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Radon Concentrations, Activities of Radon Decay Products, Meteorological Conditions and Ventilation in Mystery Cave

Final Technical Report

to

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___ Consultant's Report

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INTRODUCTION

Research in Mystery Cave, ongoing for over two decades has resulted in detailed maps; isotopic ages of speleothems; sediment characterization and correlation with speleothem ages; and chemical and hydrological analyses of ground water flowing through the cave. Over the past 2 years, new scientific studies were undertaken by the Department of Natural Resources with funding provided by the Legislative Commission on Minnesota Resources (LCMR). The project, entitled: Mystery Cave Resource Evaluation, was divided into several parts: 1) provide an inventory of the present water chemistry and water quality within the cave system; 2) study the meteorology in the cave, in particular the radon environment and it relationship to meteorological parameters; 3) provide a geologic map of Mystery Cave and an inventory of minerals; and 4) provide an inventory of aquatic invertebrates within the Cave.

Richard Lively and Brian Krafthefer were responsible for studying about the cave meteorology and radon. This project began as an attempt to understand more about the nature of the radon environment in Mystery Cave. The reasons for the study were the need by the Park Service to possibly limit exposure of the guides and park rangers, depending upon measured radon concentrations and that radon concentrations had been measured only by grab samples at several locations since 1981. However these measurements did not indicate how stable radon was from day to day, or what happened to radon concentrations from season to season or between consecutive years. There was also interest in understanding the factors that controlled radon concentrations, such as ventilation and barometric pressure changes and in linking meteorological conditions outside the cave to those within. The current study evolved from gathering information solely on radon concentrations into a broader meteorological study of the cave environment and how that environment was related to radon concentrations and surface meteorological conditions.

Objectives of the proposed study:

1. Gather baseline data on radon, radon progeny and meteorological conditions in selected areas of the cave system.
2. Determine air flow produced by daily and seasonal surface weather events.
3. Compile existing radon data
4. Examine relationship of radon to air flow and ventilation.
5. Determine effects of cave renovation.
6. Correlate cave temperature and humidity levels with air movement.

BACKGROUND

Mystery Cave, located in western Fillmore County, southeastern Minnesota, is the largest cave in the Upper Midwest. Originally a private cave, it is currently owned and managed by the Department of Natural Resources as part of Forrestville State Park. Presently, the cave has more than 11 miles of mapped passages with about 1 mile maintained for public tours between Memorial Day and Labor Day. Activities in the cave include exploration, mapping, restoration and cleaning, excavation, maintenance, scientific research and guided tours.

Geologic setting

The physical characteristics of Mystery Cave have been described in detail by Milske (1983). The cave is a joint-controlled, three dimensional maze with openings and passages ranging from inches to tens of feet in diameter and hundreds of feet in length. Most of Mystery Cave has developed in the Ordovician age limestones, dolostones, and interbedded shales of the Upper Galena and Dubuque formations. Passages may contain breakdown, fine-grained sediments, or coarse fluvial sand and gravel deposits.

The cave serves, at least in part, as a meander cutoff, crossing a bend in the Root River (Figure 1). The river sinks along its bed and flows through the lower levels of Mystery, re-emerging in the valley at Seven Springs. Several small lakes and streams are also present, but above the main river level much of the cave is dry. There are two artificial entrances, one on the east end and one on the southwest end of the cave. The entrance at Mystery II is 23 feet higher than the entrance at Mystery I, and is separated by approximately 5220 feet straight line distance (Figure 2). This probably represents the maximum upper-level passage gradient between Mystery I and Mystery II. Other openings are presumed, but their number, size and distribution are unknown.

Radioactivity

The radiation environment in Mystery Cave can be divided into two related components. One is a constant background of gamma rays coming from the limestone and shales. The background gamma radiation is low, not considered a hazard, and is not part of this study. The second component is the variable concentrations of radon gas emanating from the rock and soil and forming airborne radioactive particles. The characteristics of radon and radon decay products along with probable sources in the cave are given in Appendix A and Appendix B.

Inhalation of radon and the decay products of radon at cave concentrations could result in radiation exposures that exceed current OSHA limits. This can lead to an increase in the life-time risk of contracting lung cancer (BIER IV, 1988). To reduce potential exposure, limits are usually placed on the amount of time individuals may spend in the cave. The limits apply to employees who may spend significant amounts of time in the cave and not to the general public who visit for short periods. It is important to know both the levels and the variability of the radioactivity because they affect personnel requirements, scheduling and tour operations over the course of the year.

Radon concentrations in Mystery have been measured using grab sample devices, and 3-month to 1-year alpha track detectors. Grab samples provide immediate results and alpha track detectors average values over the measurement interval. Neither was able to measure variability associated with meteorological and seasonal climates. Park employees have also been making measurements of radon decay products (working levels) at one or two week intervals over the past 2 years. The results from these measurements are described in Appendix C.

DESCRIPTION OF STUDY

The current study, which ended in May 1993, is a continuation of one that began in 1989. Radiation measurements were improved and expanded to include radon decay products. Additional studies of seasonal air movement, particle concentrations and particle size distribution were also included. All monitoring locations are shown on Figure 2, and cross-sections of cave site where radon was measured are shown in Figures 3,4 and 5.

Meteorological data were desired because the previous study correlated short-term radon fluctuations with barometric pressure changes and long-term fluctuations with seasonal changes in surface temperature. Barometric pressure, air temperature and relative humidity sensors were installed with the radioactivity monitors at Bomb Shelter. An identical set of instruments was installed outside the Mystery I entrance to monitor surface weather (Appendix D). The intent was to obtain more detailed data to help identify how radon, barometric pressure and temperature interacted.

Another objective was to determine directions of air flow within the cave, identify seasonal correlations and collect information on how the cave atmosphere interacted with the surface. The air flow monitoring, (5 different sources and 14 to 18 detectors placed in and about the tour areas) is described in Appendix E. Estimates of air velocities at different points in the cave are also included in Appendix E.

A goal of the radon study was to measure concentrations and variability in areas of the cave most used by employees and if possible, relate radon to cave and surface meteorology. As a result, all radon monitoring stations were installed in existing or past tour routes, where they were also accessible for equipment installation and data retrieval. Initially four radon monitors were placed in Mystery I and II, but because of changes to the cave and the monitors, Angel Loop in Mystery II and Bomb Shelter in Mystery I were the only sites where monitors remained for the entire project. One monitor was installed in the house for part of the study period and others were placed at different tour route locations for short intervals.

The relationship between radon decay products and radon was also studied. Detectors that could continuously measure concentrations of decay products were installed with the Bomb Shelter radon monitor (See Appendix G for descriptions of the monitors). A subsidiary objective was to determine if the continuous radon and decay product results could meaningfully be compared with the walk-through working level measurements taken along other parts of the tour routes. Discrete samples of particle concentrations and size distributions were also collected (Appendix H) because particulates in the air are known to interact with the radon decay products. The particle data were used to make estimates of volume air flow that are also included in Appendix H.

RESULTS AND DISCUSSION

Keep in mind that unless otherwise noted, all the data were collected along, or relatively near to the commercial tour areas. It is not advisable to extend the results much beyond the areas of direct measurements, such as the lower levels or Mystery III. For all plots of monthly data, numbers on the X-axis represent days of the month.

One of the most significant results of the project was a better awareness that radon concentrations in the cave were highly variable. The data presented in Appendix F show strong seasonal correlations, with the highest average radon concentrations occurring during the summer. Summer radon showed no correlation to barometric pressure, but did occasionally vary with temperature. The base radon level in Mystery I (in 1991 especially), was higher during the summer than it was in Mystery II, however, in the winter, the reverse was true and the Mystery II base level was higher. Low radon averages coupled with large variations (about factors of 50) occurred during the winter that were well correlated with some, but not all, variations in barometric pressure. We also observed that during the winter when radon reached a maximum, it did so first and was highest at Bomb Shelter in Mystery I. Peaks at Angel Loop and 17-Layer Rock lagged by several hours and were at lower concentrations. This suggested that radon was moving from Mystery I to Mystery II, and that higher concentrations were available near the Bomb Shelter. The winter radon peaks also increased and decreased much faster than could be accounted for by radon emanating from walls, reaching equilibrium and being lost by radioactive decay.

The results from the radon progeny measurements are given in Appendix G. When radon changed, the decay products would also change in phase with the radon. In other instances, unattached activity (grid) would increase while total activity (filter) would decrease. This is usually associated with changes in aerosol particle concentrations. However, the total activity would sometimes vary independently of the radon and unattached activity. Although this could also be related to aerosol particles in the cave atmosphere, we do not have sufficient aerosol data to determine the relationship. Particle measurements do indicate that aerosols in the cave were very low in concentration (Appendix H) and the majority were less than 0.5 microns in size (these have the most affect on radon decay products). It was interesting that when particulates were generated by persons near the detectors, there was no visible change in the ratio between attached and unattached activity. This implies that aerosols that affect the decay products are different (possibly in size or concentration) from those generated by people.

A question critical to the cave management is how the radon and decay products results relate to working levels measured by park employees and establishment of exposure limits. Plots of measured working levels and radon are given in Appendix G. Radon was used for the comparison rather than decay products because it had a longer record and was more consistent. Correlating the decay product results, which could vary with unmeasured aerosol changes, to intermittent working level measurements would require more working level samples than are available. Working levels showed a seasonal change similar to radon, and on the average, were about 50% lower than the radon activity. Working levels based solely on radon measurements would need to be reduced by about a factor of two. Although the data were limited, this relationship appeared to be similar in both Mystery I and Mystery II.

The interaction of the cave atmosphere with radon and the surface atmosphere became much better defined with the completion of the PFT air flow tracing in May 1993. Minimal isopleth diagrams of PFT concentrations from five sources and four collection intervals are shown in Appendix E, along with a detailed discussion of the results. Note that most of the Door to Door route has been deleted from the maps so that both cave sections are on the same figure.

The picture obtained from the PFT results is of a dominant movement of air toward the north and west in Mystery II and north-northeast between Mystery I and Mystery II during the winter. In the summer the air flow was less dominant in any one direction. An air route between Bomb Shelter (B.S.) and Garden of the Gods (GOG) was found to have a seasonally dependent flow direction (west in winter, east in summer). The north-northeast flow in the winter appeared to be accompanied by an influx of outside air that diluted the PFT concentrations. This did not appear to happen during the summer.

With the PFT results, the radon data could be placed into context with meteorology, air flow in the cave and exchange with the surface. A hypothesis for how the cave atmosphere, surface atmosphere and radon interact is described in the next several paragraphs.

The fluctuations of radon at Bomb Shelter in winter are thought to be caused by air, containing elevated levels of radon, entering the Bomb Shelter area and on occasion mixing with low-radon air coming from the surface. Based on the current data it is proposed that a fairly continuous flow of air between GOG and BS is the source of the high radon and that low radon levels result from dilution by surface air. The PFT results and the lag between radon peaks in Mystery I and Mystery II suggest that air moved from Bomb Shelter northeast along Door to Door route. Low PFT concentrations near the entrance of Mystery I could indicate that little air was moving in that direction or that surface air was diluting the PFT. However, the radon monitor at the entrance in 1990-1991 did show radon peaks that were similar in phase and magnitude to those at Bomb Shelter indicating that some air also moved east.

The rapid decreases of radon at Bomb Shelter are also attributed to high-radon air within the cave mixing with outside air that was low in radon. The high radon peaks always disappear much faster than is possible from radioactive decay alone and dilution appears the most probable cause. This agrees with the suspected dilution of the PFT observed during the winter and with the lower base radon levels in Mystery I. Because flow was traceable from Bomb Shelter into the Door to Door route, surface air was presumed to enter Mystery I and flow past Bomb Shelter. As a result, Bomb Shelter shows the greatest dilution and lowest base level. As the outside air moved toward Mystery II and mixed with the cave air, dilution was less effective and Mystery II maintained a higher base level.

Both summer radon levels and PFT concentrations appear to be less affected by dilution with outside air. This is consistent with other studies that have found higher radon levels in the summer versus the winter (Wilkening, 1976; Yarborough, 1980) and with the definition of 'right-side-up caves (Yarborough, 1980). In these caves, it was assumed that when the minimum surface temperature fell below the cave temperature, cooler, denser air from outside would enter and mix with the cave atmosphere. When the minimum temperature outside was above the cave temperature the cave atmosphere would remain relatively stable. In Mystery, radon levels did increase (no dilution), and become relatively uniform during the warm summer months. The other summertime observation was that air appeared to be moving from Bomb Shelter into Garden of the Gods, the reverse of the winter pattern. There was also more flow south and southwest from 5th avenue and Base Camp during the summer. Radon peaks, when they did occur, were not staggered in time as they were in winter and radon fluctuations between monitor locations appeared to be more independent.

The seasonal shift from summer to winter flow patterns was very abrupt, occurring over a matter of hours (in 1991), whereas the spring transition was more gradual and appears to flip-flop back and forth. This seasonal asymmetry was visible at each monitor location in the cave and was noticeable in both 1991 and 1992.

Both radon and PFT results imply that the passages containing the monitors were part of the major network for transferring air within the cave and that ventilation was best established during the winter. The ventilation characteristics of areas in the cave that were without monitors is open to question. Based on the 5th avenue and Base Camp sources, during the winter little air from Mystery III appeared to reach Mystery I or II. This also appeared to be the case, possibly to a lesser extent, in the summer.

Another possibility is that unmapped passages may be contributing to the air circulation patterns. This could account for the connection between Bomb Shelter and Garden of the Gods. It does not appear to be the mapped lower levels nor the Door to Door – 5th avenue routes that are the main avenues of PFT transfer. Rather these appear to be downstream continuances of the flow from Bomb Shelter carrying both radon-rich and diluted air.

Radon levels in Formation Room, a dead-end, side passage in Mystery I provide another clue. Radon in the Formation Room was higher than at Bomb Shelter, but lower than Angel Loop, and did not show any of the large, short-term fluctuations visible at either of those sites. This implies that there was relatively little interaction between the main routes of air flow and side passages during the more rapid ventilation events. It was initially thought that dead-end side passages connected to main trunk passages might build up radon and be a source for high radon spikes in the main passages. Although the data are limited, radon did not reach high levels in the Formation Room and was not drawn into the main passage. There are probably multiple circulation pattern within Mystery Cave, some which are quiescent much of the time, some internal (vertical and horizontal) and some which are connected to the surface. It may be that at Bomb Shelter, an internal circulation with GOG intersects with circulation from the surface.

The driving mechanism(s) for air circulation within the cave and exchange with the surface atmosphere were initially thought to relate to barometric pressure and seasonal temperature variations. This idea was supported by the strong correlation observed between winter radon peaks and dropping barometric pressure and the average seasonal radon results. However, it did not explain why only some pressure changes affected radon, why the magnitude of the pressure change did not correlate with the magnitude of the radon change nor why pressure did not show a correlation with radon during the summer. Further analysis of the meteorological data indicated that 1) temperature variations at Bomb Shelter closely reflected those on the surface particularly during the winter (Figure D-8); and 2) cycles of barometric pressure at Bomb Shelter were identical, within the resolution of the monitors, to those at the surface weather station (Figure D-1). The temperature data support the model that air was moving into Bomb Shelter from the surface. The barometric pressure data indicate that (within the resolution of the measurement periods) there was not a pressure gradient between the surface and Bomb Shelter. (It may be that pressure gradients exist between Bomb Shelter and other areas in the cave, or between the cave atmosphere and surrounding rock. The gradient may also have been smaller or of shorter duration than the instruments could detect. Those data are not available). Without a pressure gradient between the cave and surface, atmospheric barometric pressure changes would be unlikely to institute significant air flow within the cave openings.

As an alternative to barometric ventilation, the proposed model incorporates the known temperature gradient between Mystery cave and surface and slightly lower elevation of the south side of the cave (see the Palmer's report, 1993). During the winter, the slight topographic gradient causes warm cave air to move north and allow colder, dense surface air to enter on the south side, in Mystery I. This low-radon air mixes with air containing high radon entering at the Bomb Shelter (the connection with Garden of the Gods) and moves northeast along Door to Door route, continuing north and possibly west from Mystery II. When a low pressure system in the winter passes over the cave, it may bring warmer air (Figure 6) that reduces the thermal and density gradients between the cave and surface. Because the topographic gradient within the cave is very small, minor warming on the surface may be enough to restrict entry of surface air and allow radon levels to reach a peak. High pressure and cold, denser surface air increases the gradient and the amount of surface air entering the cave, causing a rapid dilution of radon concentrations at the Bomb Shelter and further into the cave. Not every low pressure system passing over the cave in the winter brings warmer air and as a result, surface air will continue to enter the cave and dilute the radon. Thus, as observed, not all low pressure events would have an associated radon peak. This also might explain why the magnitude of the pressure variation did not correlate with the magnitude of the radon peak.

The details of this process still need to be investigated. It is not clear from the limited data at what surface temperature(s) the influx of outside air will be reduced, or what other meteorological effects may be involved. Temperatures (November, 1992) may briefly rise above the cave temperature, but in December 1992 for instance, the maxima are well below the cave temperatures even though they correlate with radon maxima.

The diurnal pattern of surface temperatures in the summer did not appear to be correlated to barometric pressure (Figure 6). Surface low temperatures occasionally approached the cave temperatures and may (July 2 and 3 1992 for instance), be correlative to some radon changes. A factor that cannot be fully evaluated, is how wind speed, wind direction and surface topography affect the ventilation and circulation patterns of air in the cave.

In the summer, the pattern of air flow appears to reverse and circulate counterclockwise (Figures E-1 to E-20). It is suggested that this is also related to the topographic gradient. In summer, the colder, denser cave air is kept in the cave by the warm outside air. Gravity would induce a slight down-gradient (southwest along Door to Door route) motion consistent with the observed PFT results. The summer circulation also appears to be much weaker than the winter pattern. This was reflected in the more uniform radon levels, the occasional independent behavior of radon between different locations and the lower correlation between variations of radon and surface temperature. It is unclear why this circulation pattern moves air from the Bomb Shelter to the Garden of the Gods.

The 1992 radon concentrations at Bomb Shelter following reconstruction in Mystery I, were much lower than concentrations in 1991. It was initially thought that increased ventilation due to the construction result in lower radon levels however, levels decreased after construction was completed and all doors were in place. It is difficult to see how the reconstruction and its completion could have decreased radon levels, unless the excavations near the Mystery I entrance allow more outside air to enter the cave now than formerly. Monitoring of radon would have to a continue for several more years to determine if the change was permanent and thus likely related to the construction, or temporary and related to climatic changes such as temperature and rainfall patterns.

CONCLUSIONS

Conclusions resulting from this study are given below:

1) Radon levels in the cave were highly variable. In the winter, daily radon levels changed by factors of 50, usually correlated to changes in barometric pressure, in the summer, daily radon changes were much smaller and showed no apparent correlation to barometric pressure. On a longer time scale, average summer radon concentrations were as much as a factor of 3 higher than average winter levels. However, maximum winter values could be as high as, or higher than summer values. Seasonal changes in radon have been observed in other caves (Yarborough, 1980), but not the extreme, rapid winter variations observed in Mystery.

2) Radon variations were observed at multiple monitoring locations. Winter changes in radon in Mystery II consistently lagged behind those observed in Mystery I.

3) A strong seasonal effect on air flow patterns was observed throughout the cave. Air flow in winter appeared to develop stronger patterns than summer and showed more exchange with

surface air. Tracing also indicated internal circulation and mixed internal and surface circulation.

4) Averaged temperature changes between 9.4 to 9.6 °C at Bomb Shelter correlated very well with averaged surface temperature changes between 20°C and -20°C. Correlations were observed on time scales as short as 4 hours and over a change of seasons.

5) Air flow was observed between Bomb Shelter and Garden of the Gods that appeared to bypass the Door to Door route and 5th avenue. The connection is postulated to be a source for the winter radon peaks at Bomb Shelter. Although a connection was established, the exact route remains unknown. It could be through the lower levels, however the lack of tracer in the Drop Down and an apparent wintertime flow along Door to Door route from Bomb Shelter implies that there may be another connection.

6) A model was developed that suggests cave ventilation is controlled in winter by a thermal, density gradient between the cave and surface. Wintertime radon variations resulted from entry or blockage of surface air and were correlated with but not caused by barometric pressure changes. Low pressure systems in winter sometimes bring warmer surface air over the cave. It is thought that the warmer surface air prevents outside air from entering the cave and the result is a radon maximum. This could explain why not all barometric pressure events correlated with radon and why the magnitude of radon change did not correlate with the magnitude of the pressure change. Further investigation may explain how warmer air, even if still below the cave temperature can prevent surface air from entering the cave.

7) Activities of radon decay products fluctuated in phase with radon, but also at times acted independently of the radon. Radon decay products did not appear to be affected by particulates generated by people in the cave. Behavior independent of radon however, does indicate that the radon decay products were affected by other types or sizes of particulates.

8) Given limited data, working level measurements in the cave roughly followed the radon concentrations. The equilibrium ratio between radon and progeny, estimated from the working levels, was about 50%, but could be higher or lower at any given time.

9) Particle concentrations in the cave air were very low and sizes were mostly less than 1 micron. Particulates produced by people were removed from the air of the area where they were generated, within about 3 hours.

This study has demonstrated that the cave atmospheric environment is complex but understandable. The existing data provide a good base for designing and establishing future research needs and projects. Because of the new data base, future studies do not need to take a shotgun approach, but can study certain areas of the system or a particular phenomenon with targeted data collection arrays.

RECOMMENDATIONS FOR FUTURE RESEARCH

1. Test the model that air flow into Mystery Cave is controlled by temperature gradients and not barometric pressure.

Does (as it appears), surface air enter mostly in the Mystery I region and move toward Mystery II? Additional tracer studies and use of gases such as SF_6 may be of use to study long and short-term air movement. As part of this research, measurements should also be made of wind speed and direction relative to topographic features on the surface. This would require sensors outside of the valley and electrical power in areas not readily available.

2. Measure the volume, flow velocity and short-term directional changes in flow of air entering the cave during winter. Compare with summer measurements. This might be most effective in Mystery I if Mystery I is the main source of surface air to the rest of the cave in Winter.

3. Determine if, or to what extent, barometric pressure changes contribute to the emanation of radon from the rock into the cave air or to air exchange within the cave. The present data imply very little barometric effect.

4. Identify the connecting route for air flow between Bomb Shelter and Garden of the Gods. This could involve further experiments with PFT tracer gases and radon as well as physical inspection of possible routes.

5. Test the model that radon at Bomb Shelter is being drawn from passage(s) connecting to Garden of the Gods.

6. Along with more complete air flow data into and within the cave, other aspects of the cave atmosphere such as humidity, evaporation and CO2 concentrations should be studied in relationship to the cave's static and dynamic atmosphere.

7. Resume continuous radon monitoring to determine if the low 1992 levels are related to construction changes at entrance and therefore may be permanent, or are related to long-cycle climatic factors.

8. With the variations in radon in the Mystery Cave system, ranging from 25 pCi/L to above 600 pCi/L, dependent upon meteorological factors (e.g., temperature and possibly pressure differences between the outside air and the interior of the cave) the exposure of DNR personnel also depends on these factors. Exposures on certain days could be a factor of 2 - 4 greater or lower than the average or spot working level values would indicate.

In addition to working level measurements, the weather and seasonal factors could be used to predict what the radon levels would be in the cave system. This could be done by logging the weather data and using predictive equations to determine the radon. These predictions could then be used to estimate relative exposure of someone entering the cave at that time.

The development of such a system would occur in 2 phases. The first phase would be to develop the predictive algorithm from the existing weather and radon data. This algorithm would consist of a set of equations which would use the data from the existing surface weather station outside of Mystery I.

The second phase would involve development of an indicator display for the headquarters at Mystery Cave. The indicator would provide a pCi/L readout based on the input from the weather station. The advantage of such a system is that no interactions or data analysis is needed by cave personnel. It is likely that over time, the indicator would give a better estimate of exposure than the random walk through measurements that are currently being conducted. Additional analysis of the radon to radon progeny ratio would be needed as an addition to the predictive radon algorithm.

8a. Another way that radon could be monitored and exposures estimated would be to have continuous radon monitor(s) in the caves with a telemetering readout capability back at headquarters. This system would be more expensive from the standpoint of hardware costs but would give actual readings of radon in the cave system before the tour guides or other employees enter the cave and would be active at all times.

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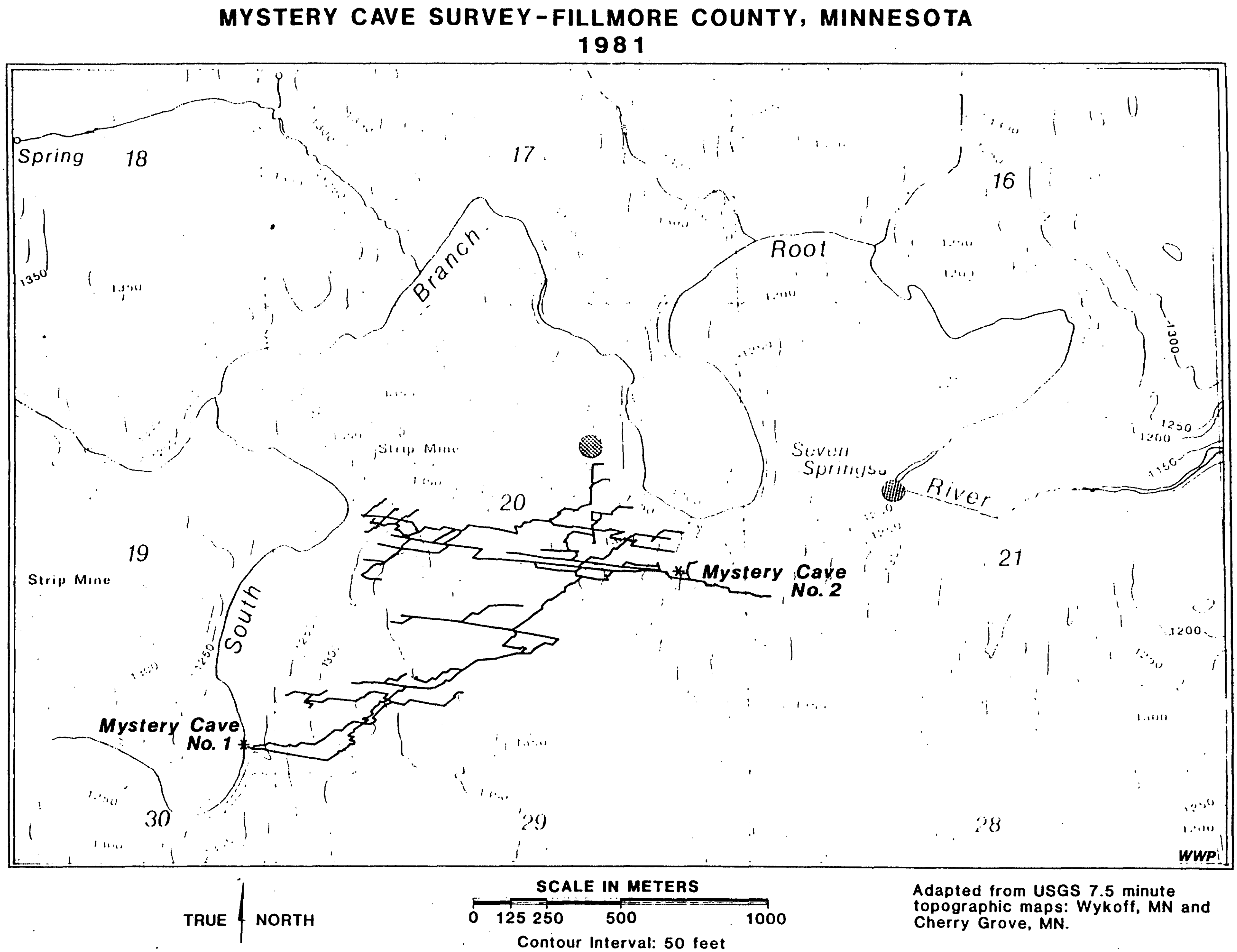


Figure 1. Map showing a plan view of stery Cave and surrounding topography.

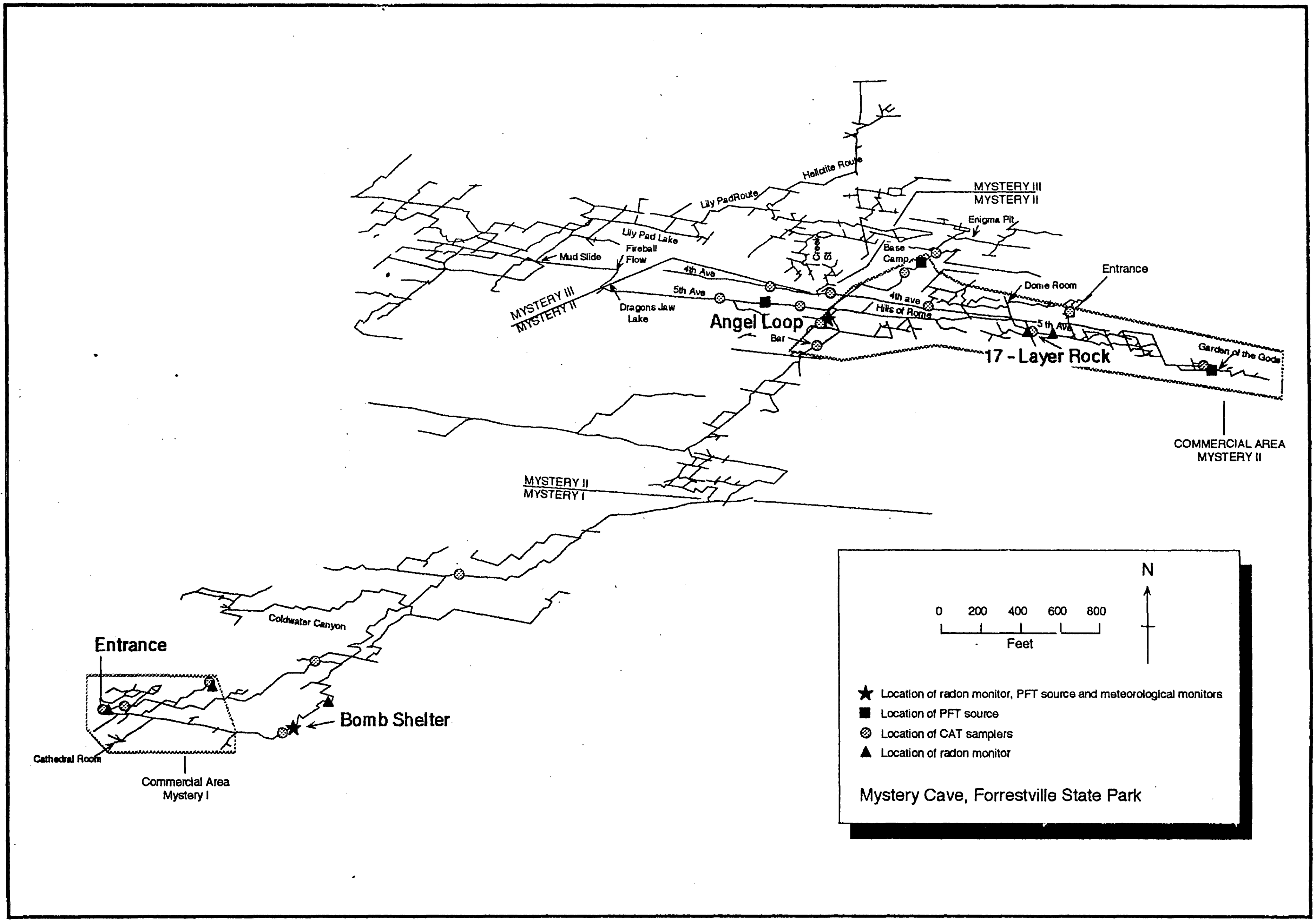


Figure 2. Plan view of Mystery Cave showing locations of radon monitors, PFT source locations and CATS sampling locations.

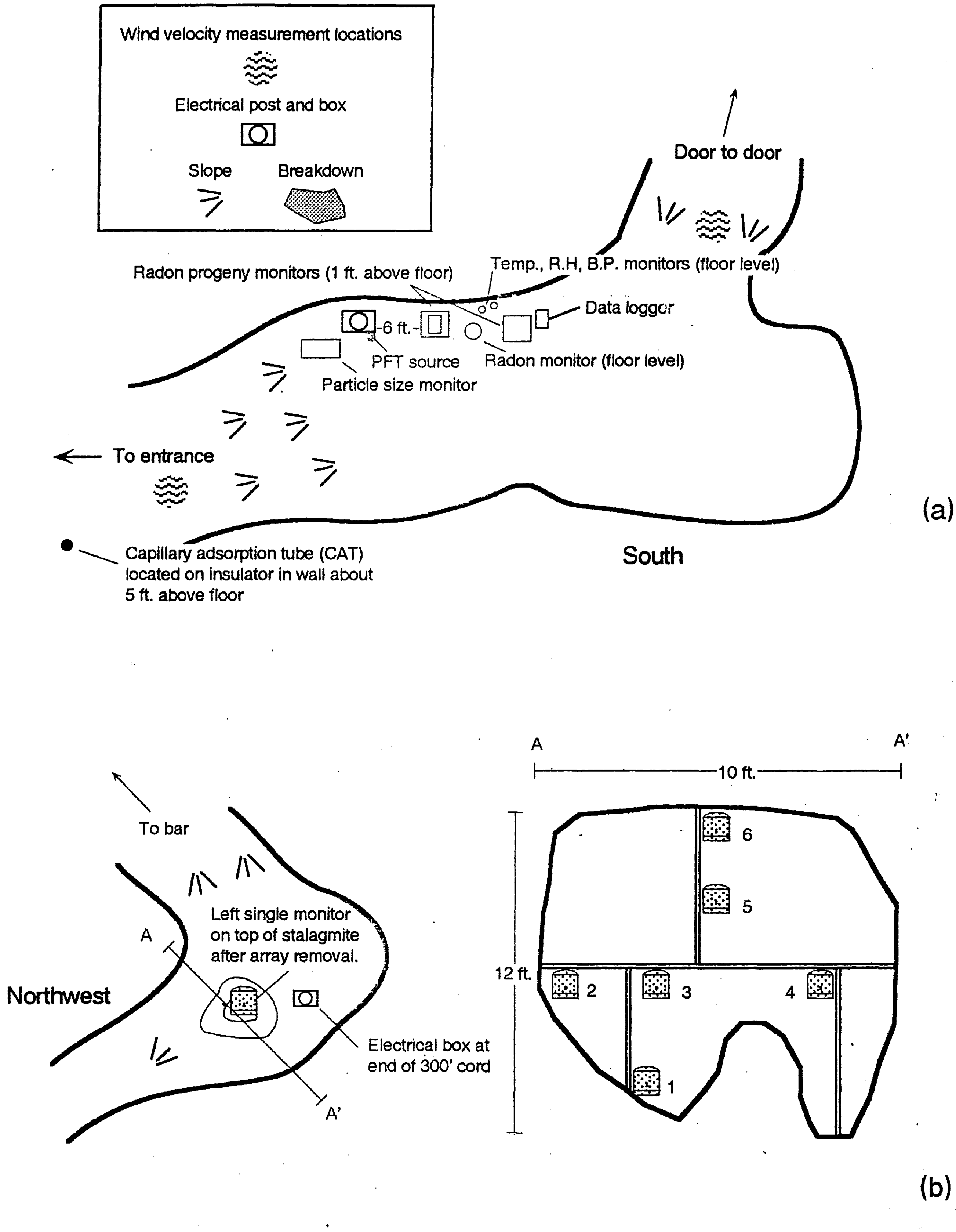


Figure 3. Plan view of Bomb Shelter (a) and Beyond Bomb Shelter (b), Mystery I showing locations of monitoring equipment and cross section of array.

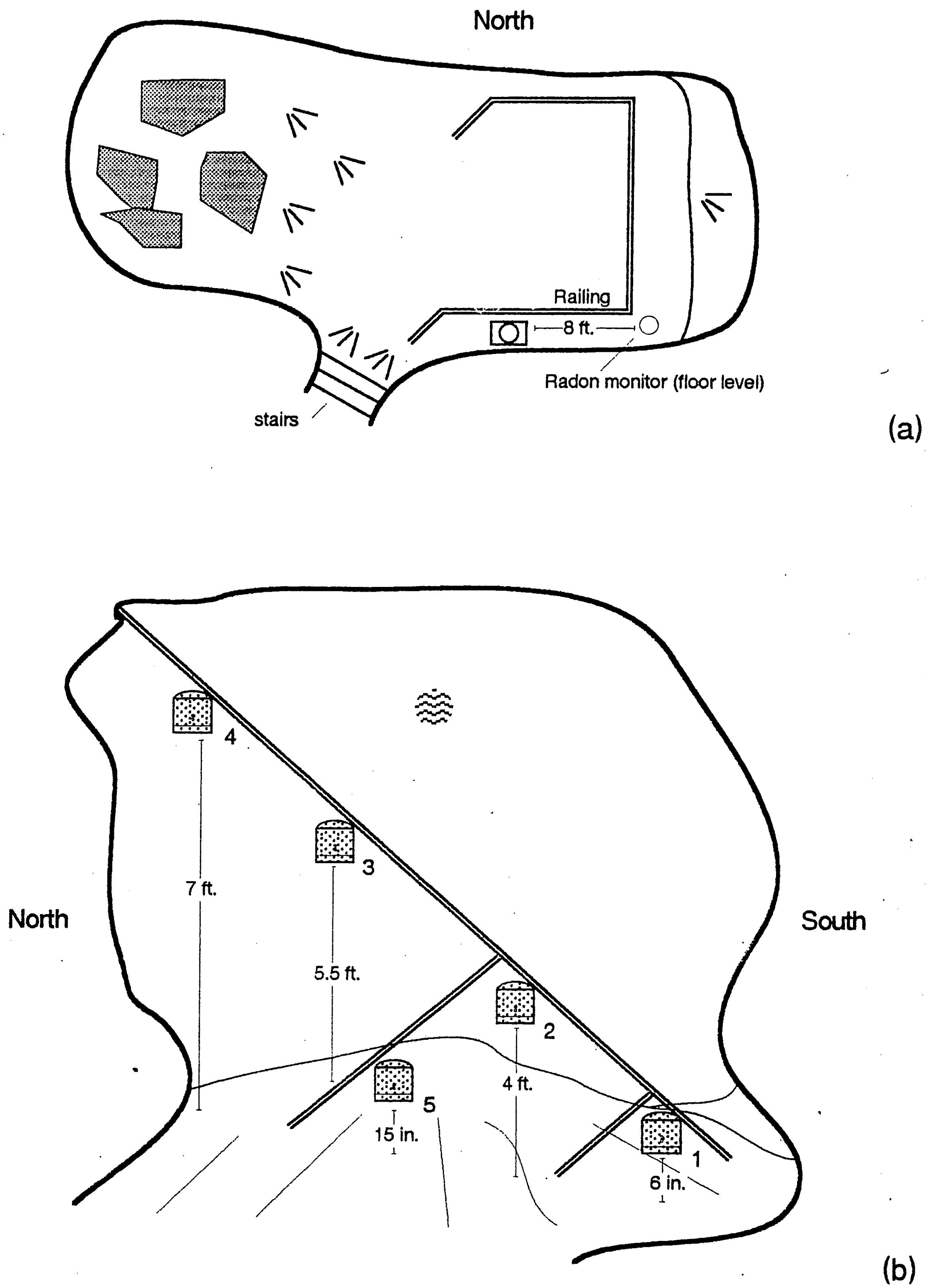


Figure 4. Plan view of Formation Room, Mystery I (a) and cross section of array near 17-Layer Rock, Mystery II (b).

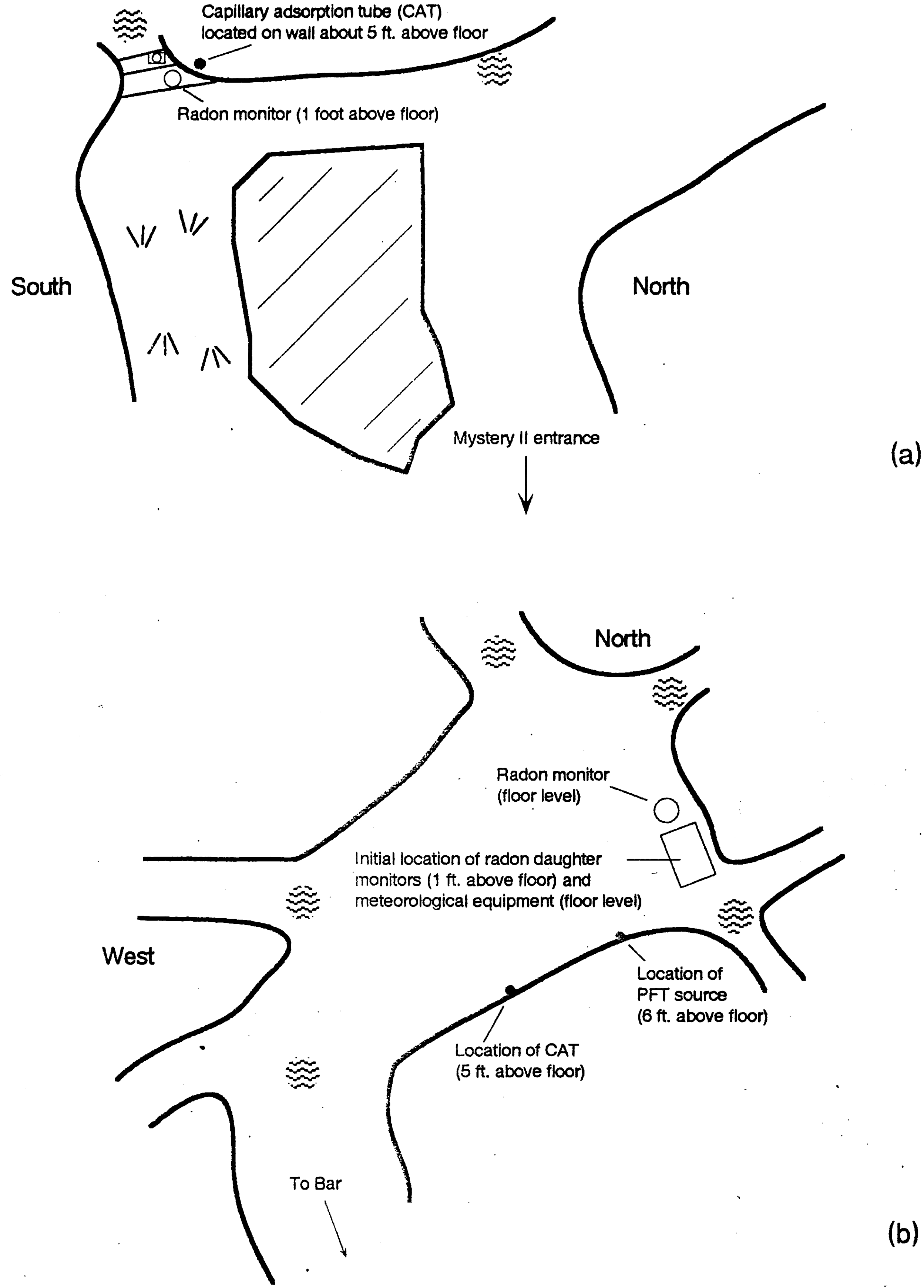


Figure 5. Plan view of 17-Layer Rock (a) and Angel Loop (b), Mystery II showing locations of monitoring equipment .

