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Exposure to Radon and Progeny in a Tourist Cavern

Jeri L. Anderson, **Leonard M. Zwack**, **Scott E. Brueck**
Division of Field Studies and Engineering, National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention

Abstract

Objective: The primary objective of this work was to characterize employee exposure to radon and progeny while performing guide/interpretation and concessions duties in a tourist cavern.

Methods: Radon gas and progeny concentrations, fraction of unattached progeny, and other environmental parameters were evaluated in a popular tourist cavern in Southeastern New Mexico. Alpha-track detectors were used to measure radon gas in several cavern locations during a nine-month period. Additionally, radon gas and attached and unattached fractions of radon progeny were measured at three primary cavern work locations during a one-day period using a SARAD EQF 3220.

Results: Radon gas concentrations in the cavern were elevated due to extremely low air exchange rates, with substantial seasonal variation. Mean measured radon concentrations ranged from 970 to 2600 Bq m^{-3} in the main cavern and from 5400 to 6000 Bq m^{-3} in a smaller cave associated with the regional cave system. Measurements of unattached fractions (0.40–0.60) were higher than those commonly found in mines and other workplaces, leading to the potential for relatively high worker dose.

Conclusions: Although radon gas concentrations were below the Occupational Safety and Health Administration Permissible Exposure Limit, employees working in the cavern have the potential to accrue ionizing radiation dose in excess of the annual effective dose limit recommended by the National Council on Radiation Protection and Measurements due to high unattached fraction of radon progeny. There was a strong negative correlation between unattached fractions and equilibrium factors, but these parameters should be further evaluated for seasonal variation. Introduction of engineering controls such as ventilation could damage the cavern environment, so administrative controls, such as time management, are preferred to reduce employee dose.

Corresponding Author Jeri L. Anderson, National Institute for Occupational Safety and Health, 1090 Tusculum Ave., MS R-14, Cincinnati, OH 45226, (513) 841-4510, JLAnderson@cdc.gov.

Disclaimer
The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention.

Conflicts of Interest
The authors declare no conflicts of interest.

Introduction

Radon is a naturally occurring, colorless, odorless, inert, radioactive noble gas that emanates from rocks and soil and is present in outdoor air, buildings, underground mines, and caves. ^{222}Rn, which has a half-life of 3.8 days, and its subsequent radioactive decay products (i.e., ^{218}Po, ^{214}Pb, ^{214}Bi, and ^{214}Po) present the greatest risk in most environmental and occupational settings because of its natural abundance. These progeny radionuclides exist as either unattached ions or are attached to condensation nuclei or dust particles, forming a respirable radioactive aerosol. Inhalation of the short-lived alpha-emitting progeny, ^{218}Po and ^{214}Po, contributes significantly to radiation exposure of lung tissues, potentially causing health effects.

Several studies have shown evidence of increased risk of lung cancer from exposure to radon and its progeny in underground mines (ICRP 2014). A few studies have suggested increased leukemia in uranium miners exposed to radon (Darby et al. 1995; Řeřicha et al. 2006) although most miner studies have not shown similar results (Lane et al. 2010; Laurier et al. 2004; Möhner et al. 2006; Schubauer-Berigan et al. 2009; Tomášek et al. 1993).

Radon decay products in the form of small particles (0.5–2.0 nanometers in diameter) can either attach to larger particles or remain unattached with high mobility in air. Although the unattached fraction of radon progeny has traditionally been defined as free atoms or ions, more recent studies have indicated that the unattached fraction also includes ultrafine particles or clusters of particles with diameters of less than 5 nanometers (Reineking and Porstendörfer 1990). Unattached progeny are more efficiently deposited in the lower respiratory tract (NAS/NRC 1999) and the quantity relative to attached progeny is significant in determining dose. Inhaled unattached radon progeny are deposited in the bronchial region of the lungs where basal and secretory cells are found. These cells are considered the primary cells for the initiation of bronchial carcinoma (Winkler-Heil et al. 2007).

