

## FIELD TEST OF ELECTRET ION CHAMBERS FOR ENVIRONMENTAL MONITORING

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**Abstract**—A field test of electret ion chambers was performed to evaluate their performance in making environmental exposure measurements at nuclear facilities. The objectives of the study were to determine electret ion chamber variability and to perform comparisons with thermoluminescent dosimeter and high-pressure ion chamber measurements. Three electret ion chambers were placed at each of 40 monitoring locations in the vicinity of a commercial nuclear power station during four consecutive quarters. The electret ion chamber measurements were compared to thermoluminescent dosimeter measurements made by the Nuclear Regulatory Commission and the South Carolina Department of Health and Environmental Control. Two types of comparisons were made with the high-pressure ion chamber. One used yearly average electret ion chamber measurements and instantaneous high-pressure ion chamber measurements at 15 of the monitoring locations. The other involved the simultaneous exposure of five electret ion chambers and the high-pressure ion chamber for 15 d at a single location. The mean ratios of electret ion chamber measurements to thermoluminescent dosimeter measurements was 1.06. The mean ratio of electret ion chamber measurements to instantaneous and simultaneous high-pressure ion chamber measurements were 1.06 and 1.07, respectively. Electret variability, defined here as the ratio of the standard deviation to the mean, was determined for each set of three detectors. The average variability for the 160 sets of quarterly measurements was ~7%. Among the 450 individual electret measurements, there were six outliers. Based on the results of this study, electret ion chambers appear to yield accurate measurements of environmental exposure provided that measures are taken to either minimize or correct for radon interferences and care is taken to prevent spurious discharges during handling.

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**Key words:** electrets; ionization chambers; gamma radiation; instrumentation

### INTRODUCTION

AN IMPORTANT component of environmental monitoring programs at nuclear power plants and other nuclear

facilities is the measurement of exposure rates in their vicinity. Under normal operating conditions these exposure rates are typically dominated by natural background and are on the order of  $10^{-12}$  C kg<sup>-1</sup> s<sup>-1</sup> (10  $\mu$ R h<sup>-1</sup>). For the purposes of routine environmental monitoring, the exposure is integrated over an extended time period (on the order of months) and the average exposure rate for the period of integration is reported. At the present time thermoluminescent dosimeters (TLDs) are used almost exclusively to make these integrated exposure measurements.

A potential alternative to TLDs for integrated exposure measurements are electret ion chambers (EICs). An electret is a dielectric material, such as Teflon<sup>®</sup>, with a semipermanent surface charge (Sessler 1980). An electret ion chamber consists of an electret in a closed, conducting chamber. The electret serves as one electrode and the inside wall of the chamber serves as the other. Ions generated in the chamber by ionizing radiation migrate to the electrodes, reducing the electret's surface charge. By measuring the change in electret charge or, equivalently, electret voltage, it is possible to infer exposure.

The idea of using the reduction in electret voltage as the basis of a dose measuring instrument was first suggested by Marvin (1955). Bauser and Ronge (1978), Kotrappa et al. (1982), and Pretsch and Kostel (1983) subsequently demonstrated the scientific feasibility of the concept; however, questions regarding the effect of variables such as temperature and humidity on electret stability remained to be answered before EICs could be applied to environmental measurements. Performance tests were conducted<sup>||</sup> on a prototype based on the design of a commercially available electret radon monitor<sup>¶</sup>. The chambers were calibrated for exposure measurements and relative response was measured as a function of dose rate, humidity, temperature, photon energy, detector orientation, and mechanical shock.

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<sup>||</sup>Kotrappa, P.; Hobbs, T. G. Calibration and performance evaluation of electret ion chamber system for environmental gamma radiation levels around nuclear installations. Presentation at the Health Physics Society Meeting, 24-28 June 1990; Anaheim, CA.

<sup>¶</sup>E-PERM, Rad-Elec Inc., 5714-C Industry Lane, Frederick, MD 21701.

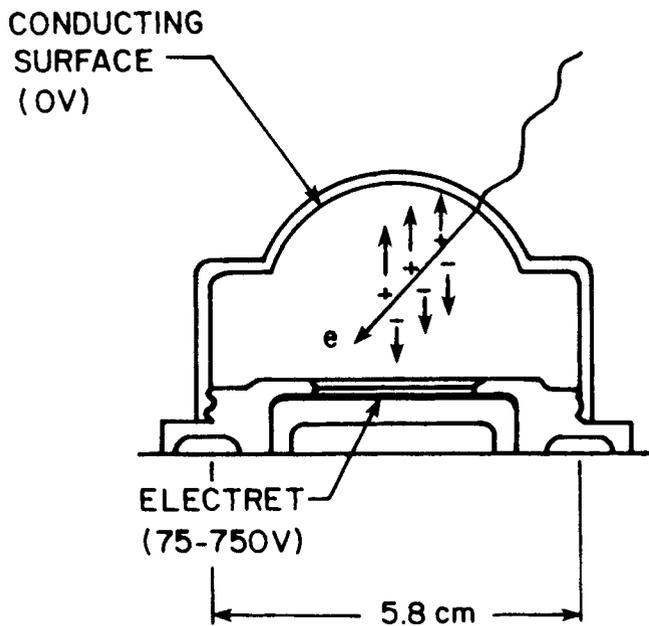


Fig. 1. Schematic of the "L" series (50-mL) electret ion chamber.

