Radon Assessment of Base Housing and Other Selected Structures at A U.S. Air Force Base

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ABSTRACT

The objectives of the Air Force Radon Assessment and Mitigation Program (RAMP) are to (1) identify all Air Force structures that have radon levels above the USEPA action level of 4 $pCiL^{-1}$, and (2) perform remedial work in those structures with elevated radon levels.

To meet the goals of RAMP, selected bases were required to conduct radon measurements in all base structures for one year. This paper describes the field sampling procedures and sampling results for one U.S. Air Force Base.

The deployment and retrieval of radon detectors was conducted over 6-week periods one year apart. In addition to the deployment and retrieval of detectors, the field effort involved (1) recruiting and training a field team, (2) conducting a pretest, (3) developing a public information campaign, and (4) verifying the integrity of the deployed detectors.

Of the 2,658 deployed detectors, eight-five percent were deployed in residential units. Measured radon concentrations ranged from a low near zero to a high of 17.6 $pCiL^{-1}$. Approximately 16 percent of the measurement results exceeded the USEPA action level.

This paper has not been reviewed by the U.S. Air Force. Therefore, the contents do not necessarily reflect the views and policies of the U.S. Air Force, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

BACKGROUND AND OBJECTIVES

BACKGROUND

The U. S. Air Force (USAF) is concerned about the increased risk of developing lung cancer faced by persons exposed to elevated levels of radon in their living quarters and in their places of work. To assess the extent of the radon problem in Air Force structures worldwide and to mitigate those structures found to have elevated radon levels, the USAF has implemented the Air Force Radon Assessment and Mitigation Program (RAMP).

The objectives of RAMP are (1) to identify all Air Force structures that have radon levels above the USEPA's recommended action level of 4 picocuries per liter (pCiL^{-1}), and (2) to perform remedial work in those structures with high radon to reduce the indoor radon levels.

To meet the goals of RAMP, the Air Force is conducting the program in several phases. The first phase, which was completed in August 1988, was the initial screen survey to identify bases where radon may be a problem. For this phase, a limited number of structures, mostly living quarters, were randomly selected on 135 different USAF installations for radon measurements.

The second phase of the measurement program is the detailed assessment survey. In this survey, radon is to be measured in all structures on USAF installations identified in the initial screen survey to have a potential radon problem. The purpose of this phase, currently in progress, is to identify structures that require mitigation to reduce indoor radon levels. Alpha track detectors (ATDs) were chosen by the USAF for use in the implementation of the initial screen phase and the detailed assessment phase of RAMP.

The third phase is the post-mitigation phase. Because a large number of structures may require mitigation, priority will be given to those having the highest radon levels. During this phase, measurements will be made in mitigated structures to verify that radon levels have been reduced below the USEPA action level of 4 pCiL^{-1}.

OBJECTIVES

Although the implementation of the detailed assessment phase of RAMP was largely implemented at the base level, one base chose to use an outside contractor to implement their program. This base was designated as "medium probability" (i.e., at least one structure was at or above the USEPA action level of 4 pCiL^{-1} and no measurements were at or above 20 pCiL^{-1}) during the initial screen phase and was required to sample for radon for one full year in all housing units, dormitories, temporary living quarters, child-care centers, and the medical center.

In order to comply with the requirements of RAMP, the base contracted with GEOMET to perform the tasks required for implementation of the detailed assessment phase. For this project, GEOMET (1) developed a comprehensive survey plan at the start of the project, (2) established a field office and hired and trained field personnel, (3) deployed and retrieved the ATDs, (4) verified the integrity of the deployed detectors, (5) developed a data base to track the progress of the program, and (6) developed software for use at the base to interface with the ORACLE™ system used by the Air Force to manage the full data base for all installations. These activities took place between July 1989 and November 1990.

The activities included in the field effort are described within. The results of the field effort are shown and include a discussion of the outcome of the integrity verification, the field monitoring results, and the quality assurance/quality control (QA/QC) results. The significance of the results is also discussed.

FIELD EFFORT

The field effort involved (1) recruiting and training the field team, (2) conducting a pretest of the survey methods and protocols, (3) developing a public information campaign to inform base personnel of the upcoming radon monitoring, and (4) verifying the integrity of deployed detectors. Each of these field activities is described together with the deployment and retrieval of detectors.

