Evaluation of Exposure to Radon and Radon Progeny in an Underground Tourist Cavern and Its Connected Buildings

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Contents

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The cover photo is a close-up image of sorbent tubes, which are used by the HHE Program to measure airborne exposures. This photo is an artistic representation that may not be related to this Health Hazard Evaluation. Photo by NIOSH.

Highlights of this Evaluation

The Health Hazard Evaluation Program received a technical assistance request from the U.S. National Park Service because they were concerned about potential exposures to radon and radon decay products at a tourist cave and a connected building.

What We Did

- We measured radon gas concentrations inside the visitor's center and other buildings in the park.
- We measured the amount of radon and radon decay products inside of two caves.
- We released tracer gas to determine how radon was entering the visitor's center.
- We looked at the ventilation systems in multiple park buildings to see if they were working properly.
- We collected information about how much time employees spent in the caves.
- We modeled employee exposures to ionizing radiation and compared them to occupational dose limits.

We measured radon gas concentrations inside a cave and its attached visitor's center, over multiple seasons. We found that radon concentrations in the visitor's center were greater than concentrations found outdoors and in other nearby park buildings. We found that radon gas was entering the visitor's center via the elevator shaft connected to the main cavern. We also conducted dose modeling to provide an estimate of the number of hours employees can work in the main cavern and remain below occupational dose limits for ionizing radiation. We recommended the park use engineering and administrative controls to decrease employee exposures.

What We Found

- Radon concentrations in the visitor's center were greater than the concentrations outdoors and in nearby park buildings.
- Tracer gas studies conducted in the visitor's center revealed that the radon gas was entering the building via the elevator shaft connected to the main cavern below.
- Radon concentrations measured inside the main cavern were below the OSHA PEL, and were similar to the levels reported in previous studies.
- Radon concentrations measured in Spider Cave were below the OSHA PEL, given that employees only spend three hours per week in the cave.
- Unattached fraction of radon progeny measured in the main cavern was higher than what is found in a typical indoor environment. A high unattached fraction leads to higher modeled ionizing radiation dose estimates.
- Dose modeling for ionizing radiation showed that most employees were below radiation dose limits. However, depending on how many hours that employees spend in

the cave, it is possible that some employees could exceed these dose limits.

What the Employer Can Do

- Isolate the main cavern elevators from the rest of the visitor's center using airlocks. This will prevent air from the main cavern mixing with the air from the visitor's center.
- Hire a licensed professional mechanical engineer to evaluate the existing ventilation system's capacity to provide outdoor air to the occupied spaces in the visitor's center.
- Hire a health physicist to create and implement a radon management program. This should include the collection of radon and radon progeny concentrations for employees working in the main cavern.
- Implement a tracking system to monitor the number of hours employees work inside of the cavern. Limit the number of hours, if necessary, to keep employees' radiation doses below applicable dose limits.
- Educate employees on the risks of radon and ionizing radiation.
- Schedule cavern work that is not time-sensitive during the winter months, when radon concentrations are lower.

What Employees Can Do

- Report work-related health concerns to park management.

Abbreviations

ACGIH®	American Conference of Governmental Industrial Hygienists
ANSI/ASHRAE	American National Standards Institute/ASHRAE
Bq/m^3	Becquerels per cubic meter
$Bq\text{-}h/m^3$	Becquerel-hour per cubic meter
DCF	Dose conversion factor
EPA	Environmental Protection Agency
HVAC	Heating, ventilation, and air-conditioning
ICRP	International Commission on Radiological Protection
J	Joule
L/min	Liter per minute
MeV/m^3	Megaelectronvolt per cubic meter
mSv	Millisieverts
NCRP	National Council on Radiation Protection and Measurements
NIOSH	National Institute for Occupational Safety and Health
NPS	National Park Service
OEL	Occupational exposure limit
OSHA	Occupational Safety and Health Administration
PEL	Permissible exposure limit
pCi/L	Picocuries per liter
ppb	Parts per billion
REL	Recommended exposure limit
rem	Roentgen equivalent man
SF_6	Sulfur hexafluoride
TLV®	Threshold limit value
TWA	Time-weighted average
VC	Visitor's Center
WLM	Working level month
WLM/yr	Working level month per year

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Introduction

In May 2014, the U.S. National Park Service (NPS) requested assistance from the Health Hazard Evaluation Program to evaluate employee exposures to radon gas at a national park. Specifically, the NPS was concerned about potentially elevated radon concentrations within the main cavern, the attached visitor's center (VC), another cave that had periodic guided tours (Spider Cave), and in other administrative buildings within the park. We visited the park four times to assess radon concentrations in different seasons: July 2014, December 2014, April 2015, and August 2016. During our visits, we met with employer and employee representatives, measured employees' exposures to radon and radon decay products, and evaluated ventilation within the VC.

Background

The VC and numerous other park buildings are located on the surface, above the cave. The VC contains office spaces, meeting rooms, a small auditorium, and a library for park rangers, law enforcement officers, and other staff. The VC also has a cafeteria, two gift shops, a ticket counter, and a small museum. Employees generally spend their workday in both the VC and the cavern. The amount of time that they spend in each varies depending on their job title.

The VC is connected to the main cavern by two large 755-foot long elevator shafts that are used for transporting visitors and staff into and out of the cave. The only other known entrance to the cave is through a large opening (referred to as the natural entrance) that visitors and staff can enter or exit on foot. Spider Cave, located within the park but several miles from the main cavern, is also open to the public. Park rangers conduct weekly guided tours of Spider Cave throughout the year. Park management reported that the tours of Spider Cave are done once a week. Park employees spend three hours inside the cave during each tour. Several different park employees rotate leading these tours.

Radon (radon-222) is a naturally-occurring radioactive noble gas resulting from the decay of radium-226, one of the radionuclides in the uranium series. It emanates from rocks and soil and is present in outdoor air, buildings, underground mines, and caves. The primary health risk from exposure to radon is lung cancer. Řeřicha et al. [2006] also suggested a potential risk for leukemia and other cancers; however, more recent research has shown no increased risk of cancers other than lung, nor any other adverse health effects [Kreuzer et al. 2010; Navaranjan et al. 2016].

Radon has a half-life of 3.8 days and decays by alpha emission. Radon decay products (polonium-218 and polonium-214) are the primary contributors to ionizing radiation dose. These radon decay products are very small particles (0.5–2.0 nanometers in diameter) that can either be "attached" to other larger particles, such as dust particles, or can be "unattached" and have a very high mobility in air. The unattached fraction of radon progeny has traditionally been defined as free atoms or ions; however, 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]. The unattached decay products can more effectively deposit in the respiratory tract than attached decay products [National Research Council 1999]. The relative proportion of attached versus unattached radon decay products can play an important role in determining dose and estimating the health effects of radon exposure.

Radon Exposure Limits

The Occupational Safety and Health Administration (OSHA) has two relevant occupational exposure limits (OELs) for radon. The OSHA permissible exposure limit (PEL) for radon gas is 100 picocuries per liter (pCi/L) or 3,700 becquerels per cubic meter (Bq/m^3), averaged over 40 hours in any workweek of 7 consecutive days. However, because radon is a radioactive material, the OSHA whole body ionizing radiation dose limits also apply. The OSHA whole body ionizing radiation dose limit is 1.25 roentgen equivalent man (rem) (12.5 millisieverts or mSv) per quarter. Given that there are four quarters per year, this implies that no one should receive a dose larger than 5 rem (50 mSv) in a year. This is the same as the National Council on Radiation Protection and Measurements (NCRP) recommended dose limit of 5 rem (50 mSv) [NCRP 1993]. Measuring radon gas concentrations alone are not sufficient to assess compliance with the OSHA ionizing radiation dose limits. Instead, dose modeling based on the radon gas concentrations must be done.

Other agencies also have recommendations for radon gas and radon progeny. The National Institute for Occupational Safety and Health (NIOSH) has a recommended exposure limit (REL) for radon progeny in underground mines of 1 working level month per year (WLM/yr). This REL is an upper limit of cumulative exposure; however, NIOSH recommends that exposures should be reduced to the lowest feasible level [NIOSH 1987]. The Environmental Protection Agency (EPA) has an action level of 4 pCi/L (148 Bq/m^3) for radon gas in homes and schools. The U.S. General Services Administration (GSA) currently has set an action level of 25 pCi/L (925 Bq/m^3) for nonchildcare or nonresidential buildings that they manage [GSA 2019].