Environmental levels of radon in the United States vary widely, with average indoor concentrations in U.S. homes of about 46 Bq m^{-3} and in Colorado homes of 96 Bq m^{-3} (Marcinowski et al. 1994). Outdoor radon concentrations tend to be much lower, with national and regional (Nevada and Colorado) averages of about 15 Bq m^{-3} (Borak and Baynes 1999; Price et al. 1994). Exposure to radon and progeny accounts for about 36% of the total effective dose received by an average member of the U.S. population annually from all sources of radiation (NCRP 2009).

Carlsbad Caverns National Park, as designated by the U.S. Congress in 1930, and located in southeastern New Mexico, consists of about 47,000 acres and 120 known caves. The caverns were formed when hydrogen sulfide, migrating through groundwater from the Permian Basin petroleum reservoirs in west Texas, was oxidized to sulfuric acid, dissolving the limestone at the water table (Polyak and Provencio 2001). The park has about 500,000 visitors annually and employs about 125 workers. Most park employees spend much of their workday in both the Visitor Center and the main cavern. In addition, some park rangers may also conduct weekly guided tours of the nearby Spider Cave throughout the year. Previous evaluations of the main cavern have indicated elevated levels of radon gas (Wilkening and Watkins, 1976; Cheng et al. 1997), which could pose a risk to workers who spend considerable time in the caverns.

At the request of the US National Park Service, several visits were made to the park in 2014 – 2016 to evaluate radon gas and progeny concentrations in in the main cavern and other areas of the park, and recommendations were provided on how to decrease potential employee exposure (NIOSH 2019). The focus of this paper was a more detailed evaluation of relationships between measured unattached fractions of radon progeny and other environmental parameters, diurnal variation in measurements, and the effect of measured unattached fractions on absorbed and equivalent lung dose and effective dose.

Methods

Radon concentrations were measured during two time periods in the main cavern and Spider Cave to capture different seasonal conditions: summer/fall (August-December 2014) and winter/spring (December 2014-April 2015). Landauer® Radtrak® alpha-track radon gas detectors (Landauer, Inc. Glenwood, Illinois 60425) were deployed in duplicate: 31 detectors at 16 locations throughout the major tour routes inside the main cavern (one sample did not have a duplicate). Two detectors were placed in a separate cave (Spider Cave) where tours also occurred. The first set of detectors were deployed in August 2014 and removed in December 2014 for analysis. A second set of detectors were deployed in the same location as the first set in December 2014, and then these were removed in April 2015 for analysis. The detectors were placed on the ground for most locations, except for the lunchroom where detectors were placed on counters at a height of about 1 meter. Because the detectors were left in position for several months at a time when the cavern was open to the public, it was necessary to place the detectors in a manner such that they were "hidden."

In August of 2016, investigators returned to the site to obtain real-time measurements of the unattached fraction of the radon progeny using a SARAD EQF 3220 (SARAD) radon/thoron gas and decay product monitor for attached and unattached decay products (SARAD GmbH, Dresden, Germany). One-hour averaged attached and unattached concentrations of radon progeny were measured over the course of one day at three locations inside the main cavern: the lunchroom, the King's Palace, and the pump room. Additionally, the SARAD measured cavern air temperature, relative humidity, and barometric pressure. The SARAD was attached to a tripod and sampling was conducted at a point approximately 1.5 m off the ground. The lunchroom is a large open area adjacent to the elevator exit. The lunchroom also had a small gift shop and multiple lunch counters that previously served food. The King's Palace is a formation along the tour path. The pump room is a mechanical equipment space also located near the elevator exit, that is not accessible by the public. The lunchroom and King's Palace sampling locations were selected to represent employee work areas inside the main cavern. The pump room was also evaluated so results could be compared to measurements collected in that location as part of a previous study (Cheng et al. 1997). Measurements of radon progeny by the SARAD taken in the three locations were used to estimate the equilibrium factor, F, and the unattached fraction of radon progeny, f_p. A RAD7 radon gas monitor (Durridge Company, Inc. Billerica, Massachusetts) was co-located with the SARAD to verify its operation.

