

## APPLICATION OF NIST $^{222}\text{Rn}$ EMANATION STANDARDS FOR CALIBRATING $^{222}\text{Rn}$ MONITORS

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**Abstract**— The NIST (National Institute of Standards and Technology) has recently made available  $^{222}\text{Rn}$  emanation standards. The NIST certified parameters include the  $^{226}\text{Ra}$  strength and the emanation coefficient. When such a source is loaded into a leak tight enclosure of a known volume,  $^{222}\text{Rn}$  accumulates over time and it is possible to calculate precisely both the  $^{222}\text{Rn}$  concentration after any accumulation time and also the time integrated average  $^{222}\text{Rn}$  concentration after any given accumulation time. Equations needed for calculations are given. For example, if a 25 Bq (676 pCi) NIST source is loaded into a jar with an air volume of 3.72 litres, the time integrated average  $^{222}\text{Rn}$  concentration is  $973 \text{ Bq}\cdot\text{m}^{-3}$  ( $26.3 \text{ pCi}\cdot\text{l}^{-1}$ ) after an accumulation time of two days. If the  $^{222}\text{Rn}$  detector placed in the jar is non-radon-absorbing and a true integrator, it must yield the theoretically predicted results. If not, an appropriate calibration correction factor can be calculated. The paper describes a study involving 34 randomly chosen commercially available E-PERM<sup>(R)</sup> (Electret-Passive Environmental Radon Monitor) and 17 NIST sources in 17 different calibration (accumulator) jars. The study indicated that E-PERM<sup>(R)</sup>S give results within about 5% of the predicted results. The study also includes a study of continuous radon monitors. The data obtained show that, in practice, NIST sources can be used to calibrate both passive and active continuous  $^{222}\text{Rn}$  monitors. The availability of NIST sources with a precisely known  $^{222}\text{Rn}$  emanation characteristic is a major advance in radon metrology. Practical problems in the successful use of these sources are discussed.

### INTRODUCTION

The NIST (National Institute of Standards and Technology) has recently made available  $^{222}\text{Rn}$  emanation standards<sup>(1)</sup>. The NIST certified parameters include the  $^{226}\text{Ra}$  strength and the emanation coefficient. When such a source is loaded into a leak tight jar of a known volume  $^{222}\text{Rn}$  will accumulate over time. It is possible to calculate precisely the time integrated average radon concentration after any given accumulation time. If the  $^{222}\text{Rn}$  detector present in the jar is non-radon-absorbing and a true integrator, this radon detector must yield the theoretically predicted results. If there is some consistent difference, suitable NIST traceable calibration corrections can be derived. The current study involves 34 randomly chosen E-PERM<sup>(R)</sup>S\* and 17 NIST sources in 17 different calibration jars. The purpose of the study is to show how a NIST source can be used in practice. The availability of NIST sources with precisely known radon emanation characteristics is considered to be a major advance in radon metrology.

### MATERIALS AND METHODS

The recently developed  $^{222}\text{Rn}$  emanation standards that are based on polyethylene-encapsulated  $^{226}\text{Ra}$  solutions<sup>(1)</sup> are used in the present study. These sources

are certified by NIST in terms of  $^{226}\text{Ra}$  content and the  $^{222}\text{Rn}$  emanation fraction. These have been demonstrated to emanate a well characterised and known quantity of  $^{222}\text{Rn}$  when employed in 'accumulation mode'<sup>(1)</sup>. A total of 17 such sources with  $^{226}\text{Ra}$  content ranging from about 4.5 Bq to about 450 Bq with an emanation fraction of 0.890 were made available by NIST for this study. Specially prepared glass jars with a capability of being made leak tight were used as accumulators (see Figure 1). Such glass jars were previously used for the measurement of  $^{222}\text{Rn}$  in water<sup>(2)</sup>. The  $^{222}\text{Rn}$  detectors used were the standard commercially available E-PERM<sup>(R)</sup> 210 ml volume 'S' chamber<sup>(3,4)</sup> configured with either short term (ST) or long term (LT) electrets.