Methods

Our primary objectives were to measure concentrations of radon and radon decay products over multiple seasons both inside the main cavern, inside Spider Cave, in the VC, and in two other park service buildings. Our work included (1) air sampling for radon, (2) air sampling for radon decay products including the unattached fraction, (3) evaluating potential pathways for radon entry into the VC using tracer gas, (4) assessing the ventilation system, and (5) conducting dose modeling of radon exposures.

Air Sampling for Radon

We deployed Landauer® Radtrak® alpha-track radon gas detectors, in duplicate, in the following locations:

- 31 detectors at 16 locations throughout the tour routes inside the main cavern (one sample did not have a duplicate)
- 2 detectors in Spider Cave
- 28 detectors at 14 locations within the VC
- 2 detectors in the passenger elevator shaft

- 4 detectors at 2 locations in superintendent's building
- 4 detectors at 2 locations in maintenance building
- 2 detectors in the outdoor parking lot (to provide outdoor background radon levels)

The complete list of all sampling locations and dates is provided in Table A1, in Appendix A. 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 superintendent's building and the maintenance building were sampled during our winter sampling session, per the request of park employees.

Tracer Gas Assessment

To identify potential pathways for radon entering the VC, we conducted two separate tracer gas tests. Specifically, we evaluated air leakage from the elevator shaft into the VC, and we separately evaluated air leakage from crawl spaces into the VC. These tests were conducted on different days to allow for the tracer gas concentrations to completely decay to background levels between tests. For both tests, we released tracer gas from lecture bottles (i.e., small compressed gas cylinders) containing sulfur hexafluoride (SF_6). The lecture bottles were fitted with regulators calibrated to 0.5 or 1.0 liter per min (L/min) and connected to one-fourth inch internal diameter Teflon® tubing. Tracer gas sampling was conducted using sequential samplers that were programmed to collect grab samples by pumping air into 1-liter Tedlar® gas sampling bags at preprogrammed intervals. For both tests, each sequential sampler was configured to collect 12 grab samples at 10-minute intervals over a two-hour sampling period. The bags were later analyzed using an Innova 1412 photoacoustic infrared analyzer calibrated to SF_6.

For the first tracer gas test, we placed 0.5 L/min and 1.0 L/min lecture bottles together in the elevator car and fed the Teflon tubing from the bottles through the exhaust fan to the top of the elevator car in the elevator shaft. During the test, tracer gas was released at a rate of 1.5 L/min for 60 minutes. Elevator mechanics programmed the elevator car to continuously travel between the VC level and cave level for the duration of the 60-minute release so that tracer gas was distributed evenly throughout the elevator shaft.

We sampled nine park employee-occupied locations in the VC to measure tracer gas that leaked from the elevator shaft into the building. These nine locations included the elevator car, elevator lobby, elevator exit, maintenance office, roost (office area), supervisor's office, cafeteria, employee cafeteria, and near the sculpture in the main lobby. We sampled for tracer gas in the VC for two hours (during the 60-minute release and for an additional 60 minutes afterwards) to evaluate its spread throughout the VC. We only sampled in the elevator car during the one-hour tracer gas release because the elevator needed to be returned to service after that.

For the second tracer gas test, we released SF_6 in two separate crawl spaces below the VC and sampled for tracer gas at the same nine park employee-occupied spaces in the VC as the first tracer gas test. Tracer gas was released at a rate of 1.0 L/min in the crawl space in the washer/dryer/grinder room and at 0.5 L/min in the crawl space behind the generator room. Tracer gas was released for about two hours while sampling was conducted in the VC during the same two-hour period.

Ventilation Assessment

We used an EBT731 Balometer® electronic air balancing capture hood to measure the volumetric flow rate of air through each supply air diffuser and return air grill in the VC during morning and afternoon operations. We used smoke tubes to visualize and assess airflow leakage through the airlocks at the bottom of the elevator shaft. We visually inspected the air-handling units located on the roof of the VC. We also inspected accessible ductwork and other components of the ventilation system and main cavern airlocks for damage.

Measuring Unattached Fraction of Radon Progeny

In August of 2016, we revisited the main cavern to take real-time measurements of the unattached fraction of the radon progeny using a SARAD EQF 3220. We measured one-hour averaged unattached fractions over the course of one day at three locations inside the main cavern: the lunchroom, King's Palace, and the pump room. We chose the lunchroom and King's Palace sampling locations to represent employee work areas inside the main cavern. We sampled in the pump room so we could compare our results to measurements collected in that location during a previous study [Cheng et al. 1997].

Dose Modeling

Dose modeling is used to compare the potential effective doses employees may receive from the average radon progeny concentrations measured in the main cavern to the OSHA whole body ionizing radiation PEL. The details of this modeling can be found in Appendix A. We used data provided to us about the average time that employees in different job titles worked in the cave, along with our measured radon gas and radon progeny concentrations, to model the effective dose. We used two types of models to do this.

The first type of model used was described in International Commission on Radiological Protection (ICRP) 137 [ICRP 2017]. For this model, we used the ICRP 137 tourist cave dose conversion factor (DCF) in mSv per working level month (WLM) to estimate effective dose. This is considered the standard way to model dose for employees in tourist caves. This model allows for using a site-specific value for the unattached fraction of the radon progeny. We also compared these calculated doses to effective doses calculated using DCFs derived using dosimetric models that also allowed us to include the unattached fraction of radon progeny that we measured. The three dosimetric models we used to do this were the RADEP/IMBA, RADOS, and IDEAL models. The details for all of these models are described in Appendix A.

Results

Radon Gas Sampling Results

A summary of the measured radon concentrations, grouped by location, are presented in Table 1. Mean radon concentrations at each individual sampling location are provided in Appendix B, Table B1.

Table 1. Measured radon concentrations

Location	Number	Mean radon concentration, July–December in pCi/L (Bq/m^3)	Number	Mean radon concentration, December–April in pCi/L (Bq/m^3)
Visitor center	28	12.9 (477)	28	11.8 (437)
Maintenance building	2	Not sampled	2	2.65 (98.1)
Superintendent's building	2	Not sampled	2	0.60 (22.2)
Elevator shaft	2	66.7 (2,470)	2	21.7 (803)
Outdoors	2	0.40 (14.8)	2	0.40 (14.8)
Main cavern	28	69.7 (2,580)	31	25.0 (925)
Spider Cave	2	161 (5,960)	2	147 (5,440)
OSHA PEL		100 (3,700)		100 (3,700)

For the VC, the mean radon concentrations did not vary much between the two sampling sessions. The mean radon concentrations for both buildings were below the OSHA PEL. They were also below the GSA value of 25 pCi/L (925 Bq/m^3), but were above the EPA action level of 4 pCi/L (148 Bq/m^3). The radon concentrations in the samples collected in the parking lot outside of the VC were much lower than the levels collected inside of the building.

Both the maintenance (2.65 pCi/L or 98.1 Bq/m^3) and superintendent's buildings (0.60 pCi/L or 22.2 Bq/m^3) had mean radon levels below the OSHA, GSA, and EPA levels. These buildings were only sampled in the December to April sampling period. Unlike the VC, these buildings did not have a direct connection to the main cavern.

For the main cavern, the mean radon concentrations were much higher than those found in the VC. Mean concentrations in the main cavern were about three times higher in the July to December sampling period (66.7 pCi/L or 2,470 Bq/m^3) than in the December to April sampling period (25 pCi/L or 925 Bq/m^3), indicating that there are seasonal differences in measured radon concentrations. These radon concentrations were below the OSHA PEL, but were at or above the GSA value and above the EPA action level.

The mean radon concentrations in Spider Cave ranged from 147 to 161 pCi/L (5,440 to 5,960 Bq/m3), which were greater than the concentrations observed in the main cavern. Unlike the main cavern, we found minimal seasonal variation of radon concentrations in Spider Cave. Currently, tours of Spider Cave are done once per week, with park employees spending about three hours in the cave during each tour. Given that employees only spend three hours per week in Spider Cave, their radon exposure would be below the OSHA PEL.

