



# National Institute of Standards & Technology

## Certificate

### Standard Reference Material 4968 Radon-222 Emanation Standard

Radionuclide	Radon-222 (Radium-226) <sup>(a)*</sup>
Source identification	SRM 4968 - 49
Source description	Liquid <sup>(b)</sup> in a polyethylene capsule <sup>(c)</sup>
Total source mass	0.336 grams <sup>(d)</sup>
Radium-226 activity, $A_{Ra}$	409.6 Bq
Uncertainty in $A_{Ra}$	0.93 percent <sup>(e)</sup>
Reference time for $A_{Ra}$	9 September 1991
Radium-226 half life	$1599 \pm 4$ years <sup>(f)</sup>
Radon-222 emanation fraction, $f$	0.890 at 21 °C <sup>(g)</sup>
Uncertainty in $f$	4.0 percent <sup>(h)</sup>
Radon-222 half life	$3.823 \pm 0.004$ days <sup>(f)</sup>
Calibration method for $A_{Ra}$	NIST pressurized "4 $\pi$ " $\gamma$ ionization chamber "A" calibrated with national radium standards <sup>(i)</sup> ; and confirmatory measurements <sup>(j)</sup>
Calibration method for $f$	Pulse-ionization chamber (PIC) measurements with the NIST primary radon measurement system <sup>(k)</sup>

This standard reference material was prepared in the Physics Laboratory, Ionizing Radiation Division, Radioactivity Group, J.M. Robin Hutchinson, Group Leader.

Gaithersburg, MD  
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\*Notes on back

## NOTES

- (a) This Standard Reference Material (SRM) is certified and intended for use in the calibration of  $^{222}\text{Rn}$  measurement systems when suitably employed. Refer to the attached Annex B (Information for Users) for details on appropriate applications and restrictions for use and storage of the capsules.
- (b) The liquid in the capsule is a calibrated  $^{226}\text{Ra}$  solution containing  $\text{Ra}^{+2}$  and approximately 2 mg of non-radioactive barium chloride per gram of approximately  $1 \text{ mol} \cdot \text{L}^{-1}$  hydrochloric acid.
- (c) The encapsulated emanation standard consists of a heat-sealed right circular cylinder of low-density polyethylene having a 0.32-cm outside diameter and a nominal 1.7-cm effective length along the emanating area (overall length is  $\approx 2 \text{ cm}$ ) and was gravimetrically filled with a calibrated  $^{226}\text{Ra}$  solution having a known activity concentration [see Note j]. The total polyethylene mass of the capsule, including the nominal 0.15-cm plugs of polyethylene at the sealed tube ends, is about 0.19 grams.
- (d) The standard should not be used if the total mass of the capsule decreases to less than 0.280 grams from the transpiration of solution. Refer to Annex B.
- (e) The tabulated uncertainty in  $A_{\text{Ra}}$  is a "relative expanded uncertainty" with a "coverage factor" of  $k = 2$ . Its magnitude, 0.93 percent, was obtained by taking two times the quadratic combination of the following "standard uncertainty" components:
- |      |   |                |
|------|---|----------------|
| i)   | four ion chamber "A" measurements on samples of 2 dilutions   | 0.069 percent  |
| ii)  | twenty-two comparative ion chamber "A" measurements on 8 "1947 (1967 recalibrated) series" of $^{226}\text{Ra}$ standards   | 0.040 percent  |
| iii) | ion chamber "A" calibration for the "1947 (1967 recalibrated) series" [with respect to the "radiation balance" primary measurements on the "1957" series" and national radium standards (see Note i)] | 0.34 percent   |
| iv)  | gravimetric dilution factors  | 0.15 percent   |
| v)   | half-life correction  | 0.0026 percent |
| vi)  | $^{226}\text{Ra}$ mass to activity conversion   | 0.25 percent   |
| vii) | gravimetric filling of capsule  | 0.1 percent    |

The standard uncertainties are standard deviations (or standard deviations of the mean where appropriate), or approximations thereof. A detailed description of how each uncertainty component was evaluated is given in attached Annex A. The expanded uncertainty is assumed to provide an uncertainty interval having a high level of confidence of roughly 90 to 95 percent. Historically, the NIST Radioactivity Group reported "overall uncertainties" that were a combined standard uncertainty expanded by a factor of three. An expansion factor of two is currently used to achieve uniformity with national and international practices [cf., B.N. Taylor and C.E. Kuyatt, **NIST Technical Note 1297**, (1993)]. Refer to Annex B for the recommended use of this uncertainty in  $A_{\text{Ra}}$  to propagate an uncertainty for an accumulated  $^{222}\text{Rn}$  activity.