APPENDIX A. DESCRIPTION OF RADON AND RADON DECAY PRODUCTS

Radon is an inert, gas produced by the radioactive decay of uranium and thorium in cave wallrock and sediments. It does not form any chemical compounds and itself undergoes radioactive decay. Radon breaks down into a series of short-lived, non-gaseous elements known as radon decay products, radon progeny or, an older, less used term, radon daughters. Radon exists naturally in three forms or isotopes; ^{219}Rn derived from ^{235}U decay, ^{220}Rn derived from ^{232}Th decay, and ^{222}Rn derived from ^{238}U decay. Figure A-1 shows the U and Th decay series beginning with the isotope ^{238}U (representing 99.9% of all uranium in a rock or soil) and ^{232}Th through a series of isotopes each with different half-lives and decay modes. Radon-222 and its decay products (isotopes of Pb, Po and Bi, Figure A-1) are the only ones present in significant quantities in Mystery Cave and are the only ones considered in this report. The radioactivity associated with ^{220}Rn was measured at 400 times less than ^{222}Rn; ^{219}Rn with a half-life of approximately 4 seconds, does not escape from the rock. Unless otherwise specified, radon refers to the isotope ^{222}Rn. Concentrations or radon activity is given as picoCuries per liter (pCi/L). One pCi/L is equivalent to 2.22 decays per minute per liter of air.

Uranium and the other elements, with the exception of radon, are non-gaseous and remain within rock matrix. Radon is able to travel by diffusion about a meter in the rock before it decays to a non-gaseous element that does not diffuse. Radon transported by moving air may travel faster and farther before decay if the rock contains many small, interconnected fractures or pores.

The radon progeny concentrations in cave air are a direct result of the decay of the airborne radon. Decay products occur in two fractions, 1) those that attach to large particulates in the air and are relatively slow moving and 2) those that remain as unattached 'free ions' or become attached to very small particles, both of which have high mobilities.

The concentration of radon decay products in air and the ratio of the two fractions are heavily influenced by particle type, concentration and particle size distribution. The attached fraction is usually associated with particles sizes of 0.1 to >1.0 microns and the unattached with sizes from 0.1 to <0.05 microns. It is not clear what effect water molecules, associated with high humidity levels, in cave have (if any), on the radon decay products.

Decay products are being formed continuously from the radon. They are also removed from the air by radioactive decay, plate-out onto surfaces, ventilation and dilution. In most environments, the activity of radon progeny will be less than the activity of the parent radon. The degree of disequilibrium is variable.

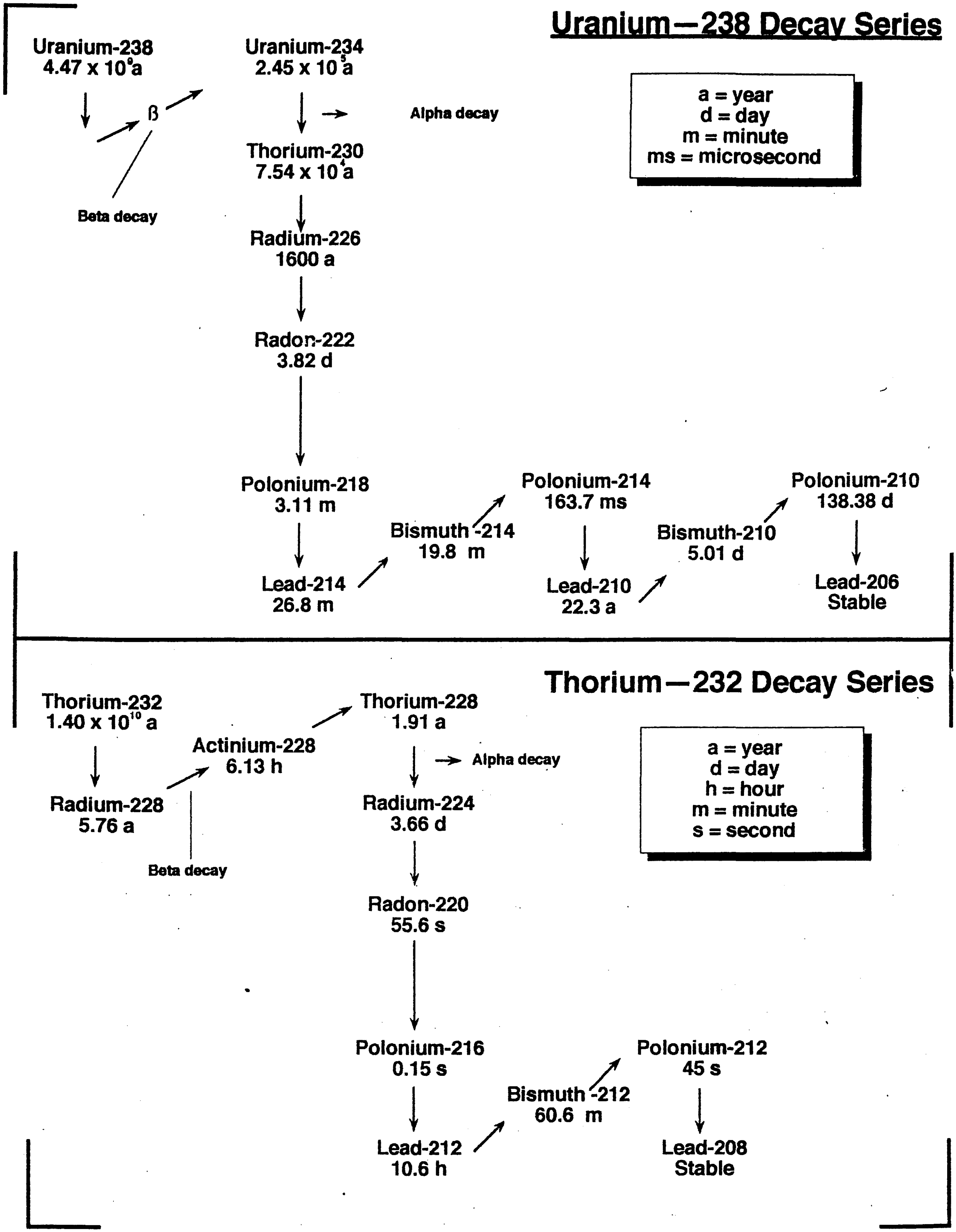


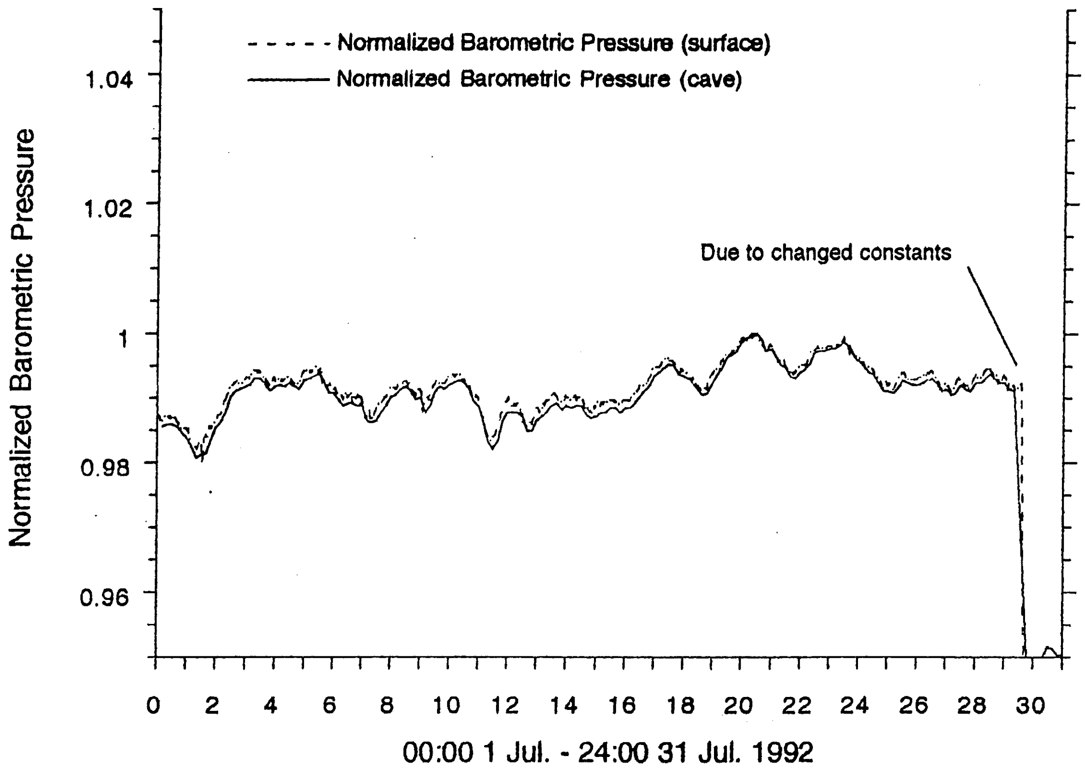
Chart of the Nuclides, Thirteenth Edition, 1983.

Figure A-1. Uranium-238 and Thorium-232 decay series.

Table B-1. Emanation rate of radon from cave sediment and limestone.

Sample	Emanating power	
	Bq/kg	Bq/m^2
Sediment from trail	4.7	1400
1" thick limestone	1.4	190
2" thick limestone	0.5	36.4
8" thick limestone	0.8	120
Typical surface soil	8	

Eventually, the data loggers were connected to small (12V, 1.9 amp hr.) batteries which in turn were connected to AC powered 12 V float chargers. During a power outage, the charged batteries could maintain the data in the loggers for about 4 weeks if necessary. The batteries would automatically be recharged when AC power was restored. Both the radon and Pylon monitors had internal backup batteries to maintain data and could operate during power outages. Other monitors would automatically resume collecting data when power was restored.



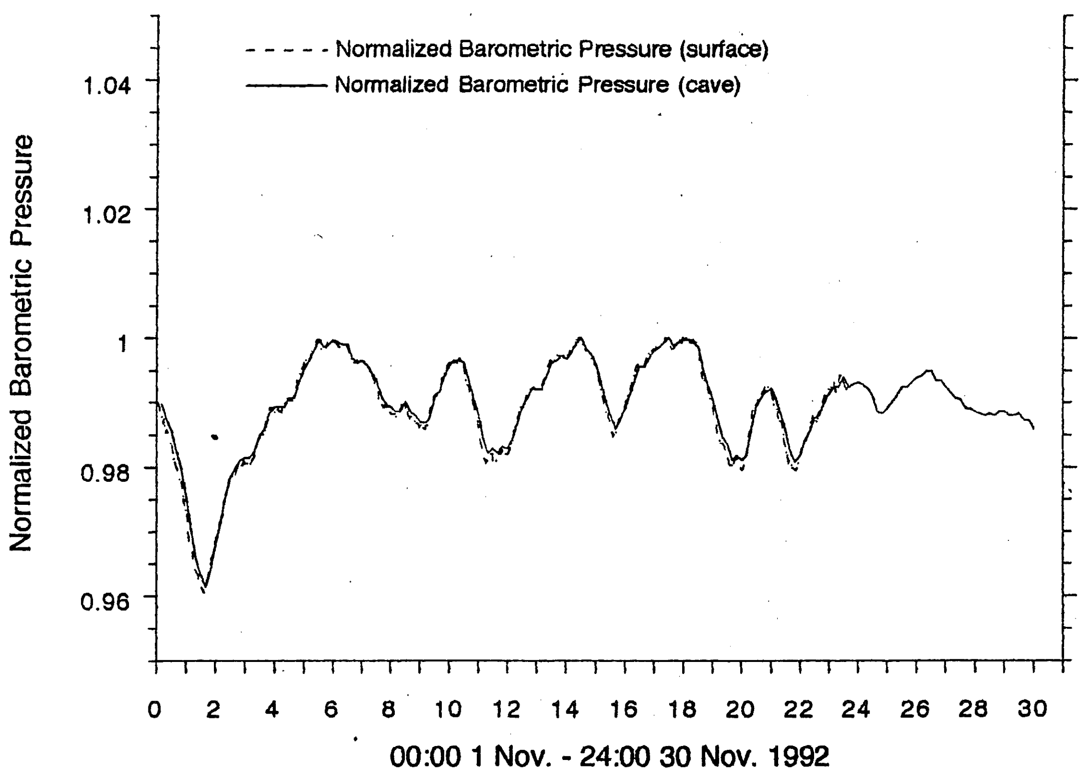


Figure D-1. Normalized plots of barometric pressure measured at Bomb Shelter and outside of Mystery I - July 1992 and November 1992.

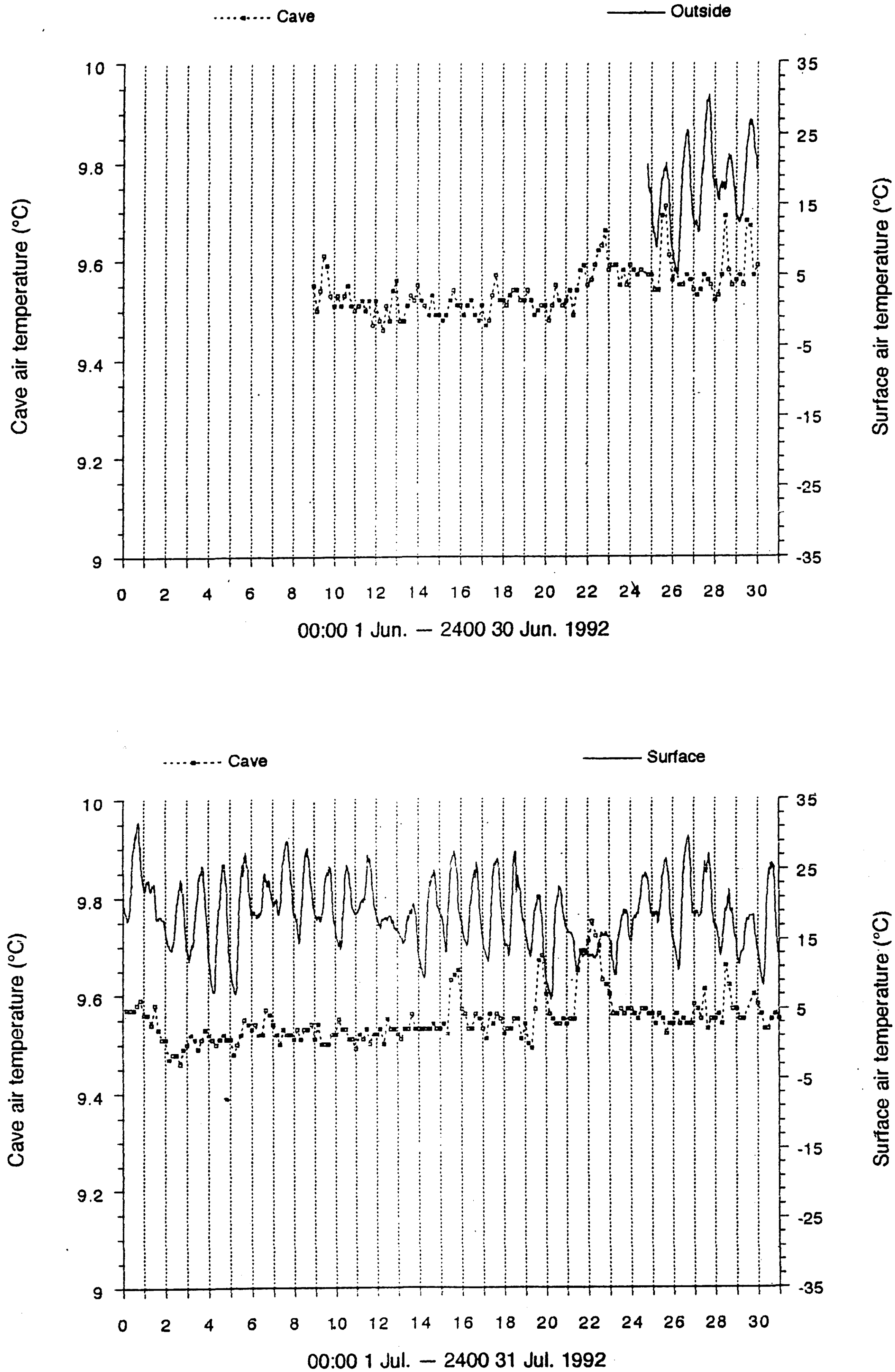
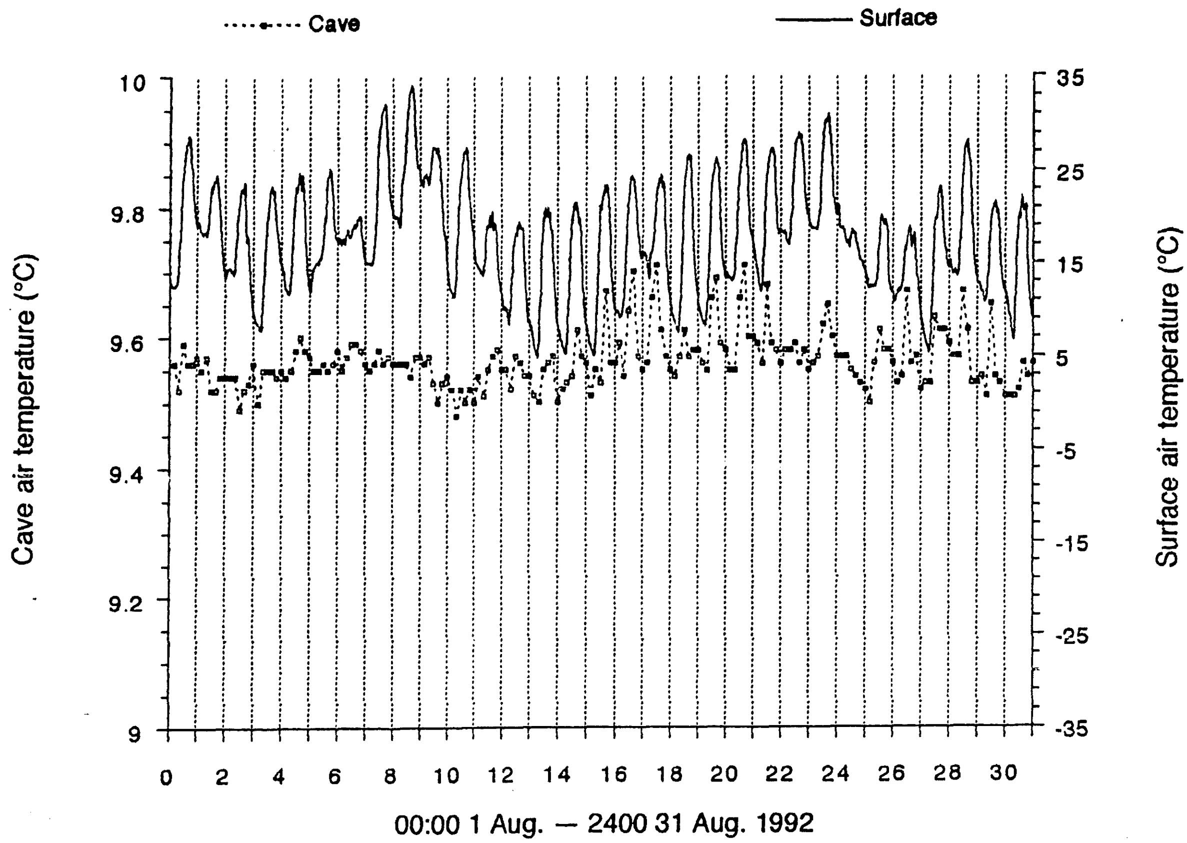


Figure D-2. Cave air temperature at Bomb Shelter and surface air temperature, June-July 1992.



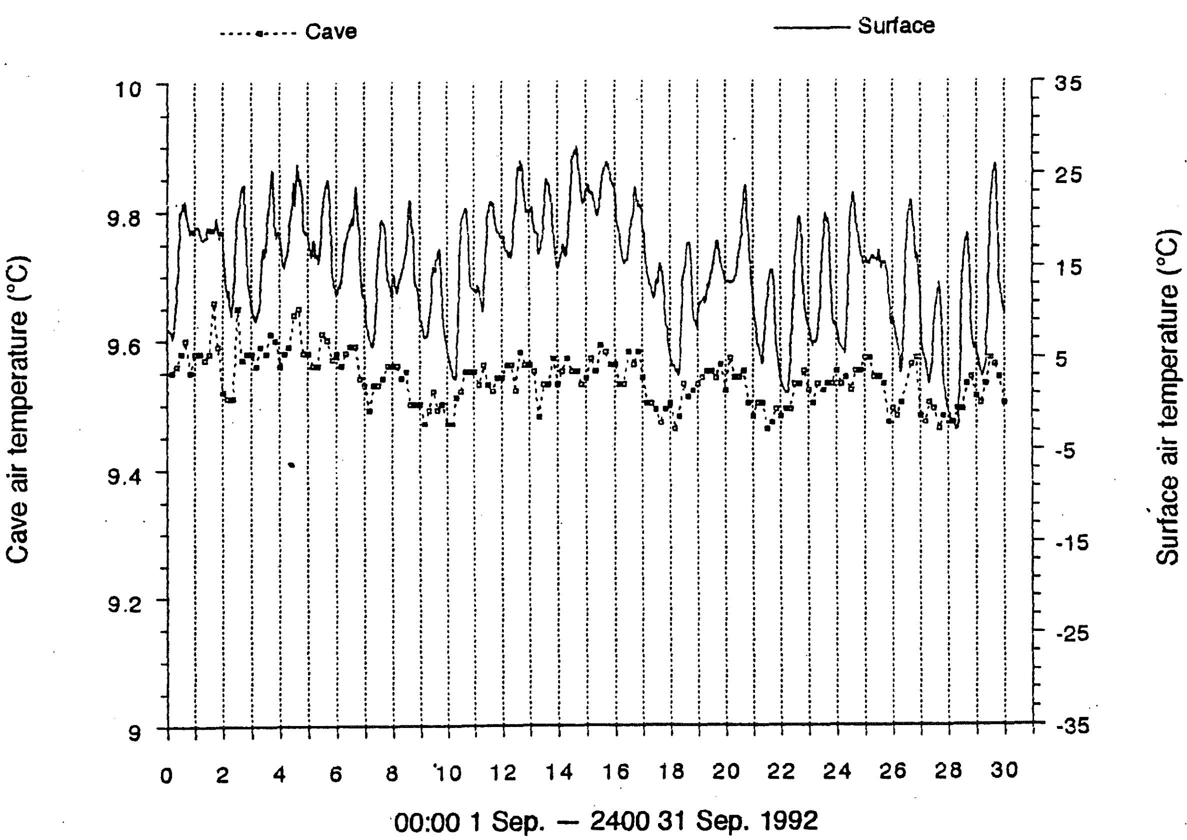


Figure D-3. Cave air temperature at Bomb Shelter and surface air temperature, August-September 1992.

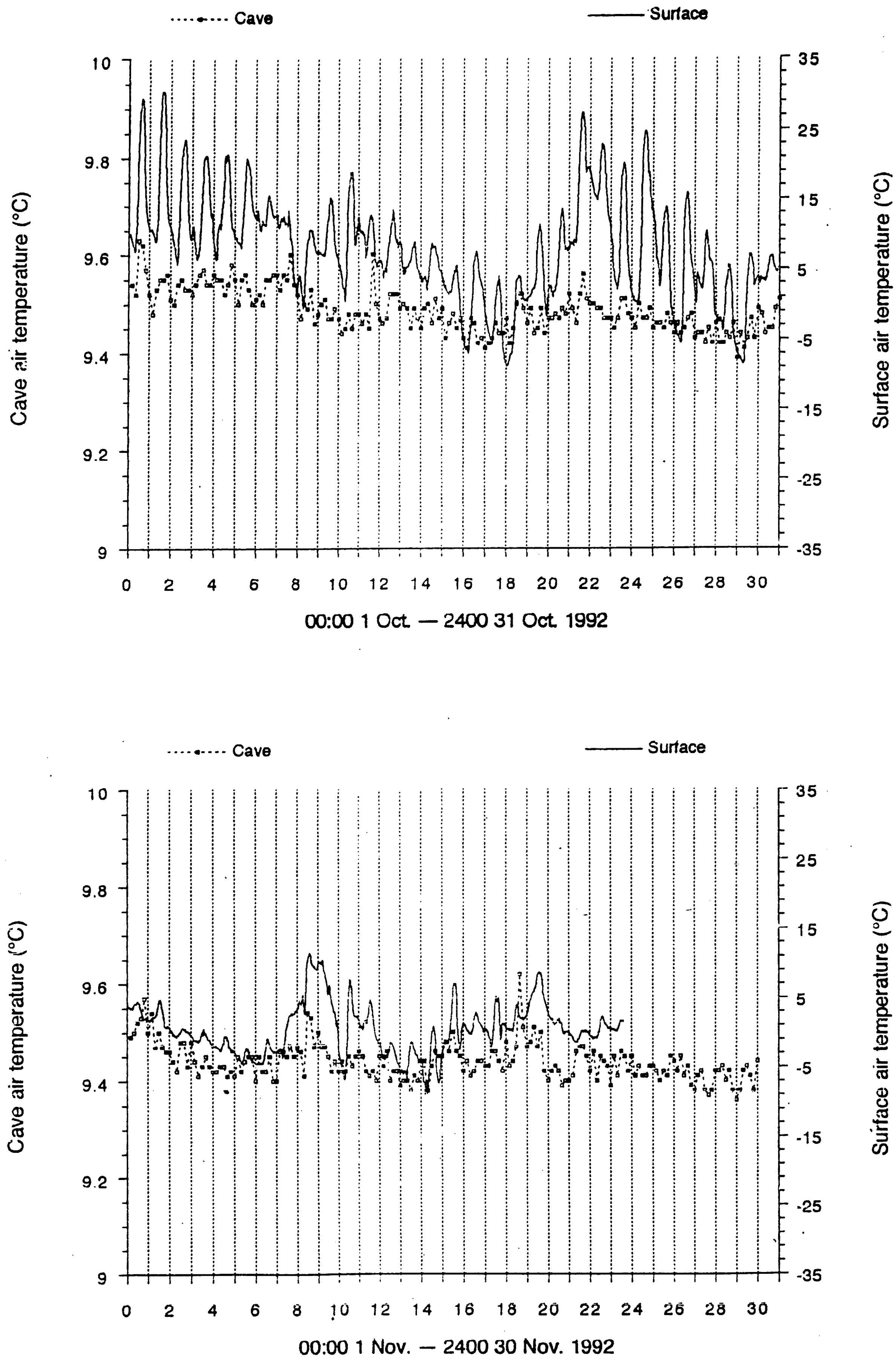


Figure D-4. Cave air temperature at Bomb Shelter and surface air temperature, October-November 1992.

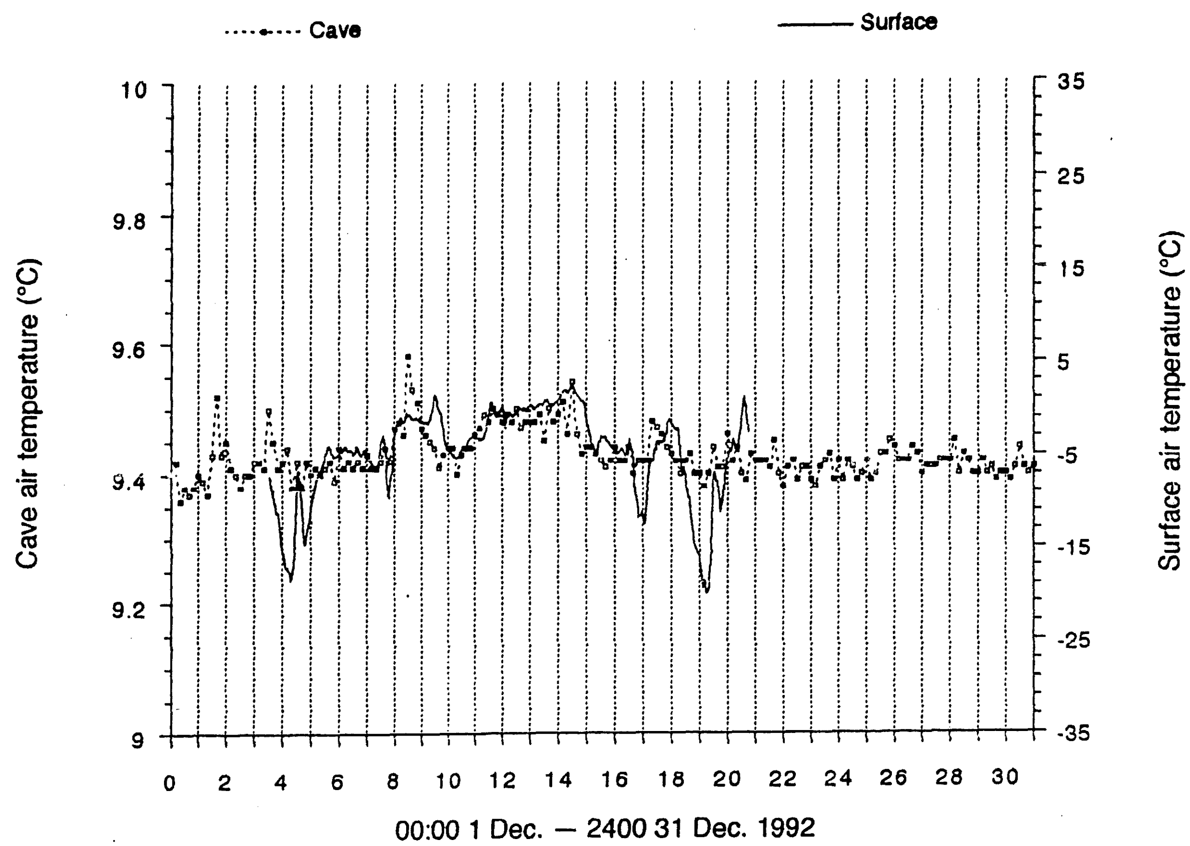


Figure D-5. Cave air temperature at Bomb Shelter and surface air temperature, December 1992.

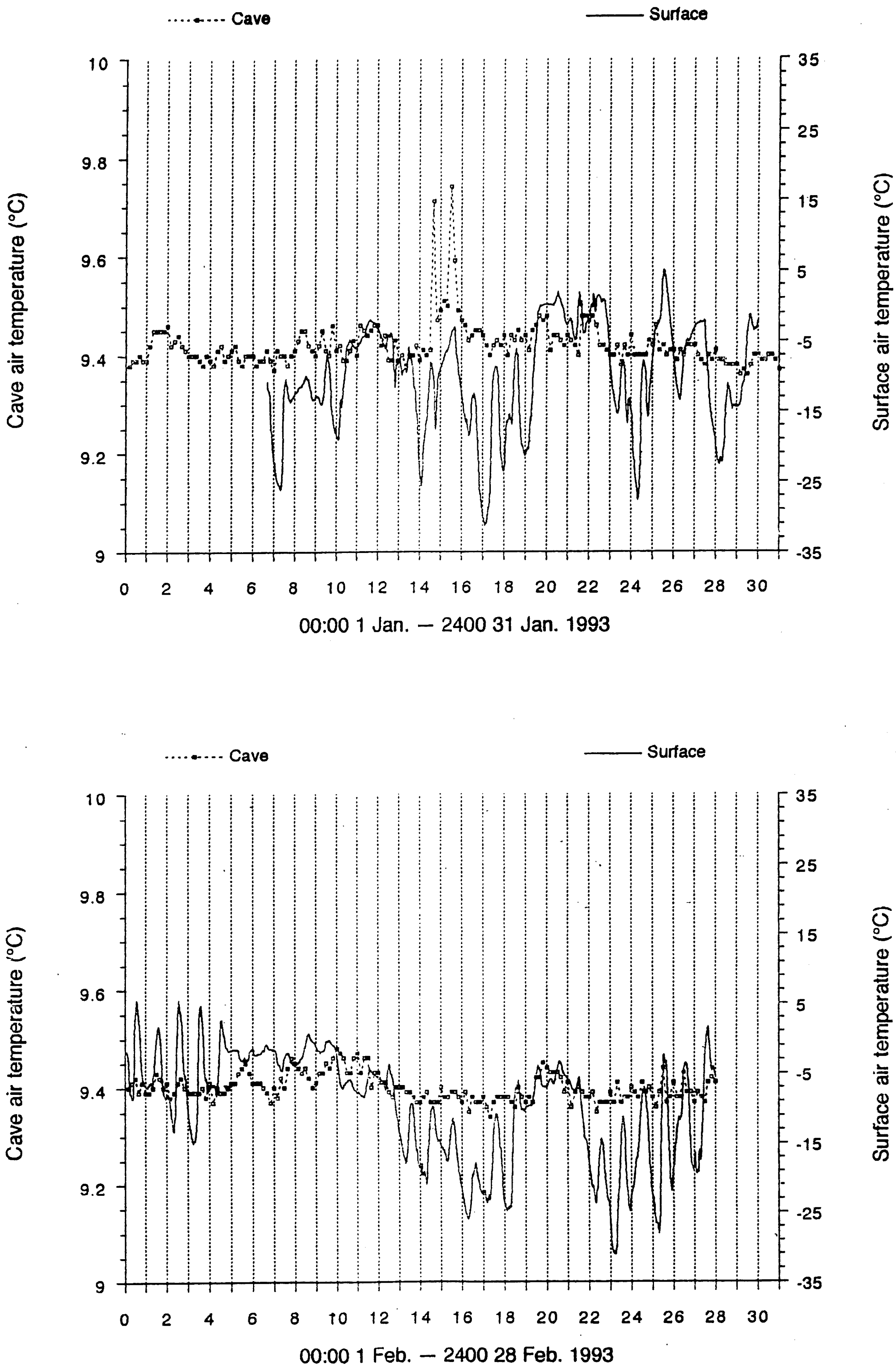


Figure D-6. Cave air temperature at Bomb Shelter and surface air temperature, January-February 1993.

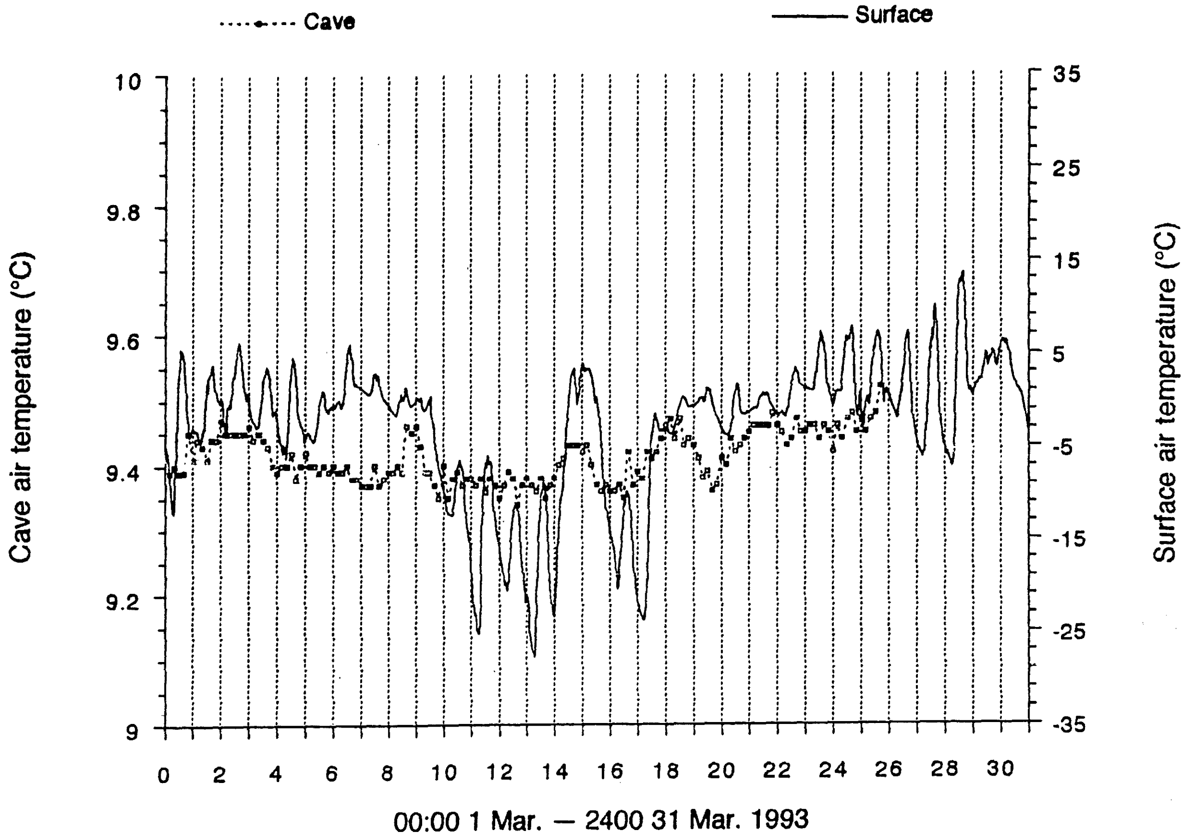


Figure D-7. Cave air temperature at Bomb Shelter and surface air temperature, March 1993.

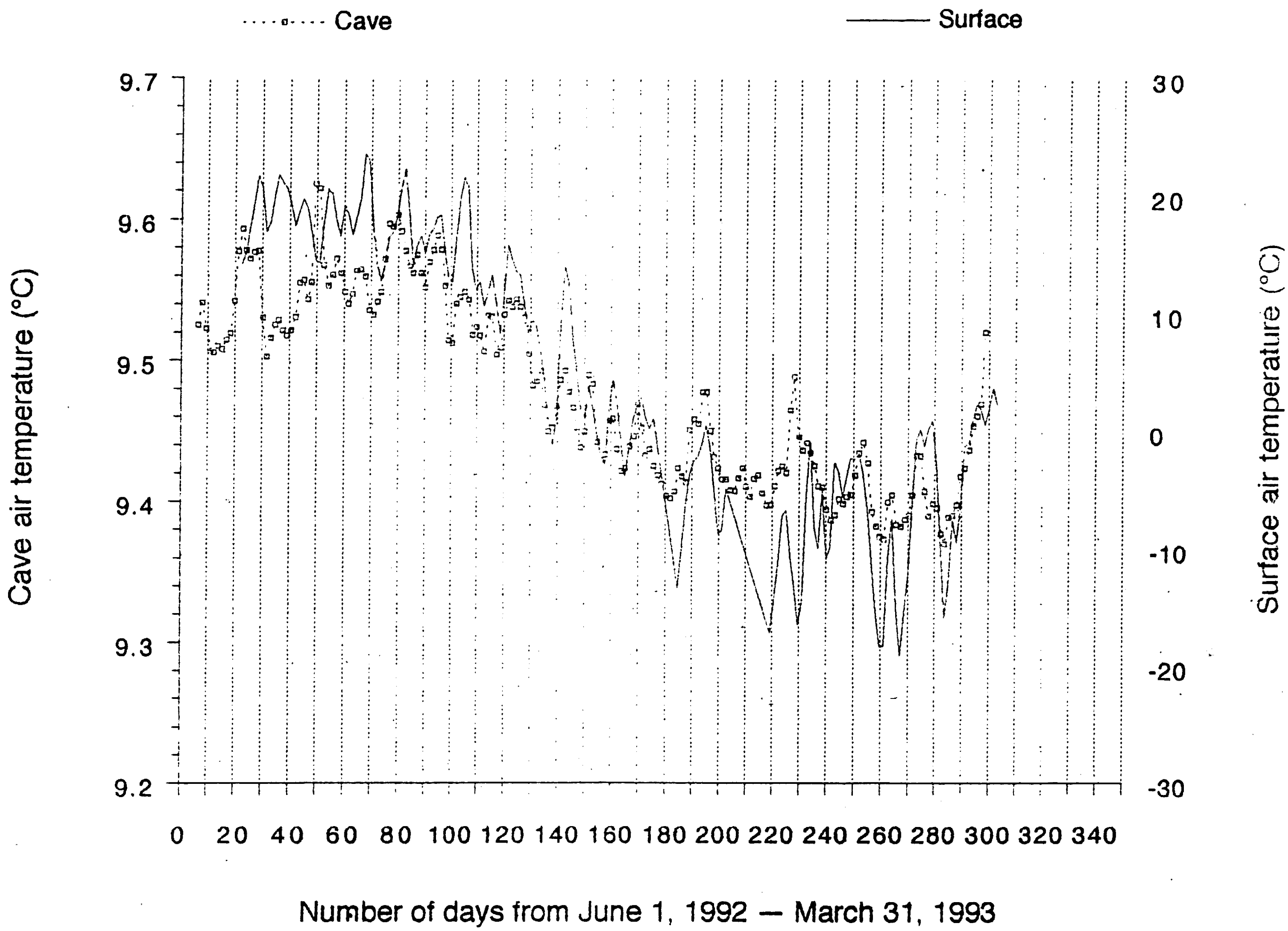


Figure D-8. The 3-day average cave air temperature at Bomb Shelter and the 3-day average surface air temperature, June 1992 - March 1993.