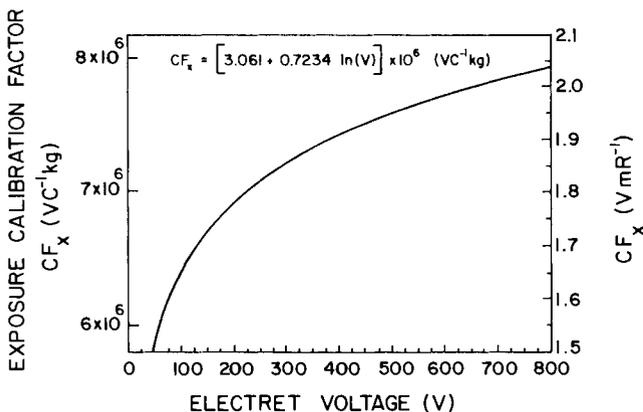


Fig. 2. Exposure calibration factor for the "L" series electret ion chamber.

Limited field was performed testing and field testing at a commercial nuclear power plant was recommended.

The goal of the present study was to evaluate EICs for making environmental exposure measurements in actual field conditions. The specific objectives were as follows: 1) to determine electret variability; 2) to compare electret measurements with TLD measurements; and 3) to compare electret measurements with high-pressure ion chamber measurements. Tests were performed in the vicinity of Duke Power Company's Oconee Nuclear Station in northwestern South Carolina (SC). The utility maintains 40 environmental TLD stations consisting of 16 locations at the fence line

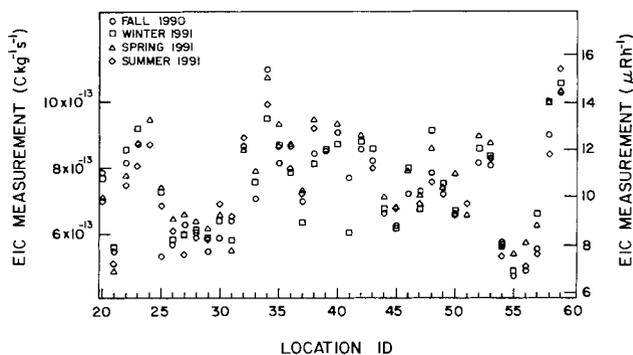


Fig. 3. Quarterly exposure rates measured by the electret ion chamber at each location.

boundary (one in each of the compass point sectors), 16 at a distance of ~8 km from the plant, and eight control locations at distances ranging from 15–20 km from the plant. Comparisons were made with TLD measurements made by the U.S. Nuclear Regulatory Commission (NRC) and the SC Department of Health and Environmental Control (DHEC) and with exposure measurements made with a high-pressure ion chamber on loan from the National Institute of Standards and Technology (NIST).

## MATERIALS AND METHODS

### Electret ion chamber

The electret ion chamber used in this study is shown in Fig. 1. It is identical to the "L" series E-PERM that is used for radon measurements except it does not have a port for radon entry. The chamber has a 50 mL volume and a 3 mm wall thickness. The walls are made of an approximately tissue equivalent, electrically conducting plastic. The electret, which is 3.3 cm in diameter and 1.5 mm thick, is mounted on a base that is threaded into the bottom of the chamber. This allows the electret to be removed so that its voltage can be measured with an electrostatic voltmeter.

Ion collection within the chamber is not complete, and the collection efficiency changes with voltage. There is no simple theoretical expression for ion collection as a function of voltage drop, and the chamber requires calibration. The EICs were calibrated at NIST. A set of six EICs with initial voltages of ~760 V were placed in a plastic grid which positioned them at equal distances from a  $^{137}\text{Cs}$  calibration source. This is a standard broad-beam calibration geometry used at NIST. The EICs were subjected to a series of  $1.3 \times 10^{-5}$  C kg $^{-1}$  (50.00 mR) exposures. The electret voltage was read after each exposure. The calibration factor was calculated by dividing the voltage drop by the exposure, and this calibration factor was associated with the midpoint of the voltage range. The process was repeated nine times, after which the final electret voltage was <50 V. The standard deviation of the voltage drop for

**Table 1.** Variability of electret ion chamber exposure measurements by quarter.

Quarter	Number of locations	Coefficient of variation (%)			
		Min	Max	Mean	S.D.
Fall 1990	37	0.0085	0.18	0.066	0.039
Winter 1991	38	0.011	0.17	0.064	0.038
Spring 1991	38	0.015	0.16	0.048	0.035
Summer 1991	36	0.0085	0.18	0.072	0.045