- (f) International Union of Pure and Applied Chemistry, Analytical Chemistry Division, Commission on Radiochemistry and Nuclear Techniques, *Total Half-lives for Selected Nuclides*, prepared for publication by N.E. Holden, **Pure and Applied Chemistry** 62, 941 (1990).

- (g) The emanation fraction,  $f$ , is defined as the fraction of the total  $^{222}\text{Rn}$  generated by decay of  $^{226}\text{Ra}$  that is released from the capsule and contained within the volume of an accumulation vessel. Refer to Annex B, especially section 7.
- (h) The tabulated uncertainty in  $f$  is a "relative expanded uncertainty" with a "coverage factor" of  $k = 2$ . Its magnitude, 4.0 percent, was obtained by taking two times the quadratic combination of the following "standard uncertainty" components:
- |      |  |                            |
|------|--|----------------------------|
| i)   | precision in pulse-ionization-chamber (PIC) measurements for both within-capsule and between-capsule variability | 1.90 percent               |
| ii)  | PIC calibration (see Note k), excludes $^{226}\text{Ra}$ calibration   | 0.38 percent               |
| iii) | $^{226}\text{Ra}$ calibration and filling  | 0.45 percent               |
| iv)  | $^{222}\text{Rn}$ decay corrections and accumulation factors, including timing errors                            | <0.01 percent (negligible) |
| v)   | $^{226}\text{Ra}$ decay corrections (negligible)   | <0.001 percent             |

The standard uncertainties are standard deviations (or standard deviations of the mean where appropriate), or approximations thereof. Detailed descriptions of how each uncertainty component was evaluated is given in attached Annex A. The expanded uncertainty is assumed to provide an uncertainty interval having a high level of confidence of roughly 90 to 95 percent. Historically, the NIST Radioactivity Group reported "overall uncertainties" that were a combined standard uncertainty expanded by a factor of three. An expansion factor of two is currently used to achieve uniformity with national and international practices [cf., B.N. Taylor and C.E. Kuyatt, NIST Technical Note 1297, (1993)]. Refer to Annex B for the recommended use of this uncertainty in  $f$  to propagate an uncertainty for an accumulated  $^{222}\text{Rn}$  activity.

- (i) For further details on NIST (NBS) radium series calibrations see W.B. Mann, et al., J. Res. NBS 62, 21-16 (1959). The 1967 recalibration of the "1947 series" and "1957 series" intercomparisons were made with " $4\pi\gamma$  ionization chamber "A".
- (j) For confirmation, the calibrated  $^{226}\text{Ra}$  solution used in this standard was also directly compared by liquid scintillation measurements against preparations of the 1992 series of  $^{226}\text{Ra}$  standards (SRM 4965, 4966, and 4967). The latter SRMs were, in turn, also directly compared against preparations of the "1947 (1967 recalibration)", "1978", and "1984"  $^{226}\text{Ra}$  series by  $^{222}\text{Rn}$  analyses with the NIST pulse-ionization-chamber Primary Radon Measurement System [see Note k]), by liquid scintillation counting, and by NaI(Tl) well-crystal and Ge  $\gamma$ -spectrometry.
- (k) R. Collé, J.M.R. Hutchinson, and M.P. Unterweger, *The NIST Primary Radon-222 Measurement System*, J. Res. NIST 95, 155-165 (1990); J.M.R. Hutchinson, J. Cessna, R. Collé and P. Hodge, *An International Radon-in-Air Measurement Intercomparison Using a New Transfer Standard*, Int. J. Appl. Radiat. Isot. 43, 175-189 (1992).

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## ANNEX A

### UNCERTAINTY COMPONENT DELINEATION

Following are detailed descriptions of how each standard uncertainty component in the Certificate for SRM 4968 was evaluated. This is done in compliance with the new NIST policy on uniformly expressing the uncertainty of NIST measurement results. Refer to Ref. [7] in Annex B.