The deployment and retrieval of radon detectors was conducted over 6-week periods beginning at the end of September 1989 and the end of September 1990, respectively. GEOMET was required, during both deployment and retrieval, to make at least three attempts at each structure to deploy and retrieve detectors. To facilitate scheduling in advance of each attempt, the concept of waves was introduced. This meant that unsuccessful attempts were not rescheduled until the whole base had been attempted for the first time, and then a second time. Thus, each deployment/retrieval attempt was called a wave.

In order to maximize the response rate, a letter was sent to each resident informing them of approximate visiting times approximately one week prior to each attempt. By the third wave, a request was made that the occupant call and set up a specific time, if the scheduled times were inconvenient.

ASSEMBLY AND TRAINING OF FIELD TEAM

Field personnel were required for the implementation of the detailed assessment phase at the base during two periods--one for the deployment of detectors and, 1 year later, one for the retrieval of detectors. Because field teams were composed of temporary hires, we needed to be prepared for two hiring cycles. The approach to recruiting and training the field team was identical for both deployment and retrieval.

The field staff were recruited through advertisements in the local newspaper and base newspapers. Bulletins were posted in career services centers in local colleges and universities and the base employment office was notified of the employment opportunities. Personal interviews were conducted at the base.

Following a two-day staff training period, a pretest of the survey methods associated with deployment and retrieval of detectors was conducted. Separate training sessions were conducted for the deployment and retrieval periods. The intent of the pretests were to mimic as closely as possible the actual implementation plan, albeit on a smaller scale, to ensure that all survey procedures were followed consistently and that field staff were adequately trained. Thus, the pretests encompassed elements of the public information campaign as well as deployment or retrieval of detectors and completion of forms.

Each pretest was conducted several days prior to the actual start of deployment or retrieval so that any deficiencies in the design and protocol could be corrected in a timely fashion. Feedback was requested from the occupants of the pretested structures, the deployed detectors were checked for proper placement, and documentation forms were checked for accuracy and completeness. The deployment pretest indicated that no adjustments were necessary to the prepared survey plan.

PUBLIC INFORMATION CAMPAIGN

In order to help ensure the success of the program at the base, a public information campaign was staged. This campaign included an article in the base newspaper concerning radon and the RAMP program. An initial mass-mailing program was directed at individual building occupants and provided further details on the information that was provided in the base newspaper. Subsequent mass-mailing efforts focused on specific areas of the base and indicated the 2-hour time period during which the occupant was to expect a visit from a technician.

In buildings not considered residential units, informational literature was sent to the person in charge of the building. Instead of informing these individuals of technician visits through a separate mass-mailing effort, appointments were scheduled for deployment and retrieval.

DEPLOYMENT OF DETECTORS

Detector deployment took place over a 6-week period beginning the last week of September 1989. The number of detectors to be deployed each day, and the area of the base to be visited were determined by GEOMET staff at the main office. The schedule for each technician was determined by the field supervisor.

For each deployment day, the field supervisor completed a daily assignment log which was given to each technician prior to the day's activities. At the end of the work day, the technician returned with completed forms representing successful attempts; the remainder of the structures were to be revisited. For unsuccessful attempts, the technician left a note for the occupant indicating that the attempt was made and that another visit would be scheduled. The information on these forms was used to track the structures that were revisited during subsequent waves.

The data documented on the forms by the technicians were reviewed for completeness by the field supervisor. Specifically, the field supervisor verified that all data were collected, that the detector was placed in the proper location within the structure, and that the detector number on the form matched the detector number on the empty foil pouch. If forms were deemed incomplete or inaccurate, the technician responsible was required to revisit the structure to correct the problem.

Daily assignment logs were also provided to technicians for other buildings. Because individual appointments were scheduled for these buildings, all detectors were deployed on the first attempt.

Before the technician deployed the radon detector, he or she provided one of the occupants with an informational booklet and gave the occupant a brief explanation of the program. Detectors were placed within residential units according to the protocols set forth by the USEPA.

In child-care centers, the pre-school, dormitories and visiting quarters, one detector was deployed in each room on the ground floor. The medical center received one detector for each nursing station; these stations were centrally located and distributed throughout the structure. This approach was chosen because it was assumed that detectors within patients' rooms would not remain intact over a one-year period.

Within each room in these other types of buildings, the USEPA protocol was also used. Practicality was particularly important; detector deployment in rooms occupied by many people was avoided because of the possibility of disrupting the detector.