APPENDIX E. AIR FLOW MONITORING – DESCRIPTION AND RESULTS

Air velocity and direction estimates

Estimated velocities of air flow were obtained at several location in Mystery Cave in 1991 (Figures 3,4,5), using a TSI hot-wire anemometer (Model 1650). This was part of the 1990-1991 report but is included here as Table E-1.

Another device, a low-flow mass air flow sensor manufactured by Honeywell, was placed at the Bomb Shelter and connected to the data logger. The device was placed inside a 1 inch pipe and located parallel to the cave passage to provide a measure of the wind direction over time. Results from this device were not included because the low flow rates could not be reliably measured and we were not able to interpret the small perturbations the device recorded.

PFT measurements

Ventilation rates in several cave systems have been measured using a variety of techniques. These have included velocity profiles at the cave entrance and extrapolation of the profiles to the interior; tracer gas releases to measure air flow between cave systems or between the cave and the outdoor environment; and short-term measurements at discrete locations within a cave system. Air flow rates ranging form 0-40,000 cubic feet per minute (cfm) at Carlsbad Caverns (Mclean, 1971; Wilkening, 1976) to 0.5-12 cfm at Altamira Cave in Del Mar, Spain (Quindos, 1987) and 0-75,000 cfm at Mullamullang Cave in Western Australia (Wigley, 1967) have been determined. For comparison, outdoor air brought into a commercial building by a ventilation system is around 10,000 cfm and houses range from 30 to 600 cfm.

Air exchange and seasonal air flow patterns in Mystery were studied by using passive perfluorocarbon tracers (Dietz, 1986). This technique developed by Brookhaven National Laboratory (BNL) was first used to evaluate and track stack emissions. It was later modified to monitor building ventilation and air exchange systems.

The cave study involved placing perfluorocarbon tracer (PFT) sources with unique signatures at selected locations. The PFT source is a small permeation tube which at a given temperature emits the PFT vapor at a constant rate. During a sampling interval, air was passively collected at many locations with capillary absorption tube samplers (CATS). The CATS is a small glass tube containing a charcoal-like absorbent with one end open to the cave air. Each CATS provided a measure of the amount and type of tracer that reached that location in the cave. The PFT sources were left in the cave for the entire year, the CATS were placed in the cave for intervals of 2+ weeks. CATS were shipped to BNL for analysis using a gas chromatograph.

Five separate sources were placed in the Mystery Cave system to obtain information on air exchange within major developed areas. The location, type of source and source strength are shown in Table E-2. Map locations for the sources and the CATS are shown on Figure 2. Sources and CATS were placed in the cave at about a 45° angle from the vertical to minimize condensation water at the permeation and collection ends of the tubes. The tubes were placed off of the floor by at least 3 feet and were no closer to walls or ceilings than 6 inches. Two CATS were also placed outside of the cave system, one at Copmans Cave on the north side of Mystery and one at 7-Springs where the Root River resurges (approximate locations shown on Figure 1). All of the sampled location are listed in Table E-3, however not everyone was used each time.

The results of the PFT measurements are shown in Figures E-1 to E-20. Concentrations (picoliters of PFT/liter of air), were normalized to the emission rate of the PFT before isopleths were drawn. The normalized values (hours/liter) allow for more comparable results. Note that most of the Door to Door route has been deleted from the maps to show the results from both caves simultaneously. Sampling periods emphasized the summer and winter cave environments. Blanks (CATS place in the cave but not opened), gave zero or near zero results, and replicate CATS were comparable. CATS locations shown without an associated numeric value were not sampled at that time. The two CATS from outside Mystery cave were not included, however they did collect small quantities of each tracer source during the exposure interval. These CATS also were in areas where surface air may have caused significant dilution.

Relatively higher concentrations indicate that more air, carrying a particular PFT, had passed one collector relative to another. It should be remembered that the tracers were limited to present and former commercial tour areas and nearby sections of 4th and 5th avenues. This represents only a fraction of the total cave volume and limits the interpretation placed on air flow results.

On the north side of the cave, the source at Base Camp appears to have the most limited range. During June 1992 and May 1993, the tracer moved both north and south of the source with nearly equal strength. Once south of the Base Camp, the PFT was carried mostly west into 4th and 5th avenues. Minor amounts were moved east toward Garden of the Gods or south into Mystery I, but were not principal flow directions. In November 1992 and January 1993, the pattern shifted dramatically from the summer. Concentrations of PFT were elevated only north of Base Camp. This suggests two possibilities, flow was only to the north in winter or northward moving air diluted any southbound PFT.

The PFT source in 5th avenue showed trends similar to those at Base Camp. Flow was predominantly west along 5th avenue, and east-northeast toward 4th avenue and into Base Camp. The tracer was more widely dispersed in the summer versus winter. Minor amounts of tracer moved toward Garden of the Gods and Mystery I. June 1992 showed more flow toward 17-Layer Rock than occurred in May 1993. In November and January, most of the air flow was to the west, although November 1992 had a little more east-northeast movement. In neither month did significant air move toward Mystery I. As above, dilution is also a possibility.

The PFT source at Angel Loop, although not far removed from the one at 5th avenue has a more complex pattern. The seasonal difference between the flow patterns was less, but there was a substantial reduction in wintertime concentrations near the source. Each measurement period showed similar levels of air flow to the northeast into Base Camp and west into 4th and 5th avenues. Significant levels of Angel Loop tracer were also collected at Garden of the Gods. This was contrary to the Base Camp and 5th avenue sources because they gradually decreased to the east. The Angel Loop PFT was also more concentrated at Garden of the Gods than at intermediate sites during all four tests. This implies that air going between Angel Loop and Garden of the Gods may be bypassing some of 5th avenue. Alternatively, the low concentrations near 17-Layer Rock could indicate an entry of surface air, causing localized dilution of the PFT. However, this would be expected to create a similar pattern for the PFT's from 5th avenue and Base Camp. They do not show the low concentration saddle. Another odd feature was that during the summer, relatively less tracer appears to reach Mystery I from the Angel Loop source than from either 5th avenue or Base Camp.

The source at Garden of the Gods also developed a seasonal distribution pattern. The unusual aspect of this pattern was that during November 1992 and January 1993 the strongest connection was to the Bomb Shelter in Mystery I. The tracer does not appear to have moved through 5th avenue or Door to Door route to reach the Bomb Shelter. In January 1993, the concentration at Bomb Shelter was higher than near the source and about twice the other areas in Mystery II. Concentrations of the Garden of the Gods tracer were low near the entrance at Mystery I. This, as it did above could indicate lack of movement in that direction or dilution by air more frequently moving the other way. The GOG tracer appears to have moved northeast from Bomb Shelter through the Door to Door route (see Figure E-10, November 1992). A low concentration saddle was visible near 17-Layer Rock, but in this instance the suggested explanation is that some of the PFT entering the Angel Loop area from Bomb Shelter also dispersed toward 17-Layer rock. Some may even have completed a loop and returned to Garden of the Gods. In January 1993, (Figure E-15) there was also a low saddle near 17-Layer Rock. Because overall concentrations were lower, a connection between Mystery I and the Angel Loop area in Mystery II was less easy to visualize. In June 1992 and May 1993, air moved west along 5th avenue from Garden of the Gods in a fairly uniform distribution and concentrations of PFT reaching the Bomb Shelter were equivalent to or less than those at the other sites. The connection visible in winter was not apparent.

The fifth PFT source was in Bomb Shelter in Mystery I. Like the others, this tracer showed a seasonal variability. This source also showed a strong connection with the Garden of the Gods in Mystery II, again apparently bypassing the obvious connection through the Door to Door route and 5th avenue. The major difference was that this time, the connection occurred in the summer and the tracer moved in the opposite direction, from Bomb Shelter toward Garden of the Gods. The Bomb Shelter source also showed a distinct eastward movement toward the Mystery I entrance, but only in June and May. This could correspond with the minor summer flow observed between Mystery II and Mystery I of the PFT sources in 5th avenue and Base Camp.

Bomb Shelter concentrations at the source were also significantly lower in the winter than during the summer. The November and January Bomb Shelter results were low both near the source and throughout the cave. These seasonal changes in concentration are attributed to dilution. Higher values in Mystery II indicate that during the winter, surface air was moving past the Bomb Shelter toward Mystery II both diluting the source and carrying it into Mystery II. This would be consistent with the direction of winter air motion (north and northwest) seen from the sources north of Bomb Shelter. The high value of 11.07 for January 1993 (Figure E-14) was extremely anomalous relative to the other values and was considered to be an analytical error.

These PFT air flow results were not directly comparable to the one-time measurements made with the hot-wire anemometer (Table E-1) because of the difference in time and the scale of coverage. However, both types of measurements provided evidence of time dependent variations.

Air exchange estimates

Rough estimates of air exchange rates and net volume exchange between different zones in the cave were made using the measured PFT concentrations. This was done by defining a set of zones, (shown by the example in Figure E-21), and using the different perfluorocarbon results to calculate air flow between the zones.

From the following source strengths and concentrations measured at three locations in the cave, the air flow rate in cubic feet per hour ($ft^3\ h^{-1}$) between these zones was estimated.

Location	Source Type	Source Strength nL/L	Sample Site	Concentration nL/L
Base Camp	PTCH1	0.117	Base Camp	0.417
			Angel Loop	0.204
			5th Ave.	0.092
5th Avenue	ocPDCH	0.209	5th Ave.	0.454
			Angel Loop	0.295
			Base Camp	0.171
Angel Loop	ptPDCH	0.281	Angel Loop	1.270
			Base Camp	0.367
			5th Ave.	0.129

The air flow rate between these zones becomes:

Flow from zone to zone	cubic feet/hour
Base Camp - Base Camp*	10,000
Base Camp - Angel Loop	20,000
Base Camp - 5th Ave.	45,000
5th Ave. - 5th Ave.*	16,000
5th Ave - Angel Loop	25,000
5th Ave - Base Camp	43,000
Angel Loop - Angel Loop*	35,000
Angel Loop - Base Camp	27,000
Angel Loop - 5th Ave	77,000

*These values indicate the rate at which the air in the source zone was affected by flow.

From these calculated values, the net flow into 5th Avenue was 70,000 $ft^3\ h^{-1}$, the net flow into base Camp was 15,000 $ft^3\ h^{-1}$, and the net flow out of Angel Loop was 23,000 $ft^3\ h^{-1}$.

This procedure could also be expanded to other regions of the cave system and include the other PFT sources.

Table E-1. Measured airflow rates in Mystery I and II, September 14, 1991.

Location	Airflow (ft/min.)
Mystery I	
Entrance into Door-to-Door from Bomb Shelter	
0.5' from ceiling	2-5 moving from II
0.5' above floor	15-80 moving from II
Mystery II	
5th Ave. 100 feet east of entrance	
Left side upper passage	12 max.
Right side crevice	
6' above floor	5-8
0.5' above floor	3
17-Layer Rock	
Center of passage, 7' above floor	11 max.
1 inch from left wall	0
Crevice at station	
Center 5' above floor	0
Center 3' above floor	5 max.
Crevice left of station	0
Entrance to Angel Loop from 5th ave.	
6' above floor	10
Angel Loop - Light switch beyond Carrot Sticks	1-2
Angel Loop Station area	
Entrance to 4th Ave	
1' from ceiling	2-8 moving north
1' above floor	13
Passage toward Bar	1-2
Crevices on east and south	2-20
In Passage from A.L. to Bar	
1' from ceiling	2-5 moving towards II
1' above floor	5-10 moving towards I
Connecting passage from 4th to 3rd	3-5
Hills of Rome, west side	1-2
Entrance into Diamond Caverns	4-5
Dome Room	1-5 moving to outside

Table E-2. PFT Source Type and Location

Location	Source Type	Source Strength nanoliters (nL)/hour
Garden of the Gods	P-methylcyclopentane (PMCP)	0.1227
5th Avenue	ortho-P-dimethylcyclohexane (ocPDCH)	0.209
Angel Loop	para-P-dimethylcyclohexane (ptPDCH)	0.281
Bomb Shelter	P-methylcyclohexane (PMCH)	0.810
Base Camp	P-trimethylcyclohexane (PTCH1)	0.117

Table E-3. Location of CATS Sampling Tubes

Mystery I
Entrance-Staging Room ceiling
First Passage-towards Needles Eye in floor grate
Formation Room-east rail
Bomb Shelter-south passage wall 10 feet before Bomb Shelter
Drop Down
Beyond Big Fork
Mystery II
MII entrance building above stairwell
Garden of Gods-handrail on steps
17 Layer Rock-crevice leading to Chinese Torture Chamber
Angel Loop-south wall
The Bar-rail
Blue Lake-rail on east side
5th Ave - just beyond crawl leading to Mystery Pool
5th Ave B-about 50 feet from mouth of passage
4th Ave - halfway to back of passage
4th Ave - 40 feet from mouth of passage
Base Camp-walking passage halfway to Base Camp
Base Camp-12 feet into crawl toward Enigma Pit
Outside Mystery Cave
Copman's Cave
7-Springs-crevice at S3