The historical unit of the radon potential alpha energy concentration is the working level (WL). This quantity, which was originally defined as the concentration of radon progeny in equilibrium with 3700 Bq m^{-3} of radon, was about equal to 1.3×10^8 MeV m^{-3} of potential alpha energy. The WL is now explicitly defined as the concentration of potential alpha energy equal to 1.300×10^8 MeV m^{-3}. Progeny exposure is expressed in terms of the working level month (WLM), which is exposure to the WL for 170 hours. Thus, a WLM is equal to 3.54 mJ h m^{-3} or 6.37×10^5 Bq h m^{-3} (ICRP 1993). For this study, annual exposure in WLM was calculated by:

$$\text{Annual exposure (WLM)} = \frac{C_{Rn} \times t \times F}{6.37 \times 10^5} \qquad \text{Eq. 1}$$

where C_{Rn} is the concentration of radon gas in Bq, t is the hours worked in a year, and F is the equilibrium factor. To obtain a conservative estimate of WLM, it was assumed work hours were evenly divided between Summer/Fall and Winter/Spring, with a half year consisting of 25 work weeks. Workers likely to spend the most time in the caverns were those conducting tours in both the main cavern and Spider Cave (interpretation workers) and those working in the lunchroom (concession workers). During each half year work period, concessions workers were assumed to spend 35 hours per week in the main cavern and interpretation workers were assumed to spend 20 hours per week in the main cavern and an additional 3 hours per week in Spider Cave. Time spent working above ground was not included in the calculations.

The effect of the measured unattached fraction of radon progeny on dose was evaluated by estimating the absorbed and equivalent doses to regions of the lung. Effective dose was also estimated to compare with current recommendations of the National Council for Radiation Protection and Measurements (NCRP) for dose limitation (NCRP 2018). Absorbed dose to the three regions of the lung as defined by the International Commission on Radiological Protection (ICRP): the bronchial regions (BB), the bronchiolar region (bb), and the alveolar interstitial region (AI) (ICRP 2015). Absorbed dose conversion factors (absorbed dose per WLM) for unattached and attached fractions of radon progeny for each lung region were estimated by Winkler-Heil et al. (2007) using the RADEP/IMBA code, which is a deterministic regional compartment model based on the ICRP Human Respiratory Tract Model. These absorbed dose conversion factors were used in combination with estimated WLM and measured unattached fractions (f_p) to estimate annual absorbed dose (D_i) to each lung region using Eqs. 2–4.

$$D_{BB} = \text{Annual WLM} \times \left[76.5 f_p + 7.9\left(1 - f_p\right)\right] \qquad \text{Eq. 2}$$

$$D_{bb} = \text{Annual WLM} \times \left[25.0 f_p + 5.6\left(1 - f_p\right)\right] \qquad \text{Eq. 3}$$

$$D_{AI} = \text{ Annual WLM } \times \left[0.01 f_p + 0.4\left(1 - f_p\right)\right] \quad \text{Eq. 4}$$

Equivalent dose (H_i) for each region was calculated by multiplying the absorbed dose to the lung region by the radiation weighting factor (w_R) of 20 assumed for alpha radiation. Equivalent dose to the lung (H_{Lung}) was then calculated using the following equation:

$$H_{Lung} = H_{BB}A_{BB} + H_{bb}A_{bb} + H_{AI}A_{AI} \quad \text{Eq. 5}$$

where A_i is the ICRP-recommended apportionment factor and $A_{BB} = A_{bb} = A_{AI} =$ 1/3 (ICRP 2015). The weighted equivalent dose was estimated by multiplying the lung equivalent dose by the ICRP tissue weighting factor (w_T) for the lung of 0.12.

Effective dose was estimated using methods described in Appendix A of ICRP Publication 137 (ICRP 2017). The measured unattached fraction was used in the equation for a tourist cave in Table A.12 of Appendix A (ICRP 2017) to calculate an exposure (in WLM) to effective dose conversion factor (DCF_E) specific for the main cavern and Spider Cave in Carlsbad Caverns in mSv WLM^{-1}:

$$DCF_E = 86 f_p + 12\left(1 - f_p\right) \quad \text{Eq. 6}$$

where f_p is the unattached fraction of radon progeny. The estimated effective dose to workers in the caverns estimated using the site-specific DCF_E was then compared to the effective dose calculated using the ICRP 137 default DCF_E for tourist caves shown in Table A.11 of ICRP Publication 137, Appendix A.