After detector deployment, the questions on the survey form were completed. The technician was required to indicate the type of structure being sampled, the number of stories in the structure, the detector location, and the deployment date. Selected questions on the survey form were answered by building occupants.

Because this form was designed with the notion that there would be one survey form for each detector, a supplemental form was required at the base to document the deployment of detectors in buildings scheduled to receive multiple detectors. Routine building information was documented on the RAMP survey form, and information about each detector was recorded on the supplemental form.

VERIFICATION OF DETECTOR INTEGRITY

Approximately six months after the detectors were deployed, an integrity verification check was conducted. Five percent of the residential units and 5 percent of the other buildings were subjected to this check. All of the detectors within a building were checked for any compromises in integrity.

Residential units were randomly selected for these checks from all housing areas, with the chosen number proportional to the size of each housing area. Figure 1 includes a map of the base showing the location of each housing area. Table 1 shows the number of residential units sampled in each housing area and the number of those units targeted for the integrity check. A random, systematic sample was taken in each area to allow generalizations about sampler integrity at the conclusion of the visit. Of the 31 other buildings, three were targeted for the integrity verification check.

Within each structure, it was verified that the detector (1) was still located within the structure, (2) was in its original location, and (3) had not been damaged. Missing detectors, when discovered, were not replaced because this would have resulted in an overall scheduling shift by 6 months.

No advance warning was provided to occupants of the pending integrity check. Although this approach would have facilitated