**Table 2.** Ratio of minimum and maximum measurements to the mean of the remaining measurements at the 40 locations.

Ratio ranges	Percent deviation from the mean	Number of occurrences	
		Minimum	Maximum
0.9-1.0; 1.0-1.1	0-10	15	7
0.8-0.9; 1.1-1.2	10-20	23	21
0.7-0.8; 1.2-1.3	20-30	2	6
0.6-0.7; 1.3-1.4	30-40	0	1
<0.6; >1.4	>40	0	5 <sup>a</sup>

<sup>a</sup> Ratios are as follows: 1.60, 1.85, 2.00, 2.12, and 3.25.

the six EICs ranged from 3-6% for the nine exposures. A least-squares curve was fit to calibration factor vs. the logarithm of the midpoint voltage. The curve fit (correlation coefficient = 0.988) is given in Fig. 2. The minimum detectable voltage change is 1 V, which corresponds to an integrated exposure of  $\sim 10^{-7}$  C kg<sup>-1</sup> s<sup>-1</sup> (0.5  $\mu$ R). Previously, the uncertainty for a 3-mo exposure at  $7 \times 10^{-13}$  C kg<sup>-1</sup> (10  $\mu$ R h<sup>-1</sup>) was estimated to be 6%.<sup>†</sup>

The average exposure rate,  $\dot{X}$ , during a time period,  $T$ , is related to the change in electret voltage through the following:

$$\langle \dot{X} \rangle = \frac{\int_0^T \dot{X}(t) dt}{T} = -\frac{1}{T} \int_{V_i}^{V_f} \frac{dV}{CF_x(V)}, \quad (1)$$

where

- $\dot{X}$  = exposure rate (C kg<sup>-1</sup> s<sup>-1</sup>);
- $V_i$  = initial voltage (V);
- $V_f$  = final voltage (V); and
- $CF_x$  = exposure calibration factor,  
=  $[3.061 + 0.7234 \ln(V)] \times 10^6$  (V C<sup>-1</sup> kg).

The calibration factor is a slowly varying function of voltage, and the following approximation is used for modest voltage changes (<50-100 V),

$$\langle \dot{X} \rangle = \frac{V_i - V_f}{CF_x(V_{\text{mid}}) \times T}, \quad (2)$$

where  $V_{\text{mid}}$  is the midpoint voltage.

For exposure rates at environmental levels, it is necessary to reduce  $V_i$  to account for the voltage drop,  $\Delta V_{\text{Rn}}$ , caused by radon that is present in the chamber

at the time the initial voltage is read. This voltage drop can be calculated from the following:

$$\Delta V_{\text{Rn}} = \frac{CF_{\text{Rn}}(V_i)C_0}{\lambda} (1 - e^{-\lambda T}), \quad (3)$$

where

- $CF_{\text{Rn}}$  = radon calibration factor (V Bq<sup>-1</sup> m<sup>3</sup> d<sup>-1</sup>);
- $\lambda$  = decay constant for <sup>222</sup>Rn (0.18 d<sup>-1</sup>); and
- $C_0$  = initial radon concentration (Bq m<sup>-3</sup>).

The radon calibration factor for the "L" series EIC is (Rad-Elec 1990)

$$CF_{\text{Rn}} = 7.435 \times 10^{-3} + 6.140 \times 10^{-6} V, \quad (4)$$

where  $CF_{\text{Rn}}$  is given in V Bq<sup>-1</sup> m<sup>3</sup> d<sup>-1</sup>.

The EIC deployment and measurement procedure for this study was as follows. On the day before the quarterly TLD change-out at the Oconee Nuclear Station, the EICs were prepared in a clean area in laboratories at Clemson University. First, a check of the electrostatic voltmeter<sup>#</sup> was performed with two reference electrets. Then, the voltage of each electret was read and recorded. The electrets were inserted into the ion chambers which were then heat-sealed in a Mylar<sup>®</sup> bag to minimize interference from radon. Three EICs were placed in a 0.038-m<sup>3</sup> (1-gal) plastic bag. The following day, one plastic bag was placed at each of the 40 environmental TLD locations. The bags were located within 0.5 m of the TLDs and at the same distance above the ground. At the end of the quarter, a new set of EICs was deployed and the old set was removed, taken to the laboratory, and read. The electrostatic voltmeter was checked again with the reference electrets, and the voltage on each of the electrets from the ion chambers was read and recorded. The procedure was repeated for each quarter.

The same radon correction was applied to all of the data. It was based on a single *ex post facto* measurement in the laboratory where the EICs were processed. An H-series E-PERM and a pulsed ion chamber<sup>††</sup> were used to make the measurement. Both instruments gave

<sup>#</sup> Spear 1, Rad-Elec Inc., 5714-C Industry Lane, Frederick, MD 21701.