#### Components for the Uncertainty in $A_{Ra}$

- i) The uncertainty of component (i), 0.069 percent, is a relative standard deviation of the mean for  $\nu = 7$  degrees of freedom (four measurements on two dilutions). Each of these eight independent measurement results was derived from 10 to 14 replicate ionization chamber determinations, was corrected for background using an equal number of background measurement determinations, and was compared and normalized to identical radium reference sources. This uncertainty component includes background uncertainty contributions.
- ii) The uncertainty for component (ii), 0.040 percent, is the relative standard deviation of the mean for  $\nu = 7$  degrees of freedom (for eight  $^{226}\text{Ra}$  standards). The individual mean for each standard was determined by 22 comparative ionization chamber measurements (of 10 to 14 determinations each). As for component (a), the results were background corrected using an equal number of background determinations, and was compared and normalized to identical radium reference sources. Background uncertainty contributions are included.
- iii) The uncertainty for component (iii), 0.34 percent, is a relative combined standard uncertainty (assumed to correspond to a propagated standard deviation) for the calibration of "4 $\pi$ " $\gamma$  ionization chamber "A". Refer to the reference in Note i of the Certificate for SRM 4968.
- iv) The uncertainty for component (iv), 0.15 percent, is a relative combined standard uncertainty in dilution factors obtained by mass measurement determinations after appropriately normalizing the mass measurement uncertainties by their respective sensitivity coefficients. The uncertainty is that for dilution factors comprising two to four serial dilutions and includes mass measurement uncertainties in sample preparations used to confirm the gravimetrically-determined dilution factors. The dilution factor for every single dilution is independently confirmed by activity measurements. The uncertainty as a result is derived from a complex analysis which includes standard uncertainty estimates for: internal balance weights; precision in reading the smallest balance digit; air-buoyancy corrections; internal-balance weight corrections; long-term canonical precision estimators for the reproducibility between dispensed mass differences and contained mass differences (and at different tare masses); and dilution factor confirmatory measurements.
- v) The uncertainty for component (v), 0.0026 percent, is a relative standard uncertainty due to the uncertainty in the  $^{226}\text{Ra}$  half-life assuming the latter has a relative standard uncertainty of 0.25%. Additional uncertainty contributions due to the uncertainty in time for the decay corrections are negligible.
- vi) The uncertainty for component (vi), 0.25 percent, is a relative standard uncertainty propagated from the standard uncertainties in the  $^{226}\text{Ra}$  decay constant (half-life), the  $^{226}\text{Ra}$

atomic mass, and the Avogadro constant. The conversion is in statistical agreement with independent confirmatory activity measurements.

- vii) The uncertainty for component (vii), 0.10 percent, is a relative standard uncertainty based on the same mass measurement uncertainties given in component (iv) above. Additional details on the uncertainty including that due to solution mass loss on sealing are given in Ref. [1] of Annex B.

### Components for the Uncertainty in (f)

- i) The uncertainty of component (i), 1.90 percent, is a relative standard uncertainty that includes precision estimators for both within-capsule and between-capsule PIC-measurement variability. Between-capsule variability, based on the mean  $f$  obtained for 20 capsules ( $\nu = 19$ ), has a relative standard deviation of  $s_x = 1.80\%$ . Within-capsule variability has a relative standard deviation of the mean ranging from 0.04% to 1.9% for  $\nu = 2$  to 6 degrees of freedom on any given capsule. The standard deviation on this relative standard deviation  $s_m$  is 0.4%, i.e.,  $s_m = (0.7 \pm 0.4)\%$ . The combination (by variances) of  $s_x$  and  $s_m$  results in a relative standard uncertainty of 1.93% which is in agreement with a relative standard deviation of 1.87% obtained from the total of all independent measurements of  $f$  ( $\nu = 63$ ).
- ii) The uncertainty for component (ii), 0.38 percent, is a relative combined standard uncertainty (assumed to correspond to a propagated standard deviation) for the PIC calibration. Refer to the references in Note k of the Certificate for SRM 4968.
- iii) The uncertainty for component (iii), 0.45 percent, is a relative combined standard uncertainty comprised of the relative standard uncertainties for the  $^{226}\text{Ra}$  activity content of a capsule [the combined standard uncertainty in  $A_{\text{Ra}}$  given above] and the gravimetric filling of a capsule [also given above], after excluding common and correlated components.
- iv) The uncertainty for component (iv), <0.01 percent, which is negligible in the propagation, is a relative standard uncertainty due to the uncertainties in the  $^{222}\text{Rn}$  half-life, assuming the latter has a relative standard uncertainty of 0.10%, and in the uncertainties in timing the transfer of the accumulated radon to the PIC (with the contributing uncertainties appropriately normalized by their respective sensitivity coefficients).
- v) The uncertainty for component (v), <0.001 percent, which is negligible in the propagation, is a relative standard uncertainty due to the uncertainty in the  $^{226}\text{Ra}$  half-life assuming the latter has a relative standard uncertainty of 0.25%. Additional uncertainty contributions due to timing uncertainties for the decay corrections are negligible.

