

Radon Mitigation Improvements for Fossil Collections:
Case Study - Hagerman Fossil Bed National Monument

I. ABSTRACT

The Hagerman Fossil Beds National Monument is known to produce Pliocene fossils that emit high levels of radon, a colorless, odorless, cancer-causing gas. This study explored ways to quantify and mitigate excessive levels of radon in the park's collection and addressed the need to create safe working conditions for employees and researchers. Using a combination of updated technology and new mitigation strategies, protocols were developed that reduced daily radon building concentrations to recommended safe limits according to the Environmental Protection Agency (EPA).

II. INTRODUCTION

Due to the natural processes of fossil formation, it is not a rare occurrence for fossils to be radioactive, and the Hagerman Fossil Beds are known to be particularly "hot". Długosz-Lisiecka et al. describes how Uranium is incorporated into the structure of fossils (especially bone), turning them into sources of radioactivity (2021). Fossils were excavated from the Hagerman area for over 50 years before the establishment of the monument in 1988 and are housed in museums and universities around the world. Radon poses special considerations for storage and handling of not only the Fossil Beds' national collection, but for other collections and fossil beds as well.

Radon (^{222}Rn) is a heavy gas that also breaks down into radon progeny (formerly "radon daughters"), radioactive particles that can attach to dust and be inhaled. Radon can cause lung cancer in exposed individuals (Al-Zoughool 2009, Darby et al. 2005, Field et al. 2000), and it occurs naturally in certain areas of the Monument where many of the best specimens have been sourced. This is an issue since it off gasses from the rocks and fossils themselves and cannot be removed, only mitigated (Otton 1992). The EPA's Standard 29 C.F.R. 1910.1096, "Ionizing Radiation" recommends indoor radon mitigation for any levels above 4 picocuries per liter of air (pCi/L) (A Consumer's Guide to Radon Reduction 2013, 2, Radiation Protection 2024). The EPA is the government's designated source for setting environmental standards to protect human health and the environment from radioactive materials and is often the #1 source for agency policymaking.

In the spring of 2021, Hagerman's fossil collection was moved into a purpose-built storage facility. This paleontology building was intended to house radioactive fossils and had a custom vacuum port system installed for radon mitigation on a cabinet-by-cabinet basis (Image 1). The vacuum system was designed using recommendations from the 2006 Conserve-O-Gram (McDonald) but was never extensively tested in the new building. Monitoring revealed that passive radon was leaking from closed cabinets into the fossil collection room and throughout the rest of the building, including the research office where staff operated, reaching up to 6.3 pCi/L. Inside cabinets with the highest radon concentration, the meters maxed out their reading capabilities at 500+ pCi/L, which is more than 100x the EPA's safe limit.

After discovering such unsafe levels in the new storage facility despite the vacuum ports, measures were taken to: 1) identify baseline averages inside and outside of the cabinets, 2) improve mitigation strategies for



Image 1: Former vacuum port system with top port open to prevent pressure buildup.

the building and cabinets. Once those two tasks were complete, new safety protocols for staff and visitors were developed.

This study follows the risk management process for hazardous museum collections, as outlined by the federal Occupational Safety and Health Administration (OSHA) (Bomar 2008) and the National Park Service (NPS) Museum Handbook: “recognize and identify the hazards, evaluate the hazards, and reduce or eliminate the hazards to the extent possible” (Johnson et al. 2001, 2).

III. LITERATURE REVIEW

Radon at HAFO has been investigated at many points in the park’s history. An official report was conducted by the National Institute for Occupational Safety & Health in 1998 (Jiggins et al.) and Air Chek, Inc. in 2005 (though no documentation for Air Chek could be found). Staff continued to monitor radon exposure at the monument and in the collections from 2005-2015 (Williams et al. 2005, HAFO 2015). A summary of radon safety recommendations from the Idaho National Lab, Sandia Labs, United States Geological Survey (USGS), EPA, the Nuclear Energy Commission, and others was compiled prior to the construction of the current fossil storage building; the Smithsonian Institution and Washington Support Office were also consulted (HAFO 2017a-b). During this time, it was acknowledged that there was a distinct lack of radon safety standards for fossil collection buildings overall (HAFO 2017b, 1).

