Sustainable Radon Mitigation through Optimized HVAC Scheduling

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ABSTRACT

Radon is a naturally occurring radioactive gas and is the second leading cause of lung cancer after smoking tobacco. Its invisible and odorless nature often leads to it going undetected, posing a significant health threat in susceptible areas, especially schools. Although traditional mitigation strategies are reasonable for smaller private properties, their cost can become prohibitively expensive and difficult for older and larger buildings. We propose, build, and test a cost-effective, sustainable mitigation strategy that uses the existing HVAC infrastructure of susceptible buildings to remove radon before occupancy hours. We compare this to a naive approach and find that we can save time on HVAC operation and keep radon levels to an acceptable low.

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1 INTRODUCTION

Radon is a toxic gas [7, 10] and is the second leading cause of lung cancer in the United States [4, 18]. The World Health Organization (WHO) estimates that 3% to 14% of all lung cancer cases in the world are due to increased exposure to radon [1] killing more than 21,000 people every year [9]. This dangerous gas is the byproduct of minerals in soil that decay over time and then seeps into buildings through cracks in the foundation or basement. It is odorless and colorless, making it impossible to detect without special instrumentation. This causes buildings to accumulate critical gas levels without being noticed, posing a significant health hazard to their occupants.

Radon levels are measured in picoCuries per liter (pCi/L) by detecting radiation in air samples. Detection methods vary in duration, with passive approaches relying on materials affected by ambient radon. These tests, ranging from days (activated charcoal) to months (alpha tracking [12]), are cost-effective for assessing average exposure, but do not capture accumulation rates or temporal variations. This limitation can hinder mitigation efforts, making buildings susceptible to environmental, seasonal, or structural influences [2, 6, 11].

Continuous radon monitors (CRMs) address these gaps by providing real-time data, using scintillation, ionization chambers, or solid-state detection. Available as both low-cost consumer devices and certified professional tools, CRMs produce measurements as frequently as every hour after an initial burn-in period. These advancements enable building owners to detect hazardous levels promptly and monitor radon ingress trends more effectively.

Elevated radon levels in homes can be mitigated using active or passive methods. Active techniques, such as active sump, underfloor ventilation, membrane and short-circuit ventilation, and subslab depressurization, collect and expel radon through dedicated piping. Passive approaches involve sealing entry points, such as cracks or porous concrete, to reduce airflow. Although effective in homes, these solutions can be prohibitively expensive for larger buildings with complex designs and/or limited budgets. Furthermore, their lack

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of feedback mechanisms allows radon levels to gradually return to unsafe levels over time [16].

One such example of a potentially ignored and financially limited building is schools. The people in schools who are at greatest risk of being exposed to prolonged periods of harmful levels of radon are faculty and staff [8]. Faculty who work in a building affected by radon could spend decades working in a harmful environment. Many of these employees may be unaware of their dangerous conditions because schools do not have enough funding to test for radon. **To protect these teachers by reducing their exposure to radon, a low-cost and easy-to-implement system is essential to analyze and mitigate radon levels found in those areas.**

Our novel solution is to use the school's HVAC system to recycle radon-tainted indoor air with fresh outdoor air. HVAC systems have many responsibilities, among them improving indoor air quality by managing CO_2 levels through introducing fresh outdoor air through zoned ventilation. We exploit this targeted air exchange to dilute and remove radon, providing a more precise and effective mitigation solution. This method is instantly deployable and avoids adding additional modifications to the building, saving money and forming the basis for a good solution. A good system will be sustainable and ensure that it operates only long enough to maintain radon levels below a recommended action level such as 4 pCi/L per the Environmental Protection Agency (EPA) [19] or 2.8 pCi/L per the WHO [13]. It will also account for varying levels of access to HVAC controls (e.g., through an on-site operator who controls the HVAC schedule or an API). Furthermore, it should respond to the real-time information provided by the CRMs while taking into account the varied concentrations of radon throughout the school [3, 17]. To meet those goals, we propose a framework that **(1)** characterizes radon accumulation patterns within specific zones of the school using CRMs, **(2)** analyzes which times of day have the highest exposure to radon, **(3)** develops a schedule based on a specific radon concentration target that will lower the radon quantity to acceptable levels before staff arrive at school and maintain those levels for the rest of the building's occupied time, and **(4)** incurs as little extra cost through the additional HVAC operation as possible.