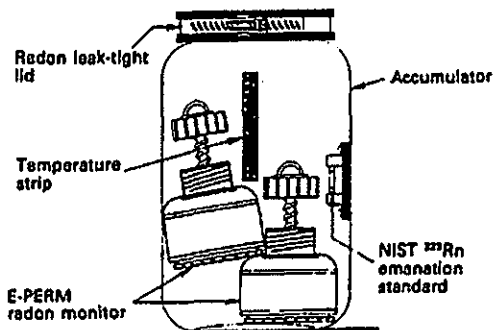


Figure 1. Experimental arrangement. Detectors used: two SST or SLT E-PERMs.

\*E-PERM<sup>(R)</sup> is a registered trade mark of the electret ion chamber system patented and manufactured by Rad Elec Inc., 5714-C Industry Lane, Frederick, MD 21701, USA.

**THEORETICAL CALCULATIONS OF <sup>222</sup>Rn IN AN ACCUMULATOR**

Equation 1 gives the <sup>222</sup>Rn concentration in the accumulator at any time T<sub>A</sub> after the start of accumulation. This is the maximum <sup>222</sup>Rn concentration seen by the detector in the accumulator. The <sup>222</sup>Rn concentration varies from zero at the start of the experiment to the concentration given by Equation 1 at the end of the accumulation time of T<sub>A</sub> days:

$$A_{Rn} = \frac{f A_{Ra} (1 - \exp(-\lambda_{Rn} T_A))}{V_A} \quad (1)$$

where A<sub>Ra</sub> is the <sup>226</sup>Ra content of the NIST source, A<sub>Rn</sub> is the <sup>222</sup>Rn concentration after an accumulation time of T<sub>A</sub> days, f is the emanation coefficient of NIST source, λ<sub>Rn</sub> is the decay constant of <sup>222</sup>Rn, V<sub>A</sub> is the air volume of the accumulator.

The time integrated concentration of <sup>222</sup>Rn is obtained by integrating Equation 1 from time zero to T<sub>A</sub>. Further, if the time integrated <sup>222</sup>Rn is divided by the accumulation time T<sub>A</sub>, we arrive at the average concentration over the time T<sub>A</sub>, C<sub>Rn</sub> (Equation 2 gives the result). This is always smaller than the maximum concentration

given by Equation 1 since the chamber starts with 0 concentration and builds up to a maximum:

$$C_{Rn} = \frac{f A_{Ra}}{V_A} \left( 1 - \frac{1 - \exp(-\lambda_{Rn} T_A)}{\lambda_{Rn} T_A} \right) \quad (2)$$

The <sup>226</sup>Ra concentration is in Bq units, f is the emanation coefficient and is determined by NIST as 0.890, the volume of the jar should be in units of cubic metres (3720 ml = 0.00372 m<sup>3</sup>), the time is in units of days and the decay constant of radon is in units of day<sup>-1</sup> (0.1812), then the <sup>222</sup>Rn concentration is in units of Bq.m<sup>-3</sup>. This is divided by 37 to get the concentration in pCi.l<sup>-1</sup>.

**AIR VOLUME OF THE ACCUMULATOR**

The air volume of the accumulator depends upon the number and the type of E-PERM<sup>(R)</sup> used in the accumulator jar. The different air volumes to be used are given in Table 1. These were determined experimentally by carefully measuring the volume of the empty jar and the volume of the jar when one, two or three 'S' chambers were loaded into the jar. The empty accumulator jars were filled with distilled water and the water needed to fill the jar weighed. Measurements were then made by loading the accumulator jar with different numbers of 'S' chambers. The difference in the weight of the water between the two measurements gives the air volume of the jars, when the respective number of detectors were loaded. Experiments were repeated at least 10 times and the values reported in the table have an error of less than 3%. Similar measurements were made for one, two, three and four 'L' chambers. The volume of the empty jar is 3996 ml and the air volume occupied by one SST or SLT E-PERM is 123 ml and one LST or LLT E-PERM is 47 ml.

Depending upon how many E-PERMs are inside the accumulator, the appropriate air volume (V<sub>A</sub>) given by Table 1 should be used. For example, if 2 SST (or SLT) are used in the accumulator, the appropriate value for V<sub>A</sub> to be used is 3720 ml. See Table 1 for the appropriate value to be used when a different number of detectors are used in the accumulator.