A peer-reviewed study from 2008 provided a thorough evaluation of radioactivity at the Hagerman Fossil Beds and fossils within the collection, and mapped fossil sites by radioactivity, with elevated concentrations most often found between 900 and 1000 meters in sand-filled river channels (such as the Horse Quarry, the most famous site) (Farmer et al. 2008). Most importantly for collection management, it was noted that “buildup of hazardous concentrations of Rn-222 and daughters in storerooms or other enclosed areas containing radioactive fossils [was] likely” (Farmer et al. 2008, 1359).

The National Park Service has recommendations in place relating to radioactive minerals and fossils; two NPS Conserve-O-Grams detail the unique safety concerns of fossils and suggest mitigation solutions (McDonald 1993 and Chure 2006). The 2006 leaflet is the first to recommend and describe a vacuum hose system for clearing fossil storage cabinets of radon gas. Methods for keeping other radioactive items, such as uranium glass (Lopes et al. 2008) and non-fossil geological specimens (Freedman 2011, Price et al. 2013), have been described in detail and are useful for formulating storage plans for hazardous items.

Other environmental conditions besides storage space and air ventilation can affect radon levels inside a closed building. Akbari et al. (2013) suggested keeping the humidity range at 50-55% RH and the temperature range at 68-71°F to achieve minimum indoor radon levels in their case study. In combination with NPS museum guidelines, this could serve as a template for how to manage a high-risk paleontology storage building.

It should be noted that there is some ongoing debate about the actual health effects and danger of low dose radon and radon daughters (Zarnke et al. 2019, Scott 2011). In the collection environment described in this paper, however, Rn-222 levels are not considered “low dose”. It is also not the purpose of this paper to prove the danger of radon or radon daughters, but to present data from one collection and apply safety parameters according to current national standards.

IV. METHODS

Several experiments were conducted to answer two main questions and to develop improved safety protocols:

1. What are the baseline radon averages for a) the building and b) inside the cabinets?
2. What are the most effective mitigation strategies for a) the building and b) individual cabinets?

Data was collected from August to December of 2022 using two types of radon meters: EcoSense RadonEye, which took floor-level measurements of each room in the building; and Airthings View Plus,

which took automatic and wifi-accessible measurements from directly within fossil cabinets. These meters were faster, safer, and more accurate than previous methods, taking readings every 10 minutes (RadonEye) to 1 hour (Airthings) vs older models that took one reading every 24 hours.

Floor-level measurements were recorded by hand 3-4 times a day, and cabinet data was accessed remotely via the Airthings Wave application for iPad. Remote data access meant that there was zero exposure risk for the data collector, and the app provided detailed charts of hourly and monthly averages and trends. It did, however, require Wi-Fi capabilities to be installed in the building.

Experiment #1: Baseline Averages

To calculate baseline levels, radon averages were calculated for each room in the building and several fossil cabinets over the course of several months. In addition, concentrations of radon at varying heights within the fossil collection room were measured to determine the average height of elevated radon.

Part 1 – Building: Radon levels were checked manually at regular intervals 2-4 times/day in each room of the building from August to December 2022. Measurements were taken at the same time each day using EcoSense RadonEye devices placed at floor-level. RadonEye measures radon every 10 minutes with reliable results within 60 minutes. It has a measurement range of 0.2 to 99.9 pCi/ℓ and utilizes a pulsed ion chamber for radon sensing.

Part 2 – Cabinets: Battery-operated Airthings View Plus radon meters were placed at the bottom of 10 cabinets. View Plus took automatic measurements to calculate monthly averages, highs, and lows. View Plus is battery-operated and measures radon every 60 minutes, with a 7-day calibration period and highest accuracy at 30+ days. It has a measurement range of 0 to 500 pCi/ℓ, utilizes a passive diffusion chamber for sampling, and detects via alpha spectrometry. We decided to use rechargeable batteries since high radon levels resulted in a shorter battery life.

Part 3 – Height: Radon is heavier than air, and therefore should lay in higher concentrations at ground level. Two EcoSense radon meters were used to identify the gas's height range. One meter was left at ground level for control. A second meter was raised to several heights using a ladder over the course of 3 to 4 hours (23.01 cm, 46.51 cm, 69.69 cm, and 92.71 cm).