Results

As measured with the SARAD during August 2016, cavern temperatures varied from 17.3 to 19.2 °C, with relative humidity varying from 82 to 96%, and barometric pressures between 898 and 900 mbar. Average temperature was highest in the pump room overnight and lowest in the King’s Palace during the day. Average relative humidity was highest in the King’s Palace at 94% and lowest in the pump room at 85%.

A summary of the radon concentrations measured in 2014–2015 with alpha-track radon gas detectors, grouped by location, are presented in Table 1. The mean radon concentration in the main cavern measured during July to December (2574 Bq m^{-3}) was about three times higher than the mean concentration measured during the December to April sampling period (968 Bq m^{-3}), demonstrating substantial seasonal differences in radon concentrations. Mean radon concentrations in Spider Cave ranged from 5,446 (winter/spring) to 5,959 Bq m^{-3} (summer/fall) which is greater than the concentrations observed in the main cavern, although with relatively little seasonal variation. The main cavern radon concentrations were below the Occupational Safety and Health Administration’s (OSHA) Permissible Exposure Limit (PEL) of 100 pCi L^{-1} (3700 Bq m^{-3})[1] for adult workers but were at or above the

[1]Note that the radon concentration units are given here in pCi L^{-1} (called traditional units) because that is the unit used by the US Occupational Safety and Health Administration. However, the Health Physics Society has adopted the SI (International System) of units and these are given in parentheses.

General Services Administration (GSA) action level of 25 pCi L^{-1} (925 Bq m^{-3})[2] for GSA-controlled federal and leased facilities. Spider Cave radon concentrations were above the OSHA PEL for a 40-hour, 7-consecutive day work period. However, the park conducts at most one Spider Cave tour per week, with employees spending no more than three hours in the cave.

The mean one-hour radon gas and attached/unattached radon progeny concentrations measured using the SARAD, and radon gas concentrations simultaneously measured using the RAD7 are presented in Fig. 1 as a function of time. Measurements obtained with the SARAD are slightly higher than those obtained with the RAD7. Radon gas concentrations appeared to decrease during the overnight hours and unattached progeny appeared to decrease, although these changes also coincide with the change in location from the King's Palace to the pump room. The temperature in the pump room was somewhat higher and the barometric pressure and relative humidity was somewhat lower than in the King's Palace and lunchroom.

Radon gas and attached and unattached progeny concentrations averaged for three sampling locations (lunchroom, King's Palace, and pump room) are presented in Table 2. Equilibrium ratios calculated from the SARAD measurements were 0.25, 0.28, and 0.41 for the lunchroom, King's Palace, and pump room, respectively. Unattached fractions measured by the SARAD were 0.55, 0.60, and 0.40 for the lunchroom, King's Palace, and the pump room, respectively. The equilibrium factors were strongly negatively correlated with the unattached fractions (Pearson correlation coefficient = −0.95).

Relative humidity was moderately correlated with measured radon gas concentrations and equilibrium equivalent concentrations of unattached progeny (Pearson correlation coefficient = 0.64 and 0.70, respectively), and to a lesser extent with unattached fractions (Pearson correlation coefficient = 0.46). There was a weak negative correlation between relative humidity and attached progeny concentrations and equilibrium fractions (Pearson correlation coefficient = −0.31 and −0.32, respectively). Barometric pressure was also moderately correlated with measured radon gas concentrations, equilibrium equivalent concentrations of unattached progeny, and unattached fractions (Pearson correlation coefficient = 0.74, 0.68, and 0.83, respectively). Attached progeny concentrations and equilibrium fractions showed a moderate negative correlation with barometric pressure (Pearson correlation coefficient = −0.79 and −0.73, respectively).

Using the average calculated equilibrium factor for the King's Palace and the lunchroom (0.26), it was estimated that park rangers performing interpretation tasks could accrue 0.53 WLM during the summer/fall time period and 0.20 WLM during the winter/spring time period, with a total annual exposure of 0.72 WLM. Assuming weekly Spider Cave tours with duration of 3 hours, if a single worker conducted this tour each week, they could accrue an additional 0.35 WLM annually. Using the average calculated equilibrium factor for the

[2]Note that the radon concentration units are given here in pCi L^{-1} (called traditional units) because that is the unit used by the US General Services Administration. However, the Health Physics Society has adopted the SI (International System) of units and these are given in parentheses.

lunchroom (0.25), it was estimated that if a single concessions worker was assigned to the lunchroom full-time, they could accrue 1.1 WLM annually.