Tracer Gas Assessment Results

To determine whether radon was potentially entering the VC via the main cavern elevator shaft or from the crawl space below a portion of the VC, we did two separate tracer gas tests. Results from the tracer gas release into the main cavern elevator shaft are shown in Figure 1. During the one-hour release of tracer gas in the elevator shaft, the tracer gas concentrations increased rapidly to relatively high levels at the elevator entrance located in the elevator lobby and in the elevator exit area located in the VC bookstore, indicating a high leakage rate of tracer gas from the elevator shaft to these areas. Tracer gas concentrations increased at a slower rate, and to relatively lower levels, in the other sampling locations in the VC. Tracer gas concentrations continued to rise in most of these locations for the additional hour after the tracer gas release stopped. These observations reveal a slow and steady migration of air from the elevator lobby and elevator exit areas to the rest of the VC.

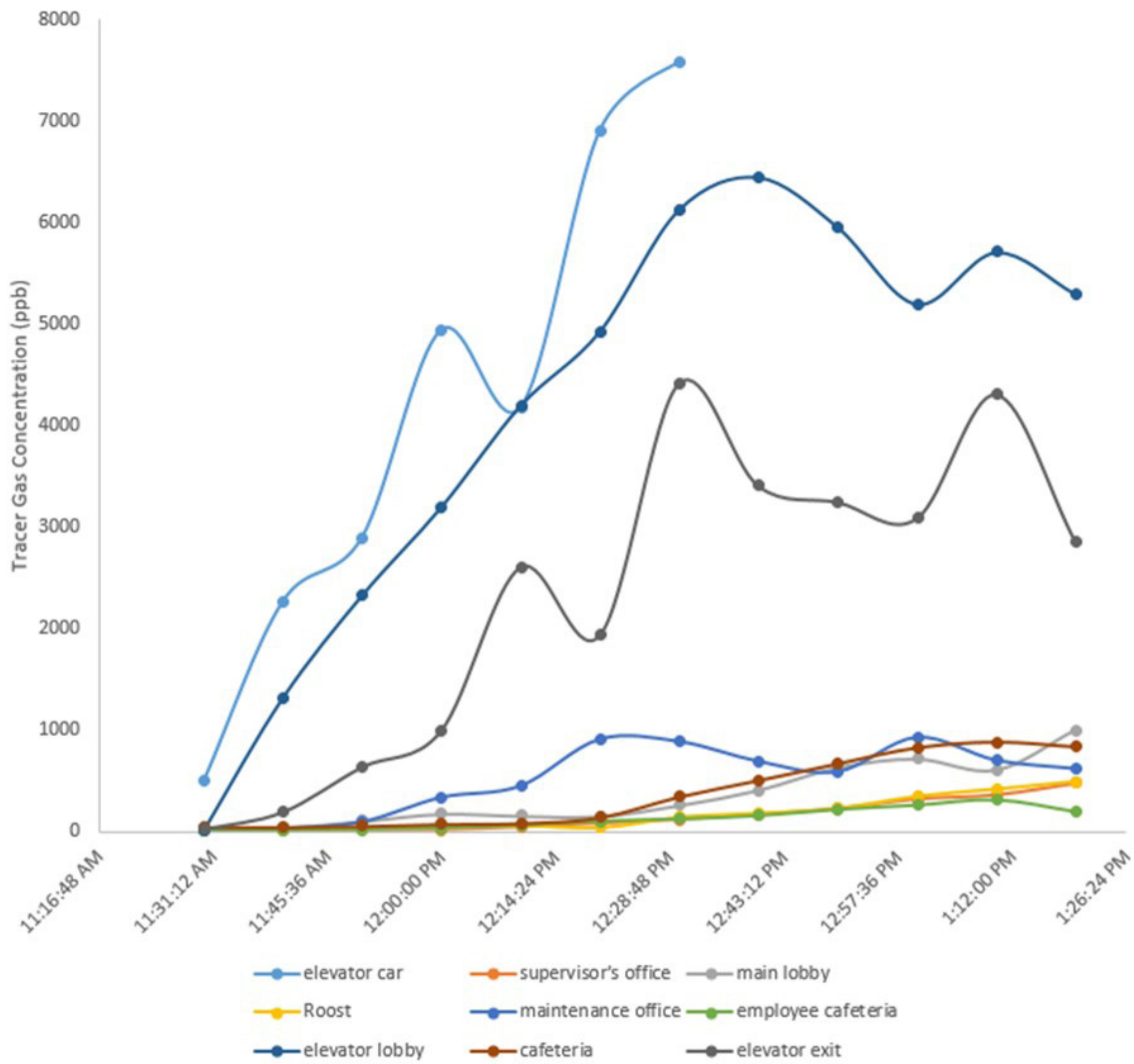

Figure 1. Tracer gas concentrations measured in the VC during elevator shaft release.

Results from the second tracer gas release test revealed only minimal tracer gas leakage from the two crawl spaces into only three of the nine areas sampled in the VC. The tracer gas concentrations measured during the two-hour tracer gas release were 24 parts per billion (ppb) in the supervisor's office, 19 ppb in the roost, and 12 ppb in the cafeteria. An additional measurement taken at those locations four hours later showed tracer gas concentrations of 180 ppb in the supervisor's office, 105 ppb in the roost, and 60 ppb in the cafeteria. These results indicated some gradual leakage of tracer gas from the two crawl spaces into the VC, but this leakage was substantially less than the leakage we measured from the elevator shaft.

Ventilation Measurements

Table B2 in Appendix B provides the results from the volumetric airflow rate measurements taken at each supply air diffuser and summed together for each employee-occupied space of the VC. These measurements were collected in the VC during morning and afternoon operations and revealed that airflow was not adequate for employee-occupied spaces during normal working hours. In particular, airflow measurements taken on the morning of April 23 indicated no airflow in almost all employee-occupied spaces of the VC.

Measurement of Unattached Fraction of Radon Progeny

The mean one-hour average unattached fractions of radon progeny measured at three sampling locations in the main cavern are presented in Table 2. The values we measured in the pump room are similar to those measured in previous studies of this national park [Cheng et al. 1997]. These values are much higher than values typically found in office spaces, which is $f = 0.096$ [Reineking and Porstendörfer 1990].

Table 2. Mean one-hour unattached fractions of radon progeny in the main cavern

Location	N	Mean unattached fraction
Lunchroom	4	0.55
King's Palace	2	0.60
Pump room	10	0.40

Dose Modeling Results

The unattached fraction of radon progeny is one of the key parameters needed for dose modeling. For the main cavern dose calculations, we used the average unattached fraction, $f = 0.56$, which we measured in the lunchroom and King's Palace. For the VC, we used a default unattached fraction for indoor workplaces of 0.08, as recommended in ICRP 137. We used the DCFs for tourist caves and indoor workplaces recommended in ICRP 137 and the DCFs calculated by Winkler-Heil et al. [2007], which were based on three different dosimetric models.

Tables B3–B6 in Appendix B show the values we used in our dose calculations. The average weekly and annual time spent in the main cavern and VC, by job title, is shown in Table B3. The mean summer and winter radon concentrations, equilibrium factors, and the unattached fraction of radon progeny for the VC, main cavern, and Spider Cave are provided in Table B4. The estimated annual exposure to radon for time spent working in the main cavern and/or VC is provided in Table B5. Dosimetrically derived DCFs used for estimating annual effective dose to workers are shown in Table B6.

Estimated annual effective radiation dose from radon exposure, by job title, based on the average time spent working in both the main cavern and VC is shown in Table 3. Table 4 shows the potential reduction in annual radiation dose if radon in the VC is mitigated. These effective dose estimates assume no radon exposure from any other sources.

