (Table 2).

We evaluated our entire TLD system and process to assess the cause of this over-response to low-energy photons. Fundamentally, the TLDs over-responded because they were calibrated at 662 keV (using a ^{137}Cs source). The regression coefficients based on regression of thermoluminescent signal (TL signal) on exposure (mR) using ^{137}Cs as a calibration source are inappropriate for exposures at the approximately 60-keV energies associated with ^{241}Am and result in calculated exposures that are too high. The physical causes for the TLD over-response are only partially understood. TLD-100 chips are generally recognized to have an approximately 25% over-response of TL signal relative to exposure at 60 keV. The remaining over-response must be caused by the materials and construction of our dosimeters.

Inside Polystyrene Jars								
Electrets				TLDs				
Electret Number	Initial Potential (V)	Final Potential (V)	Exposure (mR)	Dosimeter Number	Exposure (mR)			
ss8192	700	648	33.87	207	26.1			
ss8151	686	637	31.98	339	44.76			
ss8134	701	655	29.95	649	46.86			
ss8355	652	605	30.84	732	44.88			
sq6913	274	227	34.17	638	47.63			
sq6813	305	261	31.54	700	45.15			
sq6875	277	234	31.19	541	44.63			
sq6627	321	276	32.06	482	45.46			
mean			31.95	mean		45.62		
2 s			2.89	2 s		2.32		
No Polystyrene Jars								
Exposed on Jack Stand								
Electrets				TLDs		TLDs Exposed Hung on Thin Wire		
Electret Number	Initial Potential (V)	Final Potential (V)	Exposure (mR)	Dosimeter Number	Exposure on stand (mR)	Dosimeter Number	Exposure on wire (mR)	
ss8192	643	590	34.85	218	49.09	202	46.02	
ss8151	635	584	33.58	534	46.89	240	45.65	
ss8134	653	605	31.50	334	48.57	377	48.88	
ss8355	603	553	33.10	436	47.99	380	45.5	
sq6913	227	180	35.02	586	48.88	448	46.27	
sq6813	261	217	32.16	250	49.12	713	48.25	
sq6875	234	190	32.63	226	48.18	739	47.07	
sq6627	276	231	32.67	257	49.49	763	45.08	
mean			33.19	mean		48.53	mean	46.59
2 s			2.48	2 s		1.66	2 s	2.73

Table 2. Results of Phase II Laboratory Exposures (30 mR of 58.8-keV Photon Source). The results show clearly the approximately 50% over-response of the TLDs. The results in the upper box were obtained with all the dosimeters inside polystyrene jars mounted on a jackstand. Those in the lower box were obtained without the jars (to assess any effect of the jars) and some without the jackstand (to assess the potential effects of scatter on the stand). The polystyrene jars do not seem to cause significant attenuation. The jackstand appears to have caused a small (<10%) increase in exposures for the TLDs.

Laboratory Test Conclusions

From our tests we conclude that TLDs will not provide accurate measurements of low-energy gamma fields, such as those in the vicinity of TRU wastes. We recommend that EICs be used as the monitoring system in these situations, because they appear to provide much more accurate dose information throughout the photon energy range likely to be encountered in field measurements at Area G.

Field Tests

Exposures

In addition to the 30 TLD/EIC sites at Area G, in 1998 we deployed EICs and TLDs at many locations throughout our broad environmental monitoring network (DPRNET). The data thus obtained allow us to compare the systems under field conditions. In the field, the TLDs are hung from a stainless steel ring at about 1 m above the ground (from a fence, a tree, or any other suitable object). The EICs are sealed inside polystyrene jars, each of which is placed inside a Tyvek bag; the bags are stapled shut and hung near the TLDs. Although the bags provided a reasonably hardy enclosure, we found that they degraded in the sun and wind and required replacement after approximately two quarters. The polystyrene jars have a rubber gasket and a spring-loaded clasp that help ensure an airtight seal. Approximately 50 g of activated charcoal inside a cotton bag are enclosed within each jar to absorb as much radon as possible from the air trapped within the jar.