Table 3 shows the annual absorbed and equivalent doses to the BB, bb, and AI lung regions, lung equivalent dose, and weighted equivalent lung dose estimated using the average of the calculated unattached fractions measured in the King's Palace and lunchroom combined (0.57) and lunchroom alone (0.55) to represent interpretation and concessions workers, respectively. Using the default DCF_E for tourist caves of 23 mSv WLM^{-1} (ICRP 2017), the annual effective dose is estimated to be 17 mSv for workers performing interpretative tasks, 25 mSv if weekly Spider Cave tours are included, and 25 mSv for concessions workers assigned to the lunchroom. Using the average of the calculated unattached fractions measured in the King's Palace and lunchroom combined (0.57) and lunchroom alone (0.55) gives a site-specific DCF_E of 54 and 53 mSv WLM^{-1} for interpretation workers and concessions workers, respectively. This increases the estimated annual effective dose to 39 mSv for the interpretation workers, or 58 mSv including Spider Cave tours and 58 mSv for concessions workers.

Discussion

As in a previous study, this study has shown that the main cavern has an elevated unattached fraction of radon progeny compared to mines and other indoor work environments. The ICRP assumes unattached fractions of 0.01, 0.08, and 0.15 for mines, indoor workplaces, and tourist caves, respectively (ICRP 2017). Measurement results for the unattached fraction of radon progeny obtained over a 10-hour period overnight in the Pump Room ranged from 0.36 to 0.44 and from 0.54 to 0.60 for the Lunchroom and King's Palace during the day. Cheng et al. (1997) measured unattached fractions of radon progeny ranging from 0.25 to 0.59 in the Pump Room over a period of three days. The relatively high unattached fraction of radon progeny is due to low concentrations of condensation nuclei, partially because the cavern has very few sources of aerosol generation other than tourist activities. The relatively low aerosol concentration also results in a lower equilibrium factor, thus the inverse relationship between unattached fraction and equilibrium factor (Reineking and Portendörfer 1990). In addition, the cavern air exchange rate is relatively low. Cheng et al. (1997) measured an air exchange rate of one air change every 18 days in July. As a result of these naturally stable environmental conditions, relatively few aerosol particles enter the cave and radon gas concentrations accumulate (Cheng et al. 1997).

Evaluation of radon gas concentration indicated that, except for Spider Cave, levels are below the OSHA radon PEL for adult workers. However, estimation of annual WLM for concessions workers and interpretive workers also conducting Spider Cave tours suggested that the National Institute for Occupational Safety and Health (NIOSH) recommended exposure limit (REL) of 1 WLM annually could be exceeded, depending upon how many hours are spent inside the cavern. Additionally, due to the high unattached fraction of radon progeny in the cavern, the calculated effective dose for workers could exceed the 50 mSv annual effective dose limit recommended by National Council on Radiation Protection and Measurements (NCRP) (NCRP 2018). As shown in Table 3, much of the dose is delivered to the bronchial region of the lung, which consists of basal and secretory cells that are considered the primary cells for the induction of bronchial carcinomas (Winkler-Heil et al. 2007). The weighted lung equivalent dose makes up approximately 94% of the effective dose.

A definite seasonal difference in radon concentrations was observed in the main cavern. The summer concentrations were much higher than the winter concentrations, likely due to the variation in the number of air changes in the cave during the year. During the winter months, outside air temperatures are lower than cavern air temperatures allowing the outdoor air with relatively low radon concentration to mix with the warmer cavern air diluting the cavern radon concentrations. During the summer, the air temperatures are similar, resulting in less air exchange. (Wilkening and Romero 1981). Two radon gas sampling locations (inside the Hall of the White Giant and the Iron Pool) were in smaller caverns away from the main tourist area and showed less seasonal variation. Spider Cave, which is located deep inside the cavern system, also showed substantially less seasonal variation than other cavern locations. Cunningham and LaRock (1991) found that deeper, more remote areas of the caverns tend to have stagnant conditions due to less airflow at the sampling sites resulting in consistently elevated radon.