Table 3. Estimated annual effective radiation dose, by job title, based on the average time spent in both the cavern and the VC

Job title/Task	Annual effective dose in mSv (rem)			
	ICRP 137 Tourist Cave DCF	RADEP/IMBA	RADOS	IDEAL
Interpretation	43 (4.3)	40 (4.0)	34 (3.4)	31 (3.1)
Interpretation and Spider Cave tour	44 (4.4)	41 (4.1)	35 (3.5)	32 (3.2)
Fee personnel	11 (1.1)	10 (1.0)	7.4 (0.74)	7.4 (0.74)
Law enforcement	43 (4.3)	40 (4.0)	34 (3.4)	31 (3.1)
Dispatchers	11 (1.1)	10 (1.0)	7.4 (0.74)	7.4 (0.74)
Resources	3.7 (0.37)	3.5 (0.35)	3.1 (0.31)	2.8 (0.28)
Maintenance/ Elevator operator/Custodial	43 (4.3)	40 (4.0)	34 (3.4)	31 (3.1)
Maintenance/Elevator mechanic	19 (1.9)	17 (1.7)	14 (1.4)	13 (1.3)
Maintenance inside cavern	19 (1.9)	17 (1.7)	14 (1.4)	13 (1.3)
Concessions	**67 (6.7)**	**63 (6.3)**	**55 (5.5)**	**50 (5.0)**
NCRP recommended dose limit	50 (5)	50 (5)	50 (5)	50 (5)

Table 4. Estimated annual effective radiation dose, by job title, on the basis of the average time spent in both the cavern and the VC, assuming that radon has been mitigated such that exposure to progeny is nonexistent in the VC (WLM/yr = 0)

Job title/Task	Annual effective dose in mSv (rem)			
	ICRP 137 Tourist Cave DCF	RADEP/IMBA	RADOS	IDEAL
Interpretation	37 (3.7)	35 (3.5)	31 (3.1)	28 (2.8)
Interpretation and Spider Cave Tour	39 (3.9)	36 (3.6)	32 (3.2)	29 (2.9)
Fee personnel	0 (0)	0 (0)	0 (0)	0 (0)
Law enforcement	37 (3.7)	35 (3.5)	31 (3.1)	28 (2.8)
Dispatchers	0 (0)	0 (0)	0 (0)	0 (0)
Resources	3.7 (0.37)	3.5 (0.35)	3.1 (0.31)	2.8 (0.28)
Maintenance/ Elevator operator/Custodial	37 (3.7)	35 (3.5)	31 (3.1)	28 (2.8)
Maintenance/Elevator mechanics	9.3 (0.93)	8.8 (0.88)	7.7 (0.77)	6.9 (0.69)
Maintenance inside cavern	9.3 (0.93)	8.8 (0.88)	7.7 (0.77)	6.9 (0.69)
Concessions	**65 (6.5)**	**61 (6.1)**	**54 (5.4)**	49 (4.9)
NCRP recommended dose limit	50 (5)	50 (5)	50 (5)	50 (5)

Our estimated effective dose calculations revealed that employees working in concessions inside the main cavern have the highest annual effective doses. This is because the concession employees typically spend more time in the main cavern than other employees. Based on the DCFs derived from our measured unattached fractions of radon progeny, for all models, the concession employees were almost always over the NCRP recommended dose limit.

Figures 2a and 2b show the estimated effective dose versus time worked in the cavern for summer and winter average radon concentrations, respectively.

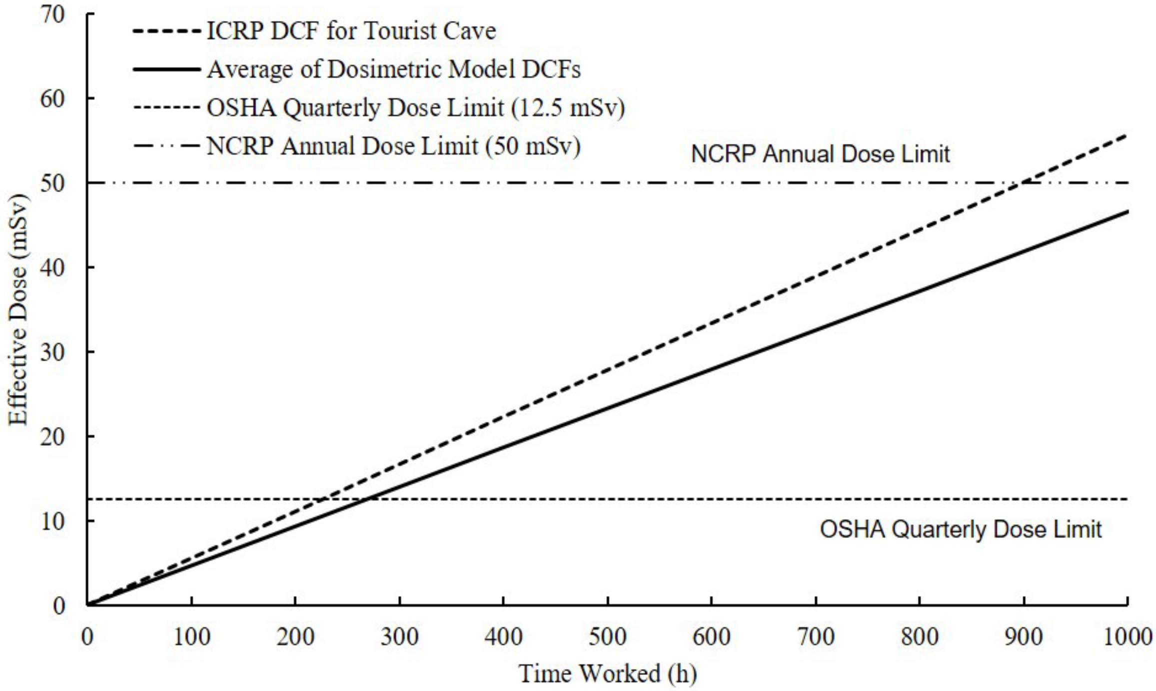

Figure 2a. Effective dose (mSv) versus hours worked in the main cavern using average radon concentration found during the summer months (July–December). Doses were estimated using the ICRP 137 DCF for tourist caves (53 mSv/WLM) and the average DCF derived from dosimetric models (45 mSv/WLM).

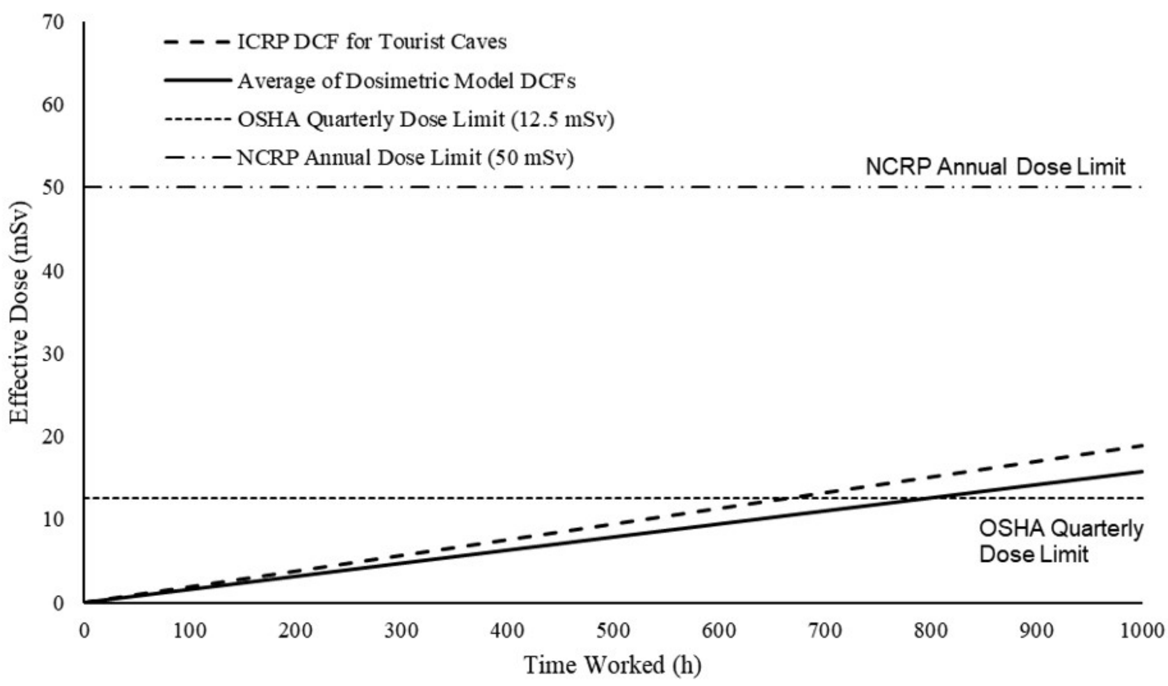

Figure 2b. Effective dose (mSv) versus hours worked in the main cavern area using average radon concentration found during the winter months (December–April). Doses were estimated using the new ICRP 137 DCF for tourist caves (53 mSv/WLM) and the average DCF derived from dosimetric models (45 mSv/WLM).