<sup>††</sup> Model R210F, Femto-TECH, Carlisle, 325 Industry Dr., OH 45005.

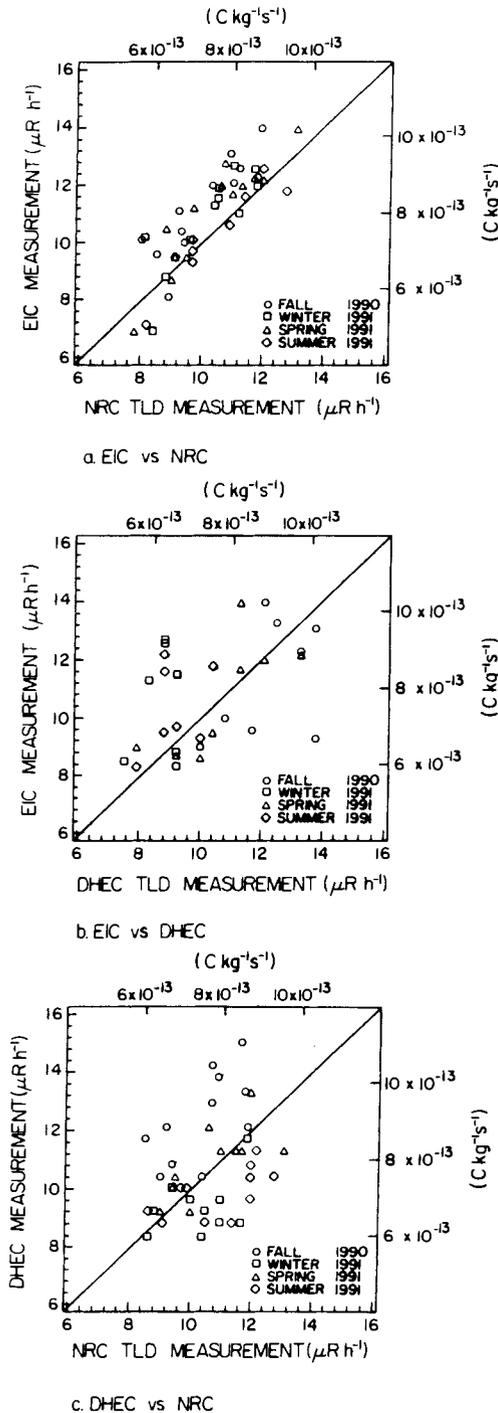


Fig. 4. Measurement comparisons of a) EIC and NRC; b) EIC and DHEC; and c) DHEC and NRC.

a 24-h average radon concentration of  $0.041 \text{ Bq m}^{-3}$  ( $1.1 \text{ pCi L}^{-1}$ ). The initial electret voltages in the study ranged from 300–600 V, and the typical voltage drop for a quarterly measurement was 40 V. Using eqn (3),  $\Delta V_{Rn}$  was 2.5 V at  $V_i = 600 \text{ V}$  and 2.1 V at  $V_i = 300$

V. The average of these, or 2.3 V, was used for the radon correction. This is equivalent to a  $3.9 \times 10^{-14} \text{ C kg}^{-1} \text{ s}^{-1}$  ( $0.54 \mu\text{R h}^{-1}$ ) reduction in the exposure rate for a 90-d measurement period.

#### Thermoluminescent dosimeters

The NRC makes quarterly exposure measurements at the Oconee Nuclear Station as part of its direct radiation monitoring program. The measurements are made with  $\text{CaSO}_4:\text{Tm}$  TLDs in a  $700 \text{ mg cm}^{-2}$  plastic and lead filter calibrated with  $^{60}\text{Co}$  (Ehrlich et al. 1984). DHEC also performs quarterly exposure measurements using TLDs. They use lithium fluoride in a  $5 \text{ mg cm}^{-2}$  plastic, aluminum, and paper filter and calibrate with  $^{137}\text{Cs}$ .

#### High-pressure ion chamber

Exposure measurements were also made with a HPIC<sup>‡‡</sup> on loan from NIST. The HPIC was calibrated with  $^{60}\text{Co}$  (DeCampo et al. 1972). The exposure rate range for the ion chamber is  $7.2 \times 10^{-14}$  to  $3.6 \times 10^{-11} \text{ C kg}^{-1} \text{ s}^{-1}$  ( $1\text{--}500 \mu\text{R h}^{-1}$ ) and the uncertainty at  $7.2 \times 10^{-13} \text{ C kg}^{-1} \text{ s}^{-1}$  ( $10 \mu\text{R h}^{-1}$ ) is  $\pm 5\%$ . The HPIC was only available for a limited time, and it was not possible to perform quarterly measurements. Instead, two short-term measurements were performed. The first consisted of instantaneous HPIC measurements at 15 of the 40 locations. At a given location, 10 exposure rate readings were obtained during a 3-min time period. These were averaged and the result was compared to yearly EIC and TLD measurements at that location. The other measurement was for a 15-d period on the roof of the Rhodes Engineering Research Center at Clemson University. Simultaneous measurements were made with five EICs. The integrated exposure during this period was too low for simultaneous TLD measurements. In all cases, the HPIC was located within 0.5 m of the EICs and TLDs.