## ANNEX B

### INFORMATION FOR USERS

#### CONTENTS:

1. Description
2. Packaging for Shipment
3. Storage
4. Pre-conditioning Requirements
5. Use for Accumulated  $^{222}\text{Rn}$  Activity Applications
6. Use for Integral  $^{222}\text{Rn}$  Activity Applications
7. Other Restrictions and Conditions
8. References

#### 1. DESCRIPTION

This new emanation standard (SRM 4968) consists of a polyethylene-encapsulated  $^{226}\text{Ra}$  solution that has been demonstrated to emanate a known quantity of  $^{222}\text{Rn}$  activity when employed in an "accumulation mode" (see notes (5) and (6) that follow, and ref. [1]).

The standard is intended to serve as a more convenient and easier-to-use alternative to the conventionally employed  $^{226}\text{Ra}$  solution standards that have been disseminated by NIST (NBS) for  $^{222}\text{Rn}$  emanation measurement calibrations for the past 50 or so years (cf., ref. [2] and [3]).

The standard is certified in terms of two parameters, the  $^{226}\text{Ra}$  activity content and the  $^{222}\text{Rn}$  emanation fraction, and therefore, of necessity, has a larger overall calibration uncertainty than that of the currently available  $^{226}\text{Ra}$  solution standards (SRM 4965, 4966, and 4967) which are only certified for  $^{226}\text{Ra}$  activity concentration. Nevertheless, it is envisaged that the encapsulated standard will be sufficiently accurate and efficacious for calibrating instruments used in a variety of measurement applications, particularly those involving routine monitoring and screening of indoor radon air quality.

The standard consists of a heat-sealed right circular cylinder of low-density polyethylene having a 0.32-cm outside diameter and a nominal 1.7-cm effective length along the emanating surface (overall length is  $\approx 2$  cm), and was gravimetrically filled with a calibrated  $^{226}\text{Ra}$  solution having a known activity concentration. The total polyethylene mass of the capsule, including the nominal 0.15-cm plugs of polyethylene at the sealed tube ends, is about 0.19 grams.

The standard is certified in terms of two parameters:

$A_{\text{Ra}}$  = total  $^{226}\text{Ra}$  activity contained in the capsule  
at some reference time  $t_r$ ; and

$f$  =  $^{222}\text{Rn}$  emanation fraction (i.e., the fraction of  
the total  $^{222}\text{Rn}$  generated by decay of  $^{226}\text{Ra}$

that is released from the capsule and contained within the volume of an accumulation vessel);

that allow calculation of the  $^{222}\text{Rn}$  activity accumulated in a suitable vessel after a given accumulation time.

Both parameters are calibrated in terms of measurements that can be directly related to the national radon measurement calibration standard (i.e., the pulse-ionization-chamber-based primary radon measurement system (see ref. [3] and [4]) and to national and international radium standards maintained by NIST (ref. [3] and [5]).

Refer to the notes in the Certificate for SRM 4968 for additional details.

## **2. PACKAGING FOR SHIPMENT**

The encapsulated standard is packaged for shipment in a nominal 22-mL glass screw-capped vial containing moist absorbent cotton and the capsule. Any observed liquid in the vial or on the capsule itself is only condensed water, and contains only minimal accumulated quantities of  $^{222}\text{Rn}$  daughter radionuclides.

## **3. STORAGE**

The standard should be stored when not in use (and, if possible, used as well [see notes (4), (5), and (6)]) at all times in water-saturated air. This may be effected by storing the capsule in the original shipping vial [see note (2)] or in any other suitable closed container in which the capsule is either immersed in water or suspended above water. The latter condition is believed to be more effective in more rapidly achieving a pre-conditioning "equilibration" before each use [see note (4)].