These two figures illustrate the amount of time employees can spend in the cavern, before they begin to reach various regulatory or recommended exposure limits. Using the most conservative model (ICRP 137 DCF; the dashed line in each figure), during the "summer" months when radon concentrations in the cavern are higher, employees would reach the OSHA quarterly dose limit after spending about 225 hours in the cavern (Figure 2a). In contrast, employees would reach the OSHA quarterly dose limit at about 665 hours during the "winter" months (Figure 2b), because the radon concentrations are lower during the winter.

Based on the radon levels measured during the summer months, and independent of the doses estimated using DCFs, employees would reach the NIOSH REL for radon progeny of 1 WLM/yr after working 960 hours in the cavern. Based on the radon levels measured during the winter months, employees could work in the caverns for more than 2,000 hours before reaching the NIOSH REL, because the radon concentrations during the winter months were lower.

Discussion

None of the radon gas concentrations we measured in the VC were above the OSHA PEL of 100 pCi/L (3,700 Bq/m^3) or the GSA standard of 25 pCi/L (925 Bq/m^3). Radon concentrations were above the EPA action level of 4 pCi/L (148 Bq/m^3). However, the EPA action level is not considered an OEL, but rather a limit intended to protect the general public from exposure to radon in homes and schools. The EPA action level was established based, in part, on the risk of lung cancer for a person exposed to 4 pCi/L for 7,000 hours per year over a lifetime. In contrast, workplace exposure limits are based on the general assumption that employees are exposed for 2,000 hours per year (equivalent to 40 hours per week for 50 weeks per year).

Our tracer gas testing revealed that radon gas was entering the VC primarily via the elevator shaft connecting the VC to the main cavern below it. These tracer gas observations also showed a slow and steady migration of air from the elevator lobby and elevator exit areas to the rest of the VC. Separate tracer gas testing found that the contribution of radon gas from the crawl spaces underneath the VC building were minimal compared to the contribution through the elevator shaft. Therefore, modifying or reconfiguring the ventilation system in the VC to prevent air from the main cavern and elevator shaft from entering and spreading throughout the VC should greatly reduce radon concentrations in the VC. Radon measurements we took in the maintenance and superintendent's buildings, which were not connected to the caverns, were all less than about 3 pCi/L (111 Bq/m^3), substantially lower than concentrations measured in the VC. Successful remediation of the VC ventilation system may reduce radon concentrations to levels similar to those found in the maintenance and superintendent's buildings.

None of the radon gas concentrations we measured in the main cavern were above the OSHA PEL. We measured a seasonal difference in radon concentrations inside the main cavern. The summer concentrations were much higher than the winter concentrations. Seasonal differences in radon concentrations are likely due to the number of air changes in the cave, and how that number varies during the course of a year. During the winter months, the cave air is warmer than the outdoor air. The warm cave air rises out of the cave, and the cold outdoor air that contains little to no radon enters the cave and dilutes the radon concentrations. This air exchange does not occur in the summer months, when the cave air is cooler than the outdoor air [Cheng et al. 1997].

Our radon measurement results in the cavern and the seasonal variation in radon concentrations were similar to those found in previous studies of the cavern [Cheng et al. 1997; Wilkening and Watkins 1976]. Wilkening and Watkins [1976] found that radon concentrations in the cavern averaged about 48 pCi/L (1,776 Bq/m^3) in the summer and about 15 pCi/L (555 Bq/m^3) in the winter. Our measurements were somewhat higher than those reported averages. However, these differences could be due to factors such as improvements in the accuracy of sampling instruments, sample location, and sampling duration.

While radon concentrations were not above the OSHA PEL, the main cavern has some unique characteristics that make this cave environment different from other work sites where radon is present. Unlike mines or other indoor environments, previous research has shown that the main cavern has an elevated unattached fraction of radon progeny [Cheng et al. 1997]. In August 2016, we used specialized instrumentation to measure and characterize the unattached fraction of radon progeny and radon concentrations. Our measurement results for the unattached fraction of radon progeny in the pump room ranged from 0.36 to 0.50. Similarly, Cheng et al. [1997] measured unattached fractions of radon progeny ranging from 0.25 to 0.59 in the pump room.

The relatively high unattached fraction of radon progeny is due to very low concentrations of condensation nuclei aerosols. This is partially because the cavern has very few sources of aerosol generation, other than tourist activities. In addition, the cavern air exchange rate is very 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 buildup [Cheng et al. 1997]. When inhaled, unattached radon progeny can be 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]. Because of greater cancer risk from deposition of unattached radon progeny in the lungs, comparing exposures solely to the PEL, which is based on exposure to radon gas and low unattached fraction of radon progeny, could underestimate cavern employees' effective radiation dose.

Due to the high unattached fraction of radon progeny and its influence on employees' effective radiation dose, we used the radon data we measured during this evaluation to model employees' whole-body radiation doses. Our models factored in the measured radon concentration, measured unattached fraction of radon progeny, dosimetrically-derived DCFs, and employees' time-activity patterns. The results of our modeling showed that most employees (except cavern concession employees) would be under the OSHA whole body radiation PEL. However, due to the high unattached fraction of radon progeny in the cavern, and depending on the time spent in the cavern, the calculated effective ionizing radiation dose for workers could exceed the OSHA dose limit of 12.5 mSv (1.25 rem) per quarter and the 50 mSv (5 rem) annual effective dose limit recommended by NCRP.

To keep ionizing radiation exposures under the OSHA quarterly dose limits, employees' time in the cavern should be limited. In the higher radon concentrations months (i.e., summer months), employees should be limited to no more than 225 hours per quarter. During the months with lower radon concentrations (i.e., winter months), employees could spend up to 665 hours per quarter in the cavern before exposures would exceed the OSHA quarterly dose limits. Because a quarter is roughly 500 work hours, employees would be able to spend their full work time in the cavern during these low radon concentration months.

Based on the currently reported Spider Cave tour durations and frequencies, employee exposures do not exceed the OSHA PEL for radon. This assumes that an employee spends only three hours inside Spider Cave per week, with the rest of their time spent in the VC and main cavern. However, the concentrations measured in Spider Cave have the potential to exceed the OSHA PEL for radon, depending upon how much time employees spend in that cave. According to the OSHA ionizing radiation standard (29 CFR 1910.1096[c][3]), when exposures are above the PEL, employees must discontinue working in the area until exposures are reduced. OSHA does not permit the use of respirators, such as a filtering facepiece respirator, as a method of reducing employee exposures. If the duration and frequency of Spider Cave tours increased and resulted in exposures above the PEL, park management would need to contact OSHA to discuss possible options, such as requesting a variance.

This evaluation had some limitations that could influence the accuracy of our findings. First, we did not measure radon concentrations over an entire calendar year. In our dose modeling, we assigned the higher mean radon concentration to the months (May, June, and July) in which we did not collect radon data. Given that environmental conditions during these months are similar to the "summer" months in which we did collect samples, we felt that it was a reasonable and appropriate assumption that radon concentrations would also be similar. Secondly, it would have been ideal to collect one-month duration samples for radon at each location, instead of collecting multiple month samples. Monthly personal dosimetry monitoring or radon measurements would allow for further refinement of dose estimates, potentially increasing their accuracy. Lastly, unattached fraction and equilibrium were only measured for a single 24-hour period, so evaluating uncertainty in these parameters over the course of a year was not possible.

Conclusions

Radon gas concentrations measured in the VC were below the OSHA PEL. Tracer gas measurements indicated that the radon was entering the VC through the elevator shafts that attach it to the main cavern below. Modifications of the building heating, ventilation, and air-conditioning (HVAC) system, which prevent the entry and mixing of cavern air with air from the VC, should reduce radon levels in the VC. Radon concentrations measured inside the main cavern were also below the OSHA PEL. However, employees working in the cavern have the potential to exceed the OSHA whole body ionizing radiation dose limits, depending upon how much time they spend in the cave. This is due to the natural radon levels found inside of the cavern, the high unattached fraction of radon progeny, and the lack of air movement. Administrative controls will be required to limit the number of hours employees spend in the cavern to prevent long-term adverse health effects. We found that radon concentrations were below the OSHA PEL in Spider Cave, on the basis of the current tour schedule of three hours per week. If the duration or frequency of tours increased, it is possible that the OSHA PEL for radon could be exceeded.