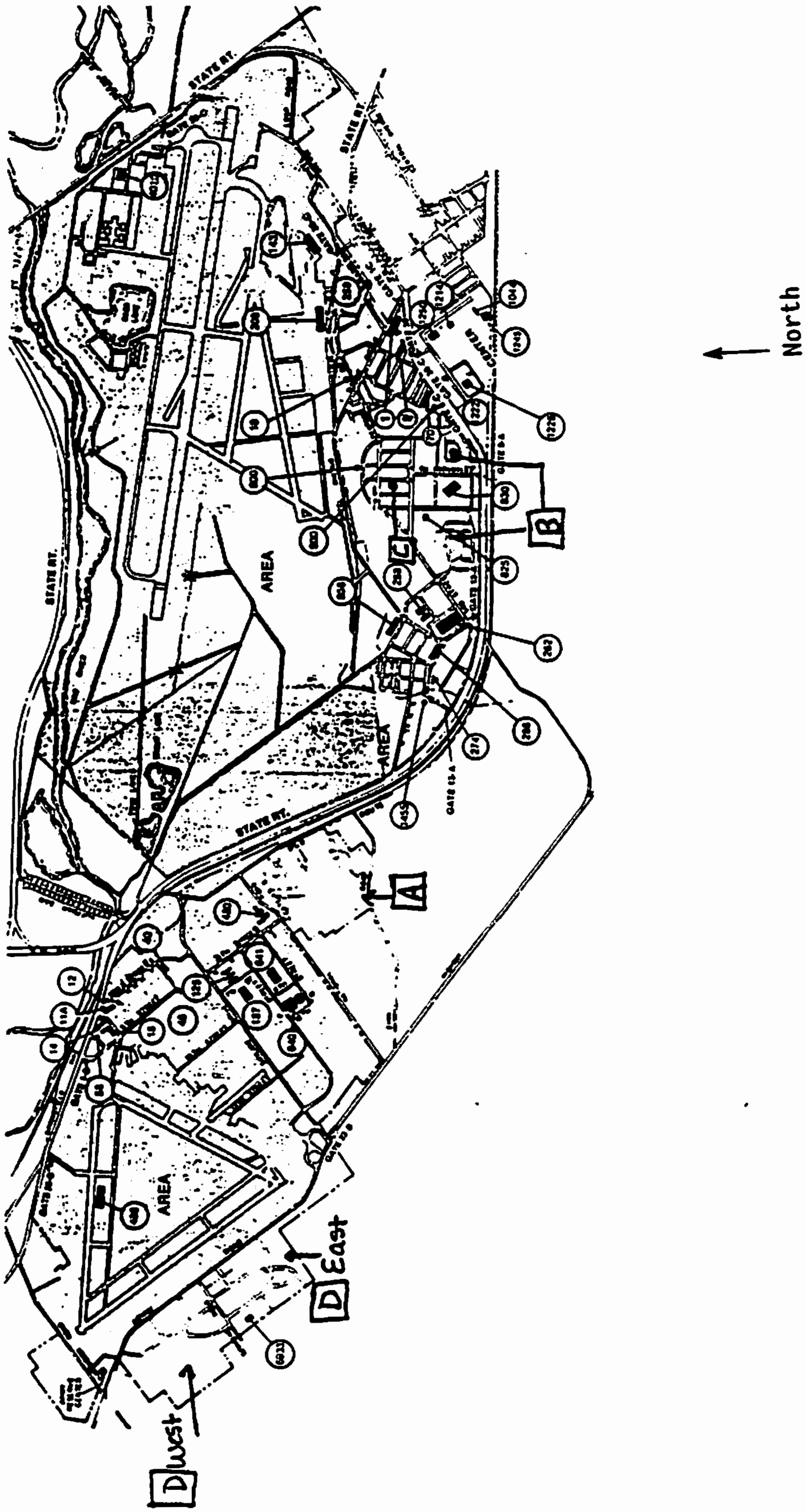

Figure 1. Map of the Air Force Base Including Identifiers for Each Housing Area Sampled.

Table 1. Number of Sampled Residential Units Requiring an Integrity Verification Check

Housing Area	Number of Residential Units Sampled	Number of Residential Units to be Checked
A	360	18
B	413	21
C	87	5
D West	555	31
D East	819	43
Total	2,234	118

the visits, it could have biased the results of the checks. For example, someone could have moved a detector to a closet but returned it to the original location after receiving notification of the visit. When a technician visited a preselected residential unit and discovered that the occupant was unavailable or unwilling to participate in the check, he or she randomly chose a unit on either side of the selected unit.

The integrity check was also conducted in three other buildings: a dormitory, a visiting officers' quarters, and a child-care center. All detectors in each of these three buildings were examined. Unlike individual residential units, appointments were made in advance to visit these buildings.

RETRIEVAL OF DETECTORS

The retrieval of detectors commenced near the end of September 1990. Like the deployment phase, the retrieval of detectors was conducted in three waves. At the start of each wave, base occupants received letters indicating that a technician would be visiting their home at a scheduled time. If the occupant was not at home, a card was left behind indicating that the appointment would be rescheduled.

Detector retrieval was coordinated in the same manner as the deployment phase. At the end of a retrieval day, the field supervisor verified that the detectors were packaged properly and that the remainder of each RAMP survey form was complete. Following this exercise, exposed detectors and the remaining portion of the survey forms were returned to the main office. Residential units for which the retrieval attempt was unsuccessful were held until the next wave.

MONITORING RESULTS

INTEGRITY VERIFICATION

The integrity verification check was completed on June 1, 1991. Tables 2 and 3 summarize the findings of this check; the first table summarizes the results for 117 residential units and the second table summarizes the results for 3 other buildings.

Table 2. Results of the Integrity Verification Check for Residential Units

Housing Area	Number of Units Visited	Number of Detectors Missing	Number of Detectors Moved	Number of Detectors Invalidated
A	18	0	0	0
B	21	1	1	1
C	5	0	0	0
D West	30	0	1	1
D East	43	0	2	0
Total:	117	1	4	2

Table 3. Results of the Integrity Verification Check for Other Buildings

Building	Number of Detectors Checked	Number of Detectors Missing	Number of Detectors Moved	Number of Detectors Invalidated
Dorm	24	2	0	1
VOQ	18	0	0	0
Child Care Center	6	0	0	1
Total:	48	2	0	2

Projecting these results to the entire group of units that were sampled, one would expect approximately 19 missing detectors and 38 invalid detectors for residential units, and 16 missing detectors and 16 invalidated detectors in other buildings. In actuality, however, for residential units, 67 detectors were lost and 3 were invalidated. The invalid detectors included one that was damaged by fire, one that was moved, and one in which the airflow was obstructed around the detector. Thirty-five detectors were lost from other buildings. Thus, although the integrity check did not enable precise estimation of the number of missing or invalid detectors, it correctly indicated that the extent of such potential problems was quite small.

FIELD RESULTS

The analysis of field results excluded duplicate detectors, lost detectors and invalid detectors. Sampling results that were returned from the analytical laboratory with concentrations less than 30 $pCiL^{-1}$-days total exposure were reported as <0.1 $pCiL^{-1}$. For the purposes of data analysis, these results were recoded to 0.05 $pCiL^{-1}$.