## **4. PRE-CONDITIONING REQUIREMENTS**

The standard must be suitably "pre-conditioned" before and between each accumulation. Before each use, the capsule should be "equilibrated" for a minimum of 24 hours in a large open space, at roughly the ambient and environmental conditions of the measurement.

Similar 24-hour, open-air "equilibrations" should be performed between any sequential accumulation trials so that each accumulation starts under as identical as possible conditions.

## **5. USE FOR ACCUMULATED $^{222}\text{Rn}$ ACTIVITY APPLICATIONS**

The standard should be employed in a suitable closed accumulation vessel that allows quantitative transfer of the accumulated  $^{222}\text{Rn}$  activity, such as the conventional "bubblers" or gas-washing bottles used with radium solution standards.

The capsule should be employed under similar (or as nearly as possible identical) conditions to the bubbler/emanation procedure routinely used in your laboratory. The bubbler should contain the same volume of blank water as would be contained in the bubbler if it were a standard radium solution.

Tests have confirmed that the emanation fraction  $f$  is invariant within our statistical precision over a range of bubbler accumulation volumes from about 100 mL to nearly 500 mL. It is believed that it is possible to accumulate in both larger (see ref. [6]) and somewhat smaller volumes.

The capsule should be *suspended above* the blank water level in the bubbler during accumulations, and not immersed in the blank water. If the capsule is immersed in water during accumulations, then much more imprecise and possibly even very erratic results for the accumulated activity may be obtained because of the less favorable diffusion boundary conditions and because of the absence of a well-defined initialization for the partitioning of  $^{222}\text{Rn}$  in the polyethylene and in the water.

For the case of a typical bubbler/accumulation application, the  $^{222}\text{Rn}$  activity ( $A_{\text{Ra}}$ ) at the end of an accumulation period from  $t = 0$  to  $t = T_A$  may be given in approximate form as:

$$A_{\text{Rn}} = f A_{\text{Ra}} e^{-\lambda_{\text{Ra}} T_D} (1 - e^{-\lambda_{\text{Rn}} T_A}) \quad (46)$$

where  $A_{\text{Rn}}$  =  $^{222}\text{Rn}$  activity accumulated in the bubbler at the *end* of an accumulation time interval (of duration  $T_A$ );

$f$  =  $^{222}\text{Rn}$  emanation fraction;

$A_{\text{Ra}}$  = total  $^{226}\text{Ra}$  activity in the capsule at reference time  $t_r$

$\lambda_{\text{Ra}}$  =  $^{226}\text{Ra}$  decay constant (given by  $\lambda_{\text{Ra}} = \ln 2 / (1599 \pm 4) \text{ yr}^{-1}$ ;

$T_D$  = time interval from the certified  $^{226}\text{Ra}$  activity reference time  $t_r$  to the *start*  $t = 0$  of the accumulation period ( $T_D = t_0 - t_r$ );

$\lambda_{\text{Rn}}$  =  $^{222}\text{Rn}$  decay constant (given by  $\lambda_{\text{Rn}} = \ln 2 / (3.823 \pm 0.004) \text{ d}^{-1}$ ;

$T_A$  = time interval for the total duration of the accumulation.

Equation (1) above assumes that there is no  $^{222}\text{Rn}$  activity initially present at  $t = 0$  in the accumulation vessel ( $A_{\text{Rn}} = A_{\text{Rn}}^0 = 0$  at  $t = 0$ ). See ref. [2] and [6] for the treatment of other cases, including that for an ambient  $A_{\text{Rn}}^0 \neq 0$  in the accumulation vessel.

The parameters  $A_{\text{Ra}}$  and  $f$  are certified with relative expanded uncertainties of  $2u_{A_{\text{Ra}}}$  and  $2u_f$  (refer to Certificate for SRM 4968). It is recommended that the relative expanded uncertainty  $u_{A_{\text{Rn}}}$  (expressed in percent) in the accumulated  $^{222}\text{Rn}$  activity  $A_{\text{Rn}}$  be approximated from the relative combined uncertainties  $u_{A_{\text{Ra}}}$  and  $u_f$  (also expressed in percent) using the relation:

$$2u_{A_{\text{Rn}}} \approx 2 \sqrt{u_{A_{\text{Ra}}}^2 + u_f^2} - 0.2 \quad (47)$$



inasmuch as the other uncertainty components are negligible in most cases compared to  $u_{ARa}$  and  $u_f$ . The third term (0.2) in the sum of the squares arises from the need to eliminate a common uncertainty component. See ref. [2] and [6] for a more exact treatment of the propagation of the component uncertainties.