Recommendations

Based on our findings, we recommend the actions listed below. We encourage the park to use a labor-management health and safety committee or working group to discuss our recommendations and develop an action plan. Those involved in the work can best set priorities and assess the feasibility of our recommendations for their workplace.

Our recommendations are based on an approach known as the hierarchy of controls (Appendix B). This approach groups actions by their likely effectiveness in reducing or removing hazards. In most cases, the preferred approach is to eliminate hazardous materials or processes and install engineering controls to reduce exposure or shield employees. Until such controls are in place, or if they are not effective or feasible, administrative measures and personal protective equipment may be needed.

Engineering Controls

Engineering controls reduce employees' exposures by removing the hazard from the process or by placing a barrier between the hazard and the employee. Engineering controls protect employees effectively without placing primary responsibility of implementation on the employee.

1. Reduce radon exposures by installing double airlocks at the VC's elevator entrance and exit areas (exits to all four elevators).
    - After the VC double airlocks are in place, install a dedicated ventilation system to serve just the space between the double airlocks. Isolate the existing VC HVAC system(s) such that they neither supply nor return air to/from the elevator-side of the airlocks. The dedicated ventilation system serving the space between the double airlocks could have supply air from the VC but should have 100% dedicated ducted exhaust to the outdoors and be balanced to establish neutral air pressure with respect to the elevator side of the airlocks. The space between the double airlocks should have a minimum of 20 air changes per hour to flush out any radon leaking in from the elevator side of the double airlocks. The humidity should be controlled to match the cave environment. The outlet of the ducted exhaust from the ventilated space between the double airlocks should meet all state and federal standards for terminal distance above the roof and be located far enough from outdoor air intakes to prevent re-entrainment. Locate elevator attendee employees on the VC side of the double airlocks and put administrative controls in place to verify that workers do not routinely work on the elevator side of the double airlocks except for elevator maintenance or other intermittent or nonroutine tasks.
2. Isolate the elevator machine room from the VC using closed doors that include weather seals and gaskets to prevent air leakage.
3. Hire a licensed professional mechanical engineer to evaluate the existing HVAC system's capacity to provide additional outdoor air to the occupied spaces in the VC to simultaneously meet American National Standards Institute (ANSI)/ASHRAE Standard 62.1 and tempering requirements [ANSI/ASHRAE 2016]. If necessary,

additional HVAC capacity, such as the use of a dedicated outdoor air system, may be required in order to meet the minimum ASHRAE outdoor air requirements and further reduce radon concentrations in employee-occupied spaces of the VC.

4. To the extent that it is compatible with the existing HVAC fan system, install ducted returns (with exterior duct insulation) on the existing HVAC system to reduce tempering demands introduced by the current return air plenum space.
5. Install solar shading for the western side of the VC. A shade structure similar to what is currently shading the main entrance to the VC could achieve this effect. One mechanism to partially offset the facility's energy demands would be to incorporate solar panels into both the main entrance and western-side shading structures.
6. Until capital improvements to the HVAC system can be made, we recommend making the following changes immediately to reduce radon concentrations in the VC:
    - Implement a preventative maintenance program to inspect the rubber flanges/brushes on the revolving doors and airlocks at the bottom of the elevator shaft area and replace when worn. Conduct this inspection at least four times a year.
    - During VC operating hours, the HVAC system should be reprogrammed to increase the delivery of outdoor air to the maximum extent allowable while maintaining thermal comfort.
    - When overnight temperatures are between 40°F and 77°F, the HVAC system should be operated overnight or for at least four hours before people arrive in the morning with the outdoor air dampers in their maximum open position. This approach will maximize the delivery of outdoor air to the VC and flush the radon-contaminated air in the building while taking advantage of favorable ambient conditions.
    - At a minimum and to the extent allowable with the current system design limitations, operate the current HVAC system in accordance with ANSI/ASHRAE Standard 62.1 [ANSI/ASHRAE 2016].
7. Improve the maintenance and calibration of the supply air system and its operating controls such as sensors and carbon dioxide detectors. A major maintenance issue is the recalibration of the system controls. If the controls are not routinely calibrated, operating set points may drift, resulting in energy waste and poor system performance.

Administrative Controls

The term "administrative controls" refers to employer-dictated work practices and policies to reduce or prevent hazardous exposures. Their effectiveness depends on employer commitment and employee acceptance. Regular monitoring and reinforcement are necessary to ensure that policies and procedures are followed consistently.

1. Limit employees' time in the cavern to no more than 225 hours per quarter (about 75 hours per month) during the higher radon concentration months in the summer. Time limits are not needed during lower radon concentration months in the winter.

These time estimates are based on the radon gas levels and the unattached fraction of radon progeny measured inside of the cavern and could be modified if additional measurements are completed. For employees that enter Spider Cave, the amount of time allowed in the cavern would be slightly lower.

2. Consult with a health physicist to create and implement a written radon management program. The program should include additional measurements of radon gas and unattached fraction of radon progeny in the cavern, which may lead to refinement of radiation dose estimates and monthly time limitations for employees in the cavern.

3. Implement a tracking system to monitor the number of hours employees work inside the cavern. This would ensure that employees' time in the cavern does not exceed the maximum allowed, on the basis of the radiation does estimates.

4. Post signs in accordance with 29 CFR 1910.1096(e)(4)(ii) indicating "Caution, Airborne Radioactivity Area" in areas where radon concentrations are greater than 25 pCi/L. This would include both the cavern and Spider Cave. OSHA requires these postings when concentrations in an employee work area are greater than 25% of the PEL [OSHA 1996].

5. Educate and train employees about the risks from exposure to radon and radon progeny.

6. Move all nonessential work, such as concessions, outside of the cavern. This would help to minimize the amount of time employees spend in the cavern and reduce their radon exposure.

7. Schedule cavern work that is not time-sensitive to the winter months, when radon concentrations are lower. This will help to reduce radon exposure.

Appendix A: Dose Modeling

To permit comparison of the radon concentrations measured in the main cavern to the OSHA whole body ionizing radiation PEL, dose modeling was required. The historical unit of radon exposure is the WLM, which is defined as the concentration of radon progeny in one liter of air in equilibrium with 100 pCi/L (3,700 Bq/m^3) of radon that will result in the emission of 1.3 × 10^8 megaelectronvolt per cubic meter (MeV/m^3) of potential alpha energy. Because one working month was assumed to equal 170 hours and 1 MeV = 1.602 × 10^{-13} joules (J), a WLM is derived to be equal to 3.54 mJ-h/m^3 or 6.37 × 10^5 Bq-h/m^3.

Based on the concentration of radon in air, the equilibrium factor, F (ratio of the concentration of radon progeny to radon), and the number of hours worked, the annual exposure in WLM can be calculated by the following:

$$\text{Annual exposure} = \frac{C_{Rn} \times t \times F}{6.37 \times 10^5}$$

where C_{Rn} is the measured radon concentration (Bq/m^3), t is the time worked in a year (hours), and F is the equilibrium factor.

The ICRP recommended estimating the effective dose per unit of radon exposure using a dose-conversion factor of 5 mSv per WLM [ICRP 1993]. This conversion factor, developed using an epidemiological approach, was calculated by dividing the estimated detriment from a unit exposure to radon derived from miner epidemiology by the detriment per unit effective dose derived from Japanese atomic bomb survivors. The values used for estimated detriments derived from miner epidemiology studies were from the 1990 Recommendations of the ICRP [ICRP 1991]. In 2010, the ICRP updated the detriment per unit effective dose for workers based on newer epidemiological studies and recommended that ICRP biokinetic and dosimetric models be used for radon and its progeny, similar to the dose modeling used for other radionuclides [ICRP 2010]. ICRP has recently published new dose coefficients for radon and its progeny and recommend values for effective dose conversion factors for inhalation of radon and its progeny [ICRP 2017].