Experiment #2: Mitigation Strategies

To determine the most effective mitigation strategies, radon averages were collected for several ventilation methods over the course of several months.

Part 1 – Building: To improve working conditions for staff and visitors in the building, two ventilation strategies were compared to baseline (aka zero mitigation) in each room: a) partial air movement via room-to-room and room-to-outside airflow, and b) total air replacement via running the HVAC fan system 24/7.

Part 2 – Cabinets: To improve user safety when opening fossil cabinets, two ventilation methods were tested. The original Conserve-O-Gram recommended running the vacuum port system for 2 minutes before opening the door, using a button-operated hose attachment between each cabinet and the wall (add diagram, cross-sectional door/ports). The second method involved running the HVAC fan 24/7 with a cabinet door open until its Airthings View Plus meter registered below 4 pCi/L. Average Rate of Loss (ARL) post-ventilation was calculated for 10 fossil cabinets with different starting radon levels to determine how long it would take them to vent.

V. RESULTS

Safer protocols were developed that reduced long-term radon building averages by up to 63% (dropping the highest room, Collection, from 4.02 to 1.51 pCi/L) and ventilated cabinets to safe levels with 48% more efficiency than the port system--removing up to 98% of radon gas within 24-26 hours.

Results #1: Baseline Averages

Baseline radon levels for the Hagerman Fossil Beds Paleo Building and fossil collection cabinets indicated unsafe ranges for the paleo office, collection, and prep lab rooms, and most of the fossil cabinets.

Part 1 – Building: Radon was highest for the Collection Room (high 6.38 / average 4.02 pCi/L) and the Research Office (high 5.62 / average 3.88 pCi/L), and lowest in the Accessions (high 2.59 / average 1.87 pCi/L)—likely due to better natural ventilation and the fact that the fossils were enclosed in plaster jackets.

Part 2 – Cabinets: Reorganizing the fossil collection and cabinets by taxonomy helped to separate the more radioactive fossils (such as the horses) from the less harmful ones (such as rodent teeth in glass vials). Cabinet averages ranged from over 1000.0* to 0.4 pCi/L post reorganization, with the highest levels sourcing from horse fossils and those from the Horse Quarry site. *One horse cabinet measured at 1013 pCi/L pre- reorganization. The measurement was not retaken post-reorg. due to safety concerns, as the meter’s mobile (and remotely accessible) app capped at 500.

Part 3 – Height: The radon height experiment proved that the gas lies thickest at ground level. Averages confirmed a small but distinct pattern of decreasing radon with increasing height (see Appendix).

Results #2: Mitigation Strategies

Part 1 – Building: The most effective strategy for mitigating the building was continuous air replacement with the HVAC system’s fan. This vastly reduced ambient radon levels in the building to safe working conditions (>2 pCi/L), and reduced Baseline averages by 40-63%. Figure 1 shows the difference between zero mitigation (A), partial air movement (B), and total air replacement (C) for the Research Office in the building. Levels are erratic and frequently too high with partial ventilation, and well above the danger line with zero ventilation. Note how levels never exceed the red danger line once with the HVAC fan goes into operation.