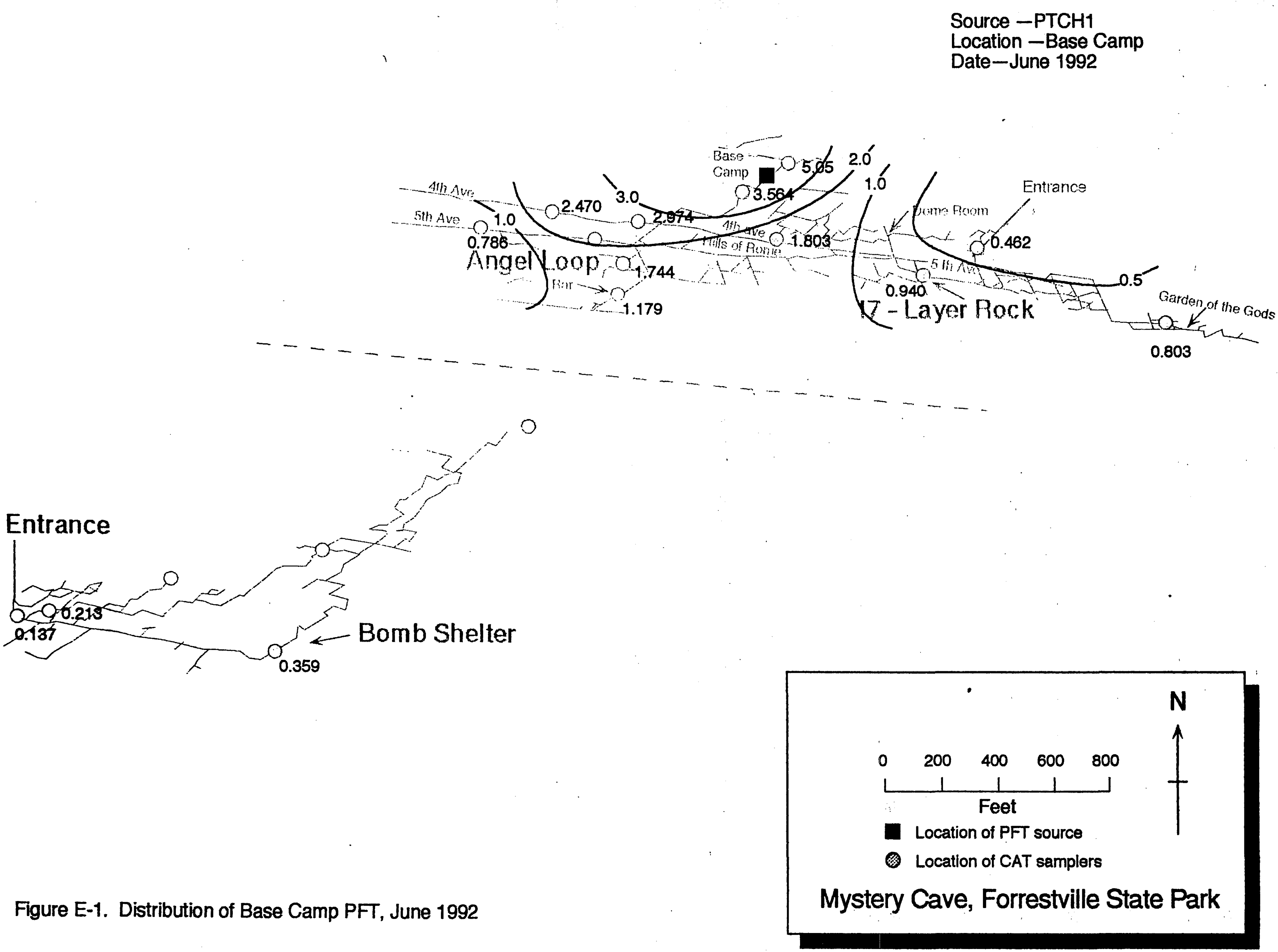


Figure E-1. Distribution of Base Camp PFT, June 1992

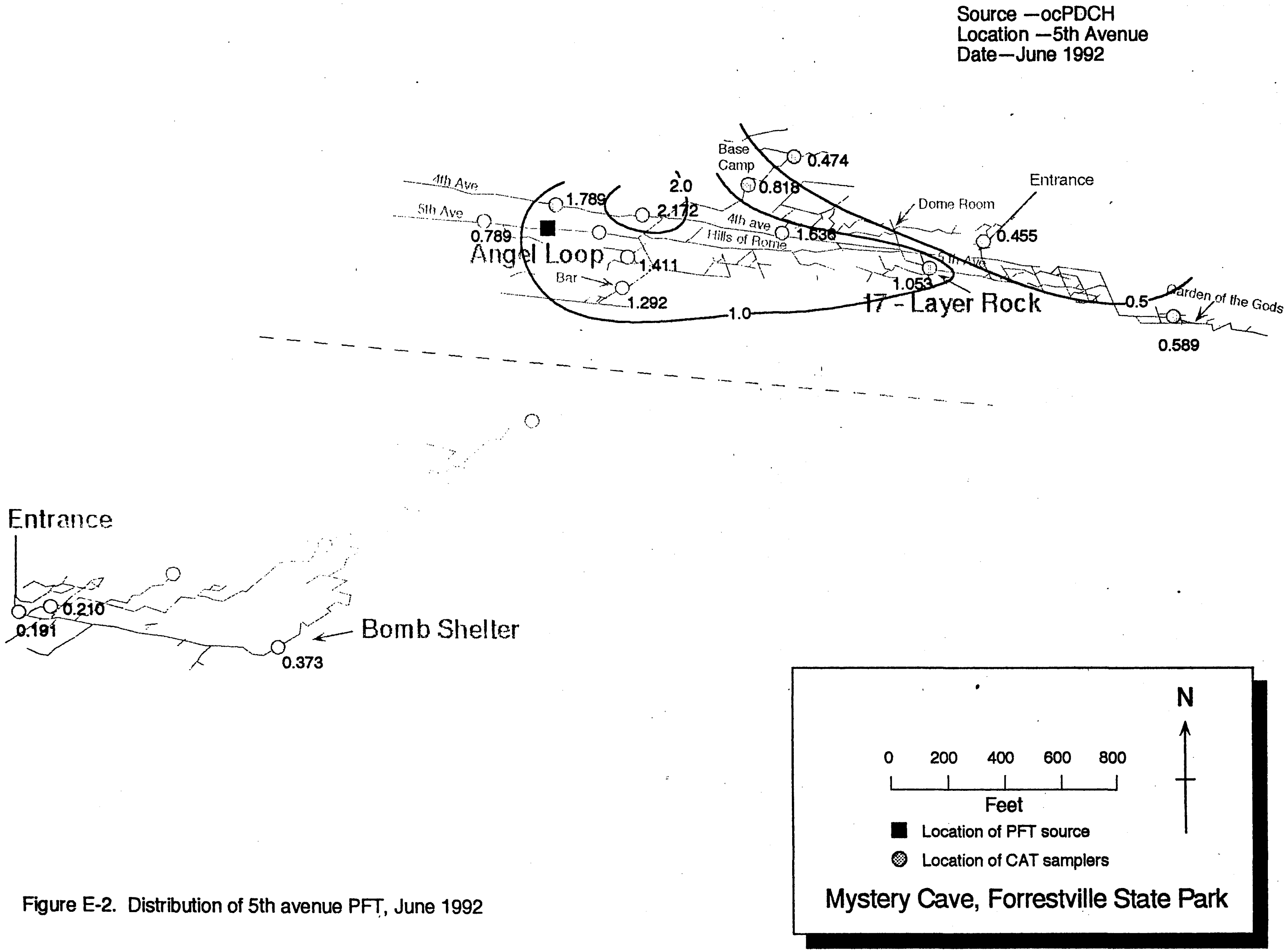


Figure E-2. Distribution of 5th avenue PFT, June 1992

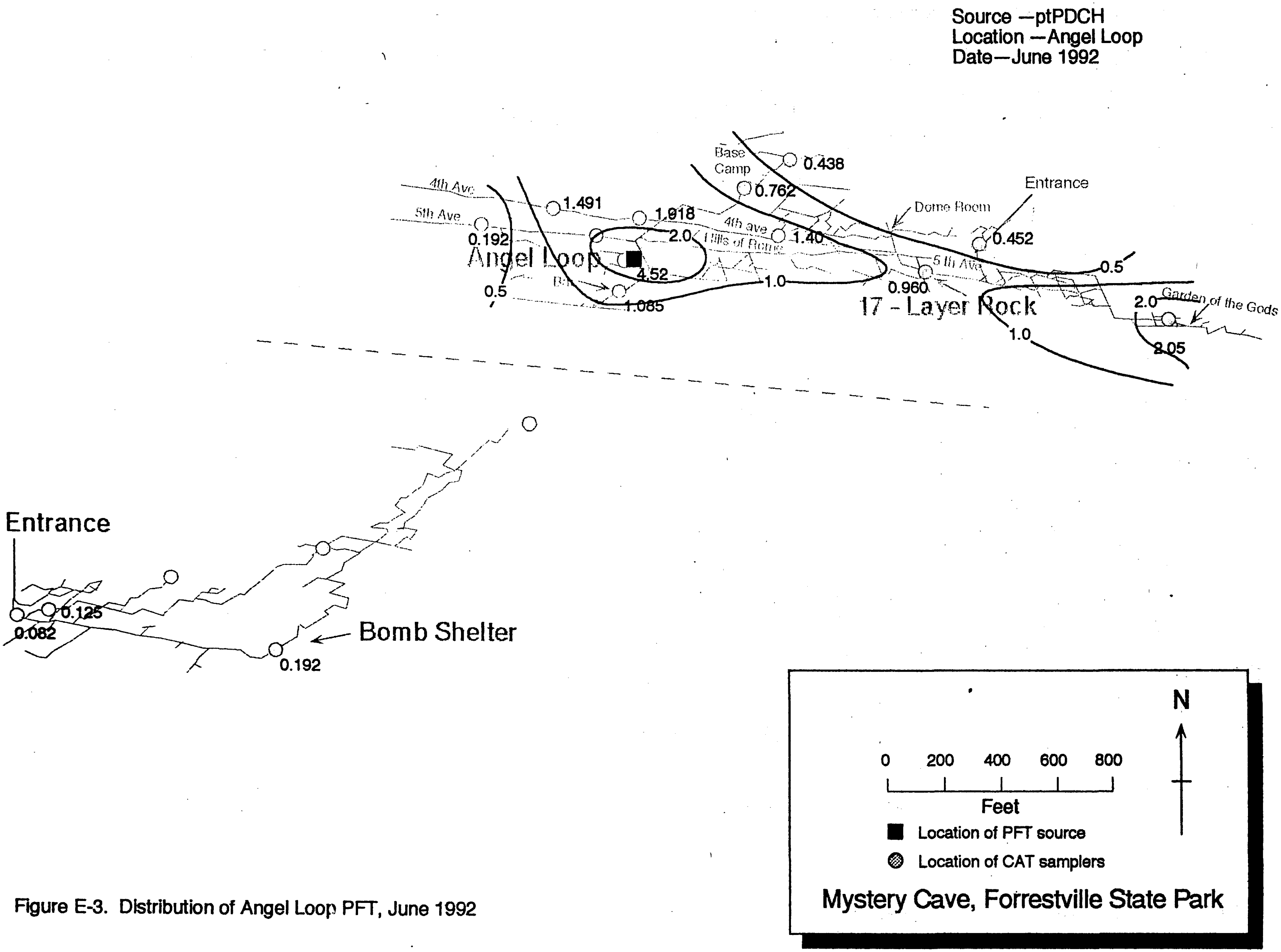


Figure E-3. Distribution of Angel Loop PFT, June 1992

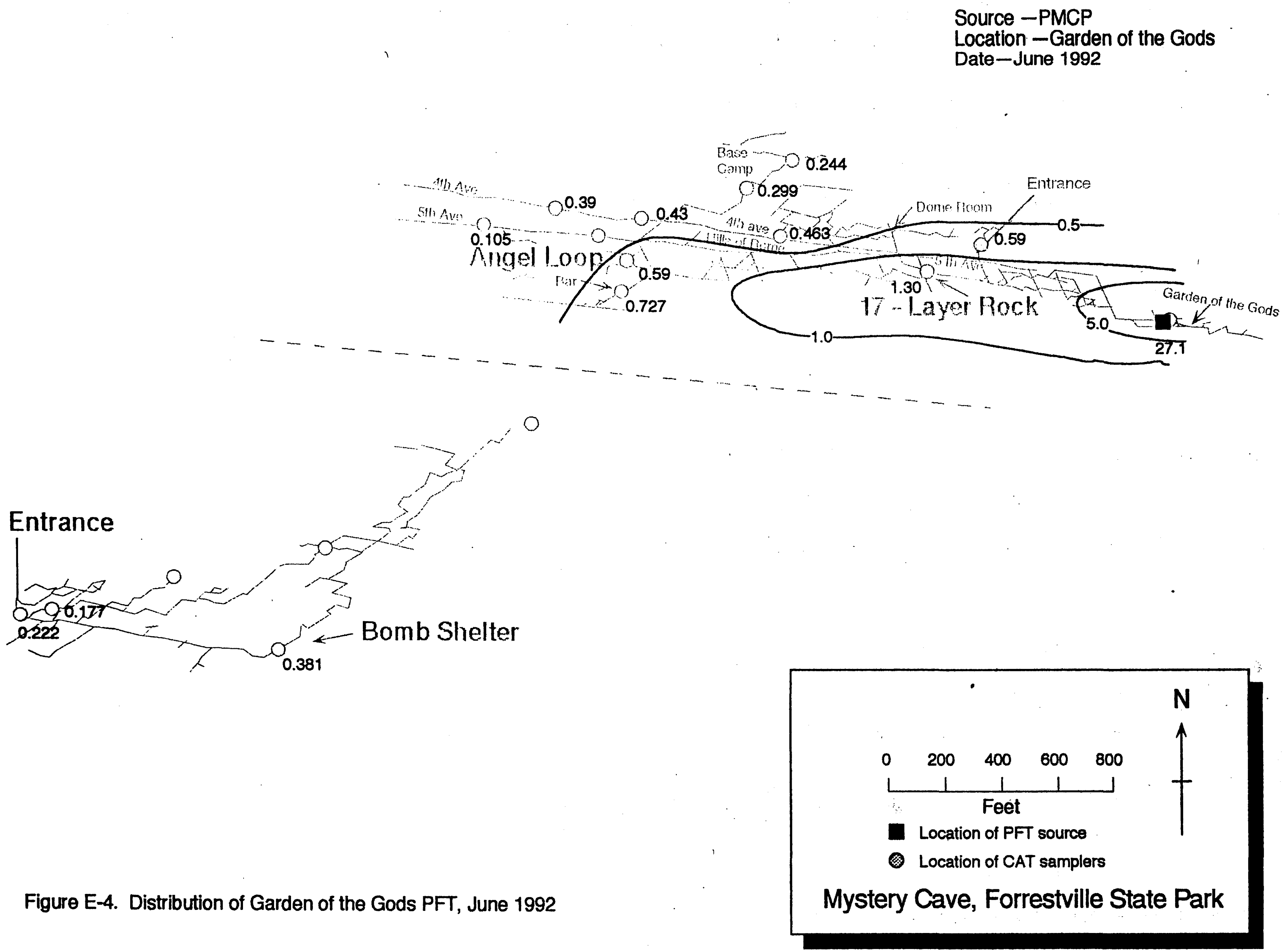


Figure E-4. Distribution of Garden of the Gods PFT, June 1992

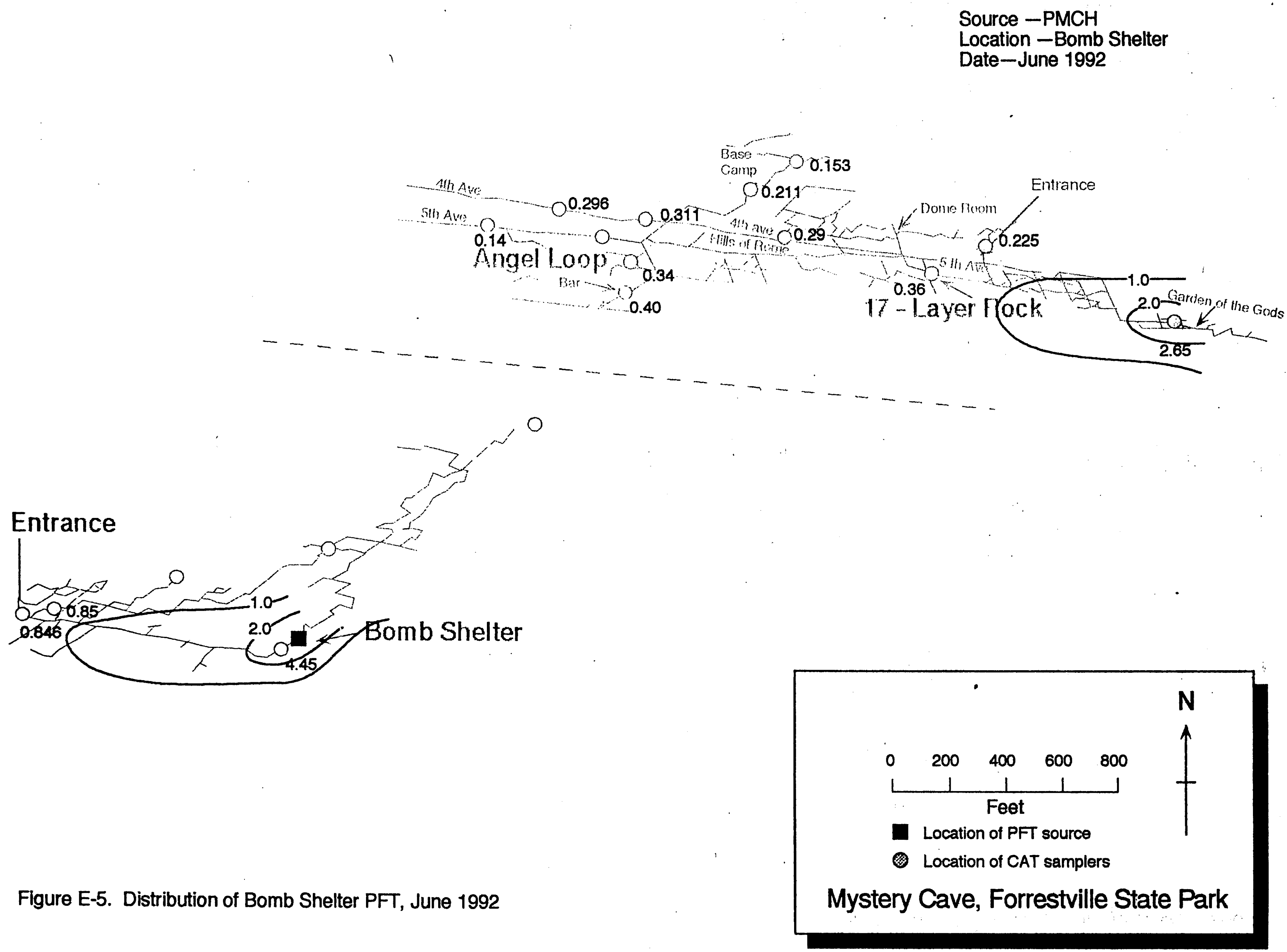


Figure E-5. Distribution of Bomb Shelter PFT, June 1992

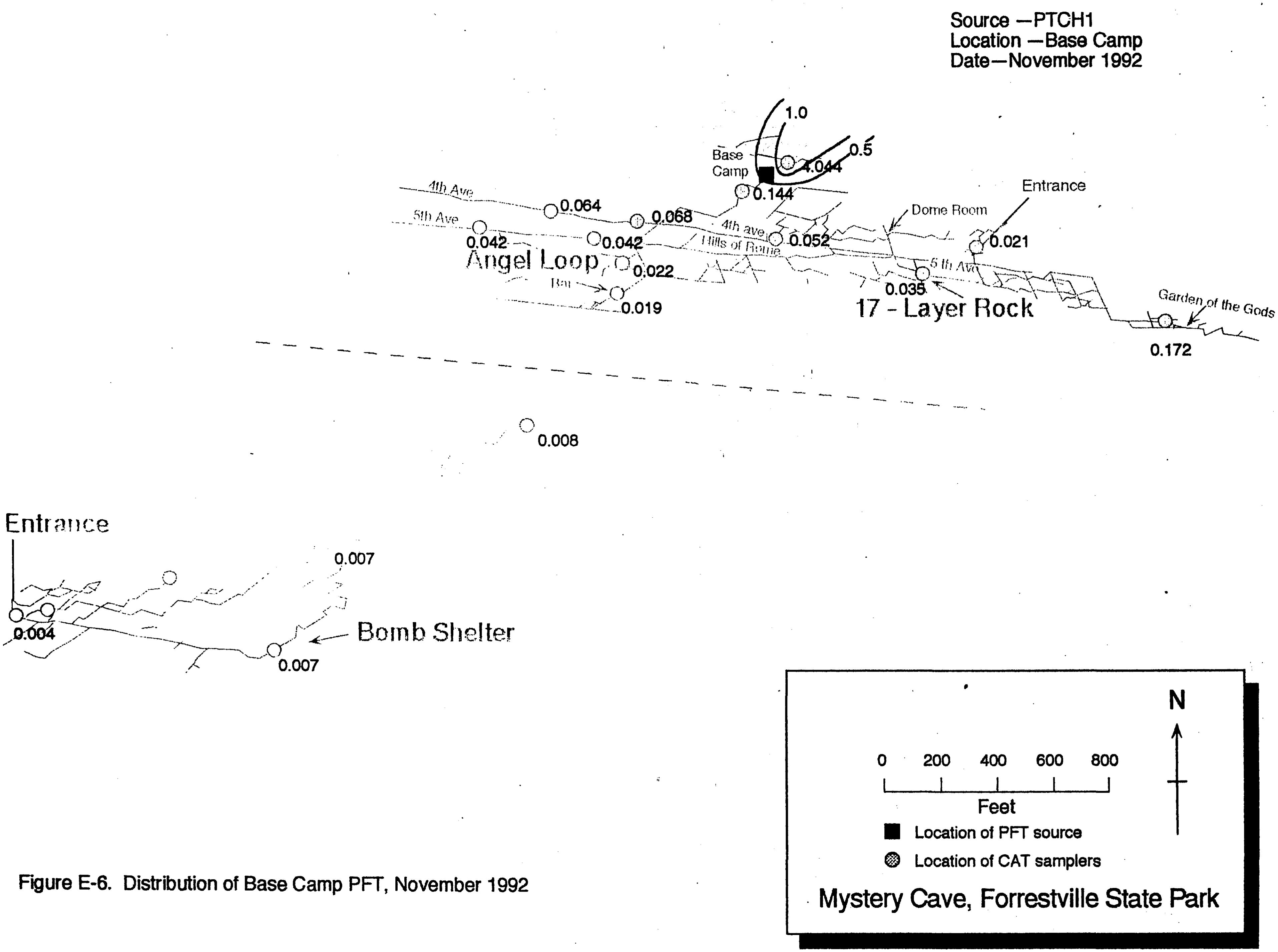


Figure E-6. Distribution of Base Camp PFT, November 1992

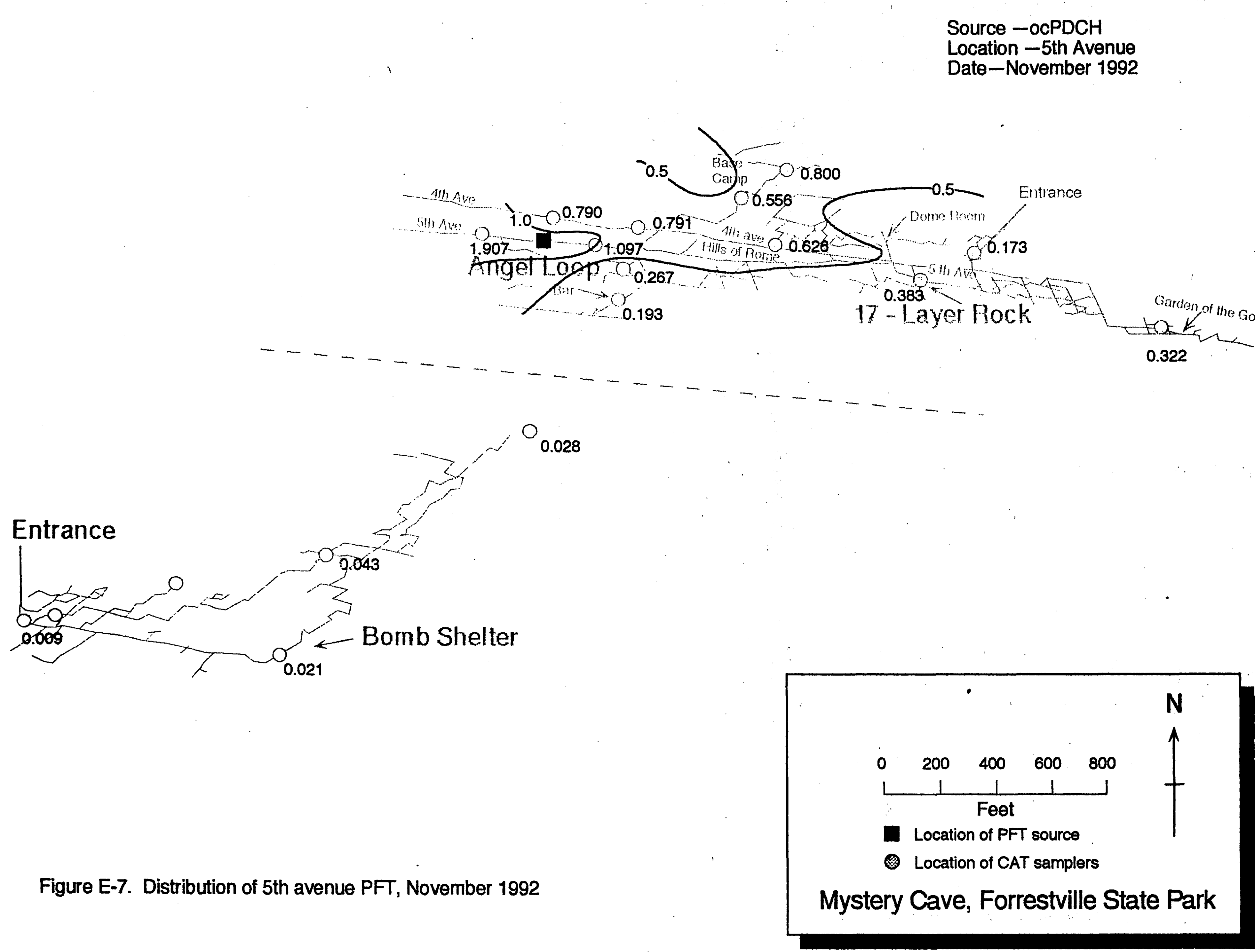


Figure E-7. Distribution of 5th avenue PFT, November 1992

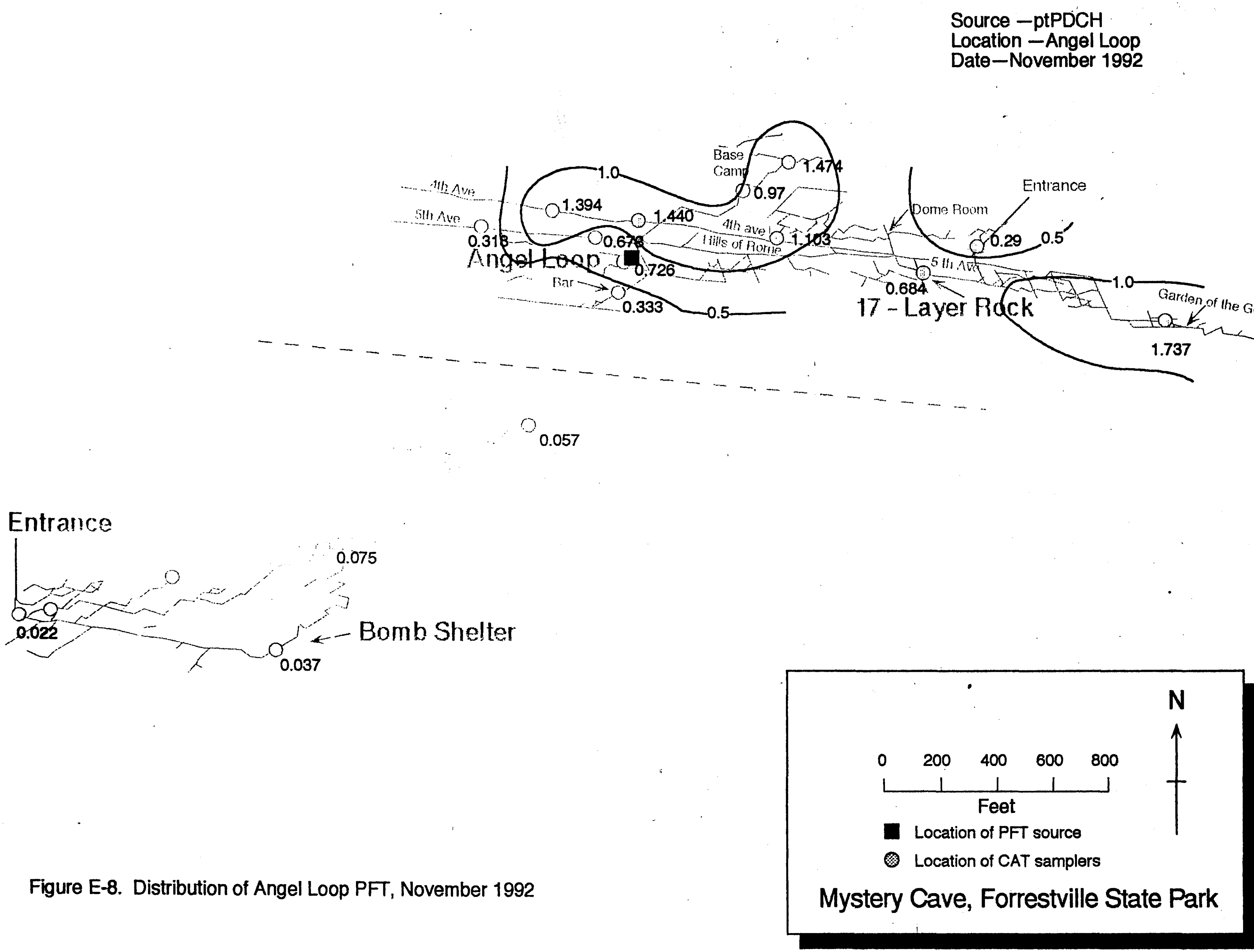


Figure E-8. Distribution of Angel Loop PFT, November 1992

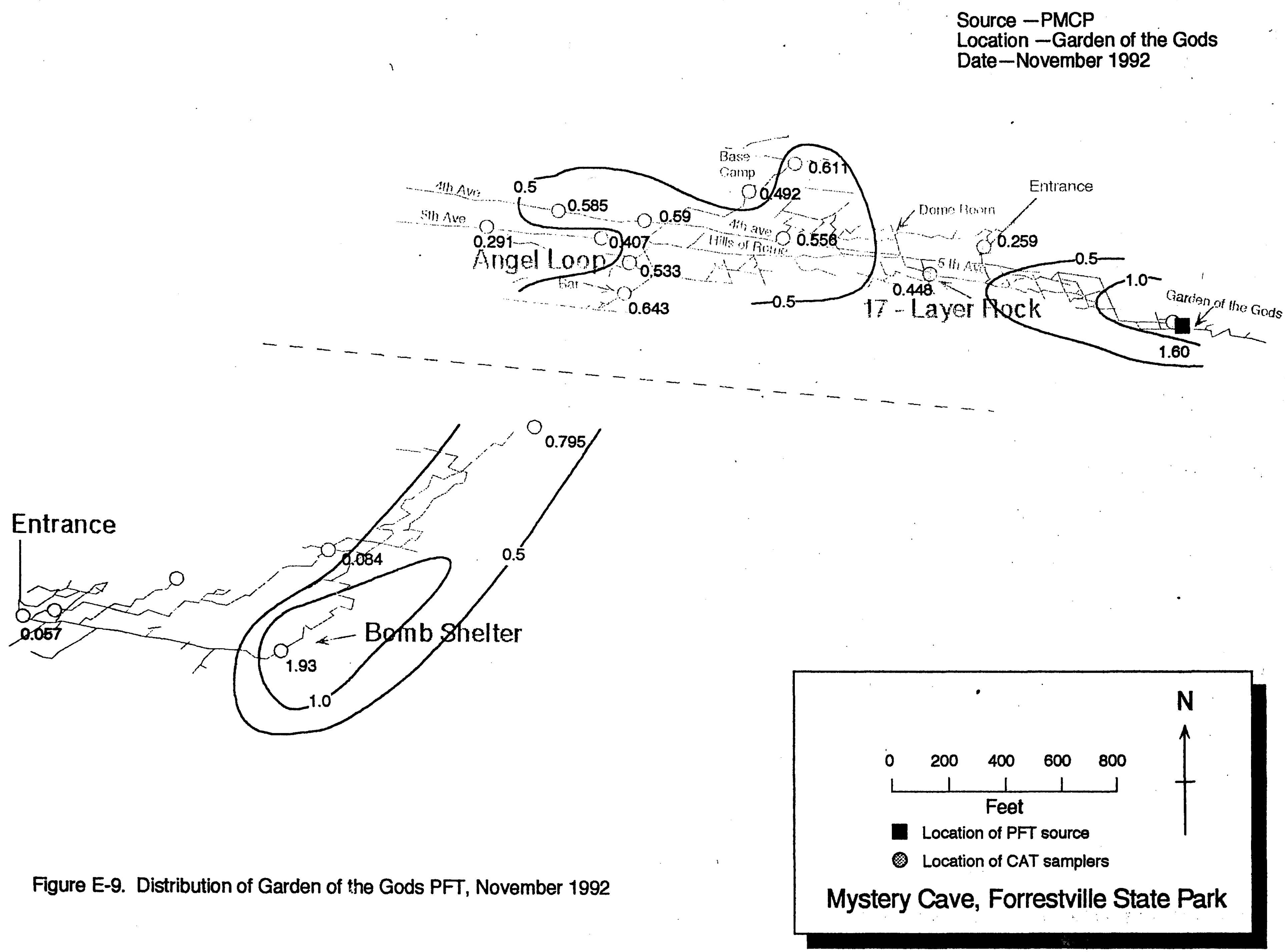


Figure E-9. Distribution of Garden of the Gods PFT, November 1992

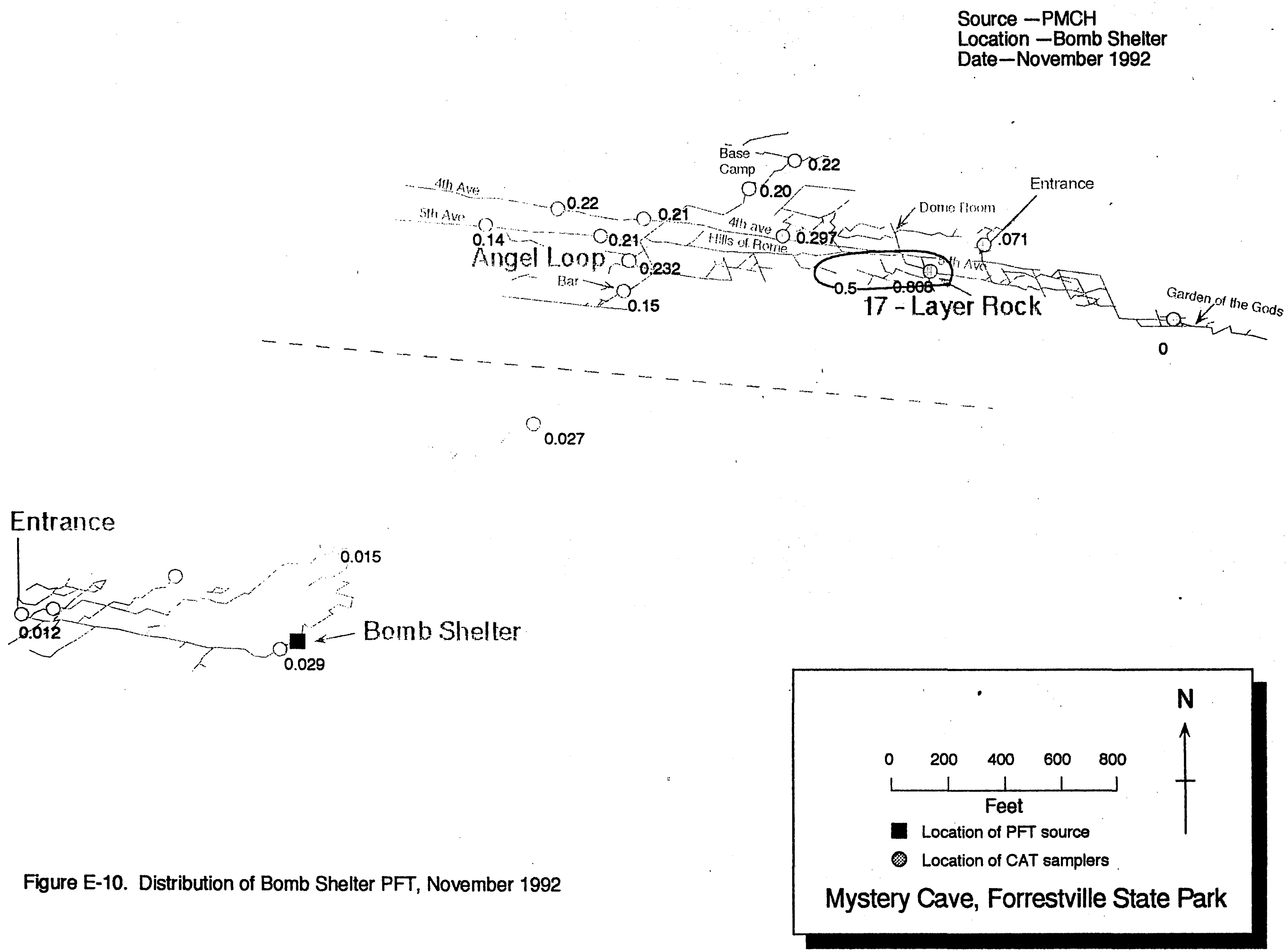


Figure E-10. Distribution of Bomb Shelter PFT, November 1992

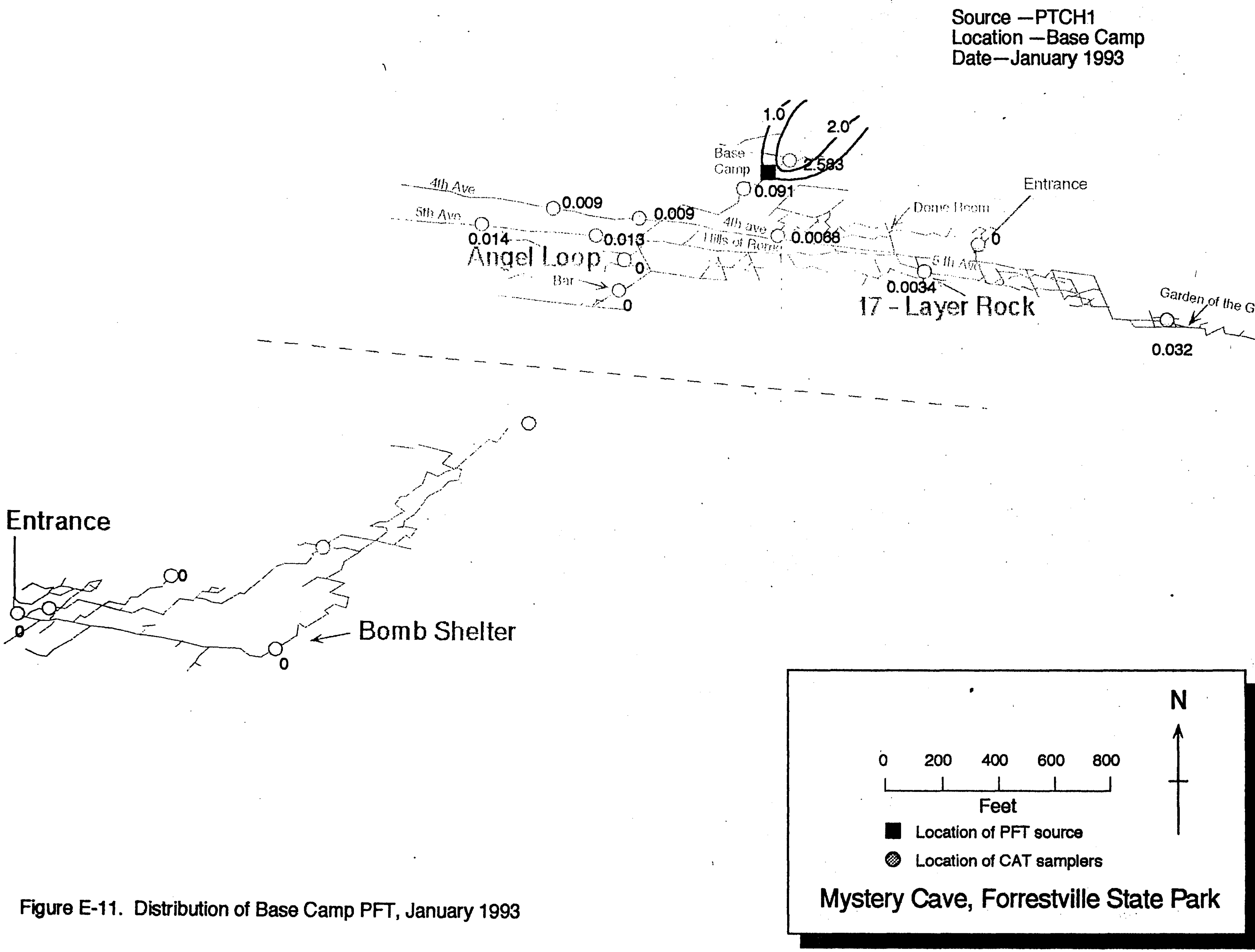


Figure E-11. Distribution of Base Camp PFT, January 1993

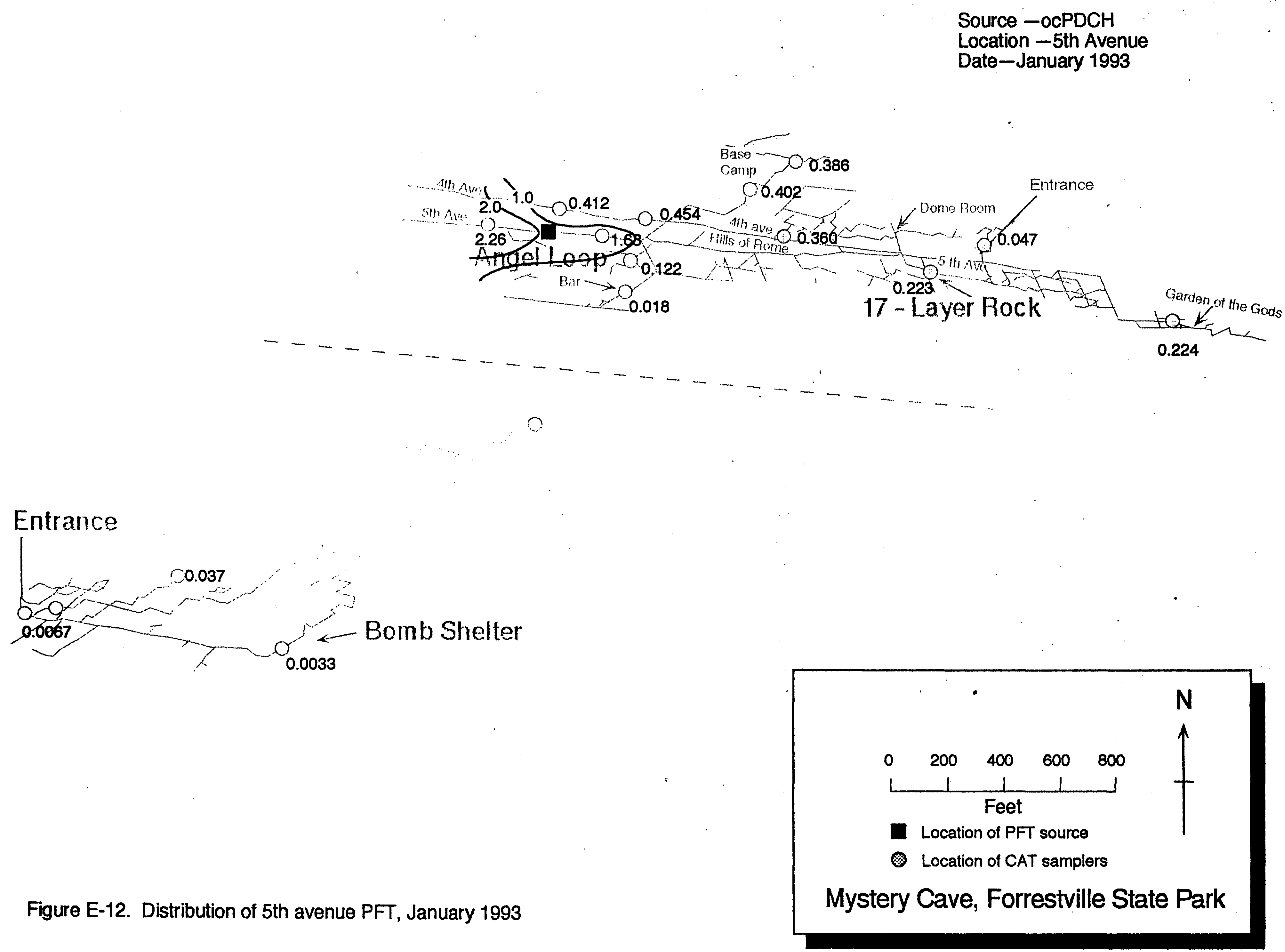


Figure E-12. Distribution of 5th avenue PFT, January 1993

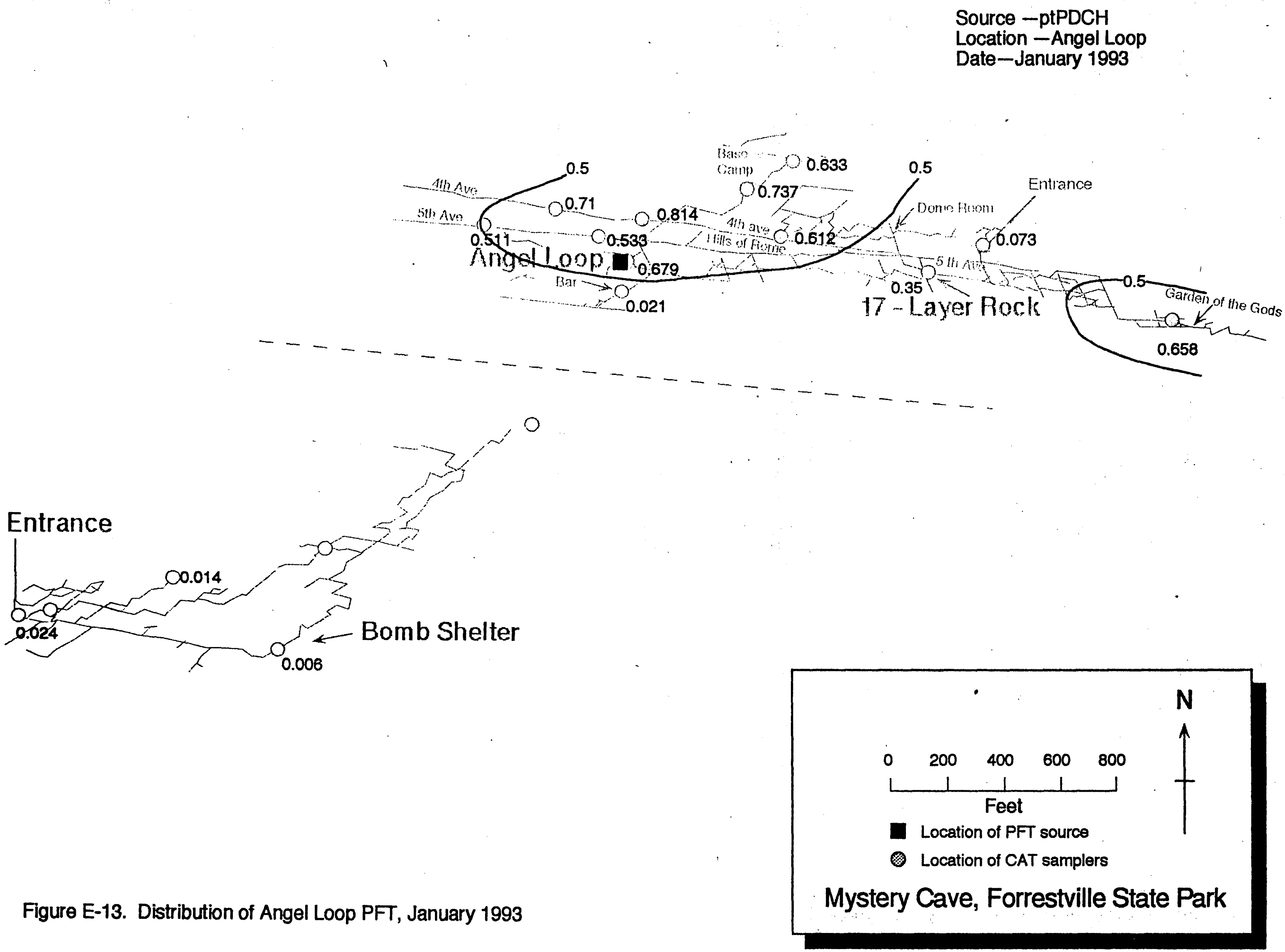


Figure E-13. Distribution of Angel Loop PFT, January 1993

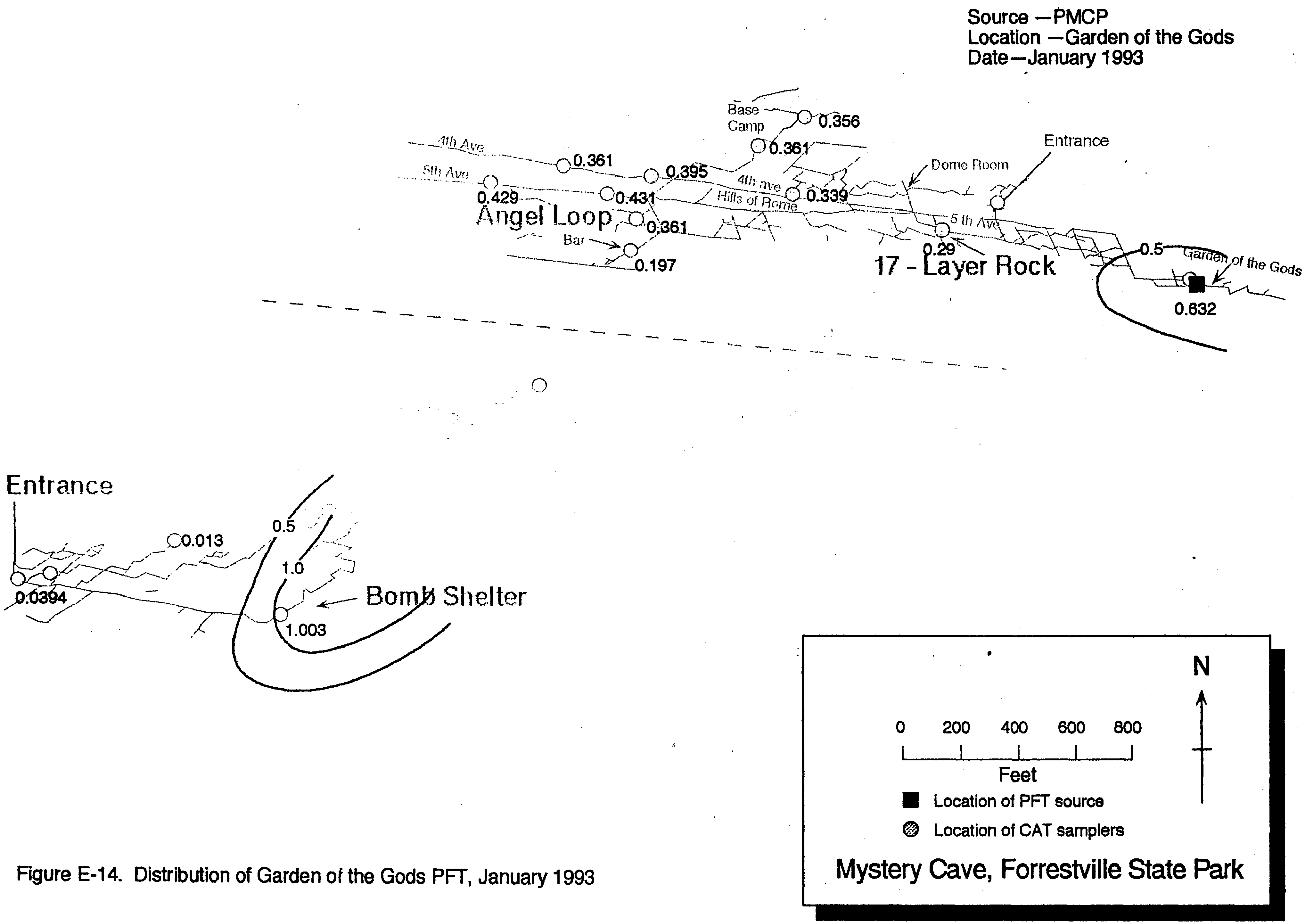


Figure E-14. Distribution of Garden of the Gods PFT, January 1993

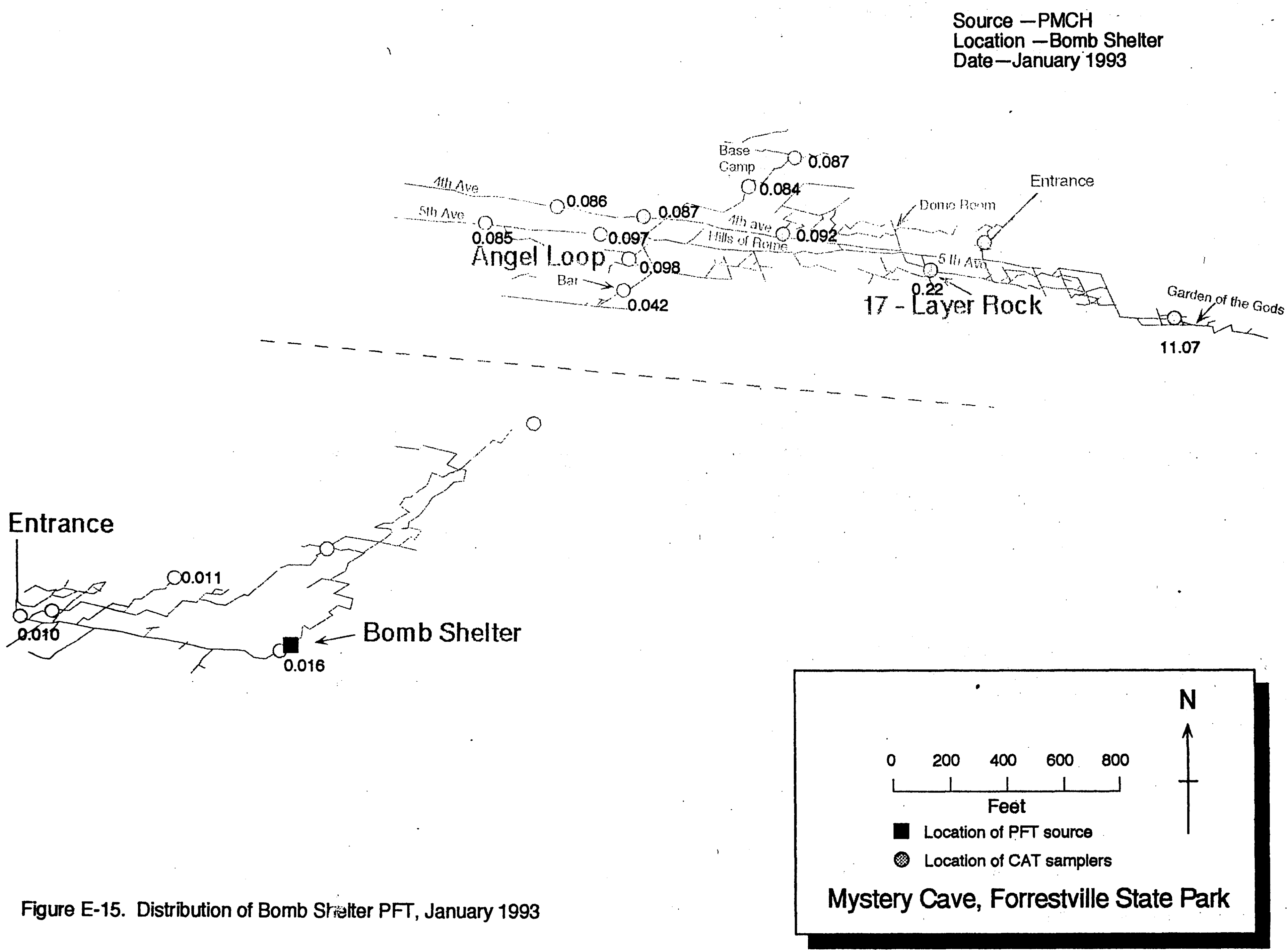


Figure E-15. Distribution of Bomb Shelter PFT, January 1993

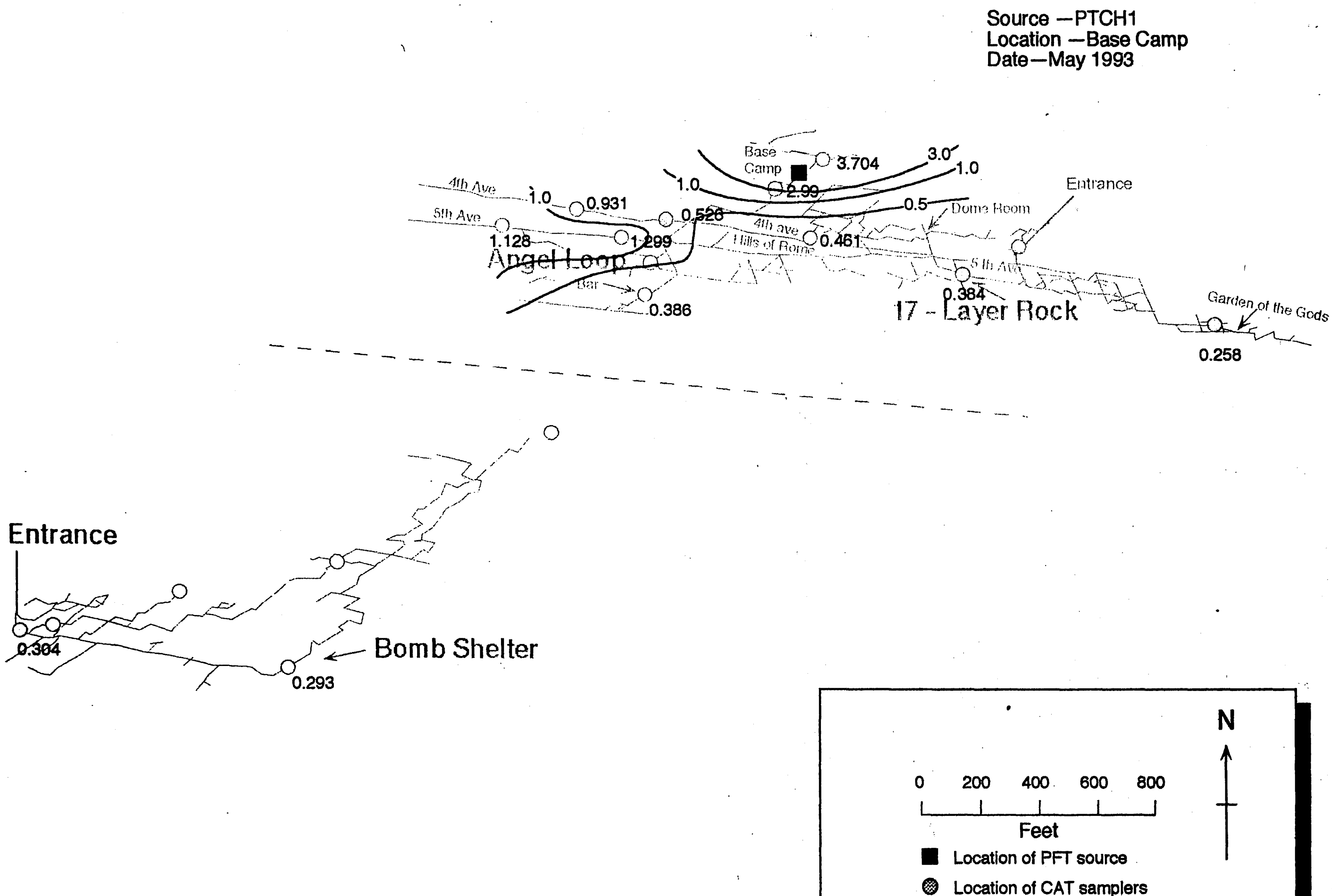


Figure E-16. Distribution of Base Camp PFT, May 1993

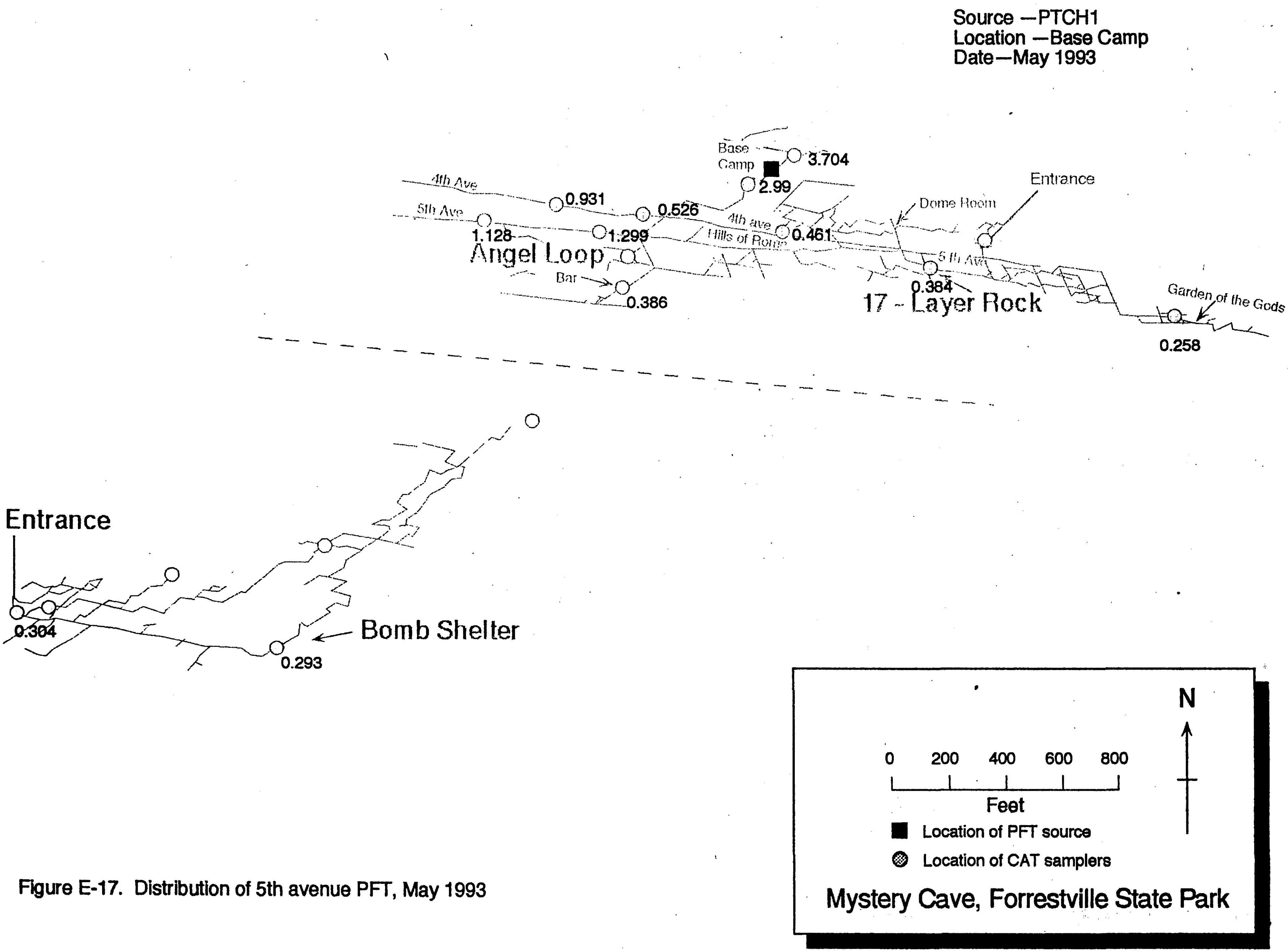


Figure E-17. Distribution of 5th avenue PFT, May 1993

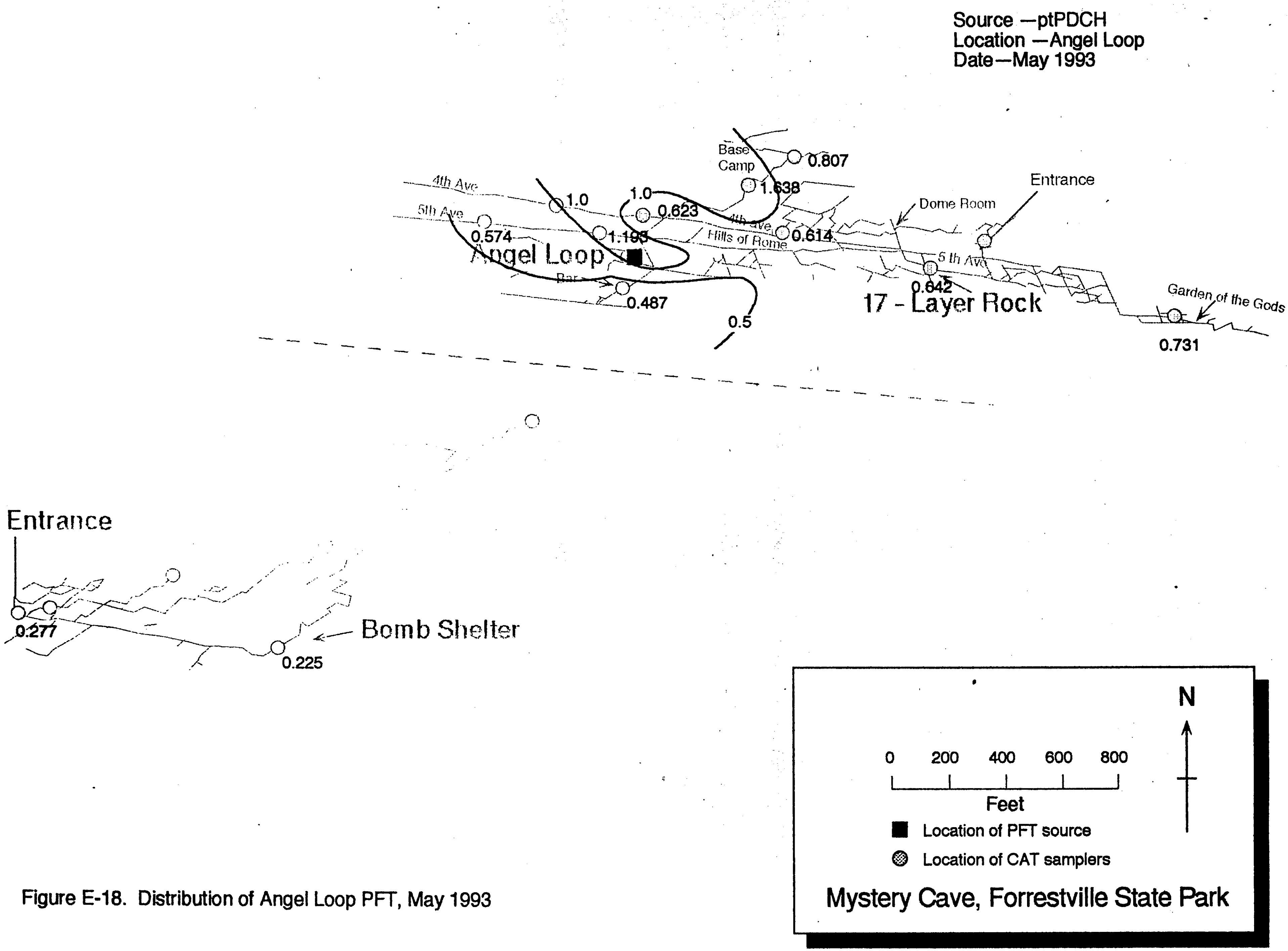


Figure E-18. Distribution of Angel Loop PFT, May 1993

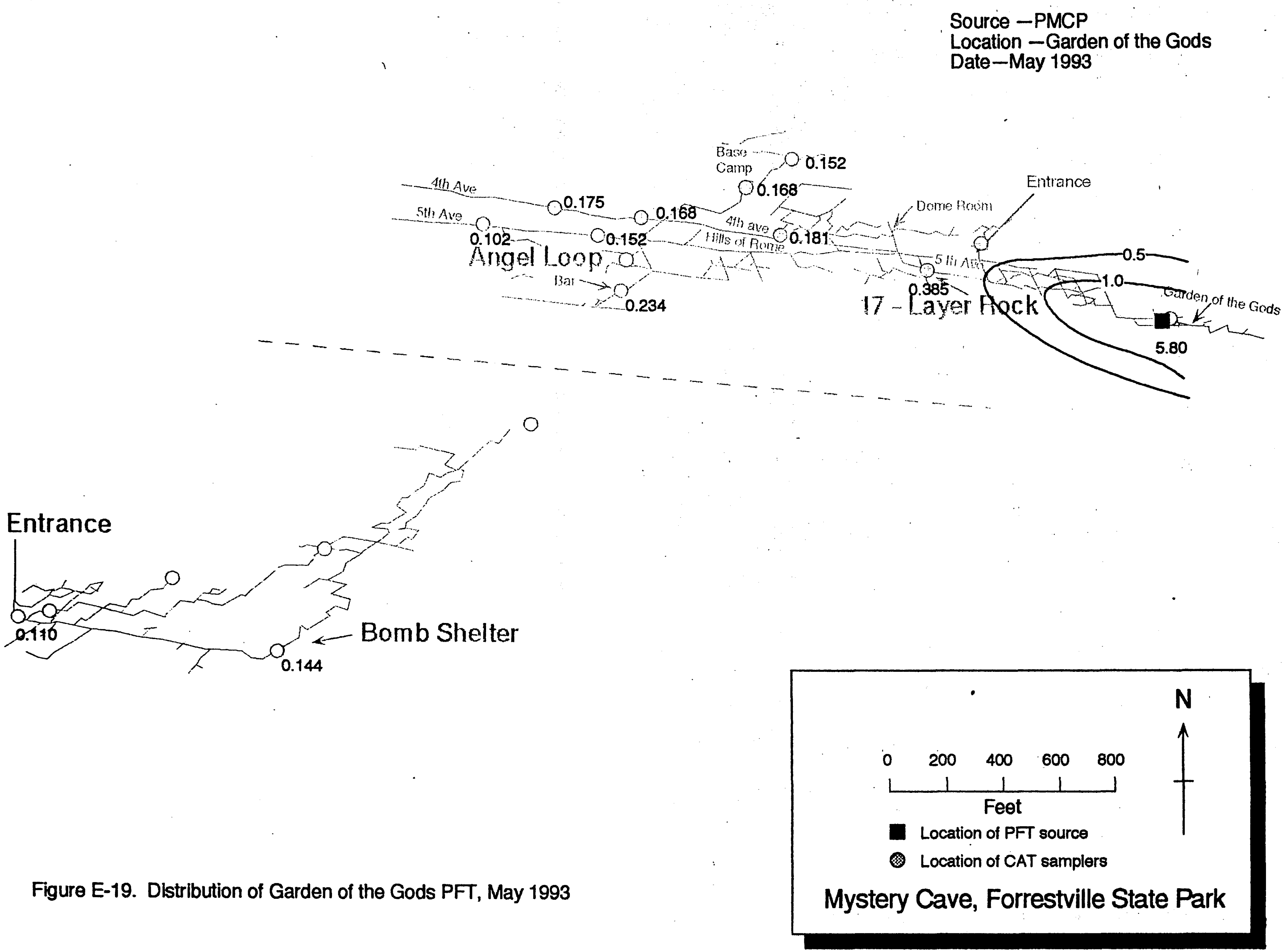


Figure E-19. Distribution of Garden of the Gods PFT, May 1993

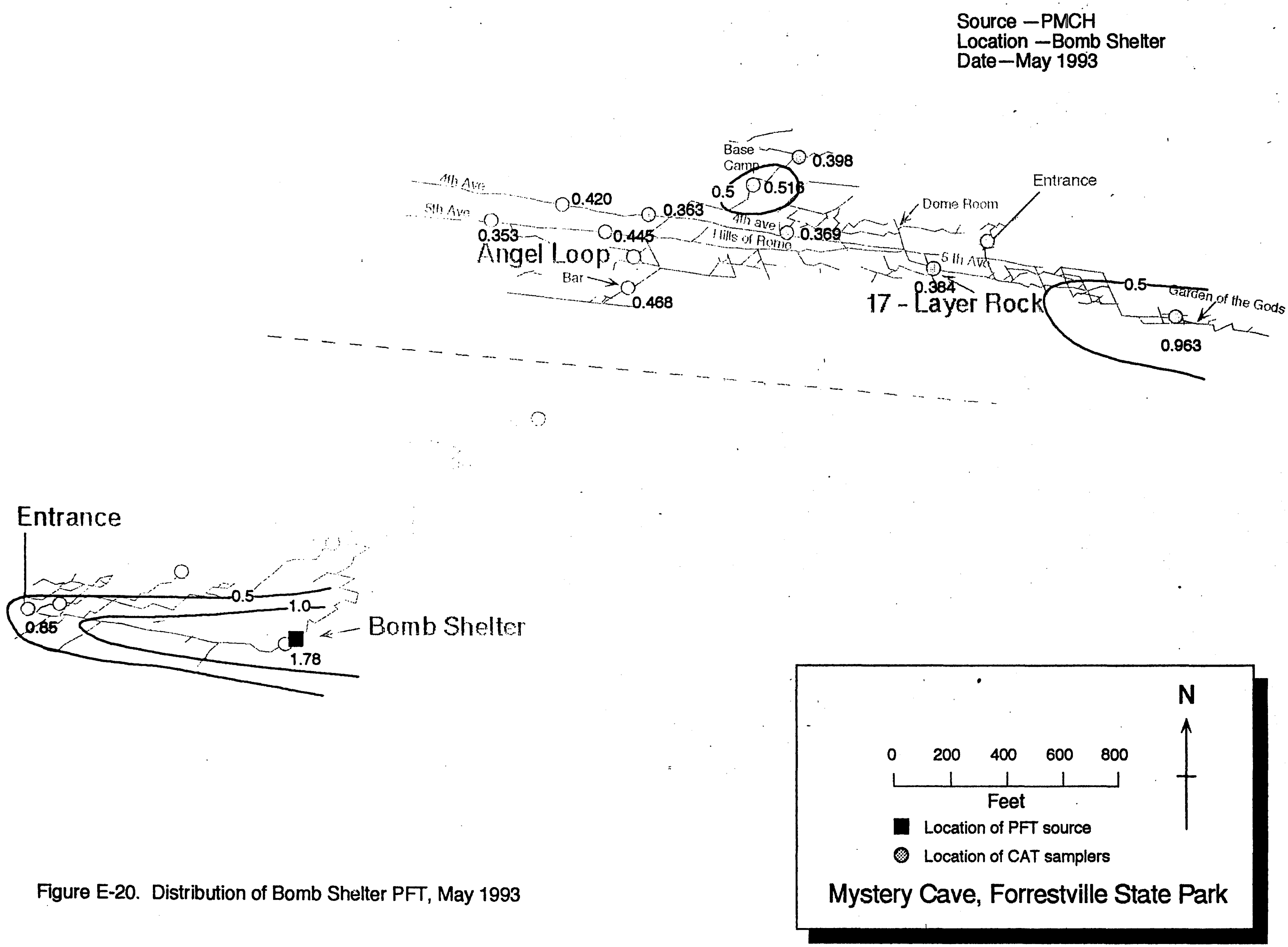


Figure E-20. Distribution of Bomb Shelter PFT, May 1993

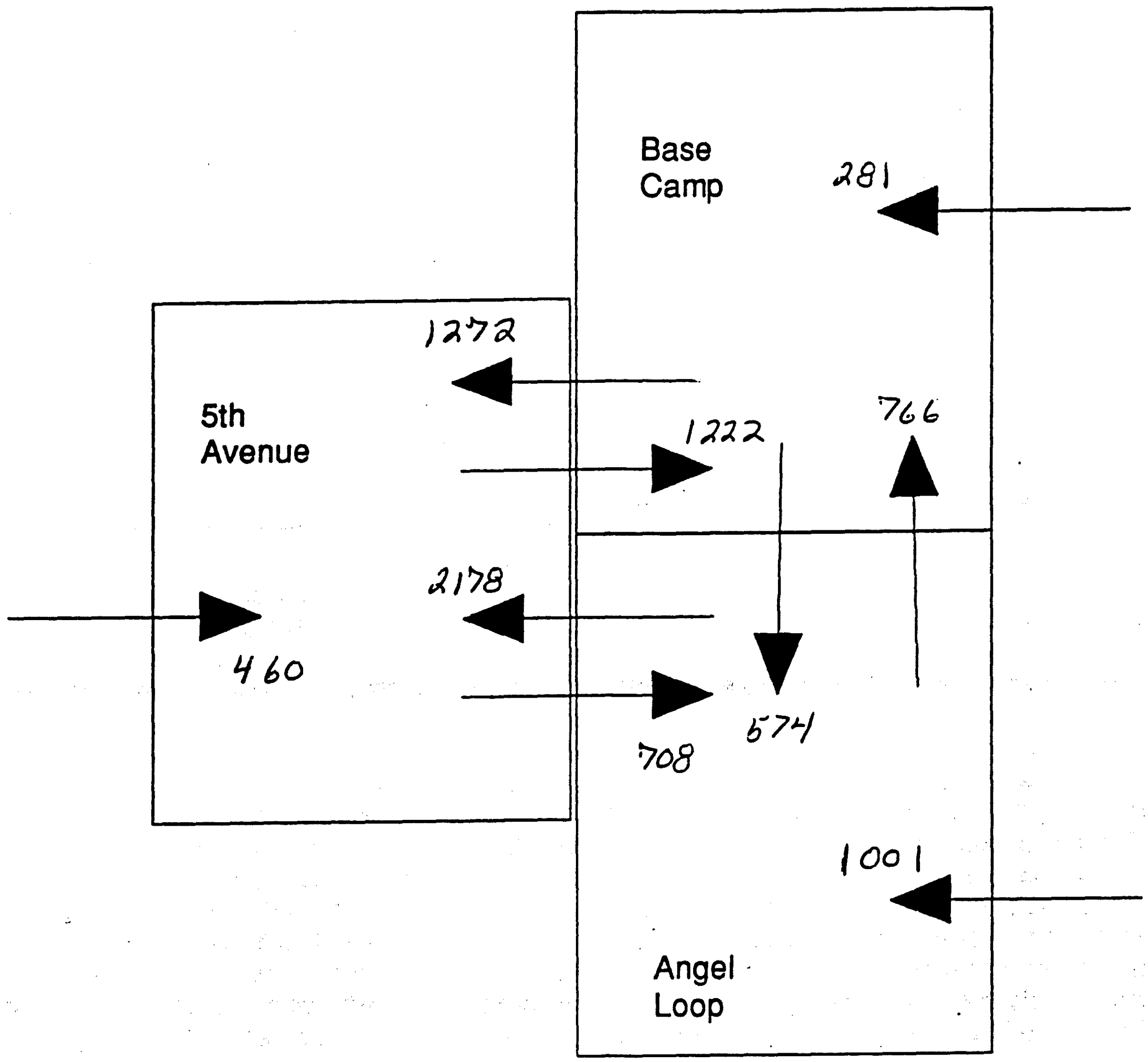


Figure E-21. Schematic diagram of zones used to calculate airflow rates in Mystery II.

pCi/L, with mean values around 200 pCi/L. The radon in Mystery II did not show as much variation as that in Mystery I. This was particularly true in 1991, where the Bomb Shelter monitor recorded more variation that either of the monitors in Mystery II. In 1992 however, the radon levels at Bomb Shelter were lower and showed variations comparable to those in Mystery II.

Graphical summaries of the radon data are presented in Figures F-4 to F-6. These show annual (Figure F-4) and seasonal (Figure F-5) averages at each sampling site and 7-day running averages (Figure F-6) of radon in years 1991 and 1992 for each site.

The most significant features of the averaged radon data were 1) a pronounced summer and winter pattern visible at each monitor location in both 1991 and 1992, 2) variations in average concentration and standard deviation between sites, and 3) variations from one year to the next. Seasonal radon levels in Mystery Cave were lowest in the winter, gradually increased through the spring, reached a maximum in the summer and rapidly declined in the fall to approach winter concentrations. The decline from high summer to low fall concentrations appears more rapid than the increase from winter to summer concentrations. At Bomb Shelter radon levels during 1992 were lower than spring and summer 1991 levels and showed much less seasonal difference. At 17-Layer Rock, 1992 average radon levels were higher and had a stronger seasonal signal than the averages in 1991. Angel Loop, the farthest monitoring point from an entrance, had slightly higher average radon in 1992 and the seasonal signal was similar for each year.

A different comparison of radon concentrations for the 3 sampling sites is provided by the 7-day running averages of radon for two years, overlain on the same axes to compare one year with the other. These plots clearly show the strong summer and winter seasonal signals. They also indicate the rates of change in radon across the seasons. Figure F-6 also shows the marked difference between the 1991 radon levels at the Bomb Shelter, Mystery I, and those in 1992. Summer radon values in 1991 were more than twice as high as those in 1992 and the difference between the highs and lows was much greater during 1991. Angel Loop shows relatively little difference between the two years, although, concentration for spring 1992 were above those in 1991 and the fall 1992 concentrations were lower than in 1991. At 17-Layer Rock, 1992 was generally higher, but the monitor was not in place for much of 1991.

Monthly radon

Detailed monthly records of radon in Mystery Cave are shown in Figures F-7 to F-21. These graphs represent radon concentrations integrated over 4 hour intervals for each sample location, beginning with the pilot study in November 1990. Where no data exists, that section of the plot is either a straight line without data markers or a long gap, as at 17-Layer Rock. The plots after November 1992 include measurements from a monitor set up 300' beyond the Bomb Shelter (toward Mystery II) and later moved (January 1993) to the Formation Room in Mystery I. Radon measurements in Mystery II continued until mid-April when the equipment was removed for calibration. In addition to radon, these plots contain the record of barometric pressure changes for the same period.

The monthly radon plots show a large number of features not visible from the averaged data. 1) large fluctuations in radon activity occurred where the radon can change by factors of 50 between peak and background in a matter of 12 to 24 hours. The cycles were most notable during the winter months, but extended into the fall and spring as well. The sharply rising radon concentrations at those times were associated with falling barometric pressure, as weather fronts move through southern Minnesota. When the barometric pressure rose, the radon levels decreased, sometimes very rapidly. The magnitude of the pressure change did not appear to correlate with the magnitude of the radon change. During the summer months, the difference between minimum and maximum radon concentrations was generally smaller and did not appear to be as highly influenced by changes in barometric pressure. Not all barometric pressure were correlative with changes in radon; 2) major variations in radon were visible at each monitor location, particularly during the winter. These major variations initially appeared to occur at the same time throughout the cave, however a closer look showed that radon in Mystery I reached maximum levels and began to decrease shortly before maximums were reached in Mystery II. However, in Mystery I, the monitors at the Entrance and at Bomb Shelter were exactly in phase. In Mystery II, radon reached a peak at Angel Loop somewhat before 17-Layer Rock; 3) During the winter of 1991, peak radon levels at the Bomb Shelter were always higher than peak values in Mystery II, yet the base concentrations between the peaks were lower (Figures F-7 to F-9 for example). During the summer of 1991 (Figures F-10, F-11), base levels at all locations increased markedly over the winter months, with the Bomb Shelter now having the highest radon concentration. In the fall of 1991, concentrations returned to a low base level and the cycle of peaks again correlated with dropping barometric pressure. The Bomb Shelter base level was once again lower than that in Mystery II (Angel Loop) and the peak maximums were higher; 4) In September, 1991 the decline in radon associated with the drop in mean outside temperature was very noticeable, occurring over the span of 16 hours (Figure F-12). It was also at this time that the pattern of radon variation moved from a summer to winter configuration. The records for September 1992, (Figure F-18), did not record a similar rapid drop, although the radon in September 1992 did show a gradual decrease in concentration. One month later, in October of 1992 (Figure F-19) the radon levels did decrease sharply, similar to 1991. The trends for both of these years are well illustrated in the averaged plots (Figure F-6); 5) In 1992, the radon concentrations at Bomb Shelter were much lower than in 1991.