We calculated an annual effective dose for workers in the main cavern and the associated VC based on measurements we obtained during July–December 2014, December 2014–April 2015, and August 2016. For the purpose of dose estimation, we assumed that the work year was 2000 hours (50 weeks): 1,000 hours (25 weeks) in summer and 1,000 hours (25 weeks) in winter. We assumed that the radon measurements taken during July–December 2014 represented the "summer" radon concentrations and the measurements taken during December 2014–April 2015 represented the "winter" radon concentrations.

We calculated exposure (in WLM) for workers based on their time spent in the main cavern and the VC, using the following equations:

$$R_c = P_{eq}\frac{t_c}{2}F_c\left(C_{c,s} + C_{c,w}\right)$$

$$R_v = P_{eq}\frac{t_v}{2}F_v\left(C_{v,s} + C_{v,w}\right)$$

where
R_c and R_v = exposure (WLM) in the cavern and VC, respectively
t_c and t_v = annual time spent in cavern and VC, respectively
F_c and F_v = equilibrium factor for cavern and VC, respectively
$C_{c,s}$ and $C_{c,w}$ = measured radon concentration in the cavern during summer and winter, respectively
$C_{v,s}$ and $C_{v,w}$ = measured radon concentration in the VC during summer and winter, respectively
P_{eq} = time-integrated exposure to equilibrium concentration of radon = 1.57×10^{-6} WLM per Bq-h/m^3.

The distribution of time that employees spent in the main cavern and VC was collected by NPS staff for various job categories, and provided to us for our analysis. The equilibrium factor, $F_c = 0.26$, used for the cavern exposure calculation, was derived from our measurements of the unattached fraction of radon progeny in the King's Palace and the main cavern lunchroom during the August 2016 site visit. No measurements were taken in the VC, so a default value of 0.4 was used for the equilibrium factor, F_v. This default value is based primarily on measurements made in homes in the United States and India [ICRP 2017].

To account for the potential effect of a larger unattached fraction present in the main cavern environment, the following equation was used with the site-specific DCFs and dosimetric model DCFs:

$$E = R_c[f_c DCF_{un} + (1 - f_c)DCF_{att}] + R_v[f_v DCF_{un} + (1 - f_v)DCF_{att}]$$

where
E = effective dose (mSv)
f_c = unattached fraction for cave
f_v = unattached fraction for VC
DCF_{un} = dose conversion factor for unattached fraction (mSv/WLM)
DCF_{att} = dose conversion factor for attached fraction (mSv/WLM)

For this dosimetric modeling, we used three different models: RADEP/IMBA, RADOS, and IDEAL. The RADEP/IMBA DCFs are based on the ICRP Human Respiratory Tract Model [ICRP 1994], which is a deterministic regional compartment model. The RADOS model is a deterministic airway generation model, consisting of 15 symmetric airway generations. The IDEAL model is a stochastic airway generation model, consisting of a variable number of asymmetric airway generations. The differences in the models are the regional deposition fractions predicted for a standard worker, the number of nuclear transformations estimated by the models due to differences in how clearance from the lungs is modeled, and how the dose to each region of the lung is calculated [Winkler-Heil et al. 2007]. Other investigators have derived DCFs using various methods and parameters that vary between 6 and 20 mSv per WLM [Brudecki et al. 2014].

Appendix B: Tables

Table B1. Measured radon gas concentrations

Location	Mean radon gas concentration July–December in pCi/L (Bq/m³)	Mean radon gas concentration December–April in pCi/L (Bq/m³)
Visitor Center measurements		
Room 014 – Ranger office	8.50 (315)	6.60 (244)
Room 019 – Employee library	7.40 (274)	6.90 (255)
Room 020 – Employee break room	8.40 (311)	8.55 (316)
Room 109 – Information desk	12.2 (451)	11.8 (437)
Room 114 – Fees area	13.9 (514)	13.4 (496)
Room 144 – Mail room	13.8 (511)	15.6 (577)
Room 150 – Roost	11.8 (437)	11.5 (426)
Room 152 – Supervisor’s office	9.80 (363)	9.60 (355)
Room 200A – Maintenance supervisor’s office	18.6 (688)	18.4 (681)
Room 200D – Passenger elevator mechanical room	26.0 (962)	18.0 (664)
Book store	17.9 (662)	13.7 (507)
Gift shop	10.9 (403)	10.2 (377)
Restaurant dining area	10.8 (400)	10.4 (385)
Crawl space below building	10.4 (385)	11.2 (414)
Cavern measurements		
Lunchroom	66.4 (2,460)	19.8 (733)
The Beach	72.6 (2,690)	25.0 (925)
Iron Pool	73.7 (2,730)	57.1 (2,110)
The Rookery	81.1 (3,000)	25.5 (944)
Blackout Spot	78.1 (2,890)	25.5 (944)
Jim White Tunnel	66.7 (2,470)	18.5 (685)
Texas Tail near Top of the Cross	67.0 (2,480)	21.6 (799)
Caveman Junction	63.5 (2,350)	21.8 (807)
Bat cave	66.6 (2,460)	16.5 (611)
Hall of the White Giant – entrance	61.3 (2,270)	20.6 (762)
Hall of the White Giant – inside	74.5 (2,760)	63.4 (2,350)
Devil’s Den	61.7 (2,280)	19.3 (714)
Green Lake Room	73.7 (2,730)	20.8 (770)
King’s Palace	72.8 (2,690)	24.9 (921)
Queens Chamber	64.3 (2,380)	19.1 (707)
Lunchroom (on counters)	—	19.6 (725)
OSHA PEL	100 (3,700)	100 (3,700)

Table B1 continued - measured radon gas concentrations

Location	Mean radon gas concentration July–December in pCi/L (Bq/m^3)	Mean radon gas concentration December–April in pCi/L (Bq/m^3)
Spider Cave measurements	161 (5,960)	147 (5,440)
Other measurements		
Passenger elevator pit	77.0 (2,850)	19.1 (707)
Inside elevator shaft	56.4 (2,090)	24.3 (899)
Superintendent's building – main room	—	0.65 (24.1)
Superintendent's building – office near conference room	—	0.55 (20.4)
Maintenance building – file cabinet outside of office	—	3.05 (113)
Maintenance building – office near entrance	—	2.25 (83.3)
Outdoors – Location 1	0.40 (15)	0.30 (11.1)
Outdoors – Location 2	0.40 (15)	0.50 (18.5)
OSHA PEL	100 (3,700)	100 (3,700)

Table B2. Sum of airflow rate in cubic feet per minute from supply air vents in employee-occupied spaces of the VC

Location of supply air diffuser	Supply air flowrate (afternoon of April 21)	Supply air flowrate (morning of April 23)
Library	140	0
CCGMA offices	86	0
Downstairs employee cafeteria	100	0
Hallway outside of Room #13	110	0
Downstairs women's restroom	54	0
Downstairs men's restroom	45	0
Theatre room	510	—
Tour training room	430	—
Bookstore and elevator exit area	350	0
Picture exhibit	21	0
Main lobby/entrance	350	71
Gift shop	250	87
Cafeteria	2,100	350
Hallway between backdoor and door to #157	0	0
Gift shop storage	0	0
Hallway near locker and outside roost	36	0
Interpreter office suite	35	20
Empty cubicle	37	23
Office #153	35	0
Office #154	26	0
Roost office (first)	30	0
Roost office (second)	34	0
Roost law enforcement office	43	0
Mailroom	62	0
Elevator 1 & 2 exit	110	130
Elevator 3 & 4 entrance	0	0
Fee office	310	0

Table B3. Average time spent in the cavern and VC

Job title/Task	Average time spent in cavern (hours)		Average time spent in visitor center (hours)		Average time spent in Spider Cave (hours)	
	Per week	Per year	Per week	Per year	Per week	Per year
Interpretation	20	1,000	20	1,000	0	0
Interpretation and Spider Cave tour	19.7	985	20	1000	0.3*	15*
Fee personnel	0	0	40	2,000	0	0
Law enforcement	20	1,000	20	1,000	0	0
Dispatchers	0	0	40	2,000	0	0
Resources	2	100	0	0	0	0
Maintenance/Elevator operator/Custodial	20	1,000	20	1,000	0	0
Maintenance/Elevator mechanics	5	250	35	1,750	0	0
Maintenance inside cavern	5	250	35	1,750	0	0
Concessions	35	1,750	5	250	0	0

*Assumes that an employee conducts five, three-hour tours per year.