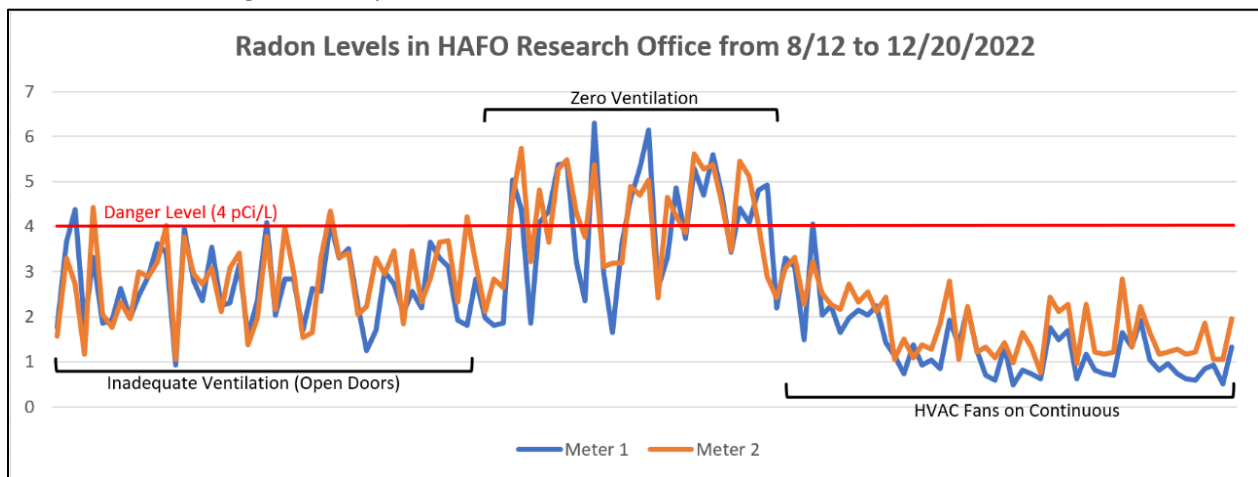


Figure 1: Radon levels in the Research Office in the three different mitigation stages: Partial Air Replacement, Zero Air Replacement (aka Baseline), and Total Air Replacement with HVAC fan.

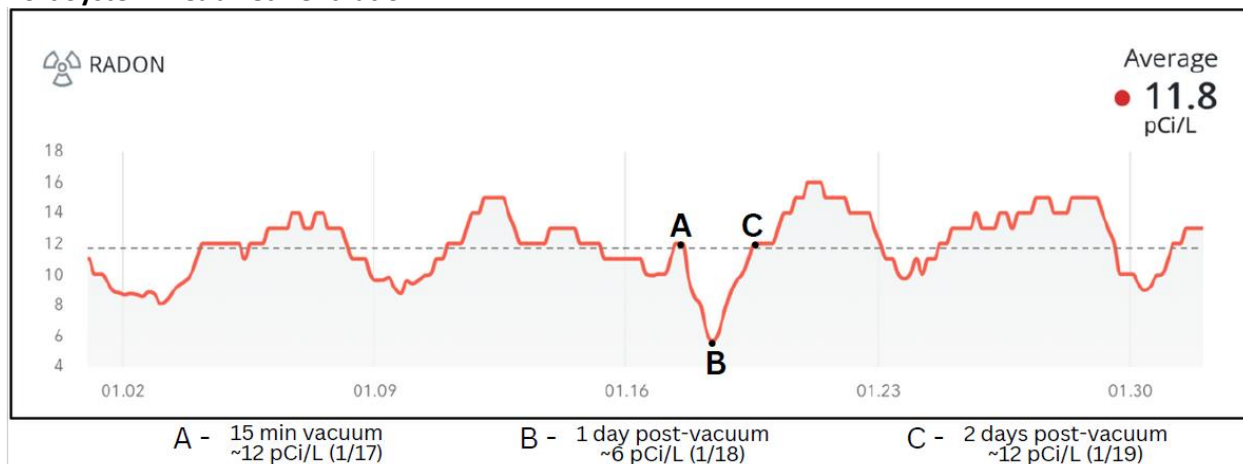
Part 2 – Cabinets: The most effective strategy for mitigating a fossil cabinet was the same as mitigating the building: continuous air replacement. While this wasn’t a new strategy, consistent data now proved the exact time at which each individual cabinet would be rendered safe. One cabinet door

was opened, and the room vacated with the HVAC fan on continuous. Data was collected remotely via the Airthings Wave application to see how long it took to drop to safe levels (below 4 pCi/L). It took an average of 24 hours to do so. Cabinets with higher levels of starting radon had a consistently higher average rate of loss, meaning they lost gas faster, possibly due to the heaviness of radon gas. For example: a starting amount of 1013 pCi/L lost radon gas at a rate of 34.76 pCi/L per hour, and a starting amount of 12 pCi/L lost radon gas at a rate of 0.37 pCi/L per hour.

Reorganizing the fossil collection and cabinets by taxonomy increased the overall number of cabinets with safe levels by 28%. All cabinets were labeled with a warning to indicate a long-term (30 days or more) average above 4 pCi/L, with a required vent time of 26 hours posted for those cabinets.