Table 4 summarizes the sampling results at the base. Excluding duplicate detectors, a total of 2,630 detectors were deployed, of which 2,525 had valid results. The average concentration for all valid measurements was 2.3 $pCiL^{-1}$ and 409 sites (16.2 percent) were at 4 $pCiL^{-1}$ or greater.

Table 4. Summary of Radon Monitoring Results

Parameter	Value
Number of Valid Results	2,525
Average Concentration, $pCiL^{-1}$	2.3
Standard Deviation, $pCiL^{-1}$	1.9
Maximum Concentration, $pCiL^{-1}$	17.6
Percent ≥ 4 $pCiL^{-1}$	16.2

The monitoring results are summarized according to the type of structure in Table 5. The highest average concentration and the highest percentage of results at or above 4 $pCiL^{-1}$ was for single-family units attached to one or more units; this is the most common structure type on the base, accounting for 83 percent of the measurements.

Table 5. Indoor Radon Results by Type of Structure

Type of Structure (Number of Measurements)	Average Radon Concentration, $pCiL^{-1}$	Standard Deviation $pCiL^{-1}$	Maximum, $pCiL^{-1}$	Percent $\geq$ 4 $pCiL^{-1}$
Single-Family Detached (80)	1.7	1.3	7.7	6.3
Single-Family Attached (2,085)	2.4	2.0	17.6	17.9
Child-Care Center (24)	1.6	1.4	4.3	12.5
Dormitory (68)	0.7	0.7	3.1	0
Transient Living Facility (247)	2.1	1.5	8.0	10.9
Medical Center (15)	0.2	0.1	0.4	0
Fire Station (5)	0.9	0.3	1.3	0

For nonresidential buildings, most measurements were taken in transient living facilities (TLFs), which had the highest average radon concentration. TLFs and child-care centers both had measurement results above 4 $pCiL^{-1}$. The 15 detectors that were placed in the medical center all had results below 0.5 $pCiL^{-1}$ and measurements in dormitories and fire stations were all below 4 $pCiL^{-1}$.

Residential Sampling Results

Table 6 summarizes the residential monitoring results by housing area. All housing areas had elevated radon levels except for Area A, which had a maximum radon concentration of 3.3 $pCiL^{-1}$. The highest radon concentration on the base--17.6 $pCiL^{-1}$--was measured in Area D East. The highest average radon concentration was in Area B, for which 36.8 percent of the monitoring results were above 4 $pCiL^{-1}$. Area D, when taken as one large area, accounts for one-third of the base results above 4 $pCiL^{-1}$, and all of the results at or above 8 $pCiL^{-1}$ are located either within Areas B or D.

To address the possibility that factors other than structure location might contribute to elevated radon levels, the following variables were cross-tabulated with housing area:

- Age of the structure
- Type of foundation
- Type of heating system
- Type of fuel used for heating
- Whether or not a floor drain is present on lowest level.

Table 6. Indoor Radon Results by Housing Area

Housing Area (Number of Units)	Average Radon Concentration, $pCiL^{-1}$	Standard Deviation $pCiL^{-1}$	Maximum, $pCiL^{-1}$	Percent $\geq 4\ pCiL^{-1}$
A (351)	0.7	0.4	3.3	0
B (397)	3.3	2.4	12.8	36.8
C (79)	2.2	1.2	7.7	7.6
D East (792)	2.8	2.0	17.6	21.1
D West (546)	2.2	1.5	12.0	11.0

Most of these factors had limited variability within each housing area. The major exceptions were as follows: (1) Area D consisted of some structures constructed during the 1960-to-1969 period with the majority constructed during 1950 to 1959; (2) Area B consisted mostly of structures using electricity for heating fuel, with some units using underground gas for heating fuel; and (3) within Area D, the presence of floor drains on the lowest level varied across housing units.

The age of the structure in Area D East and the type of fuel used for heat in Area B showed no statistically significant relationship with the average radon concentration. However, the average concentration within Area D varied according to the presence or absence of floor drains. Table 7 shows the average concentration within Area D East and Area D West for units with floor drains and units without floor drains. In Area D East, the average concentration in units with floor drains is significantly higher ($p < 0.05$) than in units without floor drains. In Area D West, the average was also higher in units with floor drains, but the difference is not statistically significant.