Table B4. Variables used for calculating radon exposure and effective dose

Location	Mean radon concentration in pCi/L (Bq/m^3)		Equilibrium factor	Unattached fraction
	Summer	Winter		
Visitor Center	12.9 (477)	11.8 (438)	0.40	0.08
Main Cavern	69.7 (2,580)	25.0 (924)	0.26	0.56
Spider Cave	161 (5,960)	147 (5,450)	0.26	0.56

Table B5. Estimated annual exposure to radon while working in the caverns or VC

Job title/Task	Cave annual exposure (WLM/yr)	Visitor center annual exposure (WLM/yr)
Interpretation	0.70	0.29
Interpretation and Spider Cave tour	0.72	0.29
Fee personnel	0.0	0.57
Law enforcement	0.70	0.29
Dispatchers	0.0	0.57
Resources	0.07	0.0
Maintenance/Elevator operator/Custodial	0.70	0.29
Maintenance/Elevator mechanics	0.17	0.50
Maintenance inside cavern	0.17	0.50
Concessions	1.2	0.072

Table B6. Dose conversion factors used for estimating annual effective dose for workers

Models	Effective Dose Conversion Factors per exposure (mSv/WLM)	
	Attached fraction	Unattached fraction
ICRP 137 (tourist cave)	12	86
ICRP 137 (indoor workplace)	14	86
RADEP/IMBA	11.1	81.1
RADOS	7.7	72.4
IDEAL	8.3	64.6

Appendix C: Occupational Exposure Limits and Health Effects

NIOSH investigators refer to mandatory (legally enforceable) and recommended OELs for chemical, physical, and biological agents when evaluating workplace hazards. OELs have been developed by federal agencies and safety and health organizations to prevent adverse health effects from workplace exposures. Generally, OELs suggest levels of exposure that most employees may be exposed to for up to 10 hours per day, 40 hours per week, for a working lifetime, without experiencing adverse health effects. However, not all employees will be protected if their exposures are maintained below these levels. Some may have adverse health effects because of individual susceptibility, a preexisting medical condition, or a hypersensitivity (allergy). In addition, some hazardous substances act in combination with other exposures, with the general environment, or with medications or personal habits of the employee to produce adverse health effects. Most OELs address airborne exposures, but some substances can be absorbed directly through the skin and mucous membranes.

Most OELs are expressed as a time-weighted average (TWA) exposure. A TWA refers to the average exposure during a normal 8- to 10-hour workday. Some chemical substances and physical agents have recommended short-term exposure limits or ceiling values. Unless otherwise noted, the short-term exposure limit is a 15-minute TWA exposure. It should not be exceeded at any time during a workday. The ceiling limit should not be exceeded at any time.

In the United States, OELs have been established by federal agencies, professional organizations, state and local governments, and other entities. Some OELs are legally enforceable limits; others are recommendations.

- OSHA, an agency of the U.S. Department of Labor, publishes PELs [29 CFR 1910 for general industry, 29 CFR 1926 for construction industry, and 29 CFR 1917 for maritime industry] called PELs. These legal limits are enforceable in workplaces covered under the Occupational Safety and Health Act of 1970.
- NIOSH RELs are recommendations based on a critical review of the scientific and technical information and the adequacy of methods to identify and control the hazard. NIOSH RELs are published in the *NIOSH Pocket Guide to Chemical Hazards* [NIOSH 2010]. NIOSH also recommends risk management practices (e.g., engineering controls, safe work practices, employee education/training, personal protective equipment, and exposure and medical monitoring) to minimize the risk of exposure and adverse health effects.
- Another set of OELs commonly used and cited in the United States is the American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit values (TLVs). The TLVs are developed by ACGIH committee members from a review of the published, peer-reviewed literature. TLVs are not consensus standards. They are considered voluntary exposure guidelines for use by industrial hygienists and others trained in this discipline "to assist in the control of health hazards" [ACGIH 2019].

Outside the United States, OELs have been established by various agencies and organizations and include legal and recommended limits. The Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung (Institute for Occupational Safety and Health of the German Social Accident Insurance) maintains a database of international OELs from European Union member states, Canada (Québec), Japan, Switzerland, and the United States. The database, available at http://www.dguv.de/ifa/GESTIS/GESTIS-Internationale-Grenzwerte-für-chemische-Substanzen-limit-values-for-chemical-agents/index-2.jsp, contains international limits for more than 2,000 hazardous substances and is updated periodically.

OSHA requires an employer to furnish employees a place of employment free from recognized hazards that cause or are likely to cause death or serious physical harm (Occupational Safety and Health Act of 1970, Public Law 91-596, sec. 5[a][1]). This is true in the absence of a specific OEL. It also is important to keep in mind that OELs may not reflect current health-based information.

When multiple OELs exist for a substance or agent, NIOSH investigators generally encourage employers to use the lowest OEL when making risk assessment and risk management decisions. NIOSH investigators also encourage use of the hierarchy of controls approach to eliminate or minimize workplace hazards. This includes, in order of preference, the use of (1) substitution or elimination of the hazardous agent, (2) engineering controls (e.g., local exhaust ventilation, process enclosure, dilution ventilation), (3) administrative controls (e.g., limiting time of exposure, employee training, work practice changes, medical surveillance), and (4) personal protective equipment (e.g., respiratory protection, gloves, eye protection, hearing protection). Control banding, a qualitative risk assessment and risk management tool, is a complementary approach to protecting employee health. Control banding focuses on how broad categories of risk should be managed. Information on control banding is available at http://www.cdc.gov/niosh/topics/ctrlbanding/. This approach can be applied in situations where OELs have not been established or can be used to supplement existing OELs.

Radon

Radon is a colorless, odorless, inert, radioactive noble gas that has three isotopic forms commonly found in nature: radon-222, which is a member of the uranium-238 decay chain; Radon-220 (known as “thoron”), which is in the decay chain of thorium-232; and radon-219 (known as “actinon”), which results from the decay of uranium-235. Of the three forms, radon-222 and its subsequent radioactive decay products present the greatest risk in most environmental and occupational settings because of its natural abundance.
Radon-222Rn undergoes radioactive decays via a series of solid short-lived radionuclides (i.e., polonium-218, lead-214, bismuth-214, and polonium-214), referred to as “radon progeny” or “radon daughters.” These decay products appear either as unattached ions or are attached to condensation nuclei or dust particles, forming a respirable radioactive aerosol.

Environmental levels of radon in the United States vary widely, with average indoor concentrations in U.S. homes of about 1.2 pCi/L (46 Bq/m^3) and in Colorado homes of 2.6 pCi/L (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 0.4 pCi/L (15 Bq/m^3) [Borak and Baynes 1999; Price et al. 1994]. Progeny equilibrium is typically greater outdoors, accounting for about 36% of the total dose received by the U.S. population annually [NCRP 2009]. The main contributor to tissue-absorbed dose is densely ionizing radiation in the form of alpha particles from the decay of respired short-lived radon progeny; therefore, the organ most at risk from exposure is the lung, primarily from deposition of radon progeny in the bronchial epithelium. Dose to other organs and the fetus from inhaled radon progeny are at least an order of magnitude less than that of the lung [Kendall and Smith 2002].

Numerous studies of underground uranium miners who were exposed to relatively high levels of radon have unequivocally established radon as a human lung carcinogen [IARC 1988]. EPA states that radon is the second leading cause of lung cancer in the United States and is the leading cause among persons who never smoked. The estimated risk from lifetime exposure at the EPA action level of 4 pCi/L (150 Bq/m^3) is 2.3% [EPA 2003].

Much less information is available on other health outcomes associated with radon exposure. There is sparse evidence suggesting 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]. Some researchers have postulated that radon progeny that is deposited on skin surfaces can result in non-negligible dose to sensitive basal cells, which may result in increased incidence of nonmelanoma skin cancer [Denman et al. 2003; Eatough and Henshaw 1991; Sevcova et al. 1978]. The current weight of evidence is insufficient to establish a causal link between radon and skin cancer in humans [Charles 2007a,b].

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Copies of this report have been sent to the employer and employees at the facility. The state and local health department and the Occupational Safety and Health Administration Regional Office have also received a copy.

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