The vacuum port system, previously installed to reduce cabinet radon prior to access, had little to no change after the recommended 2 minutes. An increase to 15 minutes resulted in a 41-50% drop of radon levels after 24 hours, just enough to make a cabinet of 6 pCi/L safe, but nothing higher. Figure 2 shows the results for two cabinets before and after vacuum use. Point B shows the maximum drop in radon post vacuum, while C shows how quickly it bounced back afterwards. This confirmed that the vacuum port system was not adequate for this particular collection's needs.

Port System – Cabinet Ventilation #1



Port System – Cabinet Ventilation #2

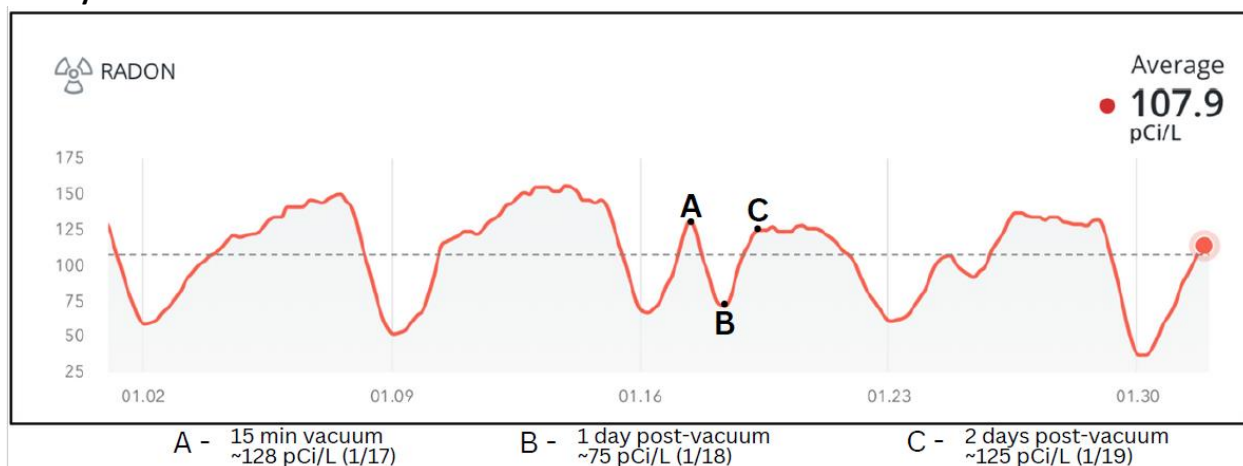


Figure 2: Results for two cabinets with low and high averages: using the port system to ventilate cabinets for 15 minutes. A = starting level, B = 24 hours after port use, C = 48 hours after port use (100% bounce back).

Improved Safety Protocols

New standard operating procedures developed from this data now require: 1) 1x/week environment readings (radon, temperature, and humidity with defined ideal ranges) for each room of the building, 2) timed venting of fossil cabinets by opening the door prior to access, 3) using personal protective equipment when handling fossils, and 4) cleaning hands and workspace after handling. The length of time for venting was dictated by the long-term average radon levels for each individual fossil cabinet. Each cabinet was labeled with its danger level and required venting time. Examples of these new safety protocols can be found in the Appendix (A-C).

A New Ventilation System

On January 6, 2023, a request was submitted for the design and installation of an Energy Recovery Ventilation (ERV) system for the building. An ERV system is “a type of mechanical equipment that features a heat exchanger combined with a ventilation system for providing controlled ventilation into a building” (Purushothama 2009). Separate ventilation systems can greatly reduce energy consumption while improving indoor air quality (Amanowicz *et al.* 2023, 1-2). A similar system is also employed at the Arizona Museum of Natural History for this same purpose (personal communication with Collections Manager Gavin McCullough in 2022). This will be a new system separate from the existing HVAC system that manages the building’s climate control. It will bring the building up to required safety codes and allow for safe access to the fossil collections for research, handling, and maintenance.

VI. CONCLUSION

Managing radon in a collection environment has unique challenges. Radon is most often mitigated in homes and cellars due to local geology, but the concept of replacing the air to remove the radon gas is the same. Other challenges, such as radioactive dust from crumbling fossils, are mitigated with personal protective equipment and a clean workspace. Although the radon dangers at Hagerman were well-known, the new fossil collection storage facility had not been sufficiently tested to know the true dangers.