Summer concentrations at the Bomb Shelter during 1992 seldom exceeded 250 pCi/L, whereas in 1991, summer levels were between 400-500 pCi/L. A comparison of the peak concentrations associated with barometric pressure changes for November 1991 vs. 1992 (Figures F-13 and F-19) showed levels greater than 400 pCi/L during 1991 and less than 250 pCi/L for 1992. Although it was not possible to rule out instrument variation, the detector at the site Beyond Bomb Shelter, also recorded lower radon than at Bomb Shelter in 1991; 6) Radon concentrations in the months of August 1992 and November 1992 were analyzed separately for average day and nighttime radon levels. There was no difference in the averages; 7) comparison of the radon variations at Bomb Shelter and Formation Room in Mystery I (Figures F-20, F-21) with earlier monitoring at the Entrance (Figures F-7 to F-10) and Beyond Bomb Shelter (Figures F-19, F-20) showed a markedly different pattern. At each location along the main trunk passage, i.e. Entrance, Bomb Shelter and Beyond Bomb Shelter, the radon variations were similar in magnitude, occurred in phase with each other and had similar base levels. At the Formation Room however, radon was continually higher than at Bomb Shelter (about halfway between Bomb Shelter and Angel Loop levels) and did not show any of the large, short-term fluctuations recorded at Bomb Shelter and Angel Loop. Because Formation Room is a dead-end side passage, the radon data imply that trunk passages were much more susceptible to major fluctuations of radon and that the fluctuations were related to ventilation. It was initially thought that dead-end side passages connected to main trunk passages might build up radon and be a source for high radon spikes in the main passages, but although the data are limited, radon did not build to high levels and did not appear to be drawn from Formation Room into the main passage.

As a final observation, Figure F-22 indicates that average radon concentrations at the Ranger house have a seasonal pattern opposite to that in the cave. This is consistent with other indoor measurements that have shown higher levels during the winter.

The arrays of radon monitors Beyond Bomb Shelter, Mystery I and at 17-Layer Rock, Mystery II were installed to determine if radon formed high concentration boundary layers near the rock surface that could be drawn out into the passage during low barometric pressure events, creating the spikes observed in radon concentrations. One of the array monitors (s021) read higher than the calibration curve, but when those results were discounted, no effect was observed; monitors near floors or walls showed the same levels and same variations over time as monitors in the middle of the passages. The monitors in the arrays were not appreciably different from the nearby routine monitors. This has lead us to conclude that the high radon peaks were not the result of a boundary layer phenomenon.

Temperature and radon

Because of the strong seasonal signal in the radon data, plots were made of the 7-day running average of the mean outside temperature and 1992 average radon activity for each of the 3 sites (Figures F-23 to F-25). It is evident from these plots that the change in outside air temperature was positively correlated, in some cases very well (Angel Loop), with changes in radon concentration. The correlation was observed when radon concentrations went up or down and was especially evident in the fall with the sharp drop in radon throughout the cave. Unfortunately, we did not have a continuous temperature record from the spring of 1992 for comparison. However, Figure F-26 (from the pilot study report), shows the average, cave radon and an surface air temperature record from the Rochester Airport for a period from February 28 to May 31, 1991. The temperature and radon show general long-term and short-term positive correlations.

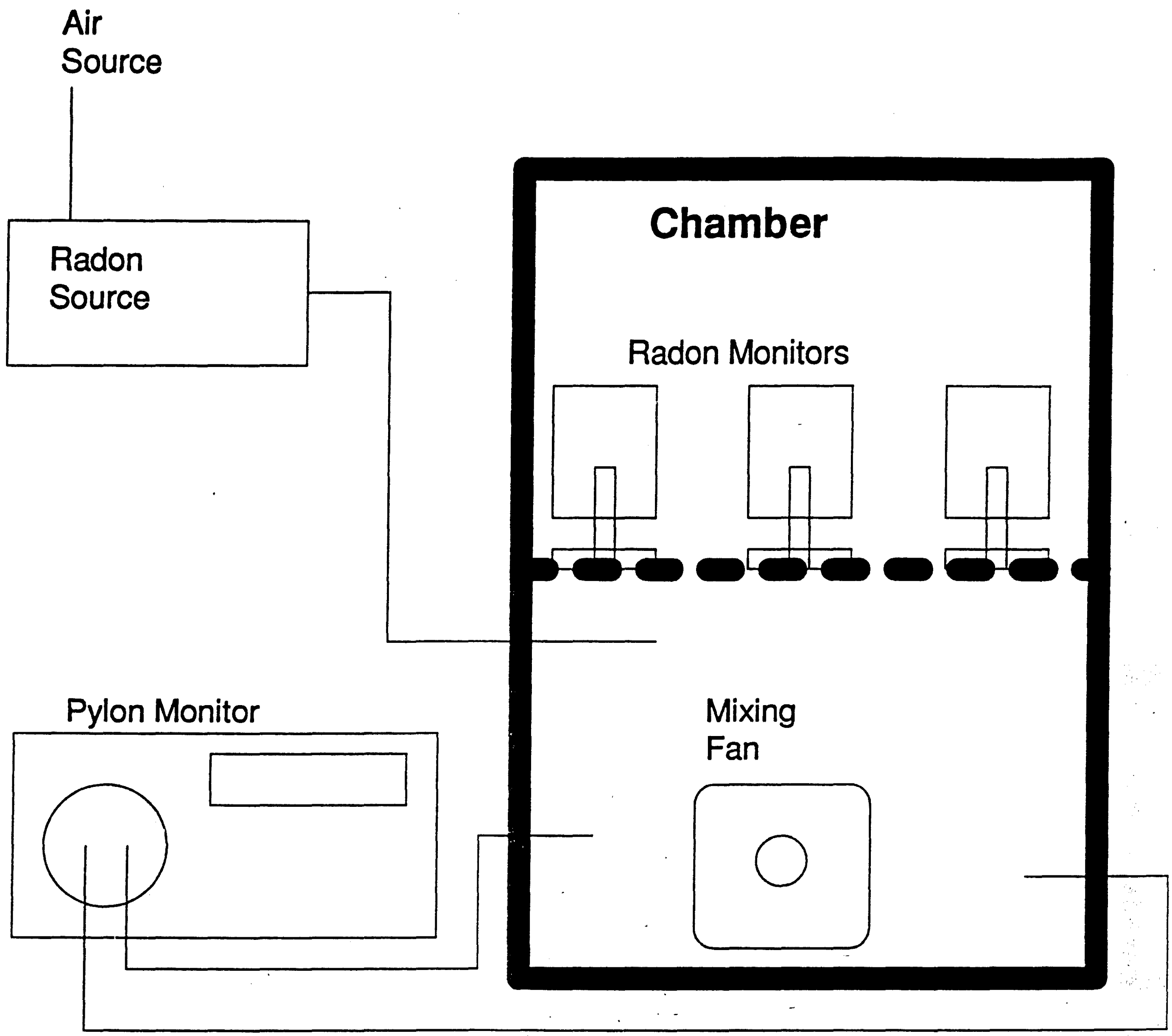
Figures F-27 to F-30 shows that some short term fluctuations in cave air temperature were related in time to some of the fluctuations in radon but there were also numerous temperature changes with no appreciable correlation to the radon. In September 1992 (Figure F-28), several major low temperature event were in phase with low radon events, others were not. In December (Figure F-30), high radon events occurred with high temperature events, although again, not all temperature events in the cave were associated with radon variations.

Mystery Cave can be considered a 'right-side-up' cave (Yarborough, 1980), that is, most of the passages are below the main commercial surface openings. Some passages, particularly in the Mystery III area may be above air inflow routes, but overall the cave appears to be right-side-up. In RSU caves, it is usually assumed that the cave atmosphere is relatively stable when the minimum outside temperature is above the cave temperature. When the minimum outside temperature falls below the cave temperature, cooler, denser outside air enters the passages, mixing with the cave atmosphere. Wilkening (1976) and Ahlstrand (1980) have published data showing that radon levels in Carlsbad Caverns decreased when temperatures were colder than the cave, presumably because of dilution with the outside air containing almost no radon. During warm periods when the cave air was stable radon levels were higher.

In general, this is the case in Mystery Cave. However, with the higher resolution radon monitoring, we have observed that the radiation environment in Mystery Cave is more complex. For instance, the transition interval in September 1991 was very short, radon (and presumably ventilation) went from a summer to winter pattern within a few hours. In 1992 radon levels declined gradually, with a sharp transition occurring in October. Spring radon concentrations increased to summer levels more slowly than they decreased in the fall.

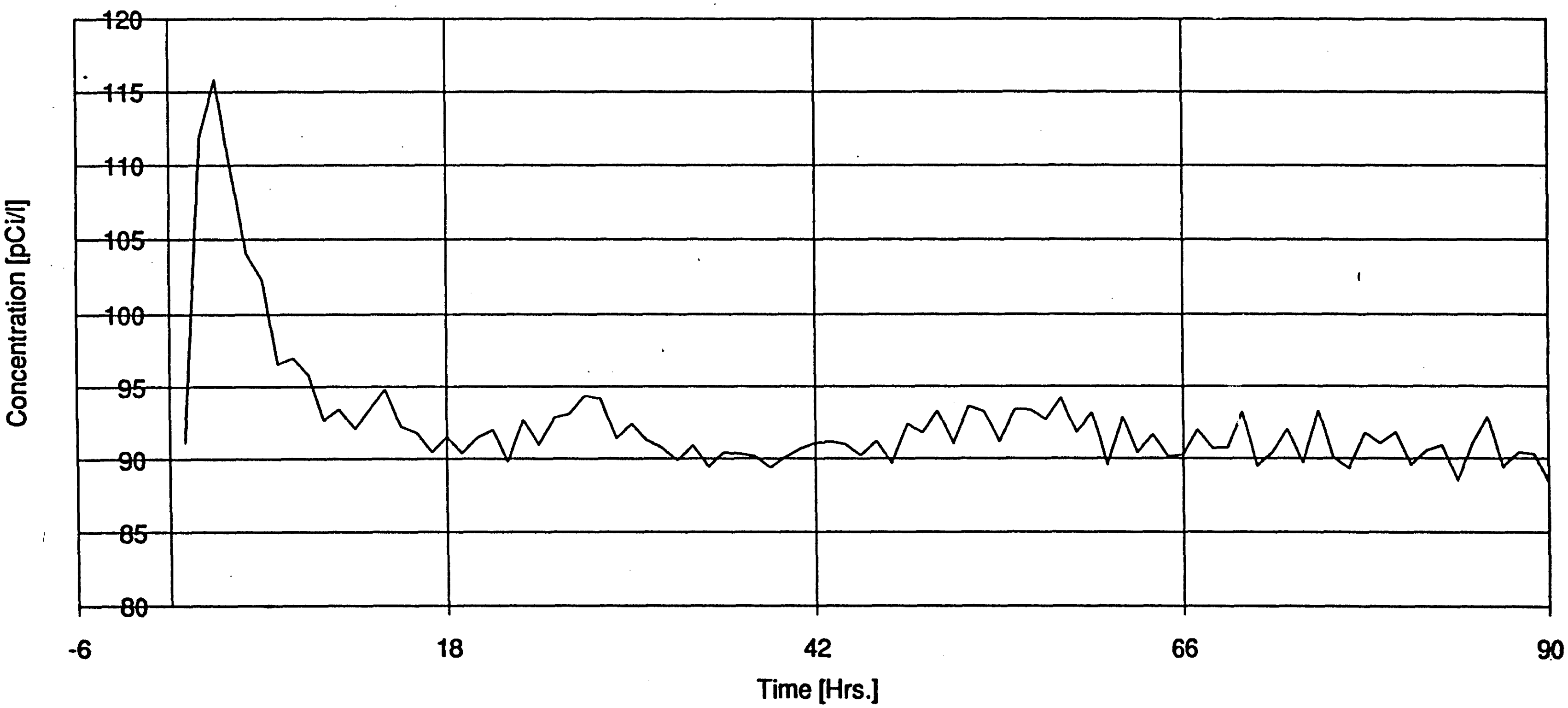
Table F-1. Seasonal and annual averages and summary statistics

Seasonal		17-Layer Rock	Angel Loop	Bomb Shelter	House	Entrance
1991						
Winter 13:00 21 Dec. 91 - 12:00 21 Mar. 92	avg.	94	121	76	no data	42.7
	Stdev.	19	37	85	no data	56.6
Spring 13:00 21 Mar. - 12:00 21 June 92	avg.	165	207	264	no data	178.6
	Stdev.	54	83	134	no data	112.0
Summer 13:00 21 June - 12:00 21 Sept. 92	avg.	180	317	360	3.1	218.4
	Stdev.	30	98	118	2.2	59.2
Fall 13:00 21 Sept. - 12:00 21 Dec. 92	avg.	no data	133	99	3.6	no data
	Stdev.	no data	41	93	1.4	no data
1992						
Winter 13:00 21 Dec. 91 - 12:00 21 Mar. 92	avg.	161	161	153	4.2	
	Stdev.	24	45	138	1.4	
Spring 13:00 21 Mar. - 12:00 21 June 92	avg.	213	248	140	3.4	
	Stdev.	48	75	70	1.4	
Summer 13:00 21 June - 12:00 21 Sept. 92	avg.	288	345	207	2.9	
	Stdev.	29	54	63	1.1	
Fall 13:00 21 Sept. - 12:00 21 Dec. 92	avg.	148	115	96	5.7	
	Stdev.	55	41	70	1.9	
1993						
Winter 13:00 21 Dec. 92 - 12:00 21 Mar. 93	avg.	109	106	56	8.4	
	Stdev.	17	24	40	17.0	
Spring 13:00 21 Mar. - 12:00 21 June 93	avg.	146	143	no data	5.4	
	Stdev.	32	39	no data	1.8	
Summer 13:00 21 June - 12:00 21 Sept. 93	avg.	no data	no data	no data	no data	
	Stdev.	no data	no data	no data	no data	
Fall 13:00 21 Sept. - 12:00 21 Dec. 93	avg.	no data	no data	no data	no data	
	Stdev.	no data	no data	no data	no data	
Annual						
1991	avg.	137	179	197	3.6	119
	Stdev.	53	96	159	1.5	109
	Max.	274	463	665	8.8	372
	Min.	59	43	14	0.3	2
	Skewness	1	1	0	0.6	1
	Median	121	148	154	3.5	61
	Count	987	1679	1942	630	900
1992	avg.	206	219	148	4.2	
	Stdev.	74	109	94	2.0	
	Max.	356	486	566	11.9	
	Min.	69	46	25	0.5	
	Skewness	0	0	1	0.8	
	Median	208	193	131	3.8	
	Count	1705	1891	1879	1898	



Experimental Set-up for Monitor Calibration

Figure F-1. Schematic diagram of Honeywell radon test chamber.



ˈigure F-2. Radon activity level in chan r during one of the calibration test periods.

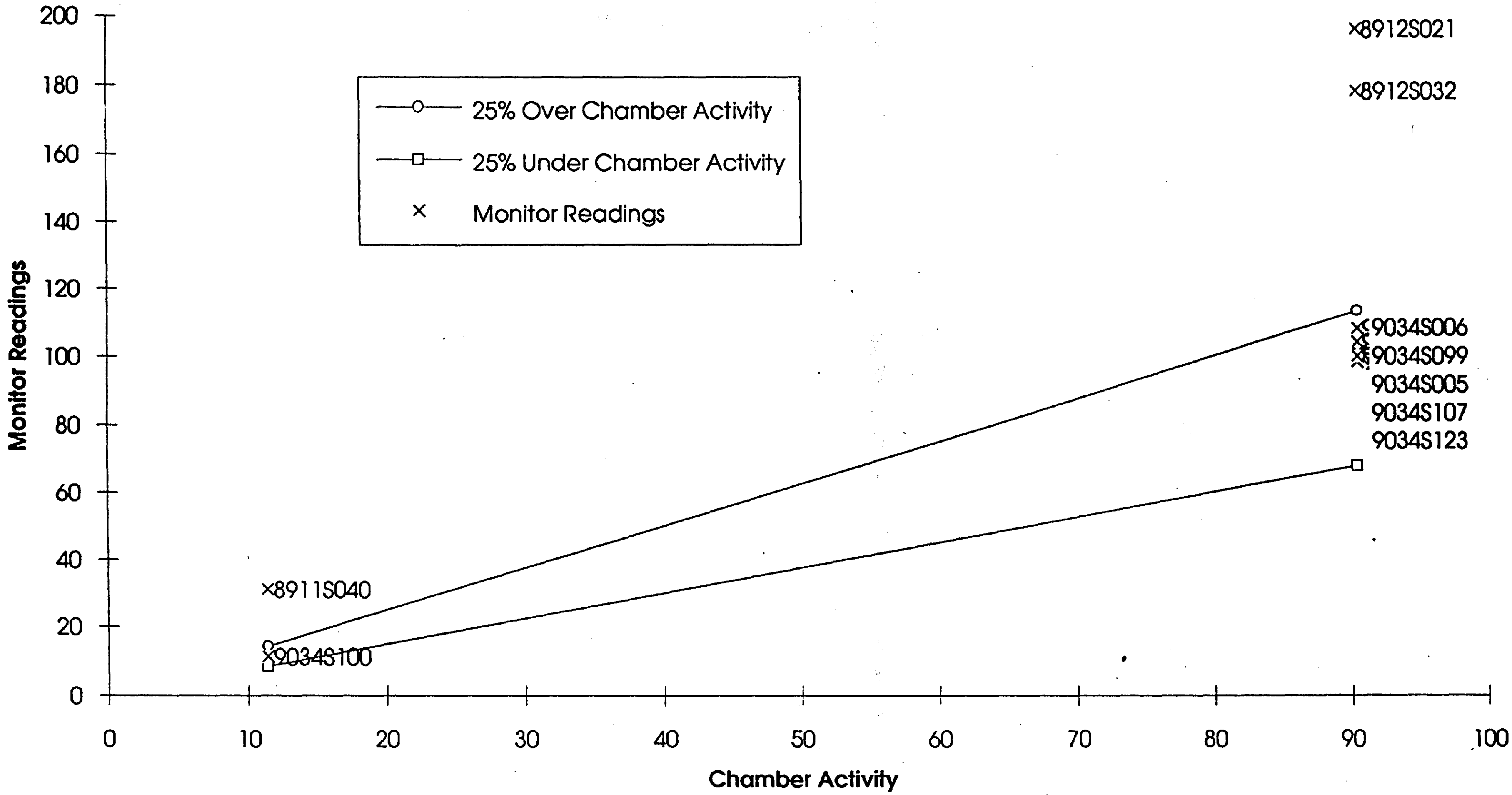


Figure F-3. Comparison of Results from Calibration Monitor and the A9000 Radon Monitors Used in Mystery Cave

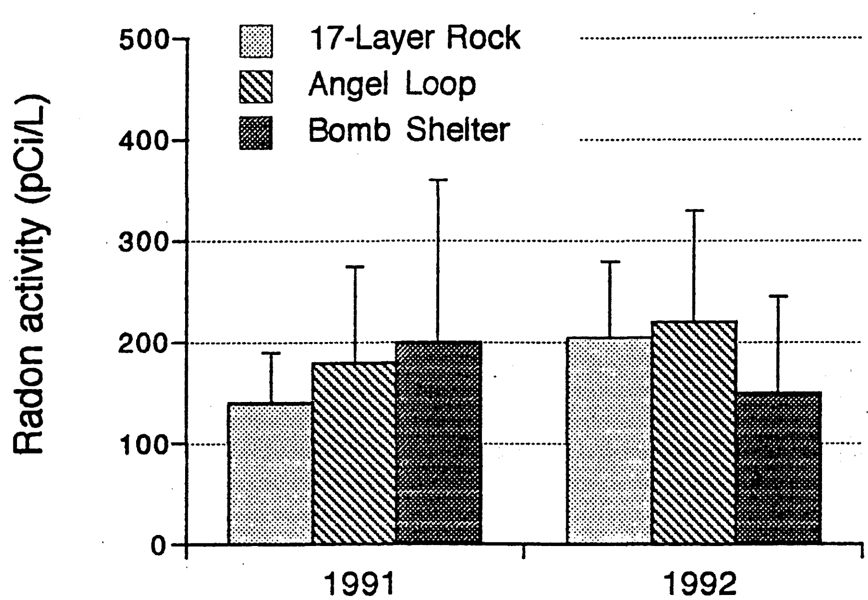


Figure F-4. The annual average radon at 17-Layer Rock and Angel Loop, Mystery II, and Bomb Shelter, Mystery I, for 1991 and 1992. Vertical lines indicate one standard deviation about the mean.

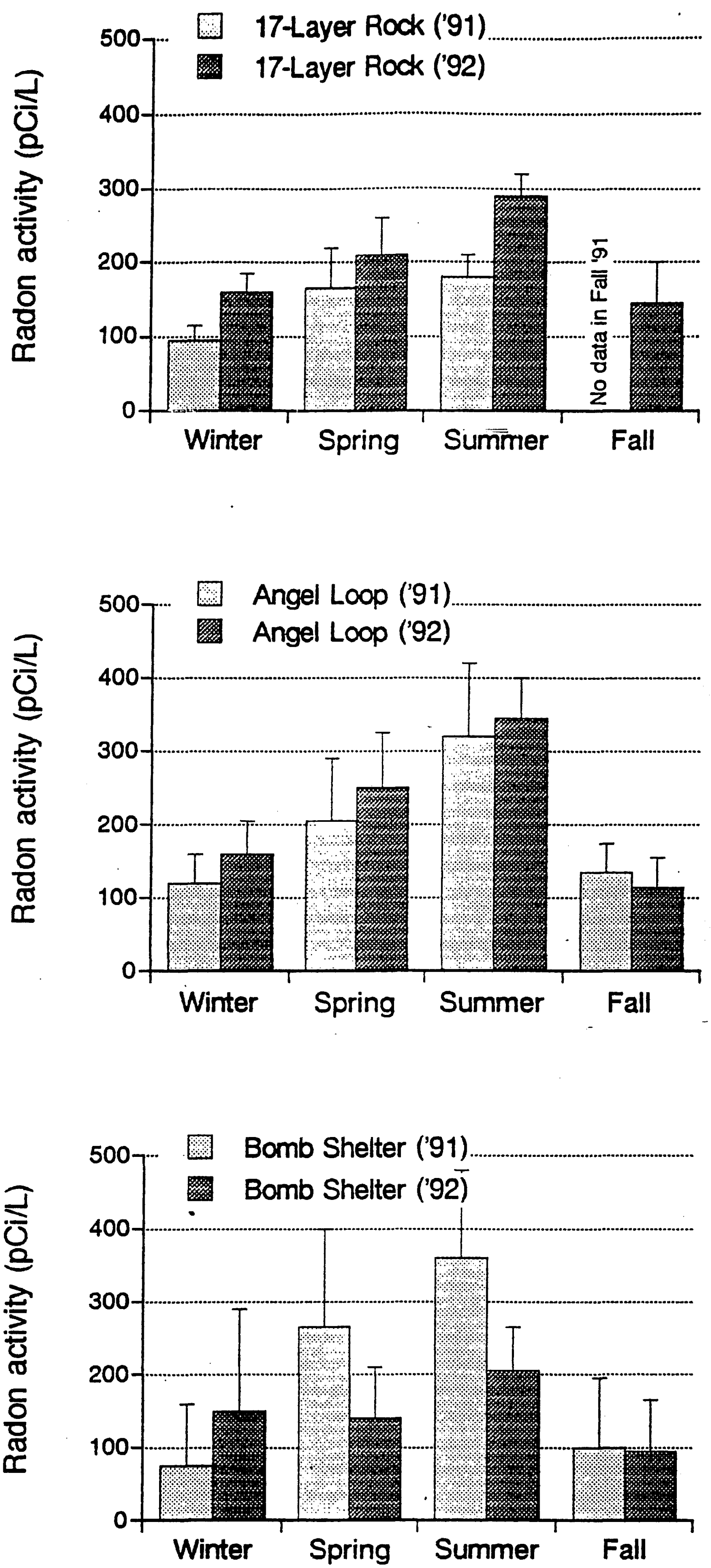


Figure F-5. The radon seasonal average and one standard deviation at 17-Layer Rock, Angel Loop, Mystery II and Bomb Shelter, Mystery I

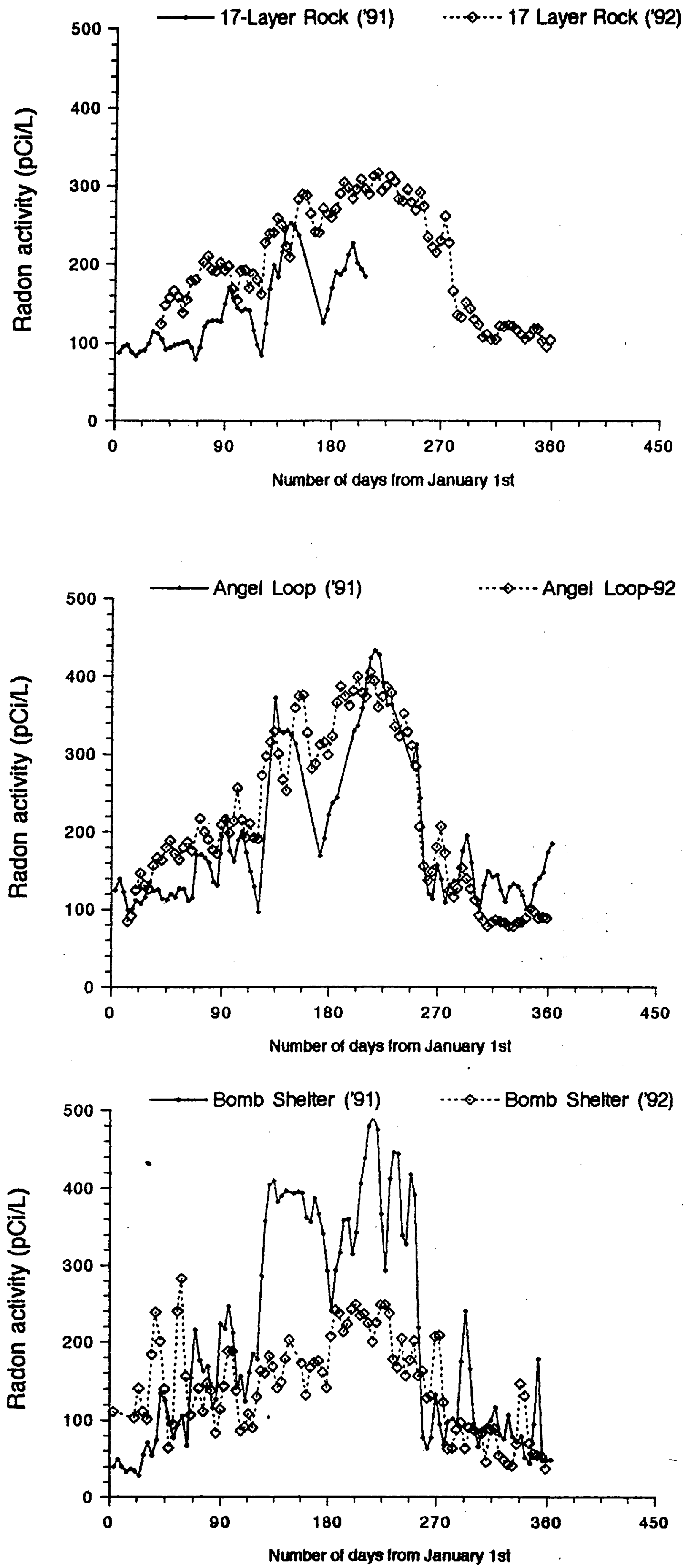
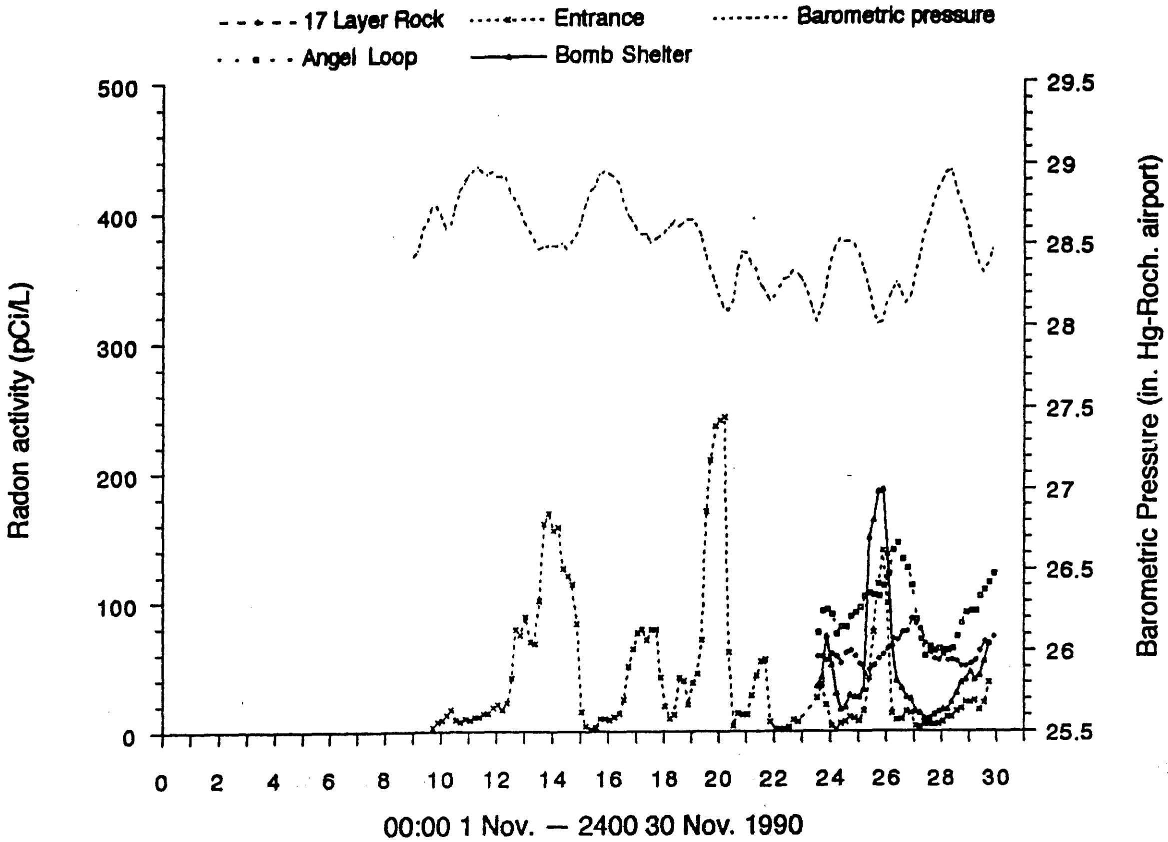


Figure F-6. The 7-day running average radon concentrations at 17-Layer Rock, Angel Loop and Bomb Shelter for 1991 and 1992.