The relative uncertainties given above are, by international convention, "expanded combined standard uncertainties" and are defined as 2 times an estimated propagated relative standard deviation  $u$  where all of the individual uncertainty components in the propagation are expressed in terms of estimated (experimental) standard deviations (of standard deviations of the mean where appropriate) or uncertainty quantities assumed to correspond to standard deviations, irrespective of the method used to evaluate their magnitude. The overall uncertainty is assumed to provide an uncertainty interval having a high level confidence of roughly 90 to 95 percent. Historically, the NIST Radioactivity Group reported "overall uncertainties" that were a combined standard uncertainty  $u$  expanded by a factor of three. An expansion factor of two is currently used to achieve uniformity with national and international practices (see ref. [7]).

## 6. USE FOR INTEGRAL $^{222}\text{Rn}$ ACTIVITY APPLICATIONS

The standard may be used to obtain the time-integrated  $^{222}\text{Rn}$  activity in a closed accumulation vessel as might be relevant for the calibration of passive, integral radon monitors.

Performance of the standard for this application was evaluated with respect to the calibration needs of electret ionization chambers (E-PERM<sup>®</sup>, Rad Elec Inc., Frederick, MD \*\*\*\*\*).

Tests have validated use of the standard in accumulation vessels ranging in volume from about 3.5 to 10 liters, and with accumulation (integral measurement) times from 1 to 33 days.

The standard has not yet been evaluated for use with other possible monitors. The standard can be used to calibrate other monitors provided that these monitors are not very sensitive to short-term  $^{222}\text{Rn}$  concentration gradients in the accumulation vessel, or are not used for short ( $\leq 1$  day) accumulation (integral measurement) times.

It is recommended that the standard be used for integral measurement applications by suspending the capsule in the approximate center of the accumulation vessel in which the passive integral monitors are located, and maintaining a reasonably humid atmosphere in the vessel.

The integrated  $^{222}\text{Rn}$  activity  $I_{\text{Rn}}$  accumulated over some total accumulation time  $T_A$  may be obtained by integrating eq. (1) from  $t = 0$  to  $t = T_A$  which gives

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\*\*\*\*\* The mention of commercial products does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products identified are necessarily the best available for the purpose.

$$I_{\text{Rn}} = f A_{\text{Ra}}^0 \left[ T_A - \left( \frac{1}{\lambda_{\text{Rn}}} \right) \left( 1 - e^{-\lambda_{\text{Rn}} T_A} \right) \right] \quad (48)$$

where  $A_{\text{Ra}}^0$  is the  $^{226}\text{Ra}$  activity at the start ( $t=0$ ) of the accumulation interval [i.e.,  $A_{\text{Ra}}^0 = A_{\text{Ra}} e^{-\lambda_{\text{Rn}} T_D}$ ] and where all other terms were defined in eq. (1) [see note (5)].

Alternatively, one may consider the time-averaged  $^{222}\text{Rn}$  activity  $\bar{A}_{\text{Rn}}$  over the time interval  $T_A$  to be

$$\bar{A}_{\text{Rn}} = \frac{I_{\text{Rn}}}{T_A} = f A_{\text{Ra}}^0 \left[ 1 - \left( \frac{1}{\lambda_{\text{Rn}} T_A} \right) \left( 1 - e^{-\lambda_{\text{Rn}} T_A} \right) \right] \quad (49)$$

Both eqs. (3) and (4) are for the simplified cases of  $A_{\text{Rn}}^0 \approx 0$ , i.e., there is a negligible, initially present  $^{222}\text{Rn}$  activity in the accumulation vessel. See ref. [6] for the treatment of the case when  $A_{\text{Rn}}^0 \neq 0$ .

The relative expanded uncertainty in the integral activity  $I_{\text{Rn}}$  or in the time-averaged activity  $\bar{A}_{\text{Rn}}$  may be approximated similar to that of eq. (2):

$$2u_{I_{\text{Rn}}} \approx 2u_{\bar{A}_{\text{Rn}}} \approx 2 \sqrt{u_f^2 + u_{A_{\text{Ra}}}^2 - 0.2} \quad (50)$$

where all of the relative uncertainties are expressed in percent.