Cavern radon measurements and the seasonal variation in radon concentrations were similar to those found in previous studies (Wilkening and Watkins 1976; Cheng et al. 1997). Wilkening and Watkins (1976) measured radon concentrations of 2035 Bq m^{-3} in the Lunchroom in the summer (August) and 537 Bq m^{-3} winter (average of January and February), compared to 2457 Bq m^{-3} measured in this study with alpha-track detectors, 2535 Bq m^{-3} measured with the SARAD, and 2395 Bq m^{-3} measured with the RAD7. Cheng et al. (1997) measured 1821 Bq m^{-3} in the Pump Room compared to 2184 and 1888 Bq m^{-3} measured in this study with the SARAD and RAD7 respectively. Temperature and relative humidity measurements measured in this study were also higher, so the difference could be due to yearly variation as the Wilkening and Watkins measurements were taken in 1973–1975 and the Cheng et al. measurements were taken in July 1994. Year-to-year variation in radon concentrations could be as much as 50% (Steck 1992). The consistently higher measurements obtained in this study could also be due to the height at which the detectors were located (Put and de Meijer 1988). For this study, alpha-track detectors were almost always placed on the ground, whereas for the other two studies, detectors were placed at a height of 1 m.

A primary limitation of this study was that radon gas concentrations were not measured during the months of May, June, and July which would affect the estimation of WL and dose. Also, unattached fractions and equilibrium factors were only determined for a time period of less than 24-hours and only during the summer when radon concentrations were highest, so it is unknown how seasonal variation would affect these parameters. Because of significant seasonal and possible year-to-year variation, to improve characterization of workplace conditions, radon concentrations should be measured monthly and unattached fractions and equilibrium factors should be evaluated for at least 24-hours per month in work areas of interest.

Conclusions

Radon concentrations measured in the main cavern (mean = 970–2600 Bq m^{-3}) and Spider Cave (5400–6000 Bq m^{-3}) were elevated above those generally found in most indoor workplaces and showed significant seasonal variation. Although concentrations were below the OSHA PEL, employees working in the cavern have the potential to exceed the NCRP recommended annual effective dose limit due to the high unattached fraction of radon progeny (mean = 0.40–0.60). In this study, unattached fractions and equilibrium factors were strongly negatively correlated, and each showed some correlation with other cavern environmental parameters. To further refine annual employee dose, these should be measured throughout the year to evaluate seasonal variation.

Introducing engineering controls such as ventilation to mitigate employee exposure could damage the natural environment of the cavern, so administrative controls such as tracking employee time spent in the cavern should be instituted. Employee dose may be reduced by limiting the time spent in the cavern during the summer months when radon gas concentrations are higher. This could be accomplished by moving non-essential work (such as concessions) outside the cavern and scheduling non-time-sensitive maintenance work during the winter months when radon gas concentrations are lower.

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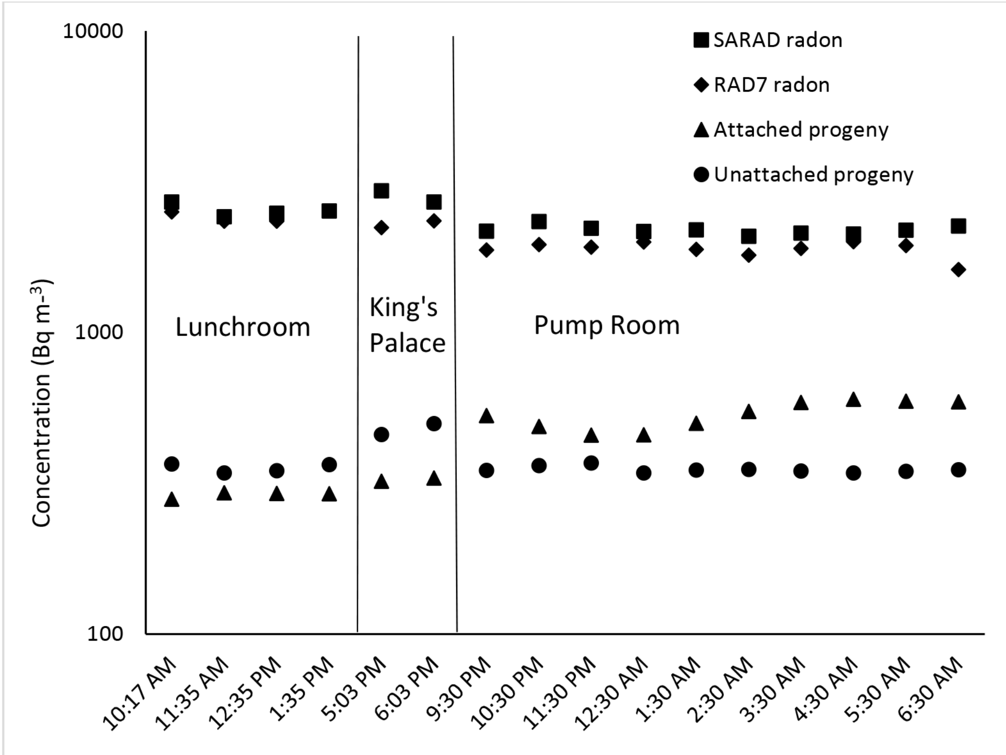