Figure 2 is a graphical representation of Equations 1 and 2. The top curve gives the maximum <sup>222</sup>Rn concentration seen by the detector (Equation 1) and the lower curve gives the time averaged concentration (Equation 2) seen by the detector. If the detector is a true integrator, the response should be in accordance with the lower curve. If a continuous radon monitor is inside the accumulator, it should track the upper curve.

Table 1. Air volume of the accumulator when different numbers and types of E-PERMs are used in the accumulator.

E-PERM type	Number of units	Air volume (ml)
SST or SLT	1	3843
SST or SLT	2	3720
SST or SLT	3	3597
LST or LLT	1	3920
LST or LLT	2	3873
LST or LLT	3	3827
LST or LLT	4	3780

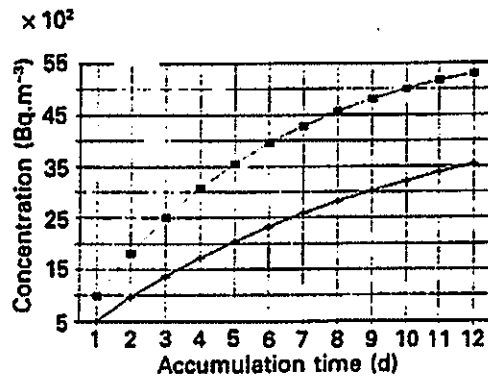


Figure 2. <sup>222</sup>Rn concentration in a 3.72 litre accumulator. Detectors used: two SST E-PERMs. Source: NIST source with 25 Bq <sup>226</sup>Ra and f of 0.890. (●) radon concentration, (+) average radon concentration.

**EXPERIMENTS AND RESULTS**

Each source was fixed inside each jar using the clip arrangement. The NIST serial number was marked on each jar. NIST instructions require that the source

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should be open to the atmosphere for at least 24 h prior to the use of the source in the accumulator mode<sup>(1)</sup>. This boundary condition was achieved by keeping the lid of the jars open for at least 24 h. The jars were also left in a low radon area (outside environment) so that the contribution from the residual radon in the jar is minimised before starting the accumulation. A pair of pre-measured E-PERMS (initial voltage IV) were loaded into each jar, lids closed, the collars tightened and the time noted (please see Figure 1). This is the start of the experiment. After the desired specific accumulation period, the E-PERMS were removed from the jar and left in a low radon area in the 'on' position for a period of 3 h. Only after this delay was the final voltage reading taken (FV<sub>2</sub>). In the normal use of E-PERMS the final reading is taken immediately after the termination of a measurement. The reasons for taking a delayed final reading in the present case warrant additional discussion. In the accumulator mode the radon concentration changes from zero at the beginning to a

maximum concentration at the end of the experiment. The <sup>222</sup>Rn and associated progeny signals at the beginning and at the end are very different. The E-PERMS are usually calibrated in a radon calibration chamber with a steady <sup>222</sup>Rn concentration<sup>(3,4)</sup>. Boundary conditions are not the same in the accumulator mode and in steady state modes. The end effect in accumulation mode is compensated by leaving the E-PERMS in a low radon area for about 3 h so that the contribution from the deposited decay products is taken into account. By following this procedure it has been found that the accumulation periods can be as short as 6 h. The <sup>222</sup>Rn concentration was calculated by the standard procedure<sup>(3,4)</sup> using the calibrations based on steady state radon concentration. It is important to note that the actual accumulation time is used in the calculation and this does not include the 3 h delay time.

Results are listed in Tables 2 to 6. In these tables, column 2 gives the source strength and column 3 gives the theoretically calculated average concentration in the

Table 2. Experimental results. Detectors used: two SST E-PERMS. Accumulation time 3.07 days.