## RESULTS

#### EIC variability

Quarterly EIC data are presented in Fig. 3 for each of the 40 locations. The number on the abscissa is the utility's location identifier. Each data point is the average of the three measurements obtained for each quarter, omitting outliers. Variability of the measurements was quantified in two ways. In the first, the coefficient of variation (the standard deviation divided by the mean) was calculated at each location for each quarter. The results are given in Table 1. The values ranged from 0.9–18%. Quarterly means were 6.6%, 6.4%, 4.8%, and 7.2%, and the yearly mean was 6.2%. In the second, the mean variance of the 149 sets of measurements was calculated. The corresponding standard deviation was then divided by the mean exposure rate, yielding a value of 7.8%.

<sup>‡‡</sup> Model RSS-111, Reuter-Stokes, Edison Park, Twinsburg, OH 44087.

**Table 3.** Statistical comparison of exposure rate measurements from EICs and NRC TLDs.

Measurement period	Number of measurements	Mean ratio EIC:NRC	Mean difference		<i>p</i> value <sup>a</sup>
			C kg <sup>-1</sup> s <sup>-1</sup>	μR h <sup>-1</sup>	
Fall 1991	13	1.06 ± 0.03	4.3 × 10 <sup>-14</sup>	0.6 ± 0.3	0.06
Winter 1991	13	1.06 ± 0.02	4.3 × 10 <sup>-14</sup>	0.6 ± 0.2	0.02
Spring 1991	13	1.12 ± 0.03	8.6 × 10 <sup>-14</sup>	1.2 ± 0.3	0.0005
Summer 1991	13	0.98 ± 0.02	-1.4 × 10 <sup>-14</sup>	-0.2 ± 0.2	0.4
Year	52	1.06 ± 0.01	4.3 × 10 <sup>-14</sup>	0.6 ± 0.1	0.0001

<sup>a</sup> *p* value for the null hypothesis that the mean difference between the two measurements is zero.

**Table 4.** Statistical comparison of exposure rate measurements from EICs and DHEC TLDs.

Measurement period	Number of measurements	Mean ratio EIC:DHEC	Mean difference		<i>p</i> value
			C kg <sup>-1</sup> s <sup>-1</sup>	μR h <sup>-1</sup>	
Fall 1990	10	1.21 ± 0.08	1.3 × 10 <sup>-13</sup>	1.3 ± 0.7	0.05
Winter 1991	10	1.00 ± 0.05	1.0 × 10 <sup>-15</sup>	0.0 ± 0.5	0.98
Spring 1991	10	0.92 ± 0.05	-7.2 × 10 <sup>-14</sup>	-1.0 ± 0.7	0.19
Summer 1991	10	1.13 ± 0.06	8.6 × 10 <sup>-14</sup>	1.2 ± 0.5	0.07
Year	40	1.06 ± 0.04	2.9 × 10 <sup>-14</sup>	0.4 ± 0.4	0.23

**Table 5.** Statistical comparison of exposure rate measurements from NRC and DHEC TLDs.

Measurement period	Number of measurements	Mean ratio DHEC:NRC	Mean difference		<i>p</i> value
			C kg <sup>-1</sup> s <sup>-1</sup>	μR h <sup>-1</sup>	
Fall 1990	12	0.91 ± 0.03	-7.2 × 10 <sup>-14</sup>	-1.0 ± 0.3	0.03
Winter 1991	12	1.05 ± 0.04	3.6 × 10 <sup>-14</sup>	0.5 ± 0.4	0.26
Spring 1991	12	1.18 ± 0.04	1.4 × 10 <sup>-13</sup>	1.9 ± 0.4	0.0004
Summer 1991	12	0.91 ± 0.03	7.9 × 10 <sup>-14</sup>	-1.1 ± 0.3	0.01
Year	48	1.02 ± 0.02	7.1 × 10 <sup>-15</sup>	0.1 ± 0.3	0.56

**Table 6.** Statistical comparison of exposure rate measurements for the tri-located stations.

Comparison	Number of measurements	Mean ratio	Mean difference		<i>p</i> value
			C kg <sup>-1</sup> s <sup>-1</sup>	μR h <sup>-1</sup>	
EIC:NRC	20	1.06 ± 0.02	4.3 × 10 <sup>-14</sup>	0.6 ± 0.2	0.003
EIC:DHEC	20	1.08 ± 0.04	5.0 × 10 <sup>-14</sup>	0.7 ± 0.4	0.11
DHEC:NRC	23	1.01 ± 0.04	6.2 × 10 <sup>-16</sup>	0.0 ± 0.4	0.98