A more complete treatment of the uncertainty propagation, applicable particularly for very long accumulation (integral measurement) times, may be found in ref. [6].

## 7. OTHER RESTRICTIONS AND CONDITIONS FOR USE

The standard should not be used if the total mass of the capsule decreases by  $\approx 60$  mg (i.e., to a total mass of  $\approx 0.280$  g). The initial capsule mass is typically in the range of 0.33 to 0.37 g, and is provided on the certificate for SRM 4968. The mass (and visibly apparent volume) of the encapsulated solution will gradually decrease with time because of transpiration/evaporation losses through the polyethylene. The rate of this loss will depend on usage; but extensive tests over three to four years show that under normal humidity usage and storage conditions, the capsules should not approach a 60 mg mass loss for at least a decade. Alternatively, the apparent solution volume inside the polyethylene capsule can be visibly observed and monitored at each use for any appreciable transpiration losses.

The emanation fraction  $f$  is virtually independent of the accumulation pressure for any conceivable range of laboratory atmospheric pressures. It is calibrated for accumulation at "atmospheric pressures". Pressure differences of 0.5 atm (i.e.,  $\delta \approx 380$  mm Hg) exhibited changes of  $f$  of less than 2.3%, and over normal laboratory atmospheric pressure variations the differences were negligible. [At 0.25 atm, however,  $f$  increased by 8%].

The emanation fraction  $f$  for the standard exhibits a temperature dependence. Preliminary results indicate that in the region of about 21 °C, the emanation fraction  $f$  varies by approximately 0.7 percent *per degree celsius*. The statistical precision estimators in our present measurements of  $f$  includes uncontrolled temperature variations. The certified value of  $f$  (within its reported uncertainty) is applicable for a temperature range of approximately 18 to 24 °C.

The reproducibility in the standard's performance may be considerably improved by controlling and reproducing the temperature at which accumulations are made.

Every effort has been made to insure the integrity of the polyethylene seals in the standard provided to you. Should any question arise as to the integrity of the standard during your use of it, please contact Dr. R. Collé of the NIST Radioactivity Group at 301-975-5527.

The standard is *not*, at the present time, certified for use to obtain  $^{222}\text{Rn}$  activity concentrations in an accumulation vessel (without a demonstrable verification of the adequacy of an external mixing or air circulation mechanism to achieve concentration homogeneity), nor is it certified to obtain activity concentrations in continuous-flow applications.

## 8. REFERENCES

1. R. Collé, P.A. Hodge, and J.M.R. Hutchinson, *The NIST Polyethylene-Encapsulated  $^{226}\text{Ra}/^{222}\text{Rn}$  Emanation (PERE) Standard*, to be published (1994). Preprints are available from the NIST Radioactivity Group.
2. R. Collé, J.M.R. Hutchinson, and P.A. Hodge, *Polyethylene-Encapsulated  $^{226}\text{Ra}$  Solution Standards: A New NIST Emanation Standard for  $^{222}\text{Rn}$  Measurement Calibrations*, to be published, (1994). Preprints are available from the NIST Radioactivity Group.
3. R. Collé, J.M.R. Hutchinson, and M.P. Unterweger, *The NIST Primary Radon-222 Measurement System*, *J. Res. NIST* **95**, 155-165 (1990).
4. J.M.R. Hutchinson, J. Cessna, R. Collé, and P. Hodge, *An International Radon-in-Air Measurement Intercomparison Using a New Transfer Standard*, *Int. J. Appl. Radiat. Isot.* **43**, 175-189 (1992).
5. W.B. Mann, L.L. Stockmann, W.J. Youden, A. Schwebel, P.A. Mullen, and S.B. Garfinkel, *Preparation of New Solution Standards of Radium*, *J. Res. NBS* **62**, 21-16 (1959).

6. R. Collé, P. Kotrappa, and J.M.R. Hutchinson, *Calibration of Electret-Based Integral Radon Monitors Using NIST Encapsulated- $^{226}\text{Ra}/^{222}\text{Rn}$ -Emanation Standards*, to be published, (1994). Preprints are available from the NIST Radioactivity Group.
7. B.N. Taylor and C.E. Kuyatt, *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*, NIST Technical Note 1297 (1993).