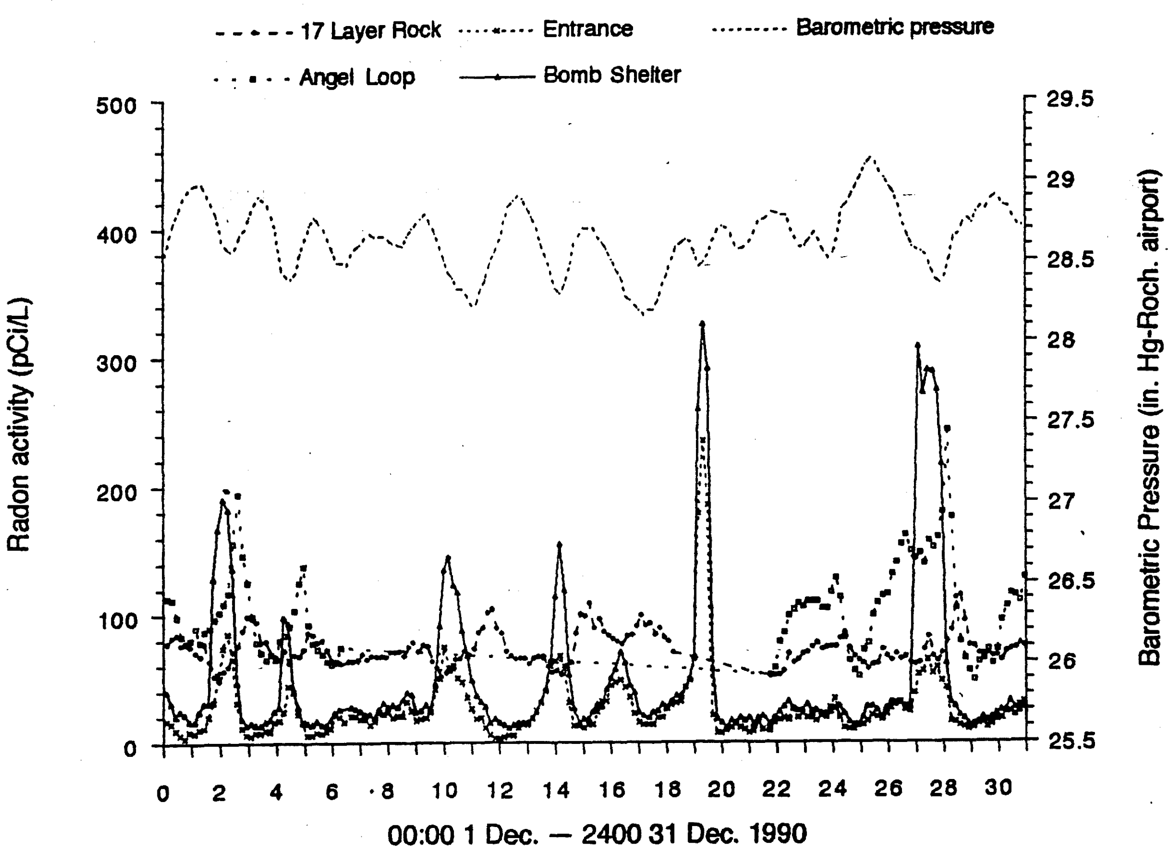
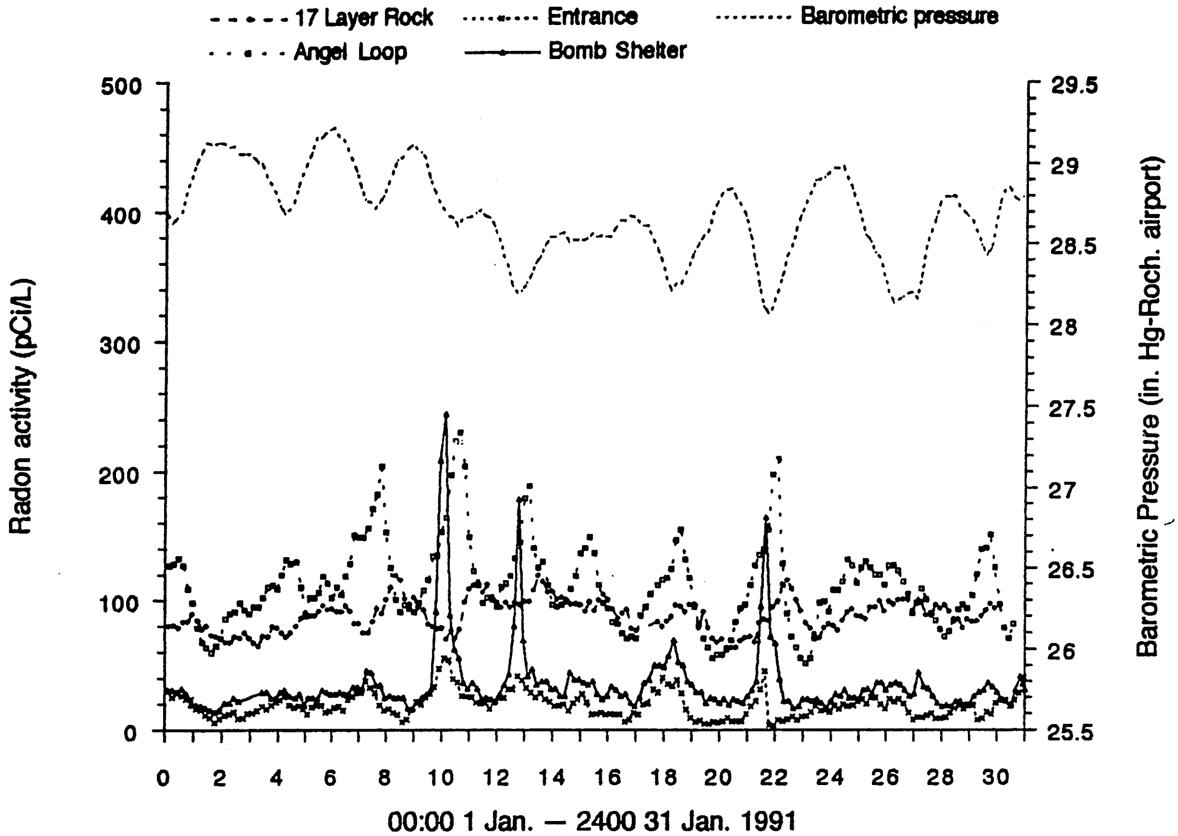


Figure F-7. Radon concentrations at locations in Mystery I and Mystery II, November 1990-December 1990.



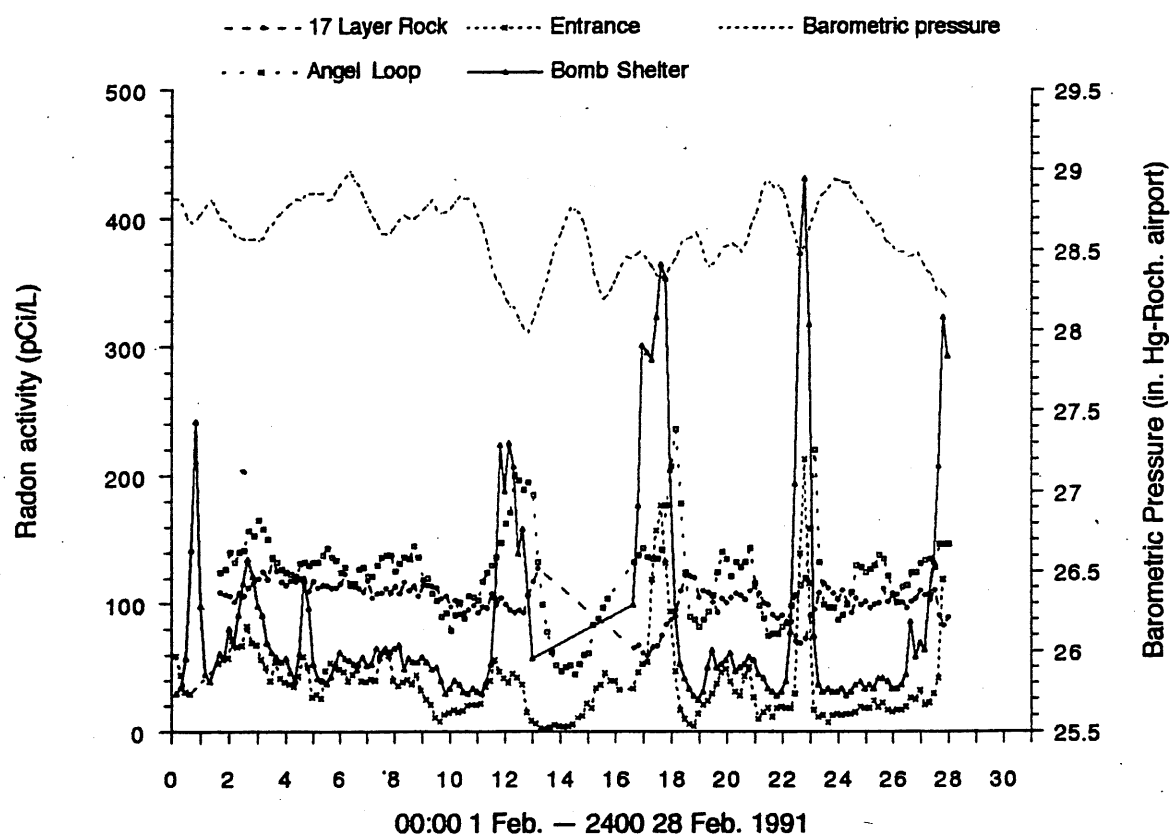
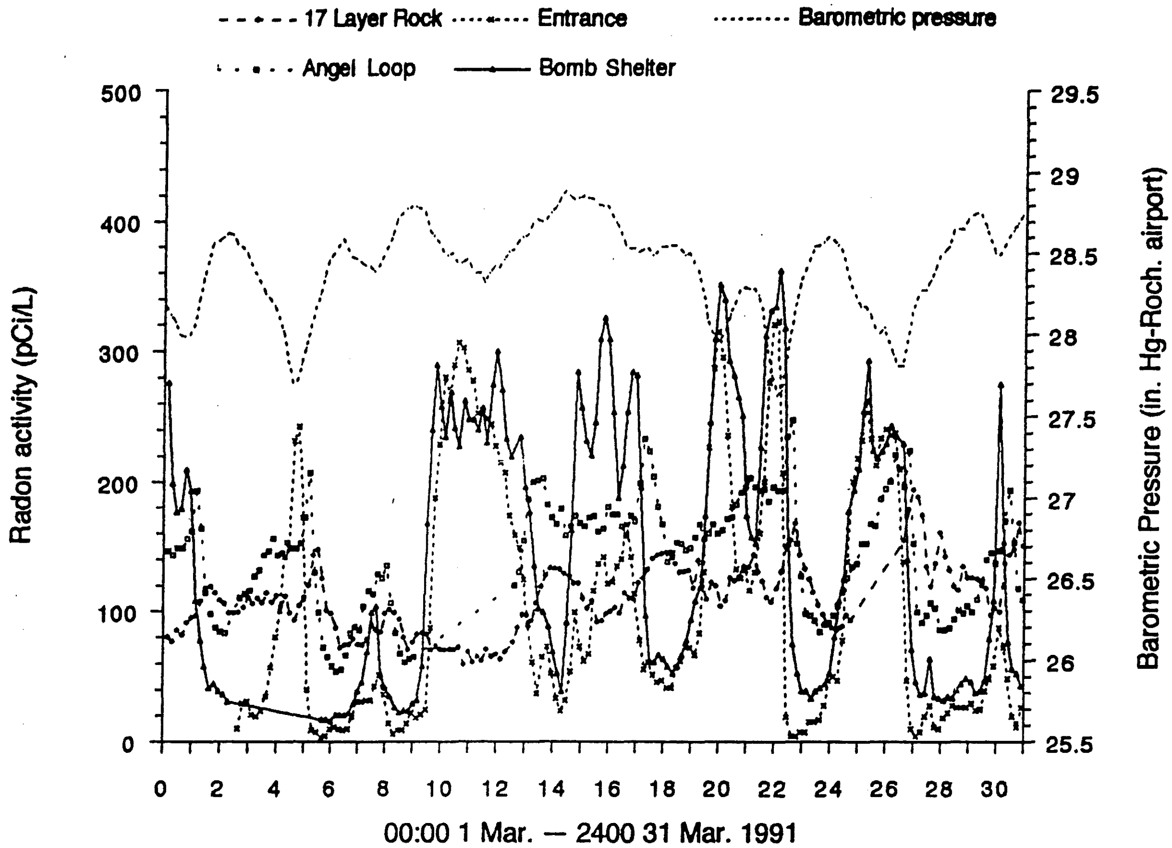


Figure F-8. Radon concentrations at locations in Mystery I and Mystery II, January-February 1991.



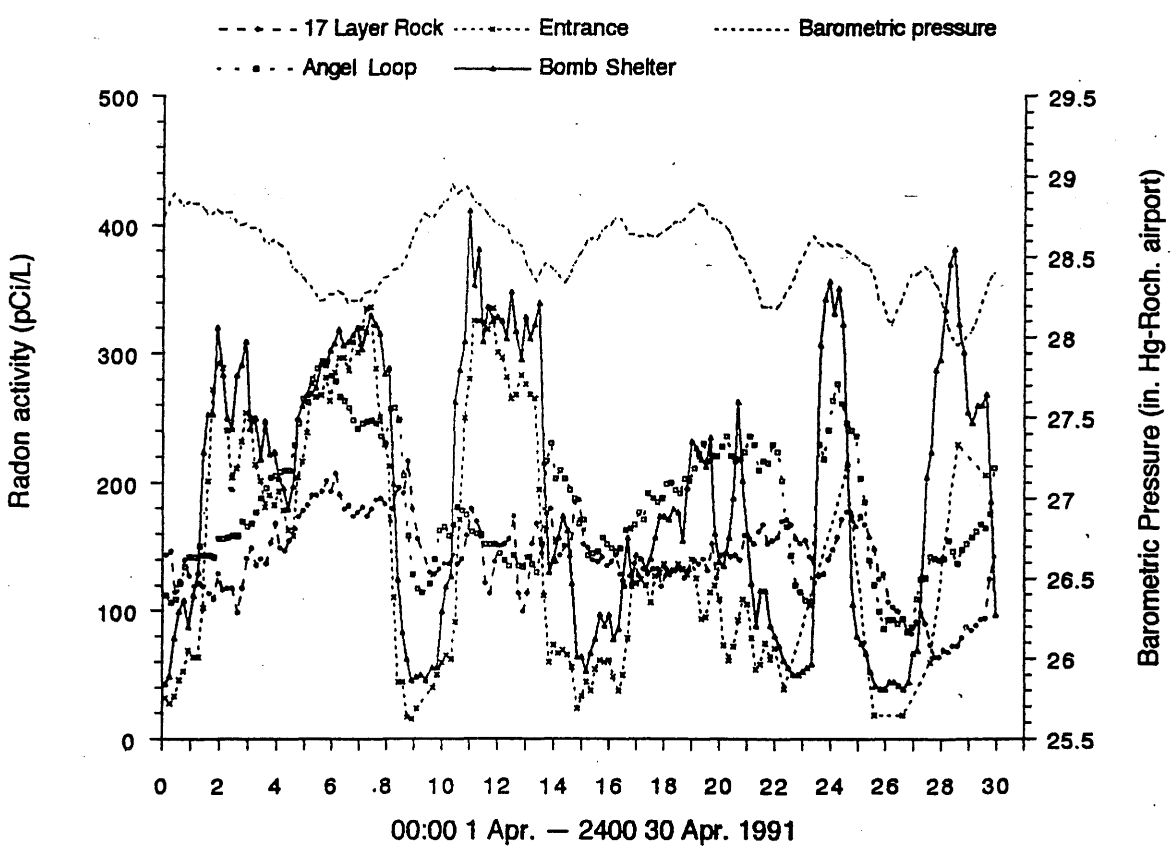


Figure F-9. Radon concentrations at locations in Mystery I and Mystery II, March-April 1991.

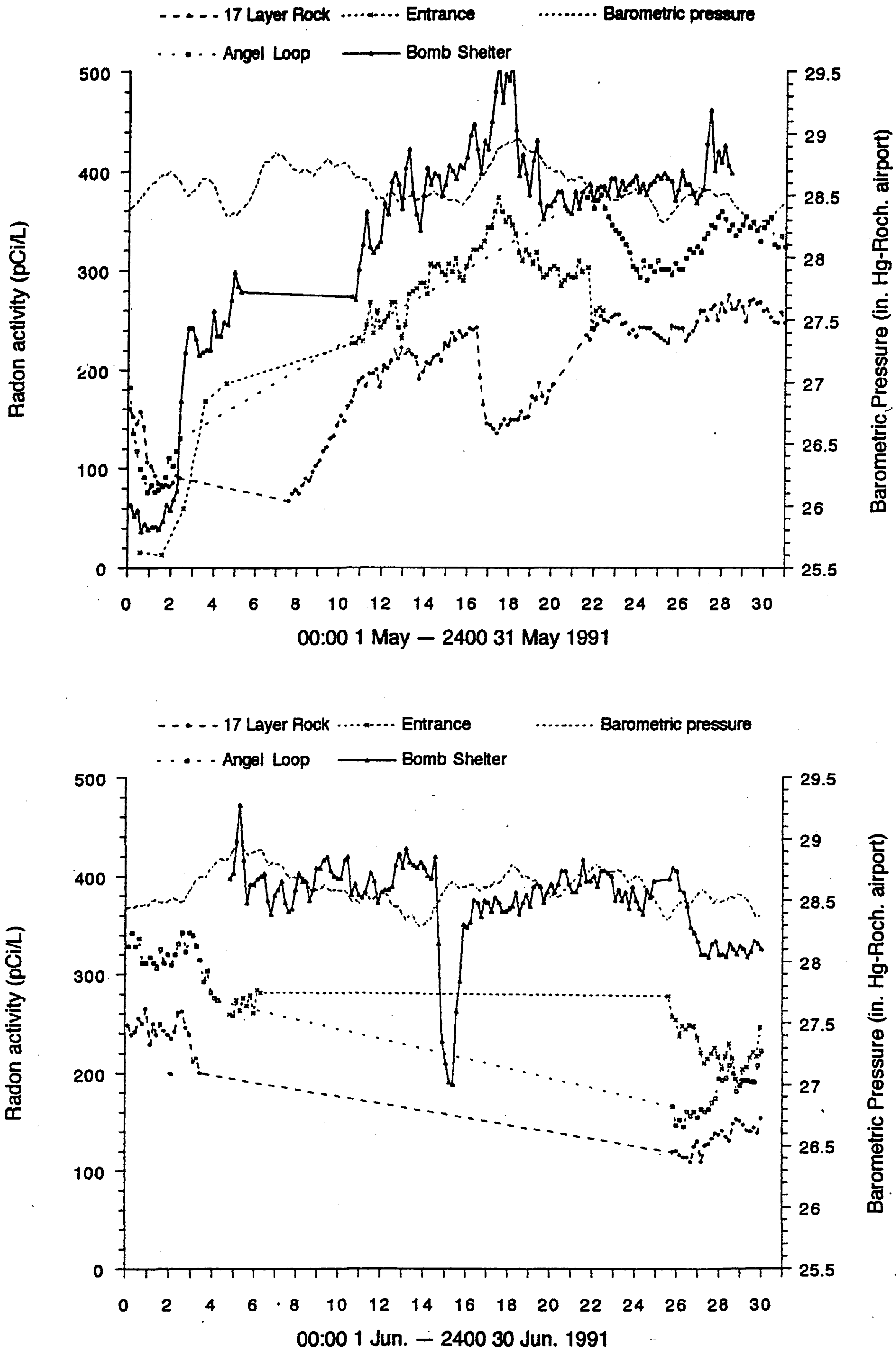
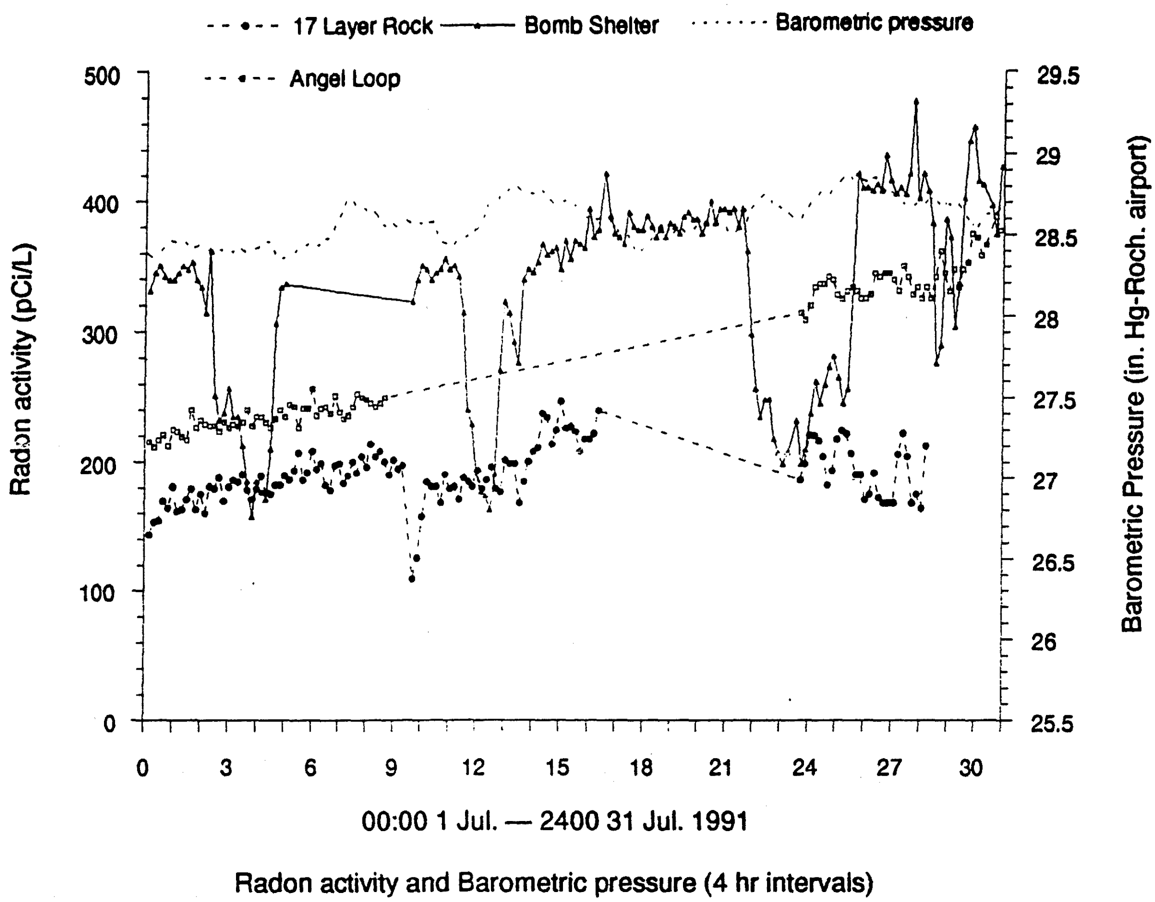


Figure F-10. Radon concentrations at locations in Mystery I and Mystery II, May-June 1991.



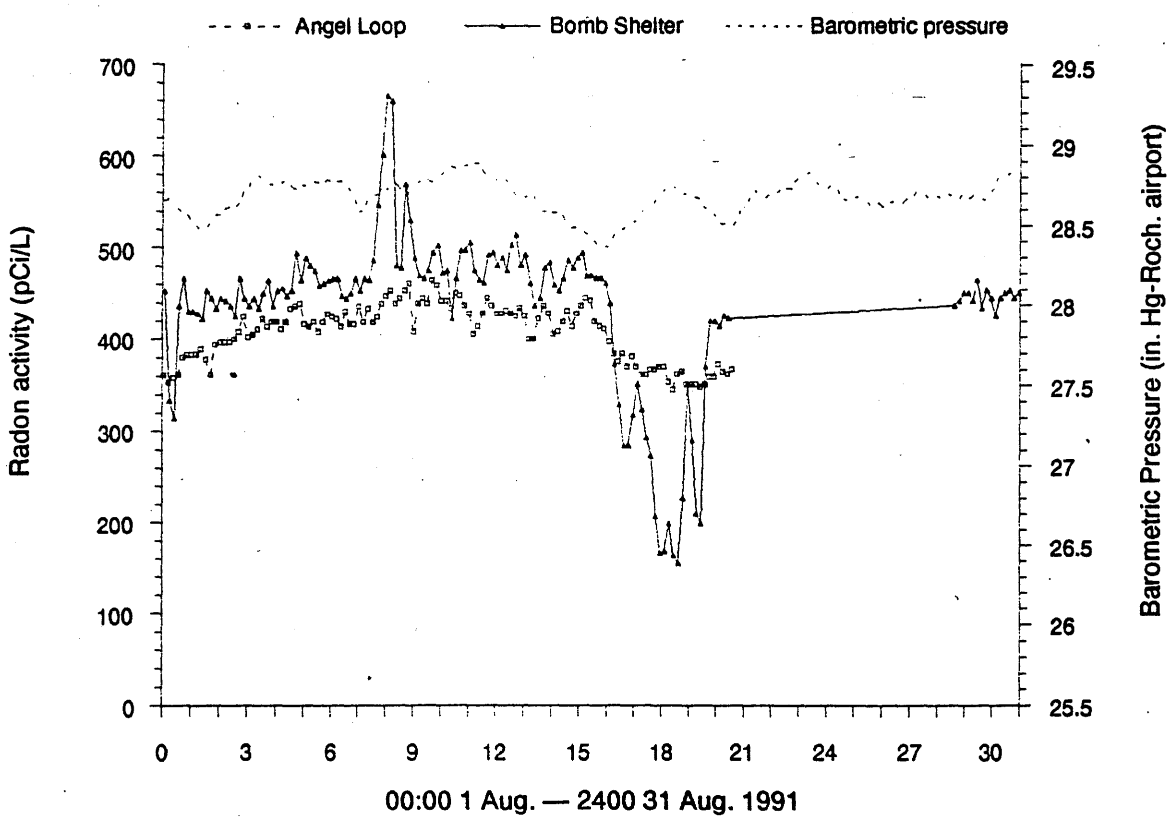
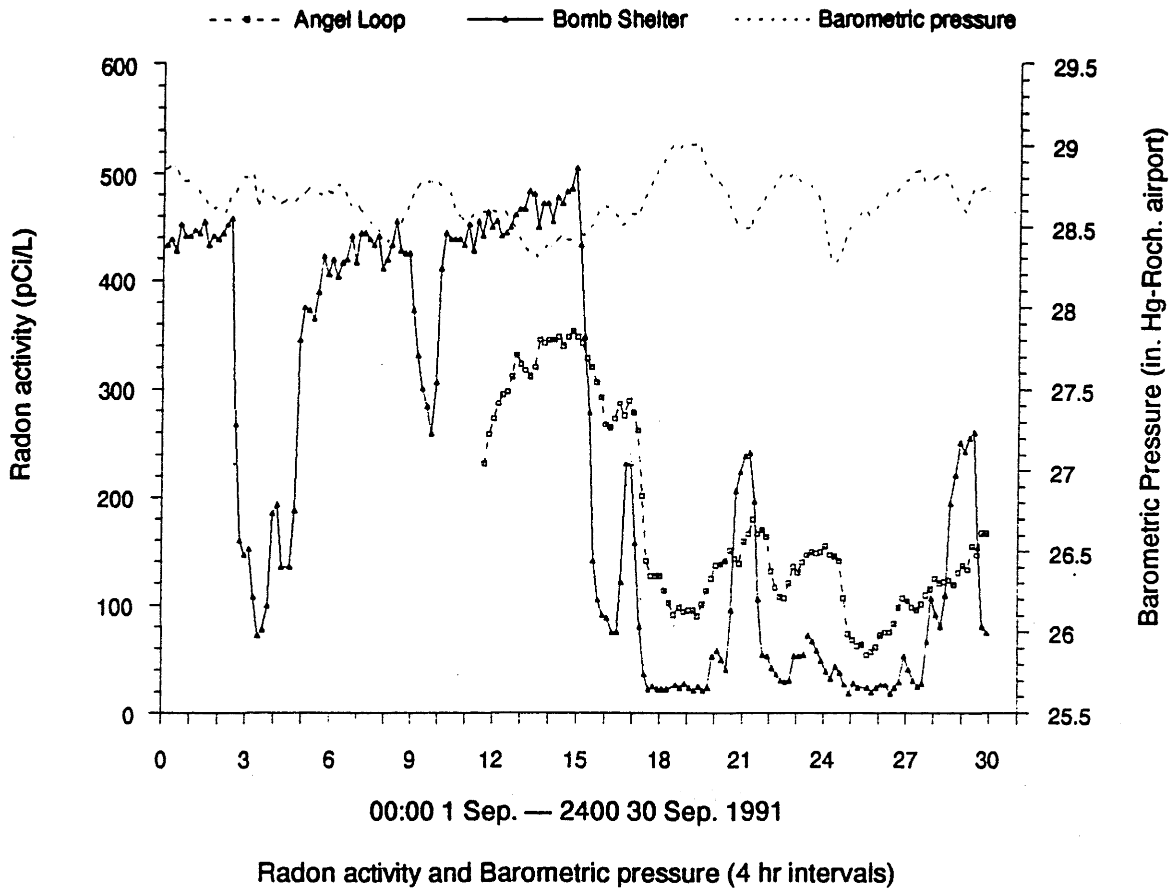


Figure F-11. Radon concentrations at locations in Mystery I and Mystery II, July-August 1991.



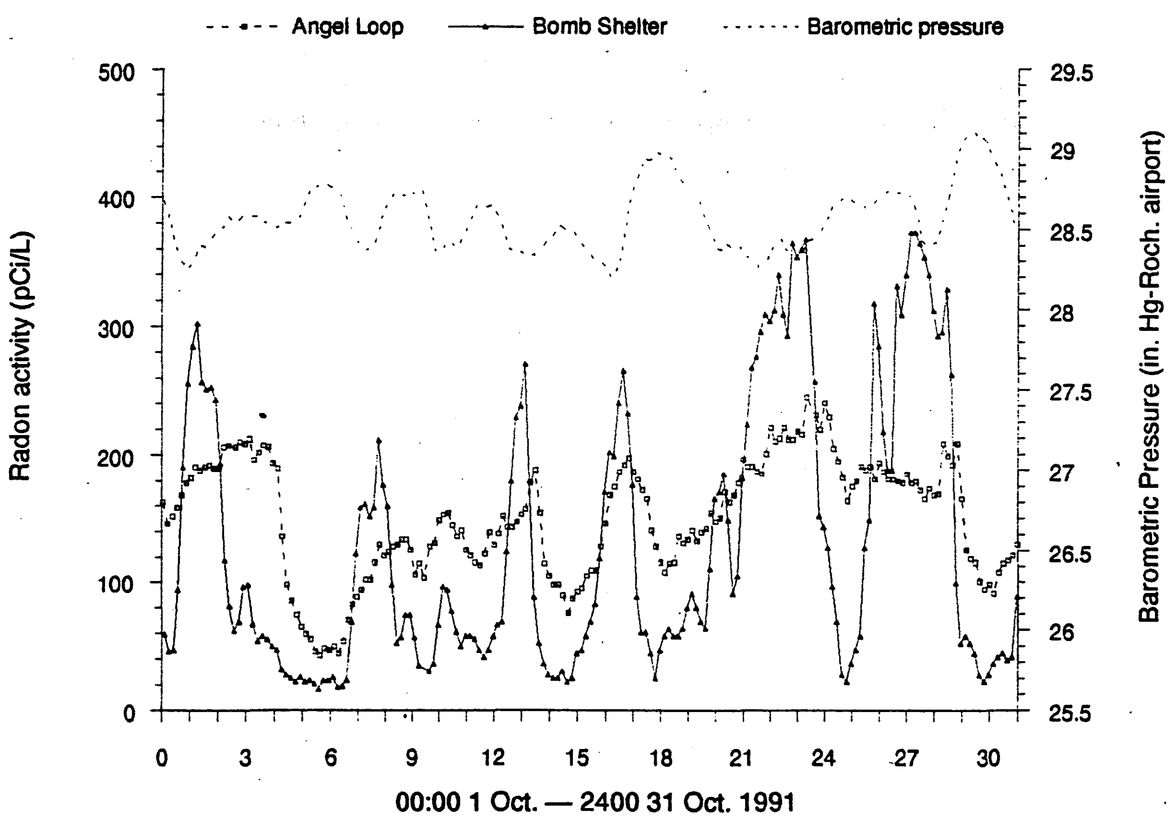


Figure F-12. Radon concentrations at locations in Mystery I and Mystery II, September-October 1991.

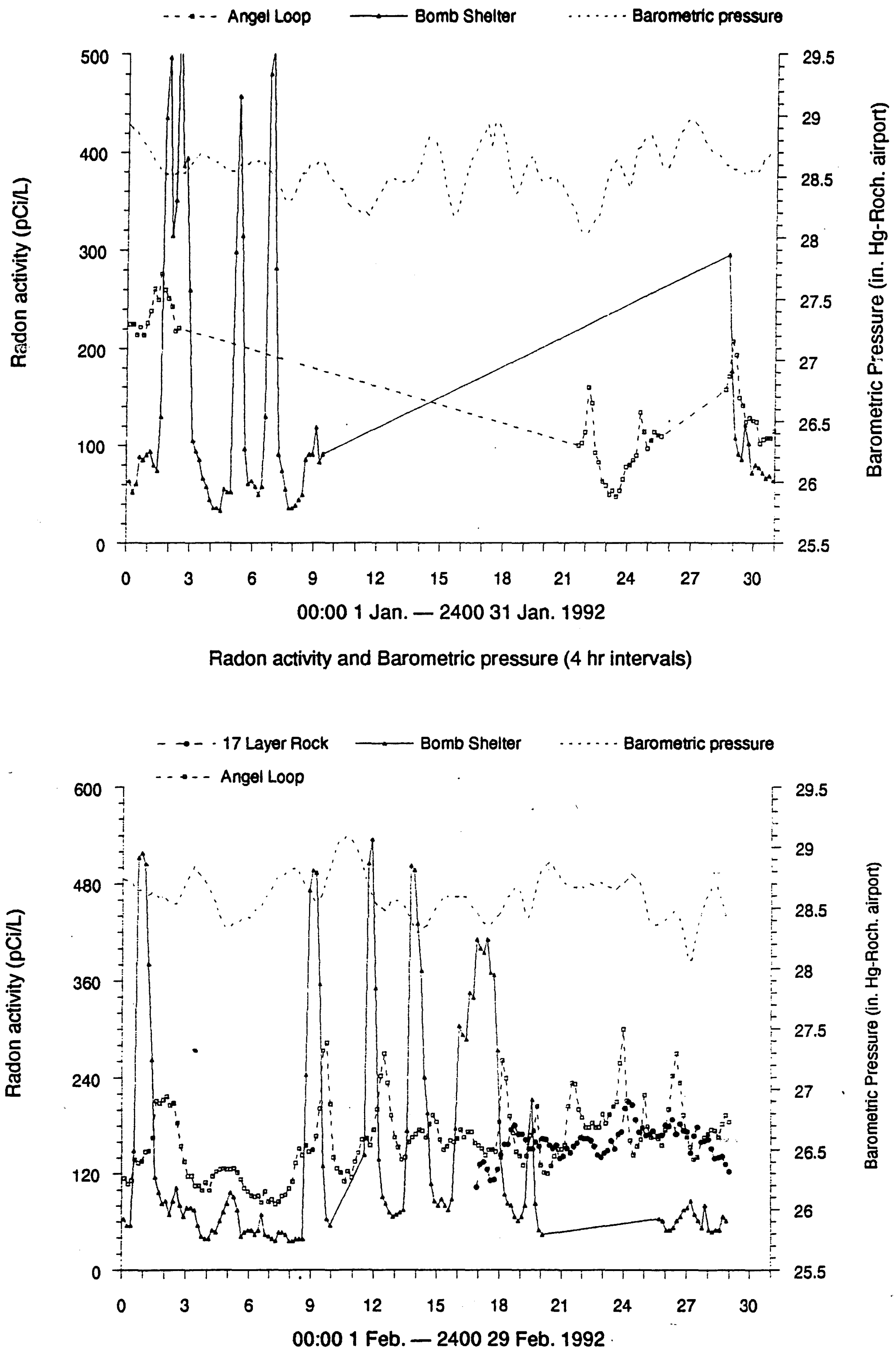
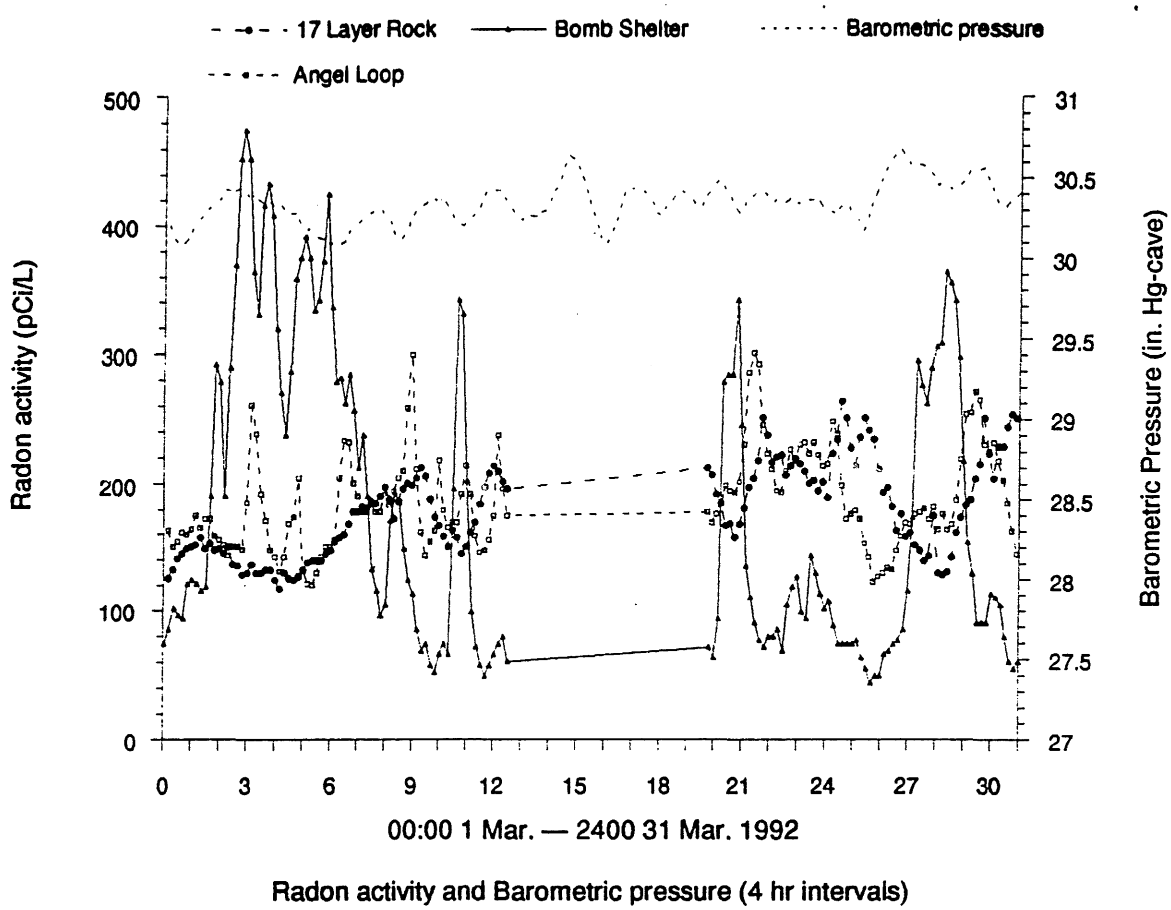


Figure F-14. Radon concentrations at locations in Mystery I and Mystery II, January-February 1992.