Without a universal standard or strategy in place for mitigating radon in a museum fossil storage setting, a series of experiments were used to identify the best equipment, baseline averages, and the most effective strategy for mitigation. Long term data for the building and storage cabinets has resulted in new safety and monitoring standards for the Hagerman collection. Continuous air replacement with the HVAC fan has dropped indoor radon to <2 pCi/L. Humidity is now kept between 50-55% RH, and temperature at 69-71°F. Other factors that have contributed to a safer work environment include weekly environment monitoring, timed cabinet venting with open doors prior to access, PPE and clean workspaces, safety labeling on the cabinets and within the paleontology building and sorting the cabinets by taxonomic family. The plan for an ERV is in development stages and will be designed to accommodate Hagerman’s specific needs. It is our hope that a well-designed system will shorten the time needed for cabinets to vent and extend the life and lower the maintenance costs for the HVAC system.

This study may serve as an example for how others may approach their fossil collection environments and serve as an anecdotal reminder that taking quantitative data whenever a fossil’s storage situation changes could be an essential part of continued collection maintenance and safety.

VII. BIBLIOGRAPHY

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APPENDIX

- A. Sample: New Standard Operating Procedures
- B. Sample: Environmental Monitoring Data Sheet
- C. Sample: Job Hazard Analysis for Radon Safety
- D. Data

A. SAMPLE: NEW STANDARD OPERATING PROCEDURES

RADON SAFETY

Standard Operating Procedure for the Southern Idaho Museum Collections

- I. PURPOSE: The purpose of Radon Safety Protocols for the Soid Museum Collections is to provide rules and guidelines for the safe handling, research, and storage of radon-bearing fossils from the Hagerman Fossil Beds National Monument. It facilitates safe access for staff and visitors alike.
- II. REQUIRED PERSONNEL: Museum staff (curator, technicians, interns) are responsible for:
 - Weekly environmental monitoring (including radon, temperature, and humidity) of the Paleo Building. → A sample data sheet can be found at: [department share drive]
 - Keeping the Paleo Building clean and dust-free with monthly vacuuming and wiping down surfaces as needed.
 - Educating visitors on safe handling procedures.
 - Venting cabinets prior to use.
- III. PROCEDURES: Follow these protocols when interacting with the fossil collection at HAFO.
 1. **Utilizing the Paleo Building:** Check floor radon meters when first entering each room. If the meter reads at or above 4.0 pCi/L: 1) alert Museum Staff, your supervisor, or the Cultural Resources Manager, and 2) vacate the building. A high level indicates that the building's built-in radon mitigation is not operating correctly and may need to be repaired.
 2. **Cleaning the Paleo Building:** All tables or working surfaces that have had fossils placed on them should be wiped down with a damp paper towel (water only) after each use. Vacuums used in fossil collection spaces should be outfitted with HEPA filters and emptied while wearing a particulate N95 mask. Radon-bearing trash should be taken directly to the outside dumpster.
 3. **Accessing Fossils from Cabinets:** Each fossil cabinet is labeled with a radon warning sign, its average radon level, and required venting time. Museum staff will open the cabinet door to vent (wear a particulate N95 mask), and all personnel should exit the collection room for the required amount of time.
 4. **Basic Handling of Fossils:** Wear a particulate N95 mask and lab coat, and wash hands afterwards.
 5. **Hand Prepping Fossils:** Wear a particulate N95 mask and eye protection, use robot arm ventilation, and wash hands afterwards.
 6. **Air-Scribe Prepping Fossils:** Wear a HEPA-filter mask and eye protection, use robot arm ventilation, and wash hands afterwards.
- IV. SPECIAL CONCERNS: Radon is a heavy gas that causes lung cancer in exposed individuals. It occurs naturally in certain areas of the monument where many of HAFO's best specimens have been sourced, such as the Horse Quarry. Since it off gasses from the rocks and fossils themselves, it cannot be removed, only mitigated through continuous ventilation and air replacement. EPA standards recommend radon mitigation for any levels above 4 picocuries per liter (pCi/L). **Radon-bearing dust particles that can be inhaled are especially dangerous.**
- V. ADDITIONAL INFORMATION: The dangers of radon and past radon monitoring conducted at HAFO.
 - [TBD – IRMA link]