2 METHODOLOGY

2.1 Experiment Setup

To characterize the radon accumulation patterns within the target building, we deployed a fleet of SunRADON 1028XP CRMs in HVAC zones of high and low radon concentration of an elementary school. The floor plan is shown in Figure 1. To avoid inaccurate readings, we ensured that the CRMs were calibrated by the manufacturer and underwent the required burn-in process. There are three different zones that have different radon accumulation behaviors, as noted in a previous study [8]. Zones 1, 2, and 3 are all within HVAC zones where faculty spend most of their work day. Zones 1 and 2 exhibited higher concentrations of radon in the past, while Zone 3 was chosen as a control for a room as it exhibited lower levels of radon.

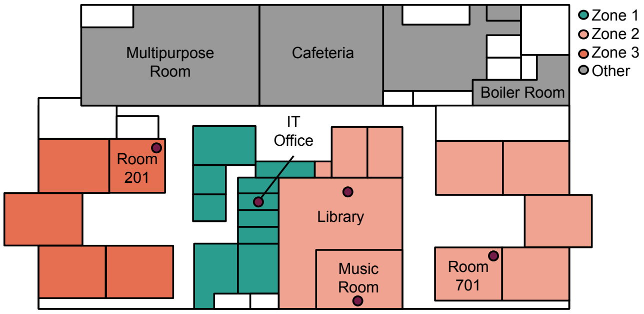

Figure 1: HVAC zones in subject elementary school.

We monitor radon levels from 12 January 2024 to 20 December 2024, since temperature levels appear to affect radon accumulation [5, 14, 15, 20] and we want to understand how well our system works in all seasons. We measure radon throughout winter, spring, and fall. We observe a second winter schedule due to the increase in radon accumulation in buildings as the weather gets colder. We distinguish the two winters: W↓ is the is the transition from winter to spring (colder to warmer season), whereas W↑ is the transition from fall to winter (warmer to colder season). We omit the summer season in our study because the school is not occupied regularly.

For each season we track, we divide it into three different measurement periods of two weeks. Each season first has a *control period*, followed by an *extended period*, and then an *optimized period*. The control period has no modifications made to the HVAC start/end times, providing an idea of what the HVAC behavior would be like without intervention. The extended period represents the naive approach of putting the HVAC system in occupied mode an hour earlier and transitioning to unoccupied mode an hour later. Although it will definitely have a positive impact on reducing radon, it comes at the expense of running the HVAC for potentially longer than necessary. Finally, the optimized period is where we determine the latest necessary HVAC start time that will allow it to reach acceptable radon levels before the occupied start time and then transition the HVAC into unoccupied mode at the building's occupied end time. This approach provides the best of both worlds: we reduce the radon levels, but avoid the extra cost of the extended approach.

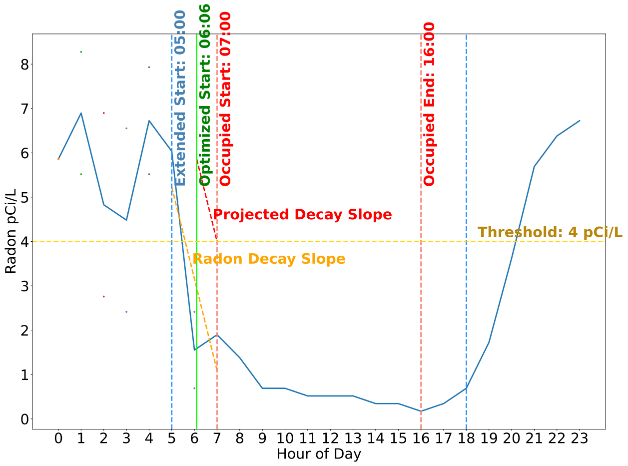

Figure 2: Process of determining rate of radon decay in specific environment to derive new HVAC start time.

2.2 Optimized Schedule Derivation

The ultimate goal of our framework is to ensure that no one is exposed to high levels of radon through an optimized HVAC schedule for each season. To derive this schedule, we develop an algorithm that takes into account several predetermined ambient factors that are unique to each school in order to make the best optimized schedule for it.

- **Occupied start/end time**: the time at which the building becomes occupied by faculty and students. For our framework, the occupied start time is set as the target time by which we want the radon to be within an acceptable threshold.
- **HVAC start/end time**: the time at which the HVAC system of the building enters its normal building operation mode.
- **Control radon decay slope**: this is the rate at which radon cycled out of the monitored room by the HVAC without any modification of its original schedule.
- **Projected radon decay slope**: this is the same as the control radon decay slope. However, it will be shifted earlier/later to ensure that radon levels are below the established threshold.
- **Radiation threshold**: the target level of radon that we want at the beginning of the occupied start time according to local regulations (i.e. <4.0 pCi/L per the EPA and <2.7 pCi/L per the WHO).