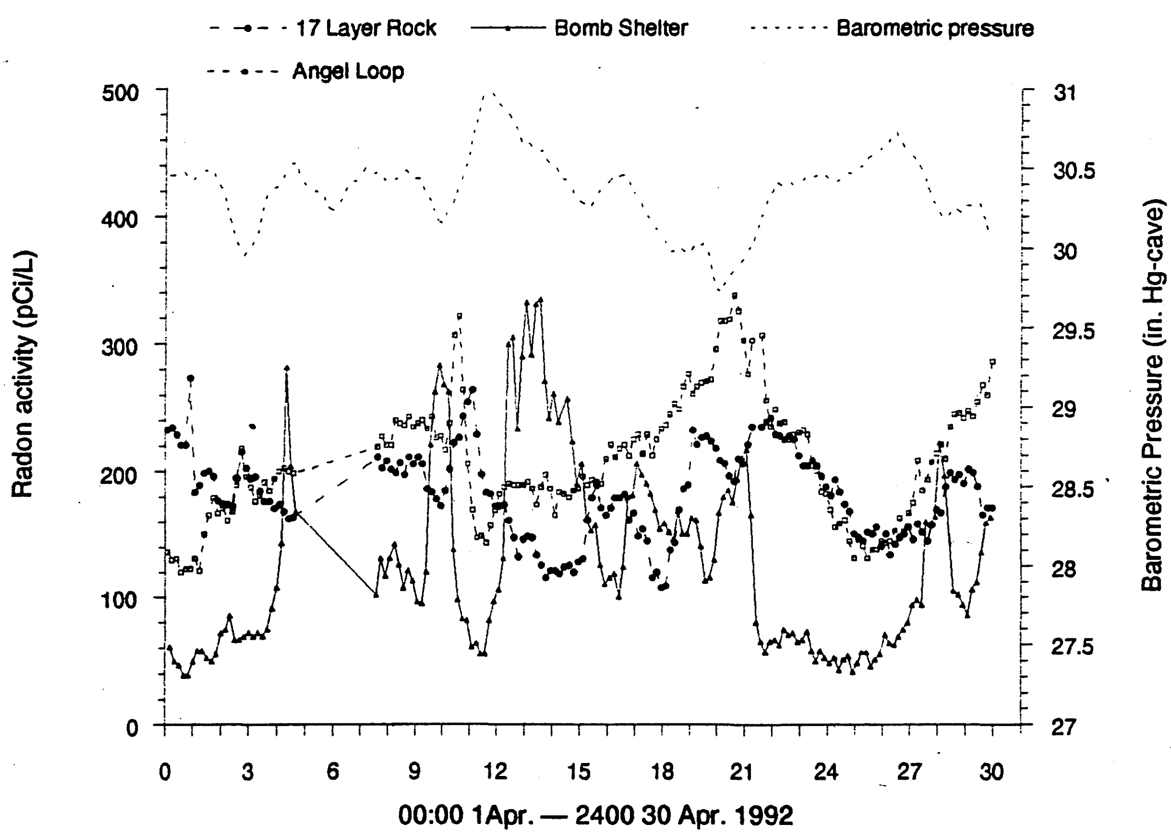
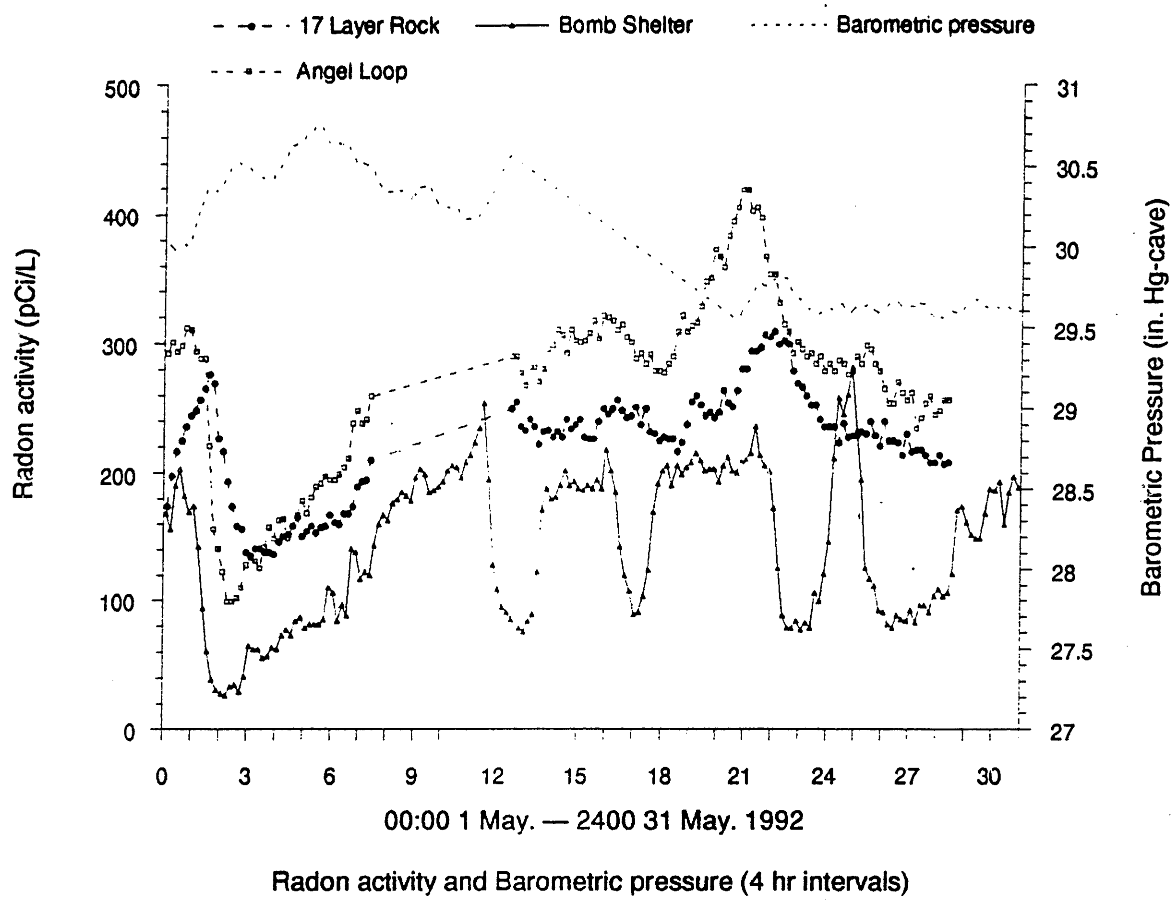


Figure F-15. Radon concentrations at locations in Mystery I and Mystery II, March-April 1992.



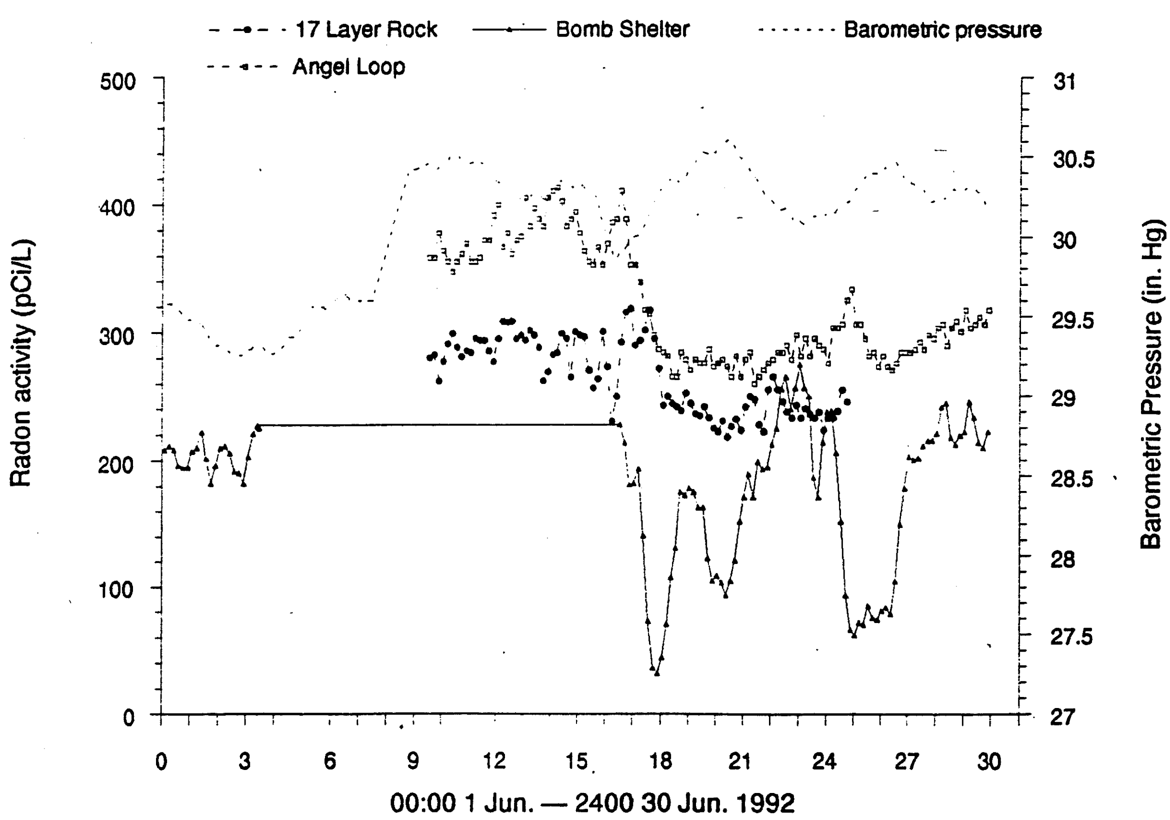
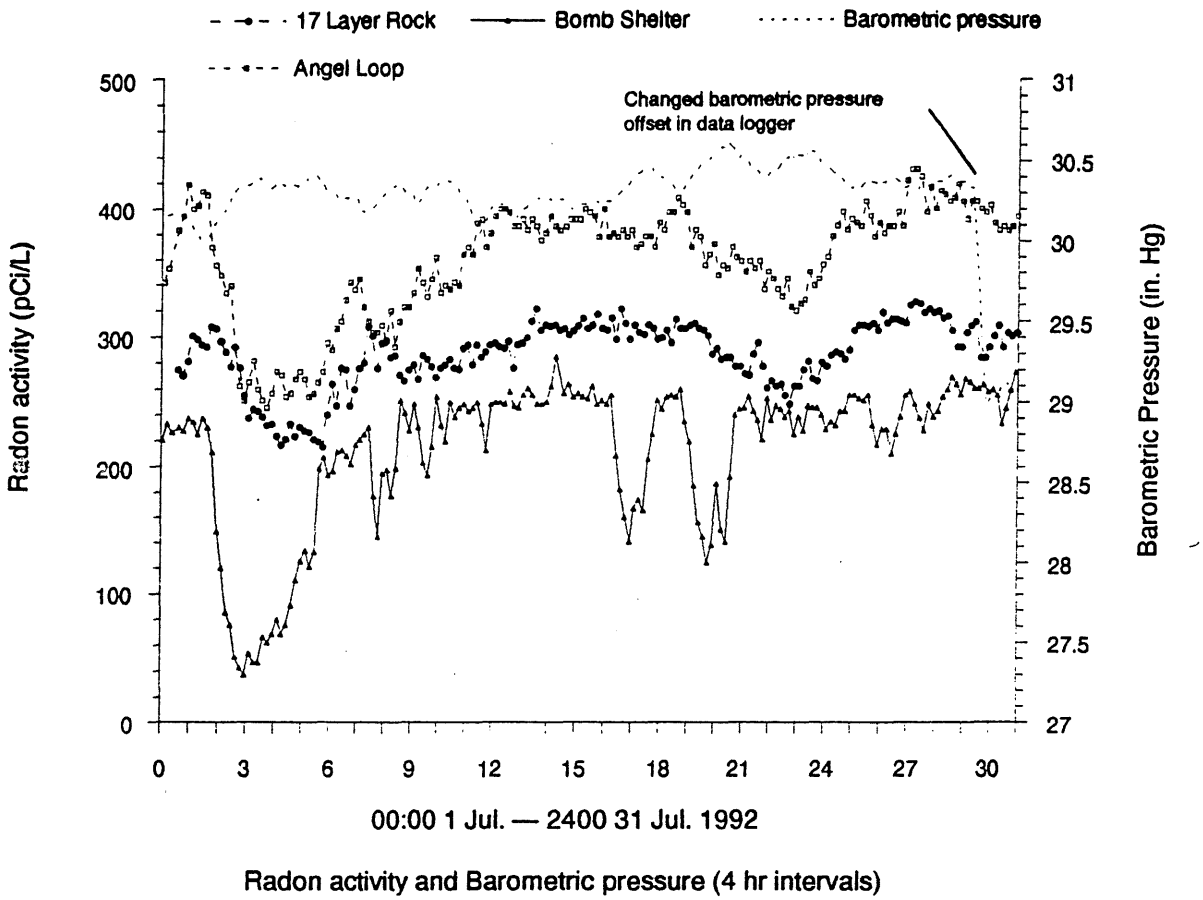


Figure F-16. Radon concentrations at locations in Mystery I and Mystery II, May–June 1992.



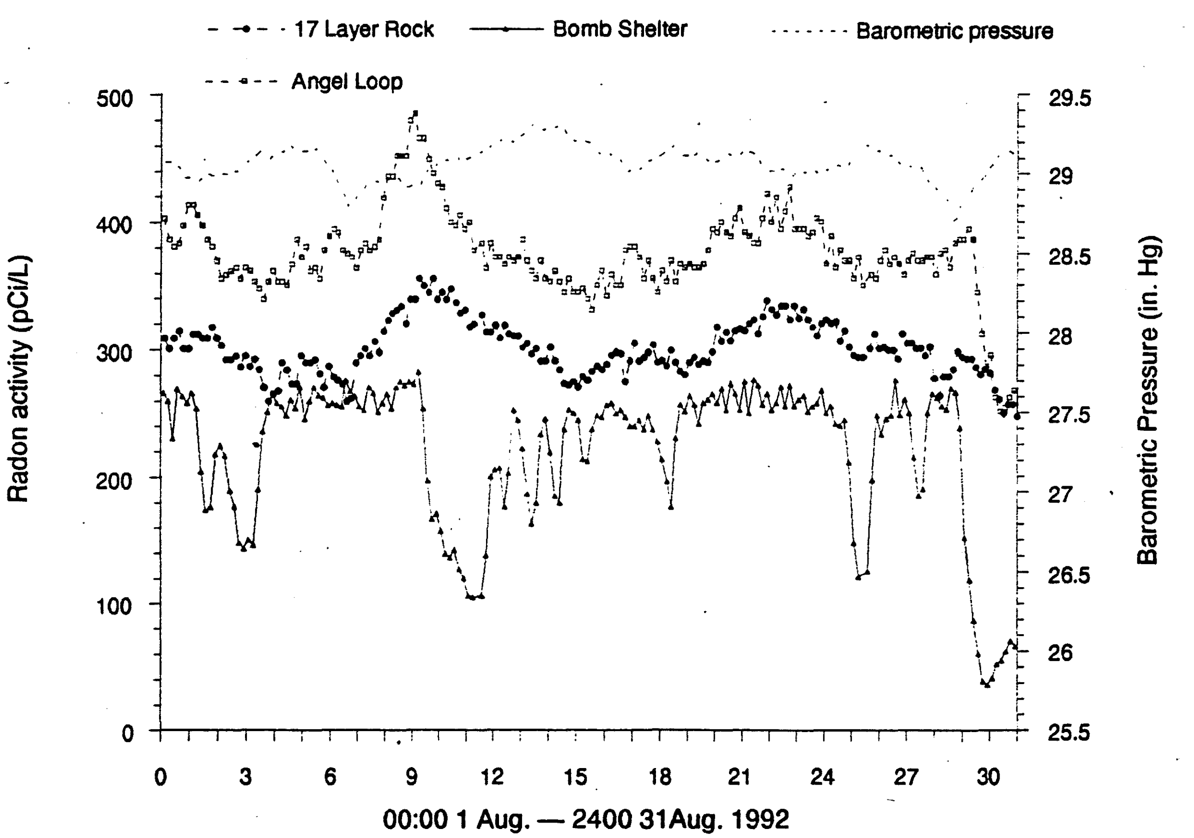
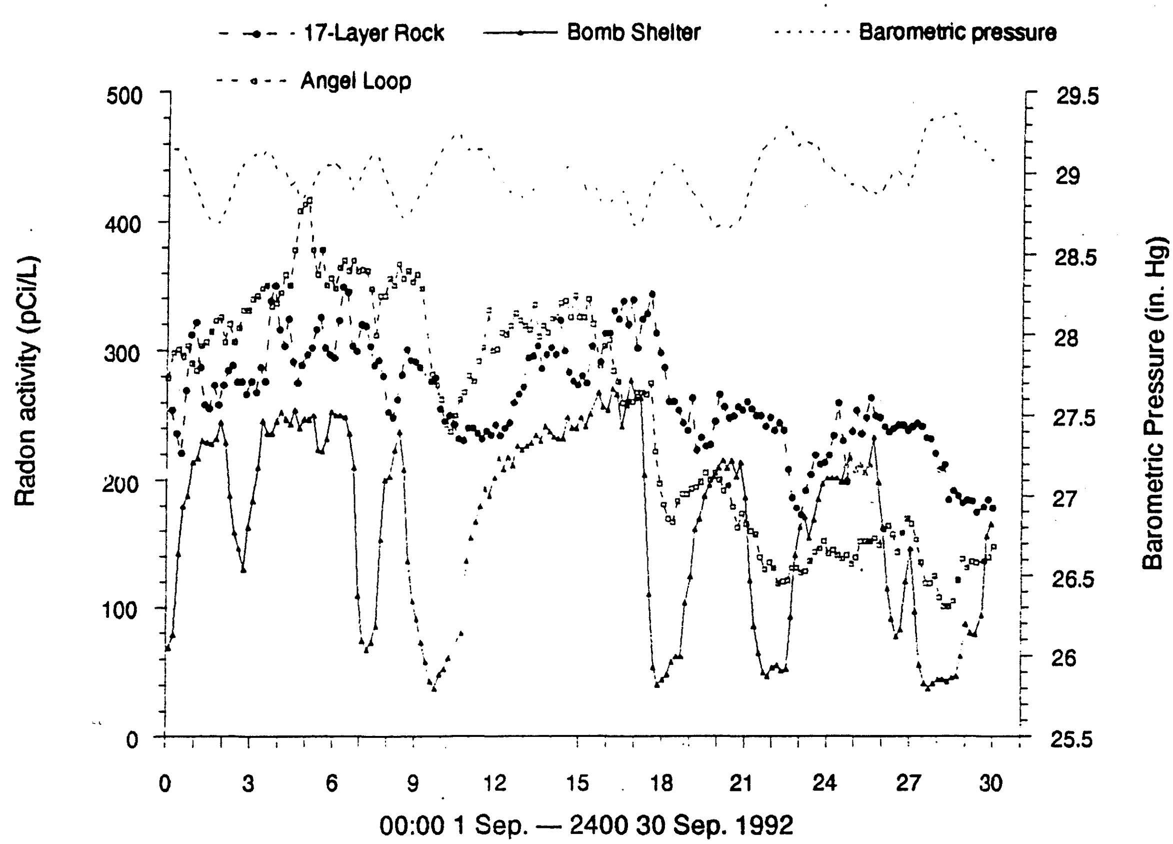


Figure F-17. Radon concentrations at locations in Mystery I and Mystery II, July-August 1992.



Radon activity and Barometric pressure (4 hr intervals)

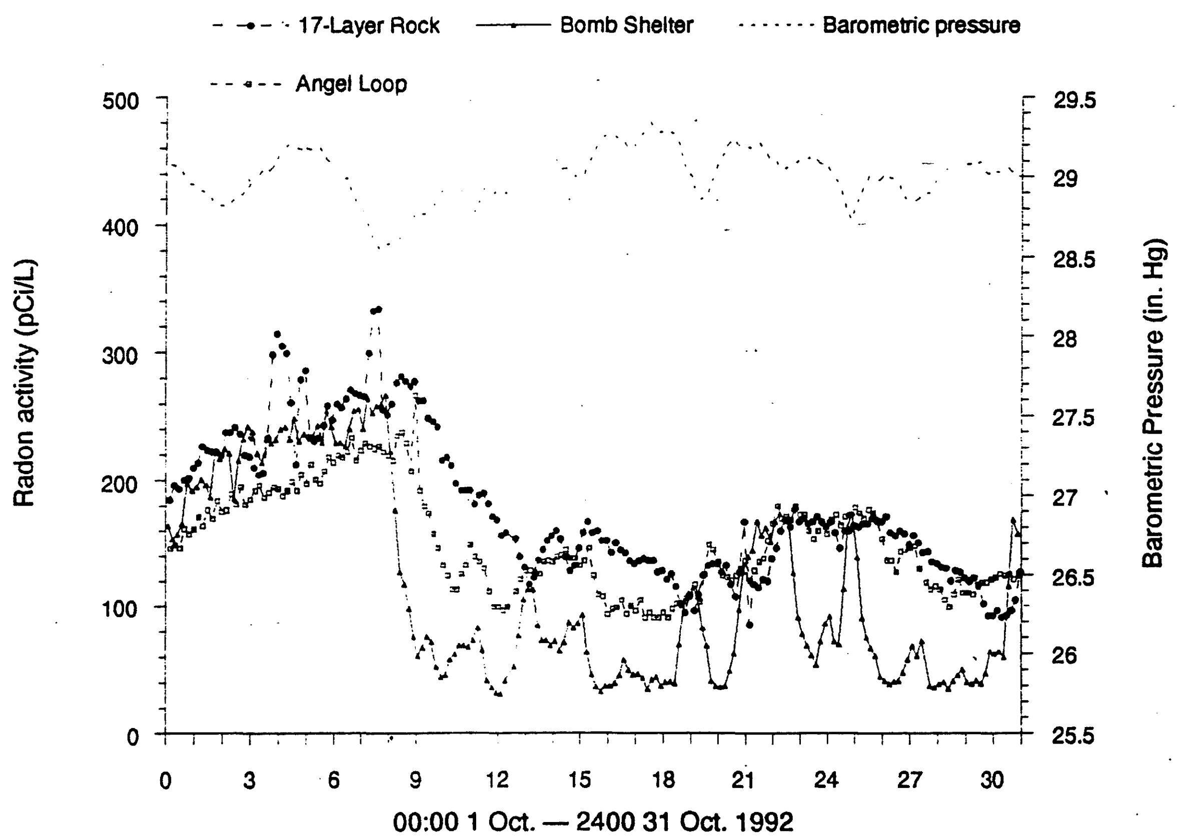
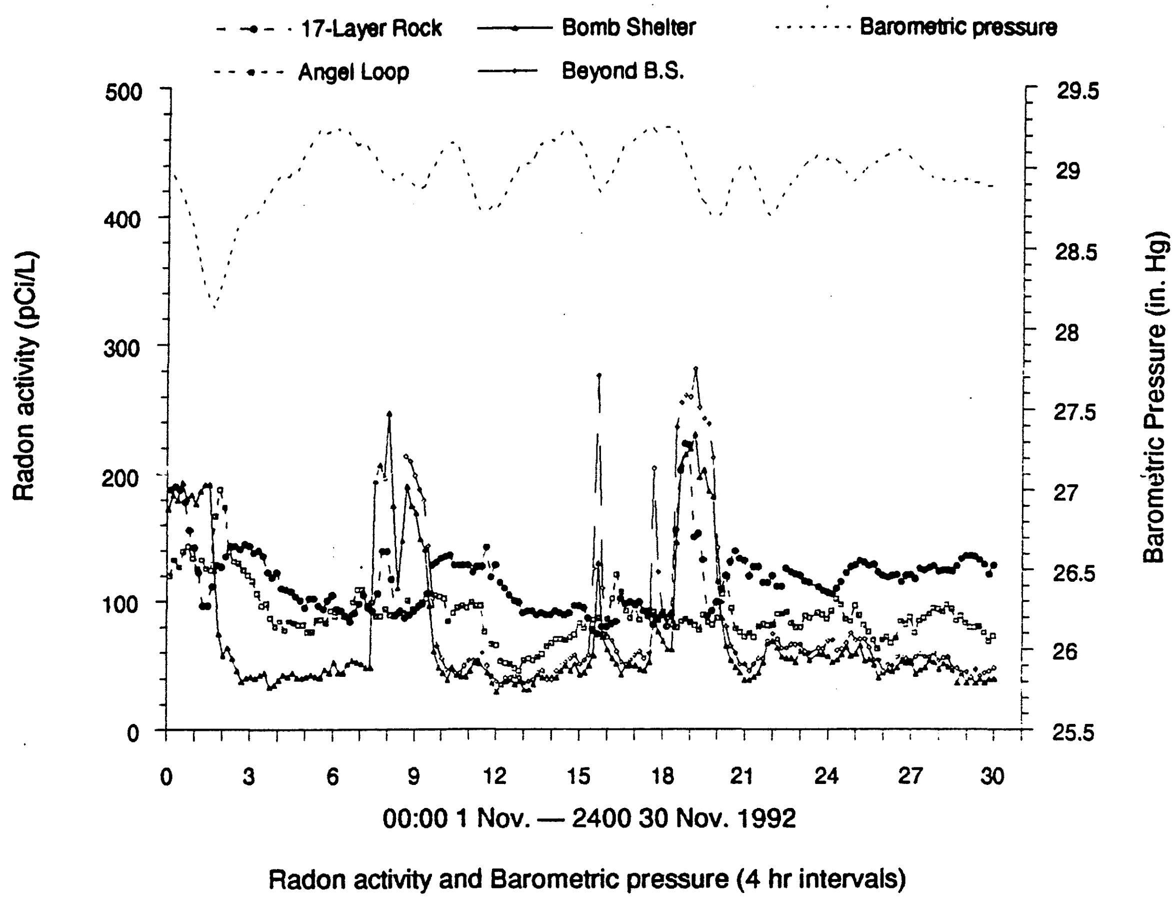


Figure F-18. Radon concentrations at locations in Mystery I and Mystery II, September-October 1992.



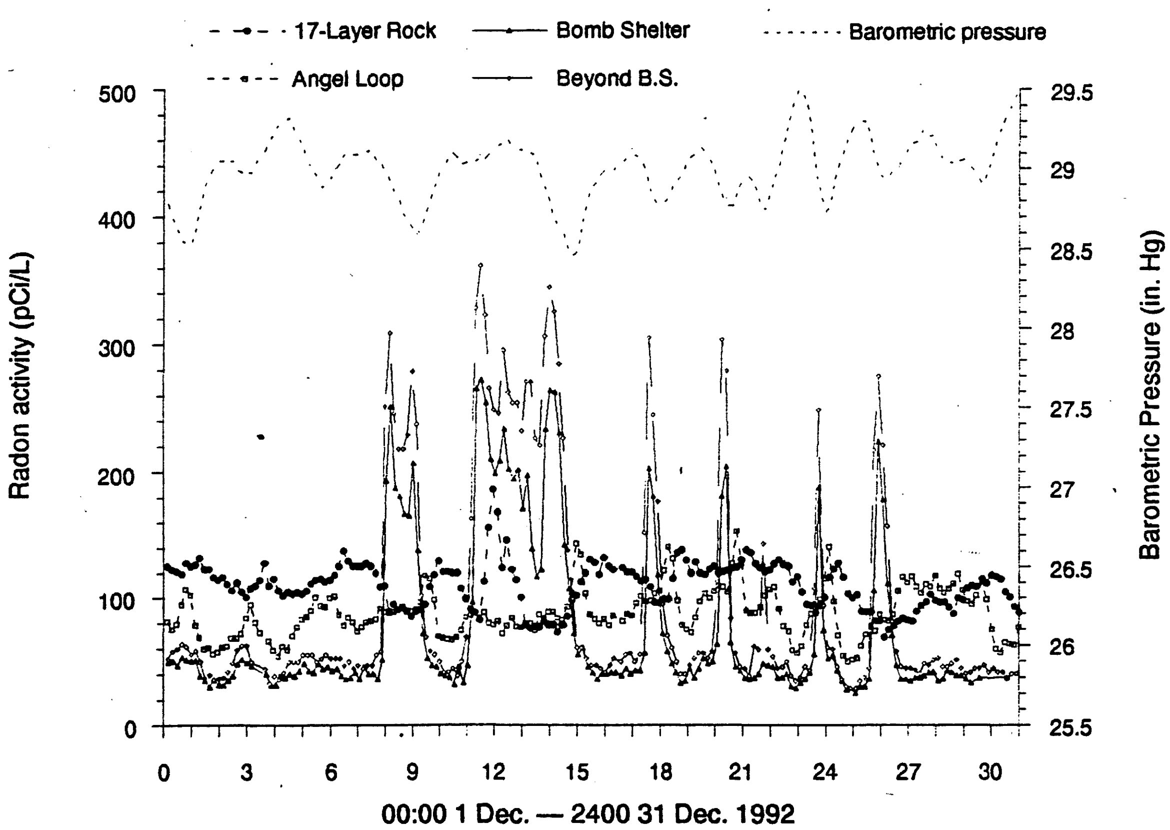
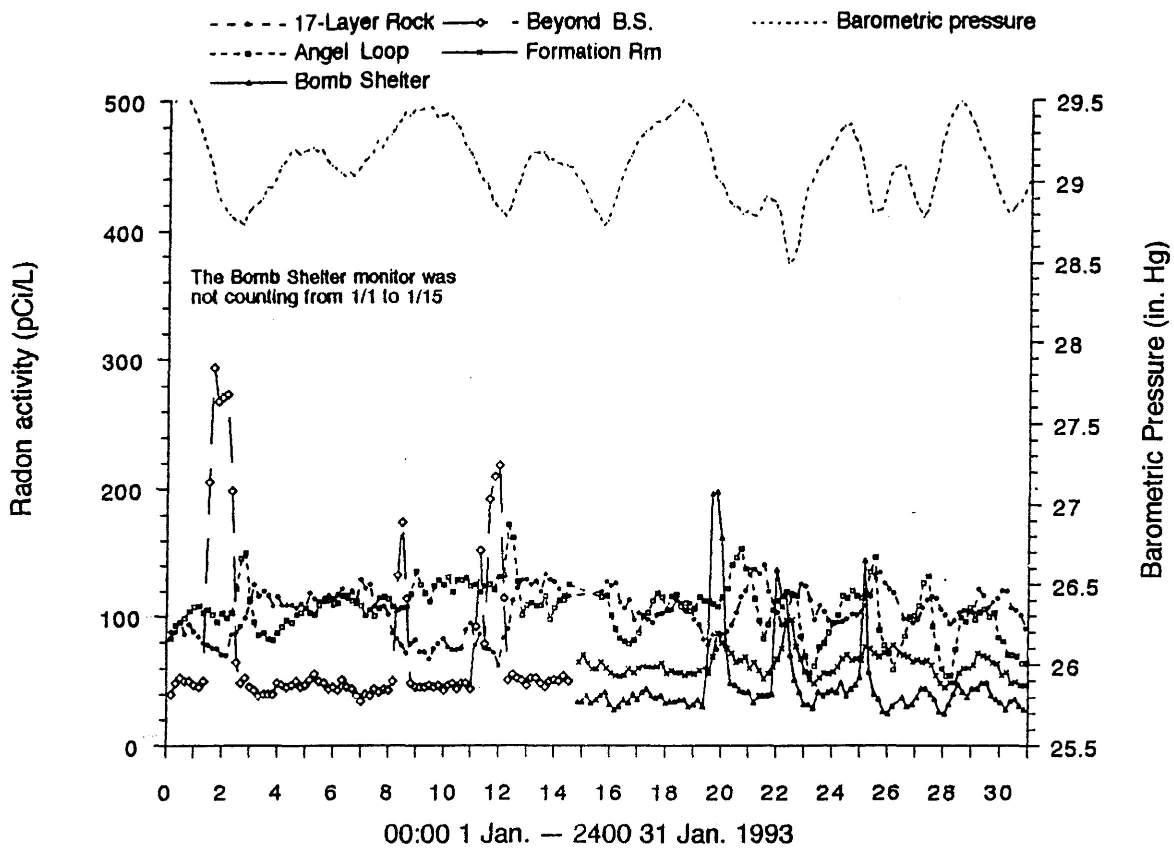


Figure F-19. Radon concentrations at locations in Mystery I and Mystery II, November-December 1992.



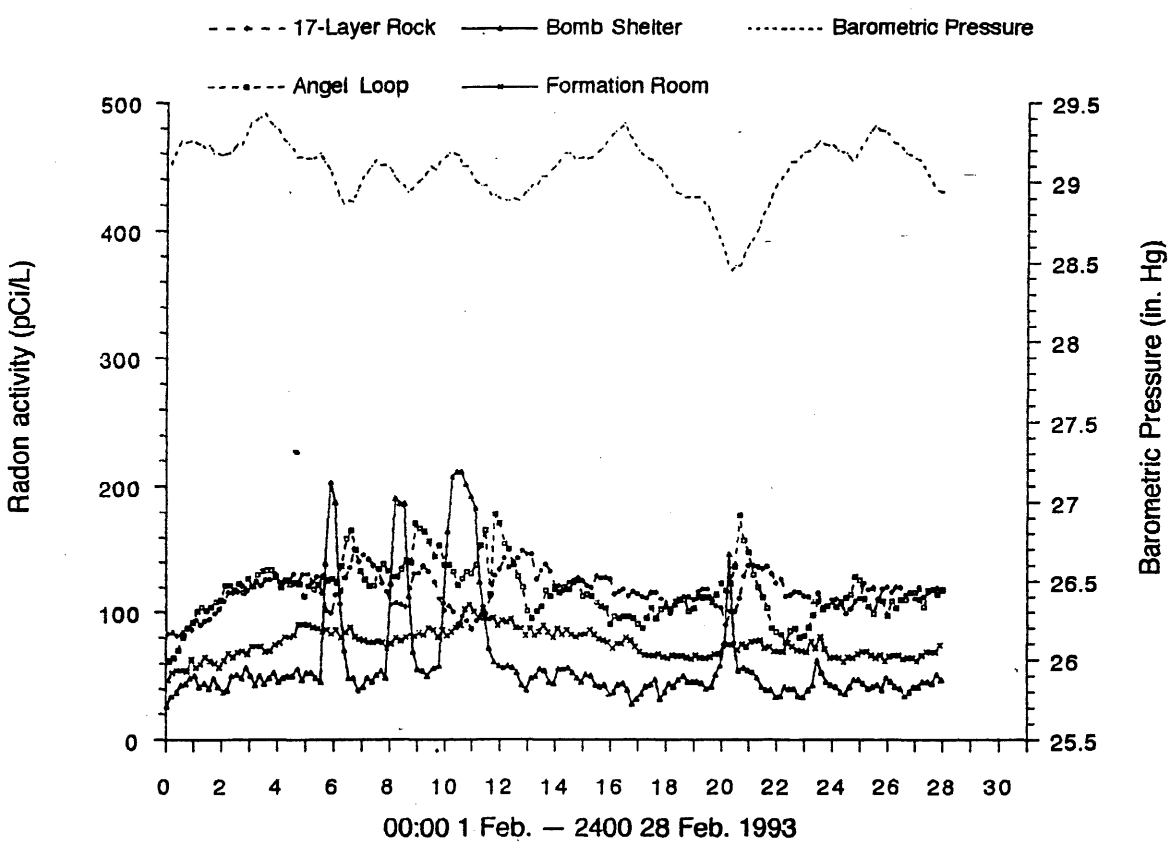
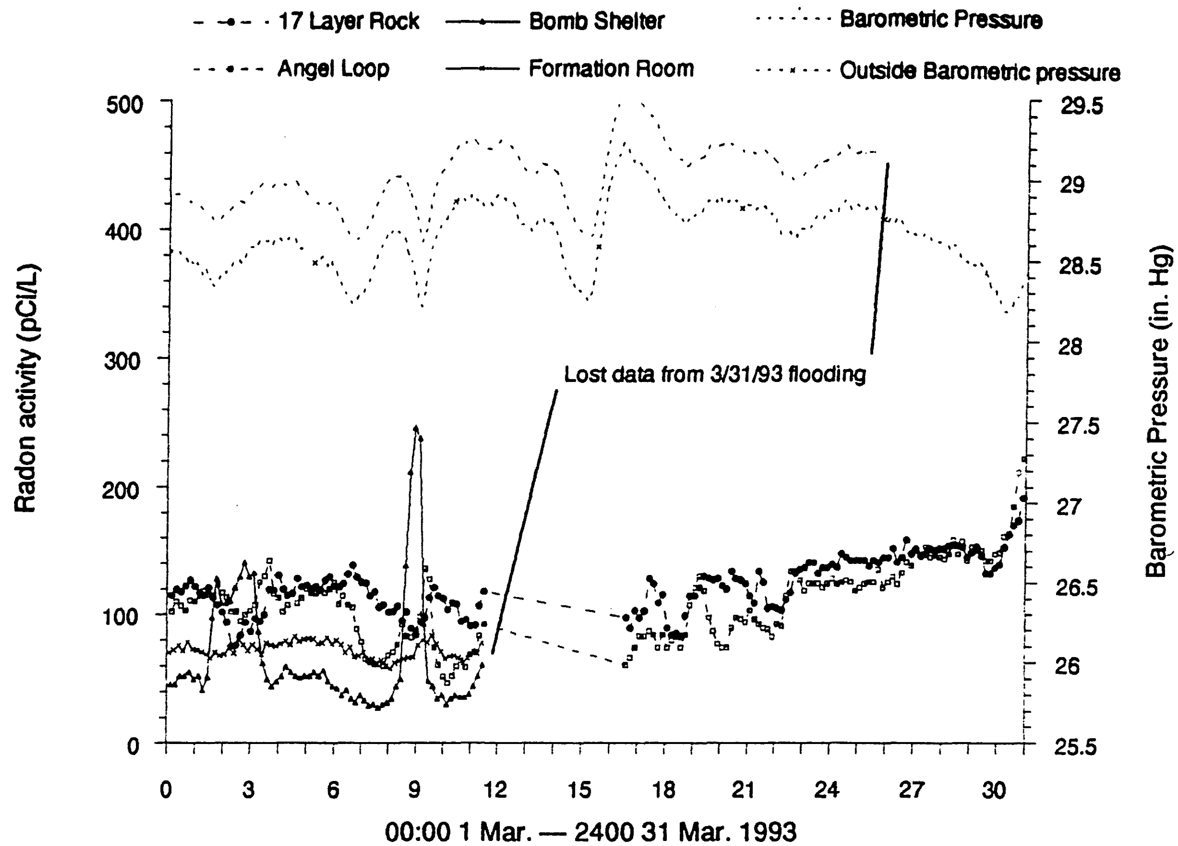


Figure F-20. Radon concentrations at locations in Mystery I and Mystery II, January-February 1993.