Table 7. Indoor Radon Results in Area D for Units With Floor Drains and Units Without Floor Drains

Presence of Floor Drains	Average Radon Concentration, $pCiL^{-1}$	Standard Deviation, $pCiL^{-1}$
<u>Area D East</u>		
No	2.6	1.7
Yes	3.2	2.2
<u>Area D West</u>		
No	2.1	1.6
Yes	2.3	1.4

Nonresidential Sampling Results

The average radon concentration was calculated for each building within the structure categories of child-care center, dormitory, TLF, hospital, and fire stations. The majority of the measurements in these types of buildings were conducted in TLFs.

Thirteen TLFs were monitored. The average concentration per building ranged from 0.6 $pCiL^{-1}$ to 3.9 $pCiL^{-1}$. Consistent with the distribution of results in residential housing areas, the 7 TLFs with the highest average concentrations (ranging from 1.5 $pCiL^{-1}$ to 3.9 $pCiL^{-1}$) were all located near Area B; for the remaining 6 TLFs, the average concentration ranged from 0.6 to 1.4 $pCiL^{-1}$.

The average concentration within child-care centers ranged from 0.4 to 4.1 $pCiL^{-1}$. The child care center with the highest average concentration was located near Area B.

All radon levels measured in the hospital were less than 0.5 $pCiL^{-1}$ and the highest concentration in any of the five fire stations monitored was 1.3 $pCiL^{-1}$ (one detector was placed in each station). The concentrations in the dormitories were also low; the highest average concentration was 1.4 $pCiL^{-1}$. Because the radon levels were low, no attempt was made to locate the dormitories on base maps to determine their proximity to specific housing areas.

Because TLFs represented the largest number of sampling sites and had the highest average radon concentration, the analysis of results for these building was taken one step further. Factors such as the age of the building, the type of foundation, and the presence of floor drains were highly variable across the thirteen buildings, enabling further analysis.

The results of this analysis indicated that average concentrations were (1) lowest in the oldest buildings, (2) higher in structures with a slab-on-grade foundation than in structures with basements, and (3) higher in buildings without floor drains than those with drains. However, as shown in Table 8, the structures built between 1970 and 1979 had only slab-on-grade foundations, and these structures had the highest average concentration. For structures built during the 1950s or 1960s, those with basements had higher average concentrations than those with slab-on-grade foundations. Further inspection of the data also indicated that floor drains are present in all of the structures built between 1950 and 1969 whereas floor drains are not present in the newest structures where the highest radon levels were found.

Table 8. Indoor Radon Results in Transient Living Facilities by Age of the Structure and Type of Foundation

Structure Age/Foundation (Number of Measurements)	Average Radon Concentration, $pCiL^{-1}$	Standard Deviation
1970-1979		
Basement (0)	--	--
Slab-on-Grade (76)	3.4	1.6
1960-1969		
Basement (36)	2.6	1.3
Slab-on-Grade (2)	1.7	1.0
1950-1959		
Basement (66)	1.5	0.8
Slab-on-Grade (11)	0.8	0.3

RESULTS FOR QA/QC DETECTORS

As part of the overall RAMP program, approximately 3 percent of the detectors are set aside for quality assurance (detectors exposed to known radon concentrations), and 10 percent are set aside for quality control. The quality control detectors consist of field blanks and duplicates; depending on batch size, either 10 percent of the detectors are set aside, or 25 field blanks and 50 duplicates, whichever number is lower.

Spikes

Spiked detectors were exposed at the radon chamber facility located at the U.S. Department of Energy (USDOE) Technical Measurements Center in Grand Junction, Colorado. Spiked detectors consisted of those that were exposed to known radon concentrations to simulate a 365-day sampling period. For RAMP, the target concentrations are for a yearly simulation of 4, 8, and 20 $pCiL^{-1}$. In order to accomplish this, the detectors were dosed at levels of 1,460, 2,920, and 7,300 $pCiL^{-1}$-days.

The spiked detectors were included with the field detectors and shipped to the analytical laboratory. The objective of using these detectors is to assess the performance of the analytical laboratory and to interpret the field results in light of the accuracy and precision for the QA detectors.

Table 9 summarizes the results for spiked detectors at each known radon concentration. The table shows the true concentration, which is slightly different than the target concentration, together with the average reported results and their standard deviations as well as estimates of accuracy and precision. At all exposure levels, both accuracy and precision meet the acceptance criteria (±25 percent) used for USEPA's Radon/Radon Progeny Measurement Proficiency Program.