The radon characterization process is run independently for each season. The measurements of the control period for the season are used as a reference to create the optimized start and end times. The hours for each day of the week are averaged with each other in order to maintain their temporal relationships (i.e., radon decay from the weekend vs. radon decay between weekdays). These values are cropped between the HVAC start and when the radon level reaches the desired threshold. The slope of the line required to reach the radiation threshold is then used to determine the new start time in the optimized period by shifting the y-intercept until that line reaches the required threshold at the building's occupied start time. This process is illustrated in Figure 2. The blue line represents the average randon levels for the control period for a given day of the week. At 05:00, the HVAC system is turned on, as shown by the blue dotted line. The orange dotted line represents the radon decay slope. The radon value is well below the threshold before anyone has occupied the building. Given the slope of the line, we can shift the start time (green line) while still reaching our threshold before the occupied start time. This allows us to turn on the HVAC system later, saving energy and cost while still providing the same health benefits. The translated radon decay slope, also called the projected radon decay slope, is shown as a red dashed line.

For the control period of our tests, the HVAC start time is 06:00 and the HVAC end time is 17:00. The extended period's HVAC start time is 05:00 and the HVAC end time is 18:00. Once the optimized schedule is derived, we use the HVAC start time of the algorithm and set the HVAC end time to the building's occupied end time. The building's occupied start time is 07:00 and its end time is 16:00. Finally, the radiation threshold we seek to meet is 4 pCi/L.

We initially planned to automate our framework and remotely control the HVAC system. Because this is a real-world study, our system was not permitted to be automated at the request of our subject's school administrators. Instead of calculating the optimizations in real time and using our algorithm's output to interface with a Supervisory Control and Data Acquisition (SCADA) controller that dictates the building's HVAC schedule (as could be accomplished in a future work), we were required to have a human-in-the-loop for each step of the process. At the end of each period, we collected data from the CRMs, processed it to create an optimized schedule, and requested that the school custodians update the HVAC settings accordingly. Although the school administration was reluctant to fully integrate our framework into the HVAC flow, the system's design affords seamless automation and adaptability in multiple environments.

3 EVALUATION

3.1 HVAC Start and End Time

3.1.1 Start Time Optimization. We first assess the efficacy of our optimization schedule by seeing how much time it saves compared to the control schedule. In Table 1, we show the optimized HVAC schedule derived as described in Section 2.2.

Table 1: Optimized HVAC Start Time per Zone for All Seasons with Hours Saved Compared to Control Start Time.

DoW	**M**			**T**			**W**			**Th**			**F**		
Zone #	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
W ↓	**05:33**	06:55	07:00	06:23	06:44	07:00	**05:48**	7:00	07:00	**05:38**	07:00	07:00	06:12	07:00	07:00
Sp	**05:15**	**04:40**	07:00	07:00	07:00	07:00	06:49	06:49	07:00	07:00	07:00	07:00	**05:12**	07:00	07:00
F	07:00	07:00	07:00	07:00	07:00	07:00	07:00	07:00	07:00	07:00	07:00	07:00	07:00	07:00	07:00
W ↑	07:00	**05:08**	07:00	07:00	07:00	07:00	07:00	07:00	07:00	07:00	07:00	07:00	07:00	07:00	07:00
Saved	0:42	**-0:17**	4:00	3:23	3:44	4:00	2:37	3:11	4:00	2:38	4:00	4:00	1:24	4:00	4:00

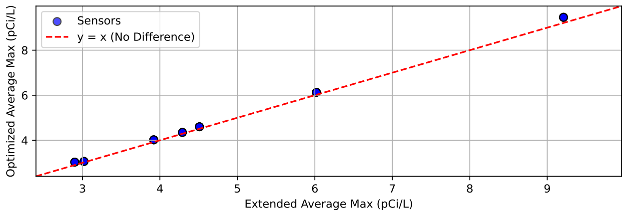

Figure 3: Average saturation comparison between Extended and Optimized schedules shows that little difference is leaving HVAC off for one more hour.