The Q-test (Dixon 1953) was applied to each set of three quarterly measurements to identify outliers. A total of three were identified; however, when applied in this way, the test underestimates the number of outliers because it treats each set of measurements independently and does not consider the overall precision of the measurement (Skoog and West 1976). Since the exposure measurements did not show significant seasonal variability, the test was also applied to the entire set of measurements at a given location. This yielded 11, 8, and 6 outliers at the 90%, 95%, and 99% confidence levels, respectively. Each of the outliers was significantly greater than the other measurements in a set. A qualitative examination of the data suggested that, in general, there were more abnormally high measurements than abnormally low ones. An attempt was made to quantify

this observation by removing the minimum and maximum values from each set of measurements, calculating the arithmetic mean of the remaining measurements, and taking the ratio of the minimum and maximum values to the mean. The results, which are presented in Table 2, support the qualitative observation of an excess of abnormally high values. For example, the number of minimum values differing from the mean by more than 20% was two while the number of maximum values was 12, and there were no minimum values differing from the mean by more than 30% compared to six maximum values. These six maximum values are the ones identified as outliers at the 99% confidence level and the decision was made to exclude them from the data set. The six outliers are likely due to handling during the process of making the voltage measurement,

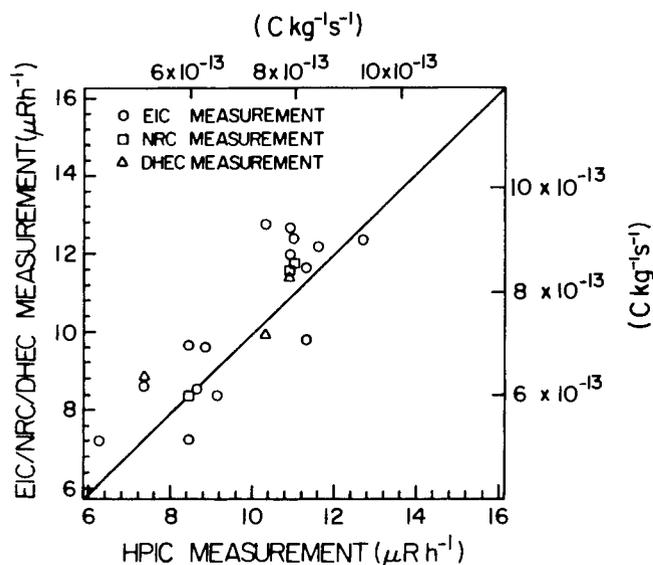


Fig. 5. Comparison of yearly EIC, NRC, and DHEC measurements with instantaneous HPIC measurements.

which requires that the electret be removed from the chamber. A partial discharge caused by contact with another object will cause a spurious drop in the electret voltage which will translate into an exposure measurement that is high.

#### Comparisons with TLD data

The NRC maintains a network of 36 TLD locations in the vicinity of the Oconee Nuclear Station. Thirteen of these are co-located with the locations used in this study. The DHEC network consists of 18 locations, 10 of which are co-located with the study locations. The NRC and DHEC have 12 co-located stations and there are six stations common among all three networks. Data from the NRC and DHEC are collected and reported on a quarterly basis.

Presented in Fig. 4 are graphical comparisons among EIC, NRC, and DHEC exposure measurements for the four quarters of the survey. EIC and NRC exposure data (Struckmeyer and McNamara 1991) are compared in Fig. 4a. The ordinate is the EIC measurement and the abscissa is the NRC measurement. Exposure rates as measured with the EICs ranged from 82–125% of NRC measurements and most (~75%) of

Table 7. Statistical comparison of instantaneous HPIC measurements with EIC, NRC TLD, and DHEC TLD measurements.

Comparison	Number of measurements	Mean ratio	Mean difference		
			$C\ kg^{-1}\ s^{-1}$	$\mu R\ h^{-1}$	<i>p</i> value
EIC:HPIC	15	$1.06 \pm 0.03$	$2.9 \times 10^{-14}$	$0.5 \pm 0.3$	0.10
NRC:HPIC	3	$1.03 \pm 0.02$	$3.6 \times 10^{-14}$	$0.4 \pm 0.2$	0.24
DHEC:HPIC	3	$1.07 \pm 0.07$	$4.3 \times 10^{-16}$	$0.6 \pm 0.6$	0.43

Table 8. Results of 15-d simultaneous exposure of EICs and the HPIC.

Measurement	Number of measurements	Exposure rate	
		$C\ kg^{-1}\ s^{-1}$	$\mu R\ h^{-1}$
EIC	5	$8.7 \times 10^{-13}$	$12.9 \pm 2.4$
HPIC	1	$9.2 \times 10^{-13}$	12.1

Table 9. Summary of comparisons for yearly data.