Source	NS (Ra Bq)	NS (Bq.m <sup>-3</sup> )	EI	IV	FV <sub>2</sub>	EP (Bq.m <sup>-3</sup> )	EP-B	(EP-B)/ NS	Av. ratio
CP5	4.2602	237	SK6439	625	574	245	213	0.898	
CP5	4.2602	237	SK4701	626	575	245	213	0.897	0.898
CP6	4.546	253	SK4697	508	448	304	272	1.075	
CP6	4.546	253	SK1126	517	462	275	243	0.962	1.018
CP7	4.7121	262	SI3944	658	598	290	258	0.984	
CP7	4.7121	262	SK3612	662	600	300	268	1.023	1.004
CP27	4.7532	265	SK1301	621	559	304	272	1.029	
CP27	4.7532	265	SK4734	618	550	337	305	1.152	1.090
CP28	4.6167	257	SJ6073	414	350	336	304	1.183	
CP28	4.6167	257	SK4733	423	368	284	252	0.980	1.082
CP30	3.6889	205	SK3574	405	355	257	225	1.096	
CP30	3.6889	205	SK3786	407	359	245	213	1.040	1.068
CP31	4.7304	263	SK1255	502	441	310	278	1.056	
CP31	4.7304	263	SK4722	502	443	299	267	1.014	1.035
CP32	4.9893	278	SK6435	430	373	295	263	0.945	
CP32	4.9893	278	SK6412	433	376	294	262	0.944	0.945
CP33	4.7321	263	SK6446	324	274	264	232	0.881	
CP33	4.7321	263	SK1118	317	262	294	262	0.995	0.938
CP35	5.0071	279	SK1217	217	162	304	272	0.976	
CP35	5.0071	279	SK4696	226	177	267	235	0.843	0.910
CP36	4.7704	266	SK3601	413	354	308	276	1.038	
CP36	4.7704	266	SK3533	397	339	303	271	1.022	1.030
CP37	5.0289	280	SK6405	319	265	288	256	0.914	
CP37	5.0289	280	SK4715	312	254	312	280	1.001	0.957
CP38	5.6069	312	SJ3779	646	575	350	318	1.018	
CP38	5.6069	312	SK3728	649	576	360	328	1.052	1.035
CP41	5.1324	286	SK4699	208	156	287	255	0.892	
CP41	5.1324	286	SK6451	213	163	274	242	0.848	0.870
CP42	5.2977	295	SK3682	219	166	292	260	0.881	
CP42	5.2977	295	SJ5778	216	162	298	266	0.903	0.892
CP44	5.3052	295	SI3986	288	231	309	277	0.937	
CP44	5.3052	295	SK3768	289	229	326	294	0.997	0.967
blank	0	0	SI1457	679	670	21		Av.	0.949
blank	0	0	SI1419	667	654	42		% STD	5.608

accumulator. Column 7 gives the average concentration as measured by E-PERMs, Column 8 gives the net E-PERM value after subtracting the blank reading<sup>(B)</sup> and column 9 gives the ratio of the concentration measured by E-PERM and the theoretically expected concentration. Column 10 gives the average ratio of the two detectors in the same accumulator. The grand average ratio and the associated standard deviation is given at the end of column 10. To obtain the blank reading, two E-PERMs were introduced into an empty jar similar to the one used for experiments. These E-PERMs were exposed for the same time that was used for the experimental ones.

### DISCUSSION OF RESULTS

Table 2 gives the results for a 3.07 day accumulation. Two SST E-PERMs were used. NIST sources used were

of 4 to 5 Bq <sup>226</sup>Ra. Because the usable range of electret surface voltage is from 700 to 200 V, electrets of different surface voltages were used to verify their performance over the entire usable voltage range. Table 3 is a repeat of the experiment, using the same detectors and same sources. Table 4 gives the results of experiments with stronger sources (33 to 460 Bq). Table 5 and Table 6 give results using SLT E-PERMs.

Results indicate that, on average, SST devices give results nearly 3% lower than the NIST predicted values. Similarly, on average, SLT devices give results nearly 6% lower than the NIST predicted values. This is within the accuracy expected from E-PERMs<sup>(3,4)</sup>. However, individual E-PERMs can vary by wider margins. For very accurate measurements, individually calibrated E-PERMs can be used (please see later section). The procedure developed in this study is demonstrated to be usable for different accumulation times, for different

Table 3. Experimental results. Detectors used: two SST E-PERMs. Accumulation time 3.00 days.