We take into account the four seasons we tested against and when the HVAC for each zone should be started according to each day of the week. At the bottom of this table is a row that shows the amount of time saved compared to the control schedule. All times that are earlier than the control start time are bolded (i.e., where we have lost efficiency) and added more runtime for the HVAC while still ensuring lower radon levels. For all days of the week in all seasons, almost every optimized schedule saves the school about an hour or more of HVAC runtime compared to the control schedule. This proves that our optimized HVAC schedule is more sustainable than even the control behavior let alone a naive approach such as the extended schedule. The only exception we see takes place on Mondays. This is because radon accumulates more during the weekend when the HVAC is in unoccupied mode, whereas it does not accumulate as much between school days.

3.1.2 End Time Optimization. In the control schedule, the HVAC is in occupied mode until one hour after the building's occupied end time (17:00), whereas the extended schedule goes for one hour longer (18:00). In the optimized schedule, we set the HVAC end time to match building's occupied end time (16:00). We do this to see if the more time a room has to accumulate radon, the harder the system will have to work to clean the room from radon the next day, starting the HVAC schedule earlier. In order to test this "saturation point", we take the maximum point of the overnight period and average it across all the days (excluding the weekend) in both the extended and optimized period. Figure 3 illustrates the similarities for averaged maxima for all CRMs. We note that stopping the HVAC when people leave the building as opposed to an hour later does not have a noticeable impact on the maximum levels that radon will accumulate at in a confined space. This also allows us to save an extra hour of HVAC runtime per zone per day of the week, making our solution even more sustainable.

3.2 Radon Mitigation Health Impact

The purpose of our system is to reduce radon in a sustainable manner. We do this by simply using the HVAC system. In this section, we evaluate its effectiveness by comparing the optimized schedule to the extended and control schedules. Figure 4 shows the average radon level during occupied hours throughout all seasons and zones. It also shows the average of the maximum values that radon levels climb to when the HVAC is in its unoccupied mode, representing what the accumulation patterns would be like in the building if there were no HVAC mitigation. These (different bars) show how effective the system is in mitigating radon, lowering the radon levels below the actionable EPA threshold. We note that the trend of radon accumulation increases as the temperature decreases as discussed by [2, 6, 11]. The radon levels are all within small margins of each other across schedules and seasons. Due to our small data set (two weeks per schedule per season), it is difficult to confidently compare the performance of the schedules with each other; however, we do see in Table 1 that the optimized schedule saves the most time and is the most sustainable and health-conscious solution.

4 CONCLUSION

In this work, we created a framework that allows larger buildings, such as schools, to effectively mitigate the accumulation of radon in specific areas. Our solution provides a custom-targeted approach that creates a new HVAC schedule by characterizing radon accumulation patterns in all occupancy

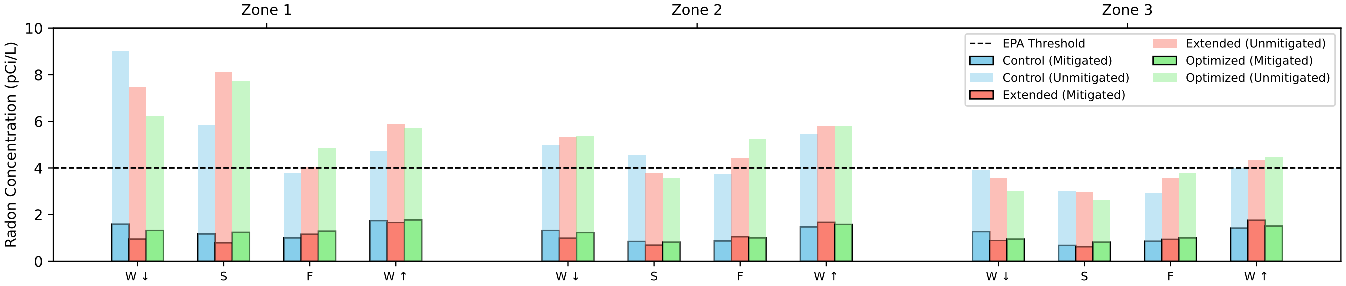

Figure 4: Average radon concentration per HVAC zone for all seasons (pCi/L).

seasons for a control period. Instead of blindly leaving the HVAC on for hours, our solution saves time and energy by finding the optimal time to start the HVAC system to bring the radon levels below the appropriate threshold. Although we lacked direct HVAC control in this study, our methodology enables full automation to minimize the radon exposure of the staff and faculty and subsequent risk of lung cancer. Future work may further analyze the statistical significance of our findings.

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