Ratio of measurements	Number of observations	Mean ratio
EIC:NRC	52	$1.06 \pm 0.01$
EIC:DHEC	40	$1.06 \pm 0.04$
EIC:HPIC <sup>a</sup>	15	$1.06 \pm 0.03$
EIC:HPIC <sup>b</sup>	5	$1.07 \pm 0.02$

<sup>a</sup> Comparison between instantaneous HPIC measurement and yearly average EIC measurement.

<sup>b</sup> Comparison between 15-d HPIC measurement and simultaneous EIC measurement.

the EIC measurements lie above the diagonal, i.e., the EIC measurements generally exceeded the NRC measurements. Comparisons of EIC and DHEC measurements are presented in Fig. 4b. There is more scatter in these data, and EIC measurements ranged from 67–138% of DHEC measurements. Although there are more points above the diagonal than below it, a qualitative comparison is difficult. Comparisons of NRC and DHEC data are presented in Fig. 4c. DHEC measurements ranged from 75–135% of NRC measurements. Overall, there are approximately equal numbers of points above and below the diagonal, although DHEC measurements were generally higher than NRC measurements for one quarter (Fall 1990) and lower for two quarters (winter 1991 and summer 1991).

Quantitative comparisons of the data are presented in Tables 3–4. Presented in each table, on a quarter-by-quarter basis and for the year as a whole, is the mean ratio between the two sets of measurements and the results of paired difference tests. The null hypothesis for these tests was that the true mean difference between the two sets of measurements was zero.

Table 3 contains the results for EIC and NRC TLD

measurements. On a quarterly basis, the average ratio of EIC measurements to NRC measurements ranged from 0.98–1.12. The yearly average was 1.06. The results of the paired difference test varied considerably from quarter to quarter, with the  $p$  value ranging from a low of 0.0005 to a high of 0.4. For the year as a whole, the difference between the two measurements was statistically significant ( $p = 0.0001$ ); however, the mean difference was only  $4.3 \times 10^{-14} \text{ C kg}^{-1} \text{ s}^{-1}$  ( $0.6 \mu\text{R h}^{-1}$ ).

Quantitative comparisons between EIC and DHEC TLD data are presented in Table 4. EIC measurements were greater than DHEC measurements for two quarters, equal for one quarter, and less for one quarter. For the year, the ratio of EIC measurements to DHEC measurements was the same as the ratio of EIC measurements to NRC measurements, or 1.06; however, the quarterly  $p$  values ranged from 0.05–0.98, the yearly value was 0.23, and the EIC measurements could not be judged to be significantly different from the DHEC measurements. The mean difference for the year was small,  $2.9 \times 10^{-14} \text{ C kg}^{-1} \text{ s}^{-1}$  ( $0.4 \mu\text{R h}^{-1}$ ).

Comparisons between DHEC TLD measurements and NRC TLD measurements are presented in Table 5. The DHEC measurements were greater than the NRC measurements for two quarters and less for two quarters, with the DHEC/NRC ratio ranging from 0.91–1.18. The mean ratio for the year was 1.02, and the  $p$  value was 0.56. The variability of the comparisons from quarter to quarter is consistent with observations made by Montague (1992). He performed statistical analyses of quarterly DHEC and NRC data from 1988 through 1991, and no trend was observed. Sometimes the DHEC measurements were higher than the NRC measurements and sometimes they were lower. Sometimes the difference between the two was statistically significant and sometimes it was not. It was concluded that this was due to variability in low-level exposure measurements with TLDs.

Comparisons were also performed for the six locations common among the three measurements. The results are presented in Table 6 as the average ratio between the three types of measurements. The mean ratio of EIC measurements to NRC and DHEC measurements was 1.06 and 1.08, respectively. There was not a statistically significant difference between DHEC and NRC measurements.

#### Comparisons with HPIC measurements

Presented in Fig. 5 is a comparison of yearly average EIC, NRC TLD, and DHEC TLD measurements with HPIC measurements. There were 15 locations where HPIC measurements were obtained for comparison with EIC measurements. Of these, three coincided with NRC TLD locations and three coincided with DHEC TLD locations. The EIC measurements were generally higher than the HPIC measurements. Statistical comparisons are presented in Table 7. The average ratio of EIC measurements to HPIC measurements was 1.06, and the difference was  $2.9 \times 10^{-14} \text{ C kg}^{-1} \text{ s}^{-1}$  ( $0.5$

$\mu\text{R h}^{-1}$ ). The NRC and DHEC TLD data are included for reference, but there were too few points to allow a meaningful comparison.