Last Updated Feb. 28, 2023

**MUSEUM ENVIRONMENT
DATA SHEET**

Year: _____

Technician: _____

B. SAMPLE: ENVIRONMENTAL MONITORING DATA SHEET

		Modern Collection		Fossil Collection		Paleo Office		Accessions		Prep Lab		Notes
Month	Date	RH%	°F LUX	RH%	°F pCi/L	°F pCi/L	°F pCi/L	°F pCi/L	°F pCi/L			
January	1											
	2											
	3											
	4											
February	1											
	2											
	3											
	4											
March	1											
	2											
	3											
	4											
April	1											
	2											
	3											
	4											
May	1											
	2											
	3											
	4											
June	1											
	2											
	3											
	4											

Ideal Conditions: Modern Collection Bldg. = RH% = 45-55 °F = 59-77 LUX = 50-150 Paleo Building = RH% = 50-55 °F = 68-71 pCi/L = <4		Key: FC = Fossil Collection Room ACC = Accessions Room MCB = Modern Collection Building PL = Prep Lab	
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Environmental measurements are taken on the 1st day of each week.

C. SAMPLE: JOB HAZARD ANALYSIS

JOB HAZARD ANALYSIS – FORM				
JOB HAZARD ANALYSIS (JHA)				Date of Last Update:
Job Title/Description: Paleontology Collection Access (Radon Safety)				Activity Location: Paleo Building
Park Unit:	Division:	Last Updated By:	Reviewed By:	Approved By:
Required Standards and General Notes:		Radon and radon daughters are present and are hazards to respiratory system. OSHA stipulates that levels above 4.0 pCi/L are unsafe. See: https://www.epa.gov/radon/health-risk-radon		
Required Personal Protective Equipment:		Particulate N95 mask, disposable Nitrile gloves, lab coat.		
Tools and Equipment:		Disposable paper towels, HEPA-filter vacuum.		
Activity		Potential Hazards	Safe Action or Procedure	
1	Check building radon levels.	E – Radon gas inhalation.	Before access, check the paleo office and collection room meters. If 4.0 pCi/L or above, the ventilation system is malfunctioning. Exit building and notify management. If below 4.0 pCi/L, proceed to step 2.	
2	Collect PPE & equipment.	None.	Collect nitrile gloves and N95 mask from bankers' box storage shelves in paleo office, and lab coat from prep lab cabinet. HEPA filter vacuum is in the collection room by herbarium cabinets.	
3	Check desired cabinet level.	CW – Radioactive particulate inhalation and contact with clothes.	Each cabinet is labeled with triangular radon warnings. If yellow with red text: open cabinet and vacate room for 24 hrs --> repeat step 2 and proceed to step 4. If gray with gray text --> proceed to step 4 directly.	
4	Move fossils to and from work surface.	CB – Large fossils can fall and crush a person's hand or foot if dropped. CW – Radioactive particulate inhalation and contact with clothes.	Carefully remove desired fossils one at a time with both hands to a worktable. Use a designated wheeled cart with a second person for large and heavy objects. Avoid any activity that causes particulate dust to spread.	
5	Clean work surface.	CW – Radioactive particulate inhalation and contact with clothes.	Wipe down all working surfaces with a damp paper towel after each use. Vacuum (with a HEPA filter) as needed, wear N95 mask when emptying. Radon-bearing trash should be disposed of directly to outside dumpster. Lab coat folded inside out in prep lab.	

Injury Source for the middle column: SB= Struck-By, SA = Struck-Against, CBY = Contacted-By, CI = Caught-In, CB = Caught-Between, CO = Caught On, FB = Fall-to-Below, CW = Contacted-With, O = Overexertion or Repetitive Motion, FS = Fall-to-Surface, BR = Bodily reaction, E = Exposure to Chemical, Noise, etc.

I ACKNOWLEDGE THAT I HAVE READ (AND UNDERSTAND) THE ABOVE HAZARD ANALYSES AND SAFE ACTIONS.

Division Supervisor Signature: _____	Date: _____
Employee Signature: _____	Date: _____
Employee Signature: _____	Date: _____
Employee Signature: _____	Date: _____
Employee Signature: _____	Date: _____
Employee Signature: _____	Date: _____

D. DATA FROM HAFO'S FOSSIL COLLECTION

(see attached Excel document)