All dosimeters remain in the field for a calendar quarter. The TLDs are simply replaced at the end of the quarter with freshly annealed units. The removed dosimeters are taken back to the TLD laboratory, where the chips are taken out and read using a Harshaw 5500 reader. The EICs are read in the field to evaluate their potential drop during the quarter; if the potential remaining is greater than 200V, the EIC is left in place for another quarter.

Results and Discussion

The results of our one-year comparison of TLDs and EICs under field conditions are provided in Table 3. To enable more accurate interpretation of the results, we separated out and eliminated the data obtained inside Area G, thus avoiding the complications introduced from the TRU waste stored within Area G (see above). We also eliminated the data from any station that did not have both EIC and TLD data for all four quarters. We compared the EICs to the TLDs on a quarterly basis, the EICs to one another from quarter to quarter, and the ratio of the EICs to the TLDs for each quarter at each station.

The EICs differed statistically from the TLDs during the first three quarters of the year. A two-tailed t-Test indicated p -values of 1.3×10^{-4} , 7.2×10^{-3} , 1.8×10^{-6} , and 0.61 for quarters 1, 2, 3, and 4, respectively. Interestingly, the TLD readings were significantly higher than those of the EICs during quarters 1 and 2, lower during quarter 3, and the same during quarter 4. To summarize the comparison: the TLDs remained more consistent than the EICs through the year, with quarterly average exposures of 38, 36, 34, and 41, whereas the EICs appear to have increased from their first two quarterly exposures of 33 to final quarterly exposures of 40 and 42. Because the differences between EICs and TLDs are not consistent temporally, we believe they represent differential responses to background radiation. As mentioned earlier, we found that the TLDs grossly over-respond to low-energy photons (~ 60 keV). We have no data comparing the measurement systems at very high energies (>10 MeV) and have no reason to believe that their responses would differ. Although we can currently offer no explanation for the response differences between the two systems, we will continue to investigate the discrepancy. Among other potential causes, the response of the systems to ambient beta radiation may be a factor.

Number	Station Location Name	Quarter 1			Quarter 2			Quarter 3			Quarter 4					
		EIC (mR)	TLD (mR)	EIC/TLD	EIC (mR)	TLD (mR)	EIC/TLD	EIC (mR)	TLD (mR)	EIC/TLD	EIC (mR)	TLD (mR)	EIC/TLD			
005	Barranca Mesa	36	38	0.95	35	34	1.02	40	29	1.36 H	42	38	1.09			
009	LA Airport	26	32	0.79	27	31	0.85	35	30	1.18	43	39	1.11			
011	Shell Station	31	39	0.78	31	37	0.85	37	33	1.11	45	43	1.03			
012	Royal Crest	29	33	0.88	26	35	0.76 L	33	33	1.01 L	37	40	0.94			
013	WR Fire Station	34	36	0.95	32	34	0.96	37	30	1.21	48	41	1.16 H			
020	PM-1 Well	37	40	0.93	34	41	0.83	40	39	1.05	47	51	0.92			
022	P-2 Booster	32	31	1.02 H	34	38	0.87	37	36	1.02 L	45	42	1.08			
025	TA-49	31	36	0.86	29	34	0.84	35	32	1.10	41	39	1.06			
041	McDonalds	32	37	0.85	27	38	0.70 L	37	31	1.19	41	45	0.92			
047	Urban Park	32	36	0.90	31	36	0.85	33	32	1.02 L	36	43	0.85 L			
050	WR Nazarene Church	21	26	0.82	19	23	0.85	28	20	1.39 H	29	27	1.07			
055	WR Monterey South	22	32	0.69 L	28	33	0.86	35	30	1.18	35	34	1.01			
058	TA-54 Old Lagoon	32	40	0.79	34	39	0.88	37	38	0.97 L	51	44	1.14 H			
060	WR, Piedra Dr,	32	36	0.89	32	32	1.00	36	28	1.29	39	32	1.23 H			
068	Trinity Church	30	40	0.73 L	28	39	0.72 L	39	34	1.15	44	46	0.94			
076	TA-16 WETF	39	36	1.08 H	35	35	1.01	43	35	1.25	36	45	0.81 L			
094	TA-33 VLBA dish	30	28	1.09 H	30	29	1.05 H	38	28	1.37 H	45	37	1.19 H			
201	TA-21 Area A-1	33	34	0.97	32	32	1.01	35	30	1.17	39	39	1.01			
254	TA-21 Area (B-14) S	37	52	0.70 L	43	36	1.19 H	51	36	1.44 H	34	37	0.91			
323	TA-21 Area T-3	63	69	0.92	68	67	1.02	91	76	1.19	62	69	0.91			
341	TA-21 Area U-1	39	39	1.01 H	34	32	1.06 H	40	32	1.23	45	41	1.10			
361	TA-21 Area V-1	31	35	0.87	33	32	1.04	45	36	1.24	32	32	0.97			
MEAN		33	38	0.88	MEAN	33	36	0.92	MEAN	40	34	1.18	MEAN	42	41	1.01
1 STANDARD DEVIATION		0.11			1s 0.12			1s 0.13			1s 0.11					
EIC vs TLD Two-tailed P Value		1.3E-04			P-Value 7.2E-03			P-Value 1.8E-06			P-Value 6.1E-01					