Results of the 15-d simultaneous exposure of the HPIC and five EICs are given in Table 8. The average exposure rate measured by the EICs was  $8.7 \times 10^{-13} \text{ C kg}^{-1} \text{ s}^{-1}$  ( $12.9 \pm 2.4 \mu\text{R h}^{-1}$ ). The HPIC measurement was  $9.2 \times 10^{-13} \text{ C kg}^{-1} \text{ s}^{-1}$  ( $12.1 \mu\text{R h}^{-1}$ ), yielding a difference of  $5.7 \times 10^{-14} \text{ C kg}^{-1} \text{ s}^{-1}$  ( $0.8 \mu\text{R h}^{-1}$ ). The ratio of the EIC measurements to the HPIC measurement was 1.07.

## DISCUSSION

Considered individually, each of the comparisons performed in this study has limitations, namely, 1) the EIC-TLD comparisons are ambiguous because it is not known which measurement was the more accurate, 2) the validity of comparing yearly average EIC and TLD measurements with instantaneous HPIC measurements depends on the temporal variability of the exposure rate, and 3) the direct comparison with HPIC measurements was for a limited time and did not include TLDs. However, when the separate comparisons are considered together (Table 9), the results are remarkably consistent. The degree to which the results are in agreement could be coincidental. This is especially true for the DHEC data, for which the difference was not statistically significant. Nonetheless, the suggestion is that the EICs yielded exposures that were slightly (between 5% and 10%) higher than TLDs and HPICs.

There are a number of possible explanations for this difference. One is partial leakage of ambient radon into the plastic bags. Full leakage at an ambient level of  $11 \text{ Bq m}^{-3}$  ( $0.3 \text{ pCi L}^{-1}$ ) would increase the signal by  $1.8 \times 10^{-13} \text{ C kg}^{-1} \text{ s}^{-1}$  ( $2.5 \mu\text{R h}^{-1}$ ). Thus, partial leakage could have easily caused the  $2.9 \times 10^{-14} \text{ C kg}^{-1} \text{ s}^{-1}$  ( $0.5 \mu\text{R h}^{-1}$ ) difference between the EIC measurement and the TLD and instantaneous HPIC measurements. A second possibility is differences in response to low-energy gammas between the EIC and the other detectors. The EIC's relative response (based on response at 662 keV) at 300 keV is 1.17<sup>11</sup> compared to  $\sim 1$  for the other detectors. At 100 keV, the EIC's relative response is close to that of the DHEC TLDs, less than that of the HPIC, and greater than that of the NRC TLDs. At 30 keV, it is about the same as that of the DHEC TLDs and greater than that of the HPIC and NRC TLDs. Thus, except near 300 keV, there is no consistent difference in response that could account for a systematic difference between the EIC and the other detectors. A third possibility is a difference in beta response; however, this is doubtful because the EIC chambers and the plastic bag containing the chambers have a combined thickness ( $500\text{--}600 \text{ mg cm}^{-2}$ ) that should be sufficient to filter betas at a height of 1 m from the ground. The filter thickness is comparable to that for the NRC TLDs ( $700 \text{ mg cm}^{-2}$ ), it is greater than that for the DHEC TLDs ( $<5 \text{ mg cm}^{-2}$ ), and it is

less than that for the HPIC ( $>2,000 \text{ mg cm}^{-2}$ ). A final possibility is the apparent occurrence of readings that are anomalously high, but not so high that they can be discarded as outliers (as seen in Table 2); however, the overall effect of these elevated readings is small. For example, from a comparison of the distribution of "minimum" and "maximum" ratios in Table 2, it is seen that there were no more than 20 "maximum" measurements that were abnormally high due to partial discharge (excluding the six outliers). If these "maximum" measurements were 20% higher than they should have been, the average exposure for the set of 450 measurements would be increased by  $<1\%$ .

Because the radon measurement in the laboratory was performed after the end of the study rather than during the times the EICs were being processed, there is some uncertainty in the correction that was applied to the data. However, if the actual concentration in the laboratory at the time of EIC processing was zero, rather than  $0.041 \text{ Bq m}^{-3}$  ( $1.1 \text{ pCi L}^{-1}$ ), the ratios in Table 9 would be 1.11 and 1.12. Thus, in this unlikely worst case, the EIC measurements would be  $\sim 10\%$  higher than the TLD and HPIC measurements. If the actual concentration was greater than that measured, the EIC measurements would move closer to the TLD and HPIC measurements.

### CONCLUSIONS

Based on the results of this study, EICs appear to yield accurate measurements of environmental exposure under field conditions. In this study the EICs yielded exposure measurements that were 6–7% higher than HPIC and TLD measurements, their variability was between 6% and 8%, and the frequency of outliers was 1% to 2%; however, there are two radon interferences that must either be minimized or considered; these are 1) radon entering the chamber while the electret is being read; and 2) radon entering the chamber during the time it is deployed in the field. It is also important that extreme care be taken in handling the

electrets to avoid spurious discharges which translate into erroneously high exposures.

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