Source	NS (Ra Bq)	NS (Bq.m <sup>-3</sup> )	EI	IV	FV <sub>2</sub>	EP (Bq.m <sup>-3</sup> )	EP-B	(EP-B)/ NS	Av. ratio
CP5	4.2602	232	SK6439	573	523	250	217	0.934	
CP5	4.2602	232	SK4701	573	525	239	206	0.886	0.910
CP6	4.5460	248	SK4697	447	390	301	268	1.079	
CP6	4.5460	248	SK1126	462	409	276	243	0.981	1.030
CP7	4.7121	257	SI3944	595	539	281	248	0.966	
CP7	4.7121	257	SK3612	598	540	292	259	1.008	0.987
CP27	4.7532	259	SK1301	557	499	296	263	1.014	
CP27	4.7532	259	SK4734	549	487	319	286	1.103	1.059
CP28	4.6167	252	SI6073	350	288	340	307	1.219	
CP28	4.6167	252	SK4733	368	315	285	252	1.000	1.110
CP30	3.6889	201	SK3574	356	307	262	229	1.139	
CP30	3.6889	201	SK3786	358	311	250	217	1.080	1.109
CP31	4.7304	258	SK1255	439	381	307	274	1.063	
CP31	4.7304	258	SK4722	443	388	290	257	0.994	1.028
CP32	4.9893	272	SK6435	367	313	291	258	0.947	
CP32	4.9893	272	SK6412	375	319	302	269	0.988	0.968
CP33	4.7321	258	SK6446	274	230	239	206	0.799	
CP33	4.7321	258	SK1118	262	211	283	250	0.968	0.884
CP35	5.0071	273	SK1217	162	110	299	266	0.975	
CP35	5.0071	273	SK4696	176	130	260	227	0.832	0.903
CP36	4.7704	260	SK3601	354	296	316	283	1.087	
CP36	4.7704	260	SK3533	339	284	300	267	1.024	1.055
CP37	5.0289	274	SK6405	266	215	283	250	0.910	
CP37	5.0289	274	SK4715	254	200	302	269	0.981	0.945
CP38	5.6069	316	SI3779	573	503	361	328	1.038	
CP38	5.6069	316	SK3728	575	505	361	328	1.037	1.037
CP40	4.9055	268	SK6434	745	688	274	241	0.901	
CP40	4.9055	268	SK6415	744	677	327	294	1.100	1.001
CP41	5.1324	280	SK4692	746	690	269	236	0.842	
CP41	5.1324	280	SK6422	748	689	285	252	0.898	0.870
CP42	5.2977	289	SK1253	749	690	284	251	0.870	
CP42	5.2977	289	SK6448	735	675	291	258	0.893	0.881
CP44	5.3052	289	SI3986	230	175	311	278	0.960	
CP44	5.3052	289	SK3768	229	171	329	296	1.024	0.992
blank	0.0000	0	SI1457	664	653	33		GRD A	0.986
blank	0.0000	0	SI1419	655	644	33		% STD	9.299

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E-PERM configurations and for sources of different strengths. E-PERMs were found to function as truly integrating <sup>222</sup>Rn measuring devices, integrating radon concentrations from near zero to the highest (17,500 Bq.m<sup>-3</sup>) encountered in the study.

Before using a certain configuration of E-PERM with a source of certain strength, one should do a theoretical analysis so as not to discharge the electret beyond the operating voltages of electrets.

In order to use NIST sources in accumulation mode:

- (1) It is important to know the exact air volume of the accumulator, when test devices are inside the

accumulator. This may be more complicated when complex instruments such as continuous radon monitors are located inside the accumulator.

- (2) The accumulator should be leak tight so that accumulated radon does not escape.
- (3) The test devices themselves should not absorb or affect the radon concentration in the accumulator.
- (4) Instruction given by NIST on the use of these sources must be followed<sup>(1)</sup>. One important requirement is to leave the source in infinite volume for at least 24 h before using the source in the accumulator. NIST recommends that the sources be stored in 100% relative humidity, when not in use.

Table 4. Experimental results. Detectors used: two SST E-PERMs. Accumulation time: 1 day for CP45 to CP59 and 2 days for CP17 to CP26.