Table 3. Results of Field Exposures (outside Area G only), TLDs vs EICs. Differences between TLDs and EICs are statistically significant for all quarters except the fourth. The shaded values are those that are outside the mean by one standard deviation. The "L," "H," and "HH" mean, respectively, LOW by more than one standard deviation; HIGH by more than one standard deviation; and HIGH by two standard deviations. Interestingly, the TLDs were higher than the EICs by about 12% for the first two quarters, the EICs were higher than the TLDs by the same amount for the third quarter, and the two systems were essentially the same for the fourth quarter. The differences do not appear to be site-specific, given that the locations of the high or low EIC/TLD ratios are not consistent from quarter to quarter. Finally, the number of high ratios is roughly equal to the number of low ratios.

We calculated the ratio of EIC/TLD to ascertain whether certain stations were consistently above or below the EIC/TLD quarterly average ratio. We thought that a pattern among the ratios might indicate areas of different background radiation that could explain differences between the monitoring systems. Stations at which the EIC/TLD ratio was more than one standard deviation above or below the mean ratio are marked in Table 3 with shading and either an "H" (high) or an "L" (low). Only one ratio exceeded two standard deviations (Station #254, Quarter 2) and is marked "HH". We saw no clear patterns in these ratios to indicate that a station was consistently different from the other stations in terms of the relative response of the EIC to the TLD. The number of "H"s is approximately equal to the number of "L"s, and no station was consistently above or below the mean. The ratios, therefore, do not appear to indicate any phenomenon other than statistical variation.

CONCLUSIONS

For general environmental radiation monitoring, where low-energy radiation provides a very small component of the overall exposure, EICs and TLDs appear to be comparable systems. Although EICs are more accurate in their response to a known radiation source in a controlled setting, it is not possible to conclude from our study which measurement system is more accurate in the field. Within restricted environments with nonnatural radiation sources (or nontypical radiation field components), the EICs provided much more accurate measurement of a broad energy spectrum than did the TLDs. Specifically, we conclude that using standard Mg:Ti-doped LiF chips in the vicinity of low-energy emitting sources, such as ^{241}Am , will result in an over-reporting of the exposures at those locations. Part of the over-response is being caused by our dosimeter geometry/material. Even if different LiF chips (with a flatter energy response) were used, we would still expect a significant over-response with our current dosimeter. Using EICs is recommended over TLDs at areas like Area G, where a significant fraction of the radiation energy spectrum is from low-energy (<100 keV) emitters.

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REFERENCES

P. Kotrappa, T. Brubaker, J. C. Dempsey, and L. R. Stieff, "Electret Ion Chamber System for Measurement of Environmental Radon and Environmental Gamma Radiation," *Radiation Protection Dosimetry* Vol. 45, No. 1/4, pp. 107-110, 1992.