Table 9. Analysis Results for QA Detectors Exposed to Known Concentrations in a Radon Chamber

True Concentration, $pCiL^{-1}$	Number of Detectors	Average Result Reported, $pCiL^{-1}$	Standard Deviation $pCiL^{-1}$	Bias[a] $pCiL^{-1}$	Accuracy[b] Percent	Precision[c] Percent
0.00	33	0.10	0.03	0.10	N/A	N/A
2.96	26	2.79	0.24	0.17	8.00	8.50
8.85	28	8.65	0.58	0.20	5.31	6.73
14.03	27	16.22	1.28	2.19	15.81	7.86

[a] Average - True

[b] Average percent difference (absolute) between measured and true

[c] Coefficient of variation (CV), or standard deviation expressed as a percentage of the average result

Duplicates

By design 50 duplicate detectors--those that are placed side-by-side with one another--were to be deployed at the base.

In actuality, 28 duplicates were deployed. The reduced number of duplicates deployed is attributable to the method by which daily assignments were issued. Duplicates to be deployed were indicated during the first wave. Units requiring a duplicate detector were flagged on the assignment logs. If the first wave attempt was unsuccessful, the designated structure was pooled with other unsuccessful attempts for deployment during the second wave. However, the flag to identify units to receive duplicates was inadvertently excluded in the second wave. Consequently, 22 units that were scheduled to receive duplicates during the first wave were rescheduled for a later wave but did not receive duplicates at that time.

The standard deviation was calculated for each set of duplicates and then summarized by concentration interval, as reported in Table 10. One of the 28 sets of duplicates was lost during the deployment period. For the remaining 27 sets of duplicates, the average precision was ±10 percent or better, consistent with the results for QA samplers. Twenty-five of the 27 sets of duplicates had a precision of ±20 percent or better. The two sets of duplicates with a poorer precision were both at low concentrations, and the two results agreed within 0.5 $pCiL^{-1}$ in both cases (i.e., 1.0 $pCiL^{-1}$ versus 1.5 $pCiL^{-1}$ and 0.6 $pCiL^{-1}$ versus 0.8 $pCiL^{-1}$). All sets of duplicates, with one exception, agreed within 0.5 $pCiL^{-1}$. The exception was one pair at 8.4 $pCiL^{-1}$ versus 6.8 $pCiL^{-1}$; nonetheless, even in this case both measurement results indicated that the radon concentration was elevated above the guidance level.

Table 10. Precision of the Duplicate Detectors Used for QC, by Concentration Interval

Concentration Interval, $pCiL^{-1}$	Number of Duplicate Sets	Average Standard Deviation, $pCiL^{-1}$	Average Precision, %
0.50-0.99	5	0.07	9.75
1.00-1.99	9	0.12	8.22
2.00-3.49	5	0.23	9.09
3.5 or higher	8	0.27	4.80

The average precision for all sets of duplicates was 7.5 percent. Nearly half (44 percent) of the duplicate sets had a precision of 5 percent or better, 30 percent had a precision between 5 and 10 percent, 11 percent had a precision between 10 and 15 percent, and 7 percent had a precision between 15 and 20 percent.

Blanks

Twenty-four field blanks were used at the base. These detectors remained, unopened, at the base environmental office for the duration of the field work. These detectors accompanied the field samplers from their origination point at the main office through their return after the year-long sampling period. Upon return for analysis, these detectors were opened and dated to correspond with the sampling period of the field detectors. The purpose of these detectors was to assess any level of contamination that may have occurred and could have impacted on the field samples.

The average result reported for the field blanks was 0.12 $pCiL^{-1}$. Comparison of this result with the average for the QA blanks (0.10 $pCiL^{-1}$) indicates that no significant contamination occurred in the course of field monitoring. The analytical results were not adjusted for field blanks; this practice could yield misleading results, especially in view of the fact that the results for QA samplers indicated a negative bias at 2.96 and 8.85 $pCiL^{-1}$ (see Table 9). The sole use of the field blanks was to assess the possibility of field contamination, as noted above.

SIGNIFICANCE OF RESULTS

Quality assurance results can be used to determine 95 percent confidence intervals to assist in the interpretation of individual sampling results. The confidence interval, calculated for each exposure level, is expressed as the average result reported by the laboratory plus or minus two times the standard deviation. Because the chamber exposures did not match the target exposures of 4, 8, and 20 $pCiL^{-1}$, it was necessary to adjust the results to those that would have been obtained at these exposure levels. This was accomplished by multiplying the lower and upper bounds of the confidence interval by the ratio of target to true concentration.