Source	NS (Ra Bq)	NS (Bq.m <sup>-3</sup> )	EI	IV	FV <sub>2</sub>	EP (Bq.m <sup>-3</sup> )	EP-B	(EP-B)/ NS	Av. ratio
CP17	33.7809	1300	SI2011	754	592	1268	1235	0.951	
CP17	33.7809	1300	SI1591	748	585	1279	1246	0.959	0.955
CP18	33.658	1295	SI0140	646	475	1384	1351	1.043	
CP18	33.658	1295	SI2032	754	586	1317	1284	0.992	1.018
CP19	35.9525	1383	SI1047	750	575	1376	1343	0.971	
CP19	35.9525	1383	SI1999	745	574	1345	1312	0.949	0.960
CP20	35.5126	1366	SI0249	738	565	1365	1332	0.975	
CP20	35.5126	1366	SI0284	745	574	1345	1312	0.961	0.968
CP21	33.0733	1272	SI1632	747	587	1255	1222	0.960	
CP21	33.0733	1272	SI2034	757	589	1316	1283	1.009	0.984
CP22	31.3056	1204	SI2040	750	594	1221	1188	0.986	
CP22	31.3056	1204	SI0302	748	596	1189	1156	0.960	0.973
CP23	30.331	1167	SI2041	753	606	1146	1113	0.954	
CP23	30.331	1167	SI2162	741	583	1240	1207	1.035	0.994
CP24	35.9959	1385	SI0265	751	585	1302	1269	0.917	
CP24	35.9959	1385	SI2019	750	588	1270	1237	0.893	0.905
CP26	32.9087	1266	SI2138	742	565	1396	1363	1.077	
CP26	32.9087	1266	SI1075	751	598	1196	1163	0.919	0.998
CP45	428.478	8846	SI2145	757	250	8355	8322	0.941	
CP45	428.478	8846	SI2010	746	238	8400	8367	0.946	0.943
CP46	398.748	8232	SI2044	753	225	8739	8706	1.058	
CP46	398.748	8232	SI2014	753	227	8703	8670	1.053	1.055
CP47	419.614	8663	SI2135	740	198	9024	8991	1.038	
CP47	419.614	8663	SI1608	698	161	9045	9012	1.040	1.039
CP48	451.396	9319	SI1628	747	197	9150	9117	0.978	
CP48	451.396	9319	SI0936	757	182	9574	9541	1.024	1.001
CP49	409.593	8456	SI1062	745	218	8742	8709	1.030	
CP49	409.593	8456	SI1571	750	228	8639	8606	1.018	1.024
CP50	403.649	8333	SI0175	772	233	8887	8854	1.062	
CP50	403.649	8333	SI1630	753	216	8900	8867	1.064	1.063
CP52	420.823	8688	SI1503	737	198	8978	8945	1.030	
CP52	420.823	8688	SI1077	746	215	8811	8778	1.010	1.020
CP53	404.359	8348	SI1115	755	220	8859	8826	1.057	
CP53	404.359	8348	SI2076	743	241	8300	8267	0.990	1.024
CP57	453.09	9354	SI2077	739	180	9334	9301	0.994	
CP57	453.09	9354	SI1368	763	237	8678	8645	0.924	0.959
CP59	464.252	9584	SI2047	725	158	9518	9485	0.990	
CP59	464.252	9584	SI2025	754	175	9654	9621	1.004	0.997
								Av.	0.994
								% STD	3.955

Table 5. Experimental results. Detectors used: two SLT E-PERMs. Accumulation time: 1 day.