Fig. 1.
Radon and attached and unattached progeny concentrations measured using the SARAD and radon gas concentration using the RAD7 in the lunchroom, King's Palace, and pump room.

Table 1.

Measured cavern radon concentrations using alpha-track radon gas detectors.

Location	Summer/fall[a] Mean radon concentration (Bq m^{-3})	Winter/spring[a] Mean radon concentration (Bq m^{-3})
Lunchroom	2457 ± 105	733 ± 20
Lunchroom (on counters)	--	723 ± 20
The Beach	2684 ± 110	923 ± 20
Iron Pool	2725 ± 111	2111 ± 96
The Rookery	2999 ± 118	944 ± 23
Blackout Spot	2890 ± 116	944 ± 23
Jim White Tunnel	2466 ± 105	683 ± 19
Texas Tail near Top of the Cross	2477 ± 105	799 ± 21
Caveman Junction	2350 ± 102	805 ± 21
Bat Cave	2464 ± 105	611 ± 18
Hall of the White Giant (entrance)[b]	2268	760 ± 20
Hall of the White Giant (inside)	2757 ± 81	2346 ± 72
Devil's Den	2283 ± 100	712 ± 20
Green Lake Room	2727 ± 111	770 ± 20
King's Palace	2692 ± 111	921 ± 23
Queen's Chamber	2379 ± 103	705 ± 19
Main Cavern Average	2574 ± 397	968 ± 143
Spider Cave	5959 ± 181	5446 ± 175

[a]Summer/fall radon concentration measurements were taken August through December 2014; Winter/spring radon concentration measurements were taken December 2014 through April 2015.

[b]Only one measurement was available for Summer/fall.

Table 2.

Mean one-hour measured concentrations of radon gas and attached and unattached progeny in three main cavern locations using the SARAD EQF 3220.

Location	N	Radon concentration (Bq m^{-3})	Attached Progeny (Bq m^{-3})	Unattached Progeny (Bq m^{-3})
Lunchroom	4	2535	289	355
King's Palace	2	2827	325	478
Pump room	10	2184	534	351

Table 3.

Annual absorbed and equivalent doses to ICRP lung regions, lung equivalent doses, and weighted equivalent doses for interpretation and concessions workers.

Annual Dose	Interpretation Workers	Concessions Workers
Absorbed dose to BB, D_{BB} (mGy)	50	50
Absorbed dose to bb, D_{bb} (mGy)	18	18
Absorbed dose to AI, D_{AI} (mGy)	0.19	0.20
Equivalent dose to BB, H_{BB} (mSv)	1008	1000
Equivalent dose to bb, H_{bb} (mSv)	357	356
Equivalent dose to AI, H_{AI} (mSv)	3.8	4.1
Equivalent dose to Lung, H_{Lung} (mSv)[a]	456	453
Weighted equivalent lung dose (mSv)	55	54

BB – bronchial, bb – bronchiolar, AI – alveolar-interstitial

[a] H_{Lung} consists of the sum of the equivalent doses to BB, bb, and AI, assuming an apportionment factor of 1/3 for each region.