To illustrate the interpretation and application of these results, the lower bound of the 95 percent confidence interval at 4 $pCiL^{-1}$ is 3.1 $pCiL^{-1}$. Therefore, if one chooses to err statistically in the direction of assuring the health of base occupants, then a result of 3.1 $pCiL^{-1}$ should be used as a cutoff for identifying structures that may require mitigation. Note that this practice does not mean that 3.1 $pCiL^{-1}$ is replacing 4.0 $pCiL^{-1}$ as the action level; rather, based on the results for QA detectors, 3.1 $pCiL^{-1}$ was determined to be the cutoff for mitigation that accommodates measurement uncertainty, given an action level of 4.0 $pCiL^{-1}$.

Tables 11 and 12 show the impact of using 3.1 $pCiL^{-1}$ as the cutoff for mitigation. Each table shows a comparison between using the lower bound of the confidence interval and 4 $pCiL^{-1}$. The number of structures with results at or above this mitigation criterion increases from 16.2 percent to 25.7 percent when 3.1 $pCiL^{-1}$ is used as the cutoff.

Table 11. Percent of Structures Requiring Mitigation, by Structure Type

	Percent of Structures Requiring Eventual Mitigation	
Type of Structure	Using 3.1 $pCiL^{-1}$ as a Cutoff	Using 4 $pCiL^{-1}$ as a Cutoff
Residential Units		
Single-Family Detached	13.8	6.3
Single-Family Attached	27.3	17.9
Other Buildings		
Child Care Center	20.8	12.5
Dormitory	1.5	0
Transient Living Facility	24.7	10.9
Hospital	0	0
Other	0	0
All Types	25.7	16.2

Table 12. Percent of Residential Units Requiring Mitigation, By Housing Area

Housing Area	Residential Units Requiring Eventual Mitigation: Using 3.1 $pCiL^{-1}$ as a Cutoff	Using 4 $pCiL^{-1}$ as a Cutoff
A	0.6	0
B	46.4	36.8
C	17.7	7.6
D East	33.3	21.1
D West	21.4	11.0

If the 4 $pCiL^{-1}$ level were to be used as a cutoff for mitigation without considering the results of the QA detectors, then 379 residential units and 6 other buildings would require mitigation. When determining the structures that may be mitigated in light of the QA results, 581 residential units and 10 other buildings would require mitigation. This is an increase of 202 residential units and 4 other buildings, respectively.

Another issue related to mitigation decisions is whether buildings measured in multiple locations should receive mitigation based on the average concentration or the highest concentration. This dilemma can be illustrated with measurements for 7 TLFs near Area B (Table 13). Four of the TLFs had an average concentration below 3.1 $pCiL^{-1}$, and three had an average radon concentration at or above 3.1 $pCiL^{-1}$. All seven of these structures had at least two individual sampling results of 3.1 $pCiL^{-1}$ or higher. Thus, failure to take any mitigation action at the structures with average levels below 3.1 $pCiL^{-1}$ would result in some individuals receiving exposures above the mitigation cutoff.

Table 13. Summary of Sampling Results For Seven TLFs Located Near Area B

Structure Number	Number of Valid Results	Average Concentration, $pCiL^{-1}$	Standard Deviation	Percent ≥ 3.1 $pCiL^{-1}$
825	66	1.5	0.8	7.6
826	36	2.6	1.3	36.1
832	18	3.7	1.8	66.7
833	18	2.1	1.0	16.7
834	22	3.9	1.5	68.2
835	17	3.7	1.7	64.7
836	21	1.7	1.0	9.5

CONCLUSIONS

Among the 2,525 valid sampling results for the base, 16.2 percent are at or above the USEPA action level of 4 $pCiL^{-1}$. An additional 9.5 percent are above the lower bound of the confidence interval of 3.1 $pCiL^{-1}$. The average radon concentration measured at the base was 2.3 $pCiL^{-1}$.

Radon levels generally were higher in structures with basements and in structures with floor drains. Analysis of the results for TLFs showed that, when controlling for the age of the building, structures with basements had higher average radon levels than slab-on-grade structures. Also, further analysis of Area D showed that structures with floor drains in the lowest level had higher average radon concentrations than those without drains.

Quality Assurance results were within generally accepted guidelines. Accuracy and precision for the QA results associated with the base were within the ±25 percent range specified by the USEPA. Accuracy was generally ±15 percent or better and precision was generally ±10 percent or better.