Source	(Ra Bq)	NS (Bq.m <sup>-3</sup> )	EI	IV	FV <sub>2</sub>	EP (Bq.m <sup>-3</sup> )	EP-B	(EP-B)/ NS	Av. ratio
CP45	428.478	8848	LD6089	305	266	8007	7964	0.901	
CP45	428.478	8848	LD5978	306	268	7797	7796	0.881	0.891
CP46	398.748	8234	LD5932	504	465	7499	7499	0.911	
CP46	398.748	8234	LD9638	502	457	8671	8670	1.053	0.982
CP47	419.614	8665	LD5845	708	665	7771	7771	0.897	
CP47	419.614	8665	LD2535	708	664	7954	7953	0.918	0.907
CP48	451.396	9321	LD6084	300	262	7813	7812	0.838	
CP48	451.396	9321	LD5983	306	265	8419	8418	0.903	0.871
CP49	409.593	8458	LD6060	597	553	8227	8226	0.973	
CP49	409.593	8458	LD5957	609	568	7633	7632	0.902	0.937
CP50	403.649	8335	LC7254	504	465	7499	7499	0.900	
CP50	403.649	8335	LD8314	508	464	8460	8459	1.015	0.957
CP52	420.823	8690	LD5921	713	668	8124	8124	0.935	
CP52	420.823	8690	LD5914	742	696	8235	8235	0.948	0.941
CP53	404.359	8350	LC7363	614	570	8184	8183	0.980	
CP53	404.359	8350	LD5768	611	570	7628	7627	0.913	0.947
CP57	453.09	9356	LD5905	408	365	8538	8537	0.912	
CP57	453.09	9356	LD5899	396	353	8571	8571	0.916	0.914
CP59	464.252	9587	LD5988	409	364	8936	8935	0.932	
CP59	464.252	9587	LD6058	408	363	8939	8938	0.932	0.932
								Av.	0.928
								% STD	3.349

Table 6. Experimental results. Detectors used: two SLT E-PERMs. Accumulation time: 2 days.

Source	NS (Ra Bq)	NS (Bq.m <sup>-3</sup> )	EI	IV	FV <sub>2</sub>	EP (Bq.m <sup>-3</sup> )	EP-B (Bq.m <sup>-3</sup> )	(EP-B)/ NS	Av. ratio
CP45	428.478	16713	LD6089	266	116	15908	15875	0.950	
CP45	428.478	16713	LD5978	268	122	15461	15428	0.923	0.936
CP46	398.748	15554	LD5932	465	316	14769	14736	0.947	
CP46	398.748	15554	LA9638	457	298	15829	15796	1.016	0.982
CP47	419.614	16368	LE5845	665	502	15198	15165	0.927	
CP47	419.614	16368	LD2535	664	490	16258	16225	0.991	0.959
CP48	451.396	17607	LD6084	262	114	15712	15679	0.890	
CP48	451.396	17607	LD5983	265	108	16678	16645	0.945	0.918
CP49	409.593	15977	LD6060	553	393	15444	15411	0.965	
CP49	409.593	15977	LD5957	568	414	14779	14746	0.923	0.944
CP50	403.649	15745	LC7254	465	320	14362	14329	0.910	
CP50	403.649	15745	LA8314	464	303	15997	15964	1.014	0.962
CP52	420.823	16415	LD5921	668	505	15184	15151	0.923	
CP52	420.823	16415	LD5914	696	533	15054	15021	0.915	0.919
CP53	404.359	15772	LC7363	570	410	15360	15327	0.972	
CP53	404.359	15772	LD5768	570	413	15065	15032	0.953	0.962
CP57	453.09	17673	LD5905	365	206	16323	16290	0.922	
CP57	453.09	17673	LD5899	353	192	16602	16569	0.938	0.930
CP59	464.252	18109	LD5988	364	192	17705	17672	0.976	
CP59	464.252	18109	LD6058	363	193	17499	17466	0.964	0.970
								Av.	0.948
								% ST	2.204

NIST STANDARDS FOR CALIBRATING  $^{222}\text{Rn}$  MONITORS

CALIBRATING CONTINUOUS RADON MONITORS

The use of NIST emanation standards also gives an elegant method of calibrating a continuous radon monitor (CRM) in a single experiment over a wide range of radon concentrations. This application is based on the fact that Equation 1 gives the radon concentration at any accumulation time and that these theoretical estimates should match the reading given by CRM. For example, if one uses a 127 litre accumulator with a source of 880 Bq, the concentration varies from 46.4 Bq.m<sup>-3</sup> after 1 h to 1980 Bq.m<sup>-3</sup> after 48 h. If such an instrument also gives a cumulative average, then this can be compared to the NIST calculated value. Larger accumulation times will yield higher concentrations.

Table 7 gives the comparison between NIST estimated values with the values given by a CRM (Femto-tech model 210, manufactured by Femto-Tech Inc., Carisle, OH, USA). The results indicate that the instrument is well calibrated.

The NIST sources have been previously used for determining the pressure correction factors, also called elevation correction factors by maintaining different pressures simulating different elevations inside the accumulators<sup>(3)</sup>.

CONCEPT OF INDIVIDUALLY CALIBRATED E-PERM or CRM

If an E-PERM shows 5% lower than what is predicted

Table 7. Experimental results. NIST source strength: 879.9 Bq. Detector used: Femto-tech 210 continuous radon monitor. Accumulation time: 17 to 48 hours. R1 is the ratio of radon measured by CRM to radon calculated. R2 is the ratio of average radon measured by CRM to the average radon calculated. Accumulator volume 126.6 litres.

(hours)	NIST Rn (Bq.m <sup>-3</sup> )	NIST Av. Rn (Bq.m <sup>-3</sup> )	CRM Rn (Bq.m <sup>-3</sup> )	CRM Av. Rn (Bq.m <sup>-3</sup> )	R1	R2
17	784.37	400.54	777.00	444.00	0.99	1.11
18	827.45	423.06	814.00	466.20	0.98	1.10
19	870.20	445.47	836.20	484.70	0.96	1.09
20	912.64	467.76	962.00	510.60	1.05	1.09
21	954.75	489.95	991.60	536.50	1.04	1.10
22	996.55	512.02	958.30	555.00	0.96	1.08
23	1038.03	533.99	1028.60	573.50	0.99	1.07
24	1079.20	555.85	1073.00	595.70	0.99	1.07
25	1120.06	577.60	1221.00	617.90	1.09	1.07
26	1160.62	599.24	1217.30	640.10	1.05	1.07
27	1200.87	620.77	1172.90	654.90	0.98	1.05
28	1240.81	642.20	1121.10	669.70	0.90	1.04
29	1280.46	663.52	1328.30	691.90	1.04	1.04
30	1319.80	684.74	1409.70	717.80	1.07	1.05
31	1358.85	705.85	1235.80	736.30	0.91	1.04
32	1397.61	726.86	1328.30	754.80	0.95	1.04
33	1436.08	747.77	1339.40	773.30	0.93	1.03
34	1474.25	768.57	1354.20	791.80	0.92	1.03
35	1512.14	789.27	1561.40	810.30	1.03	1.03
36	1549.75	809.87	1487.40	828.80	0.96	1.02
37	1587.07	830.37	1546.60	847.30	0.97	1.02
38	1624.11	850.77	1609.50	865.80	0.99	1.02
39	1660.87	871.07	1624.30	884.30	0.98	1.02
40	1697.36	891.27	1568.80	906.50	0.92	1.02
41	1733.57	911.37	1816.70	928.70	1.05	1.02
42	1769.51	931.37	1831.50	947.20	1.04	1.02
43	1805.18	951.27	1705.70	965.70	0.94	1.02
44	1840.58	971.08	1857.40	987.90	1.01	1.02
45	1875.71	990.79	1757.50	1006.40	0.94	1.02
46	1910.58	1010.40	1879.60	1024.90	0.98	1.01
47	1945.19	1029.92	1790.80	1039.70	0.92	1.01
48	1979.53	1049.35	1835.20	1058.20	0.93	1.01
				Av.	0.98	1.04
				STD	0.05	0.05

by the NIST source, the results of the measurements made by using this unit in a later measurement should be divided by 0.95 to get the correct results. Using a portion (say from 700 to 650 V) it is possible to calibrate an E-PERM to NIST traceability. This still has a large range of usable voltage. An individually calibrated E-PERM can be used as reference E-PERM or as transfer standard for calibrating continuous  $^{222}\text{Rn}$  monitors used in  $^{222}\text{Rn}$  Calibration Test Chambers. The same logic applies to a CRM calibrated using NIST source.

## CONCLUSIONS

For the first time, it is possible to calibrate both passive and continuous radon monitors to NIST traceability.

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The procedures developed in this work are usable with simple equipment. Typical passive devices (E-PERMs) were found to give predicted measurement with an accuracy of about 5%. Similarly, commercially available continuous radon monitors (Femto Tech) also gave satisfactory performances. With the availability of this technology,  $^{222}\text{Rn}$  measurement instruments can all be made NIST traceable. This is indeed a great step forward in radon metrology.

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