Radon activity and Barometric pressure (4 hr intervals)

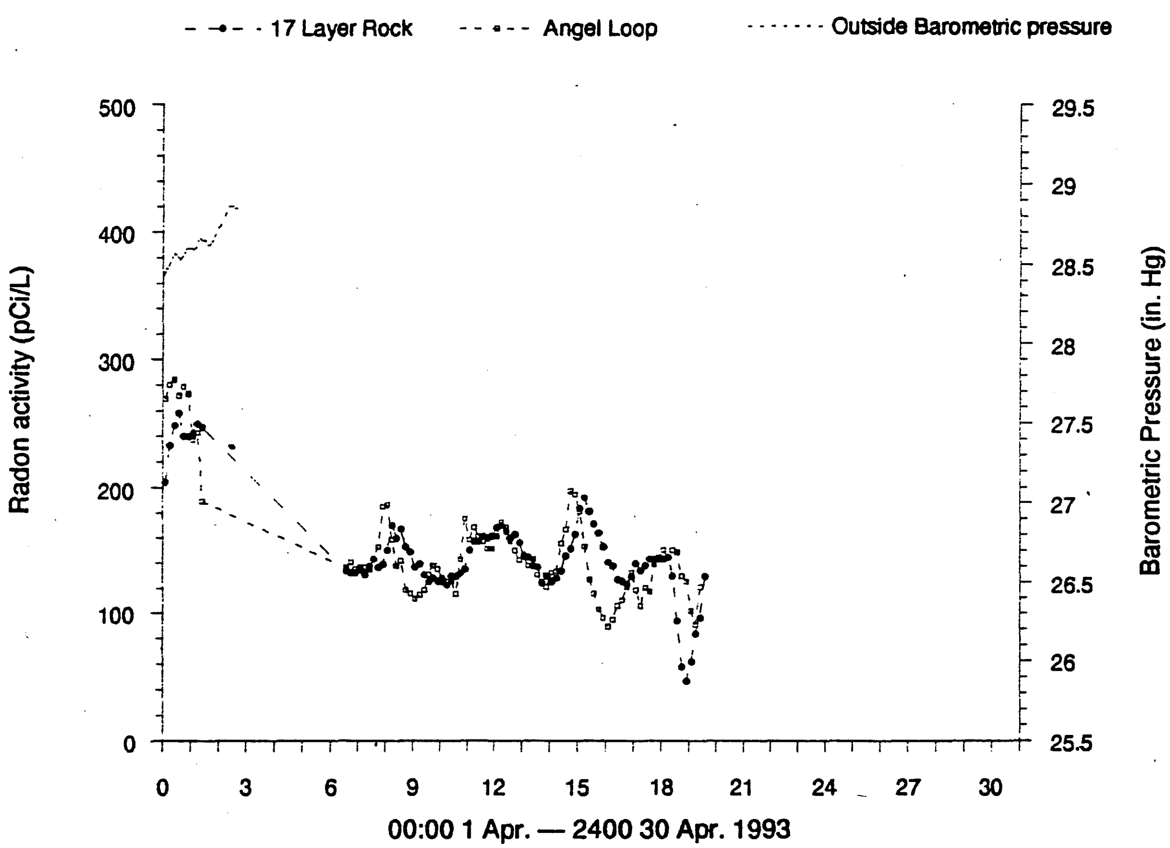


Figure F-21. Radon concentrations at locations in Mystery I and Mystery II, March-April 1993.

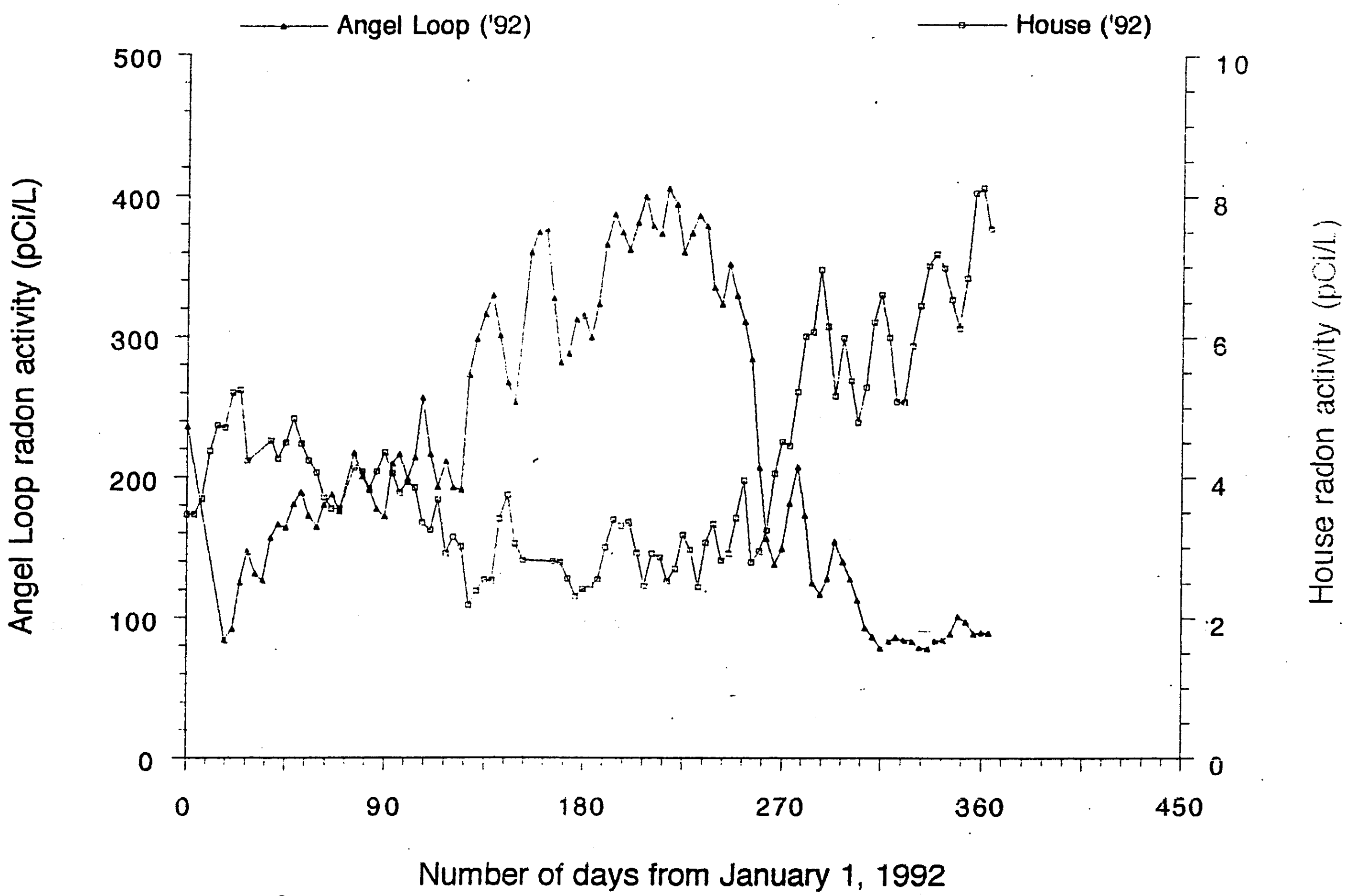
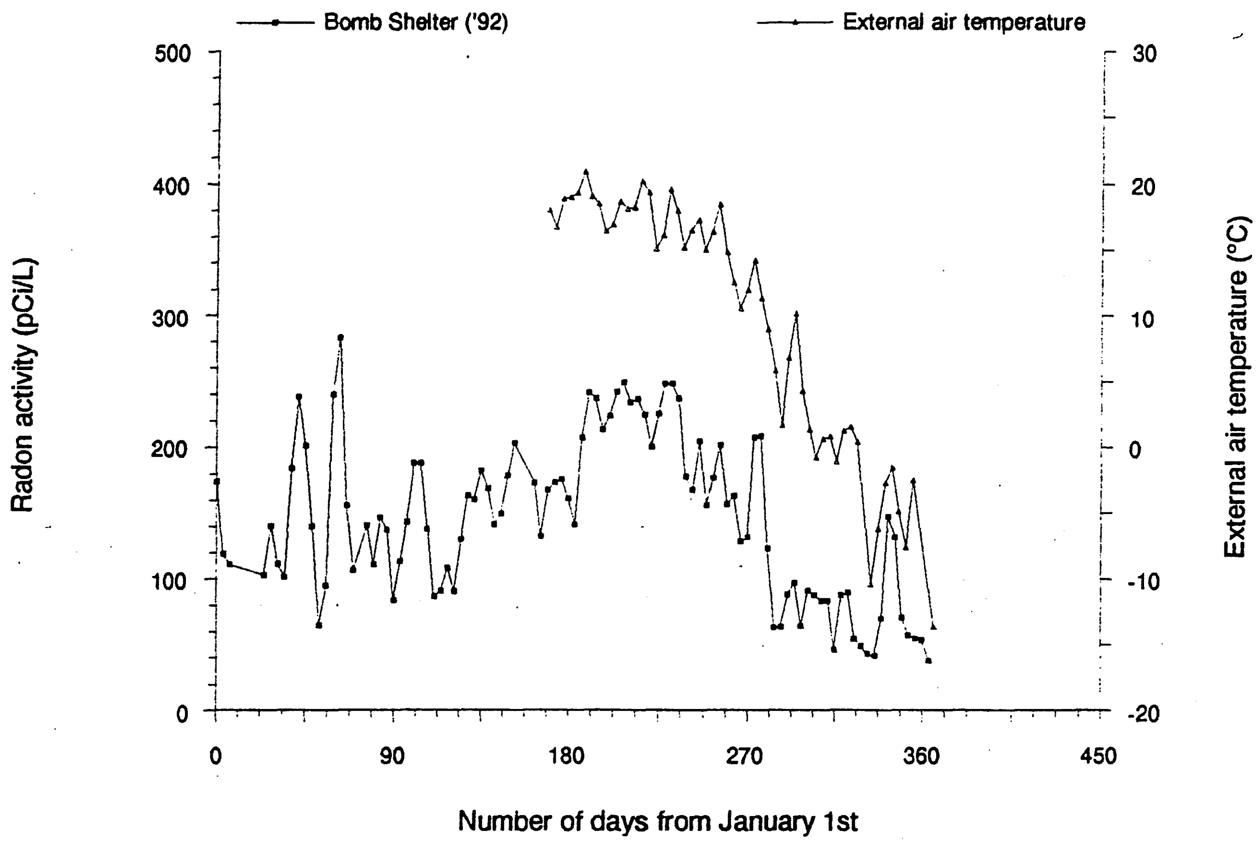
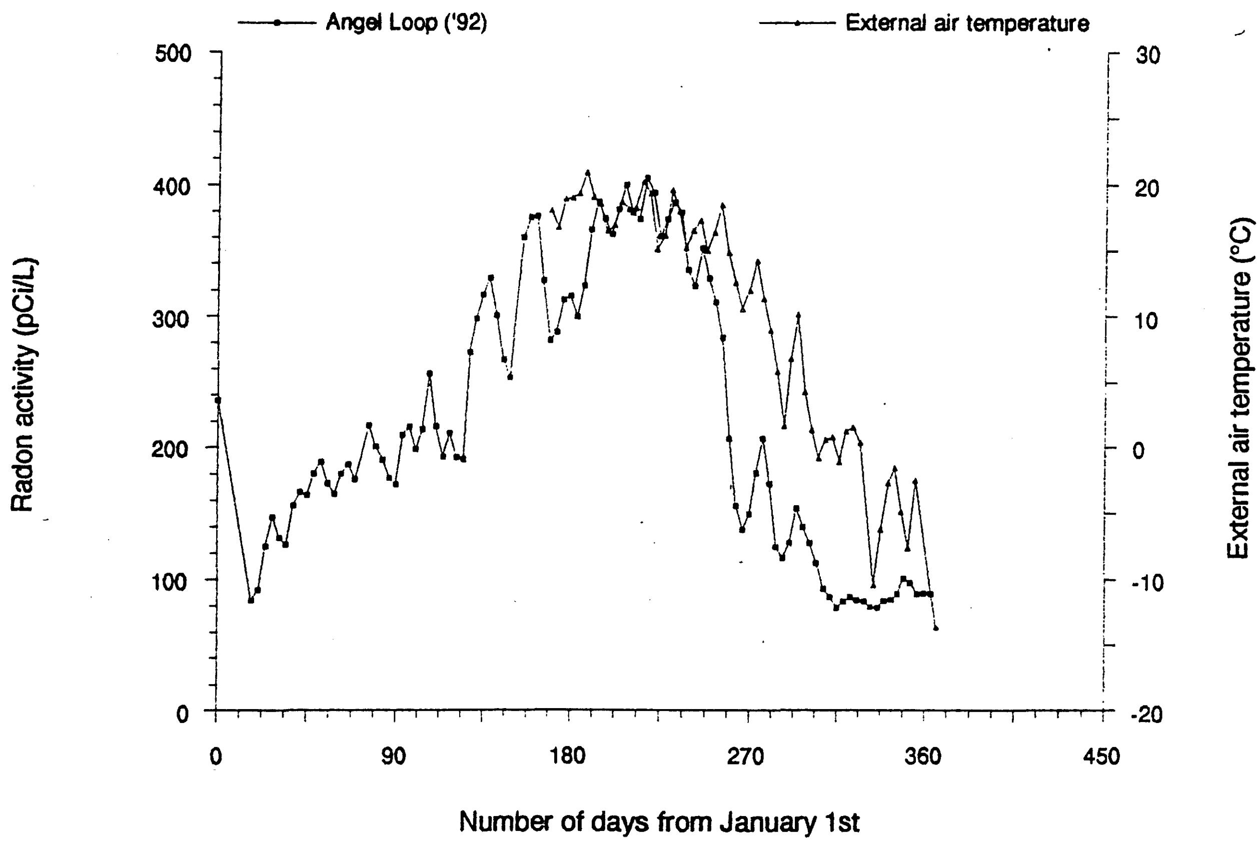


Figure F-22. **The 7-day running average radon concentrations at Angel Loop, Mystery II and the first floor of the Ranger house outside Mystery I.**



Seven day running average of radon at Bomb Shelter and outside air temperature, 1992

Figure F-23. The 7-day running average radon concentration at Bomb Shelter and the 7-day running average of surface temperature for 1992.



Seven day running average of radon at Angel Loop and outside air temperature, 1992

Figure F-24. The 7-day running average radon concentration at Angel Loop and the 7-day running average of surface temperature for 1992.

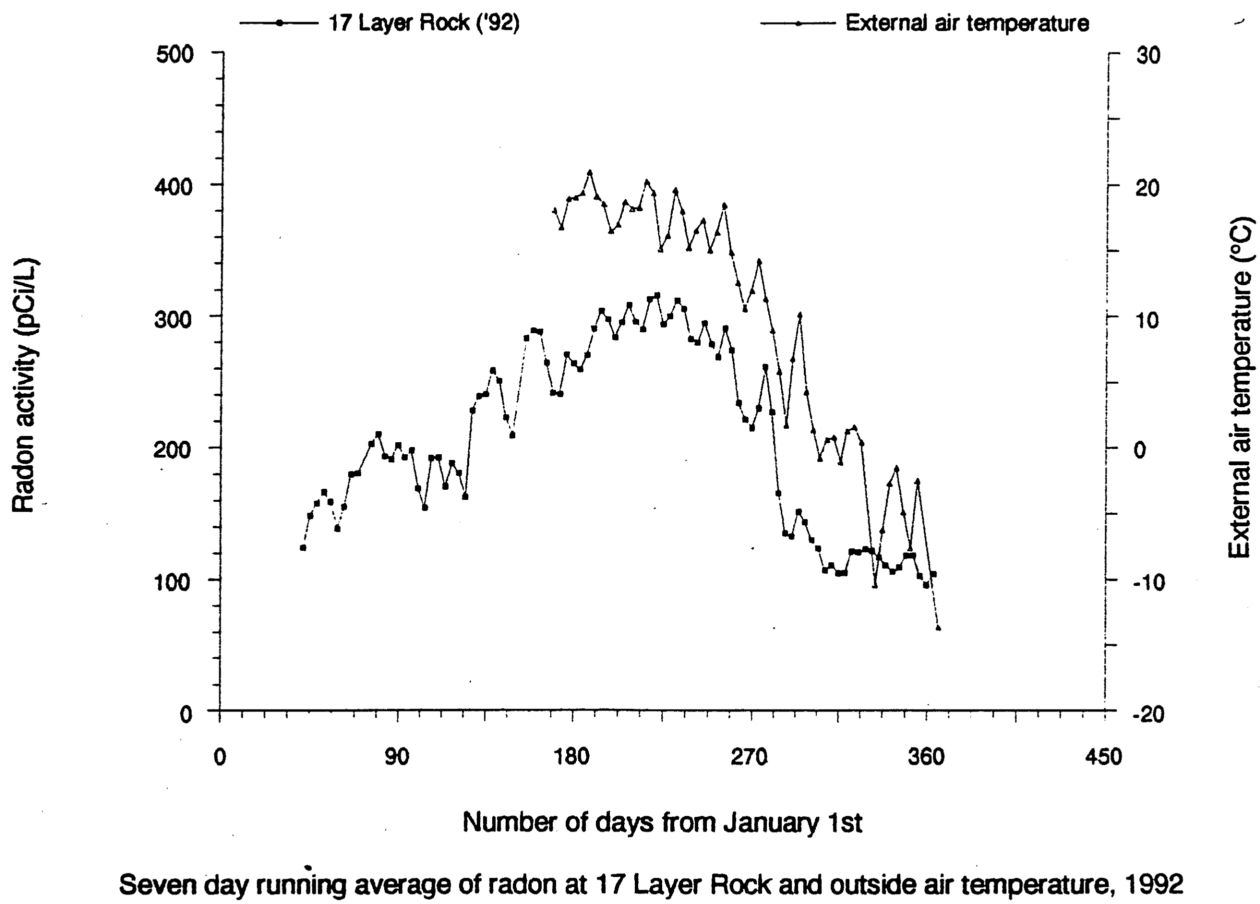


Figure F-25. The 7-day running average radon concentration at 17-Layer Rock and the 7-day running average of surface temperature for 1992.

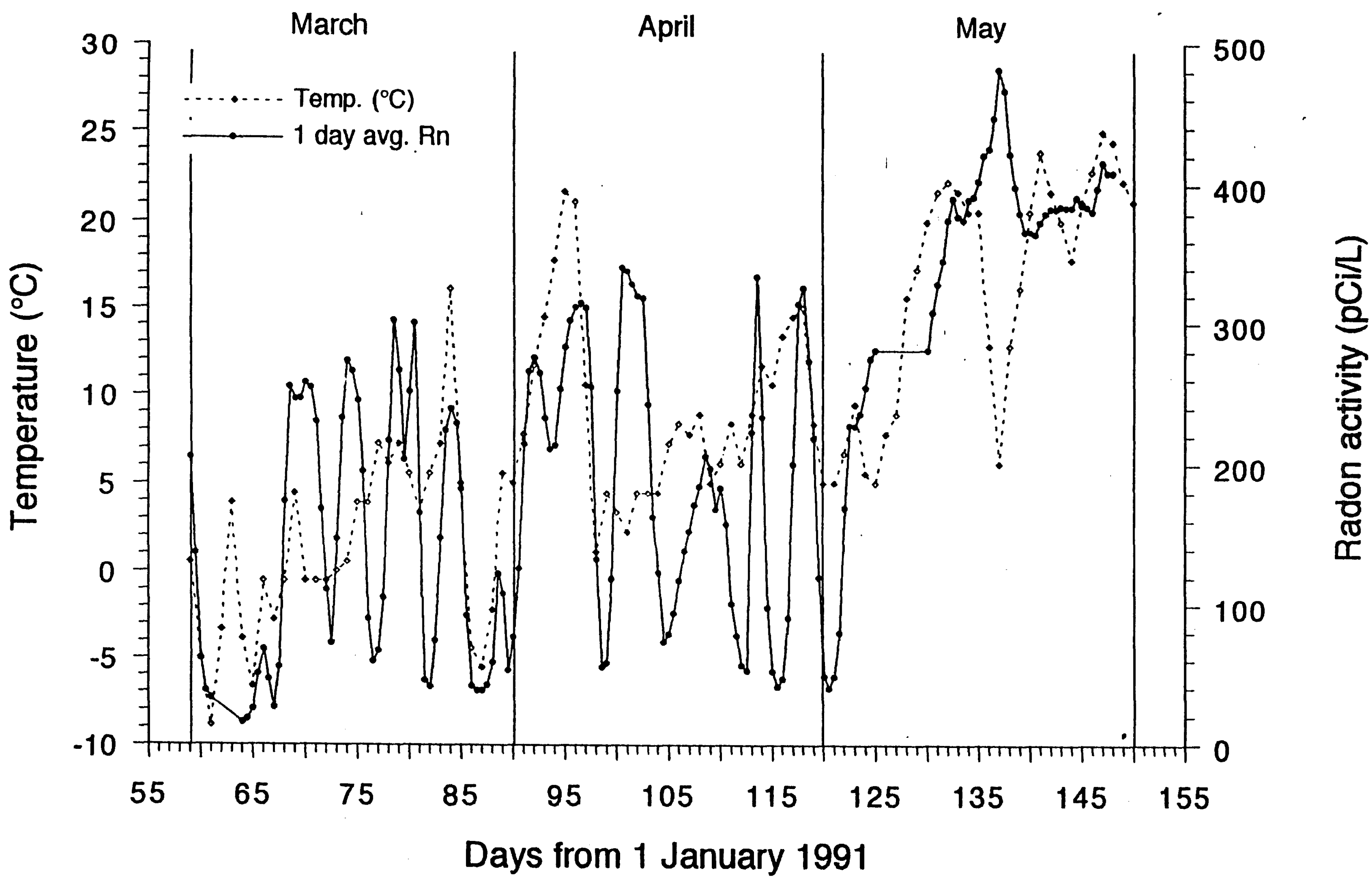
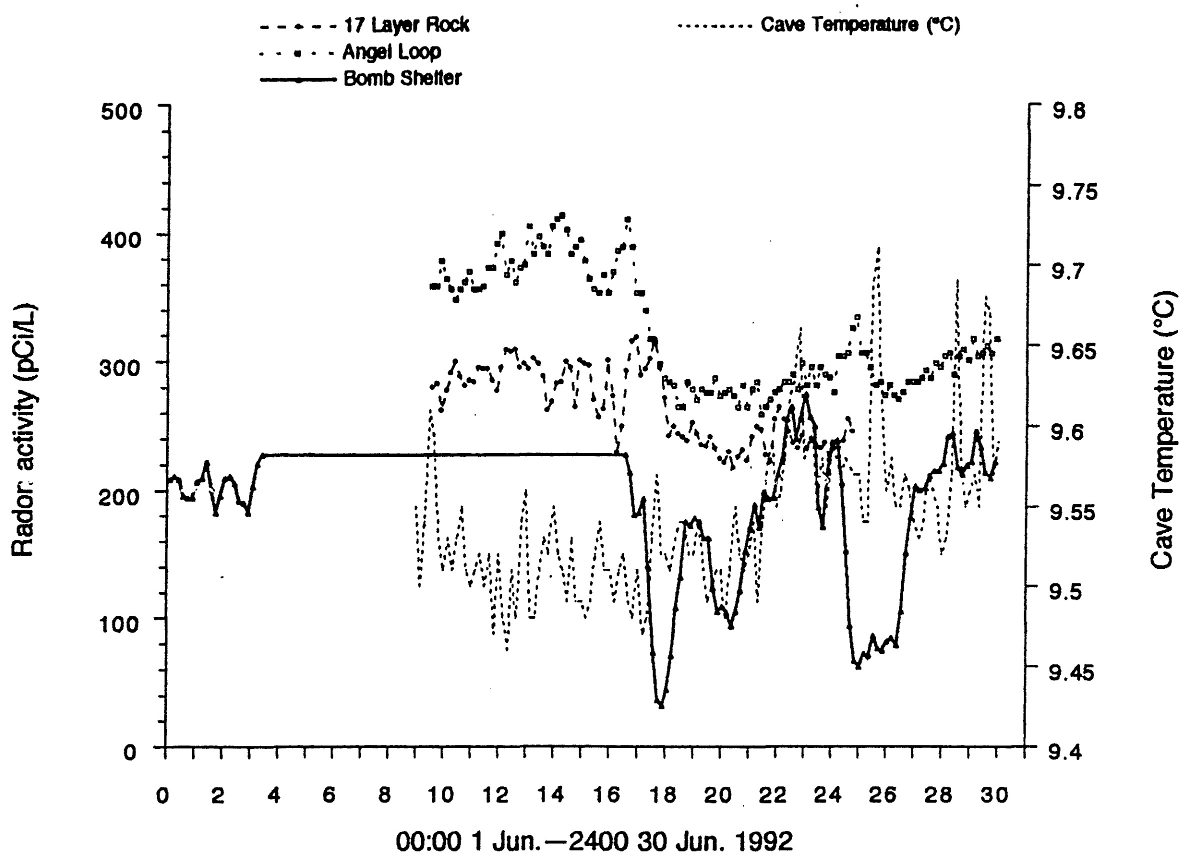


Figure F-26. The daily average radon concentration and outside air temperature during the spring, from March 1991 to May 1991.



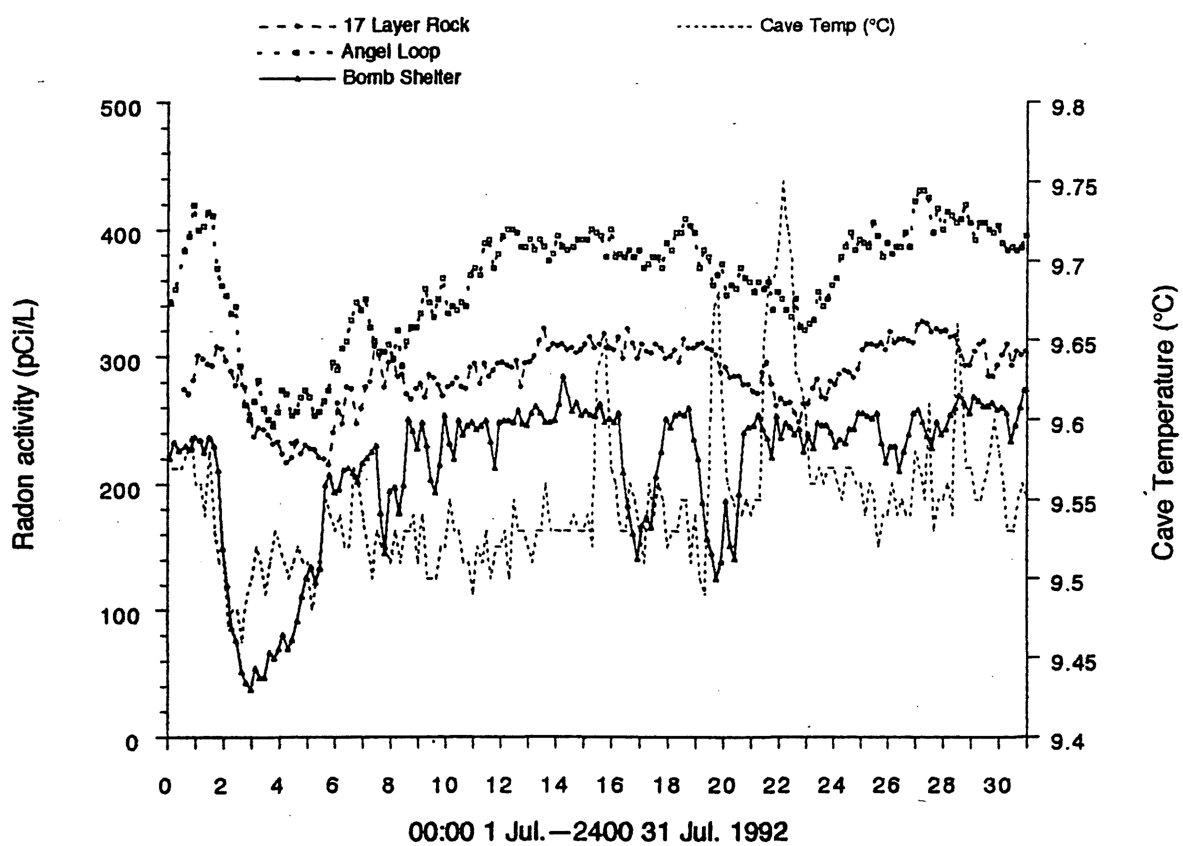
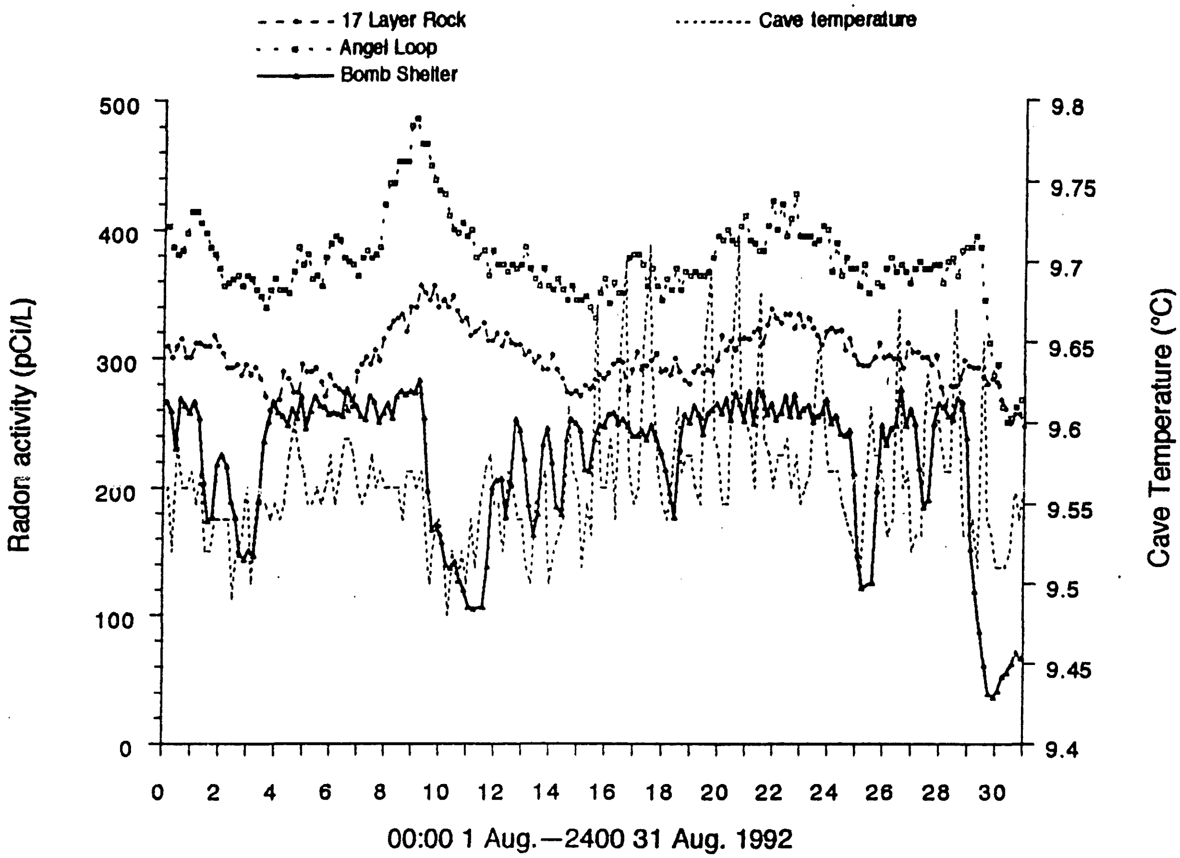


Figure F-27. The relationship between 4 hour air temperatures at Bomb Shelter and radon concentrations in Mystery I and II, June-July 1992.



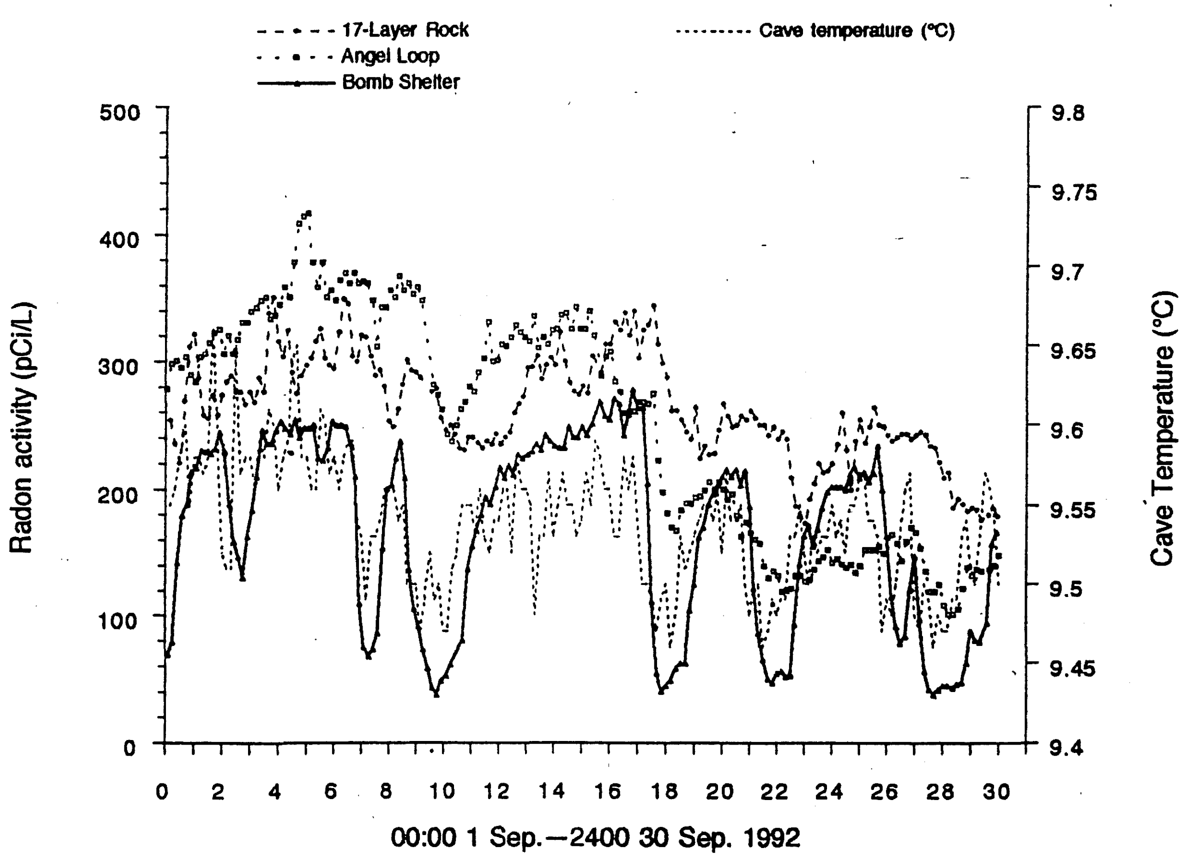
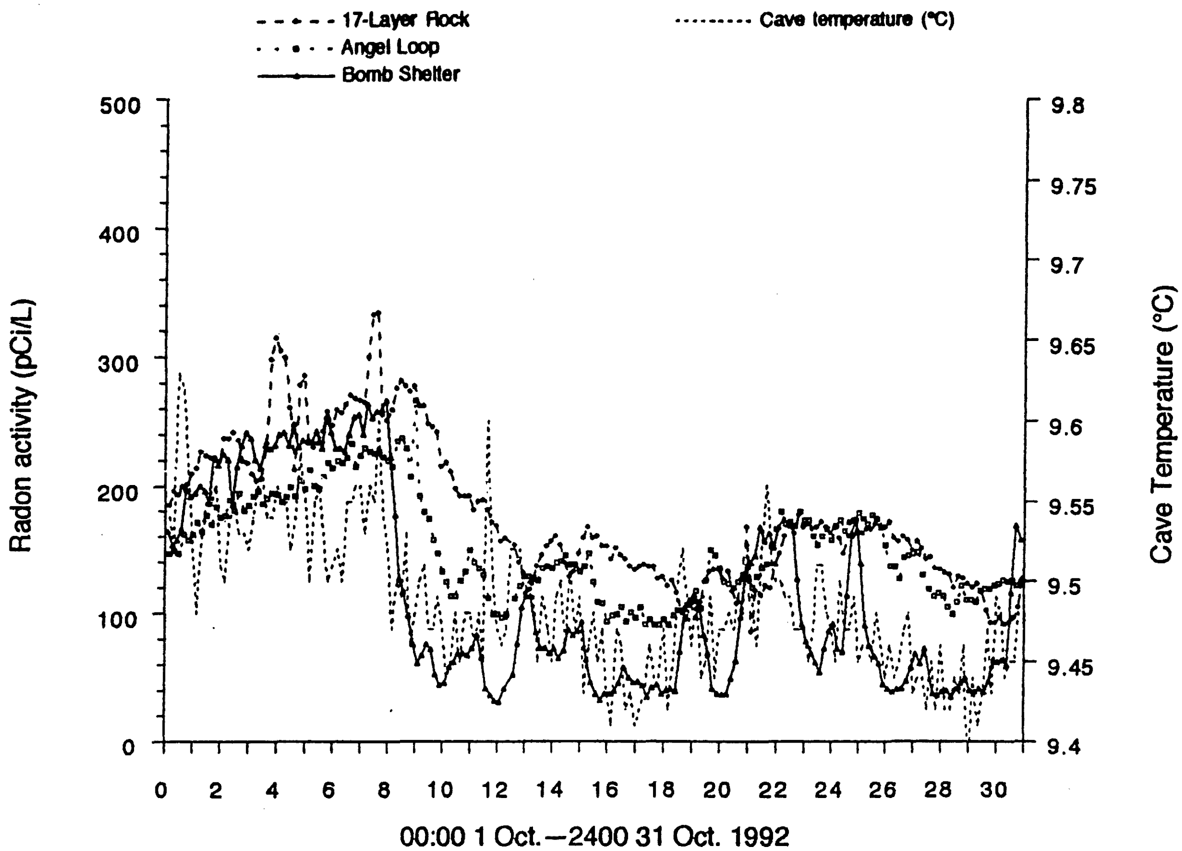


Figure F-28. The relationship between 4 hour air temperatures at Bomb Shelter and radon concentrations in Mystery I and II, August-September 1992.



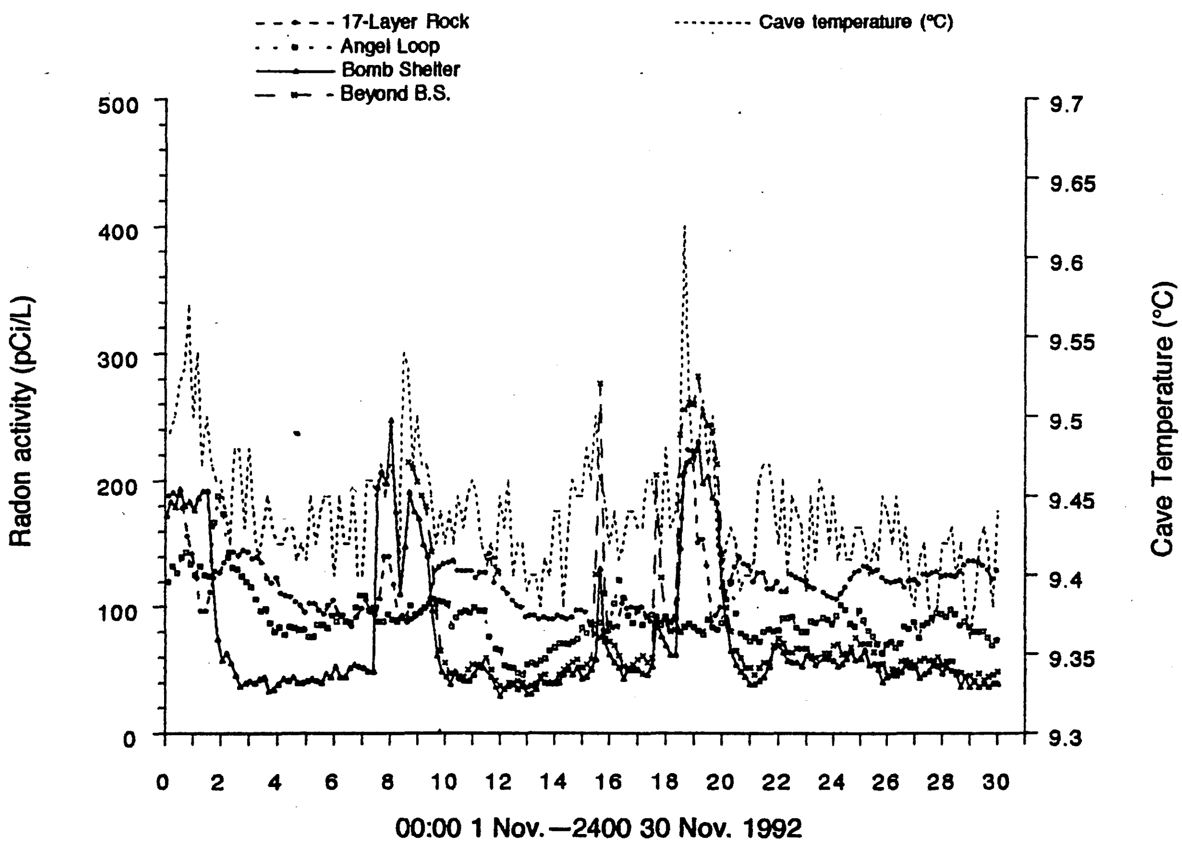
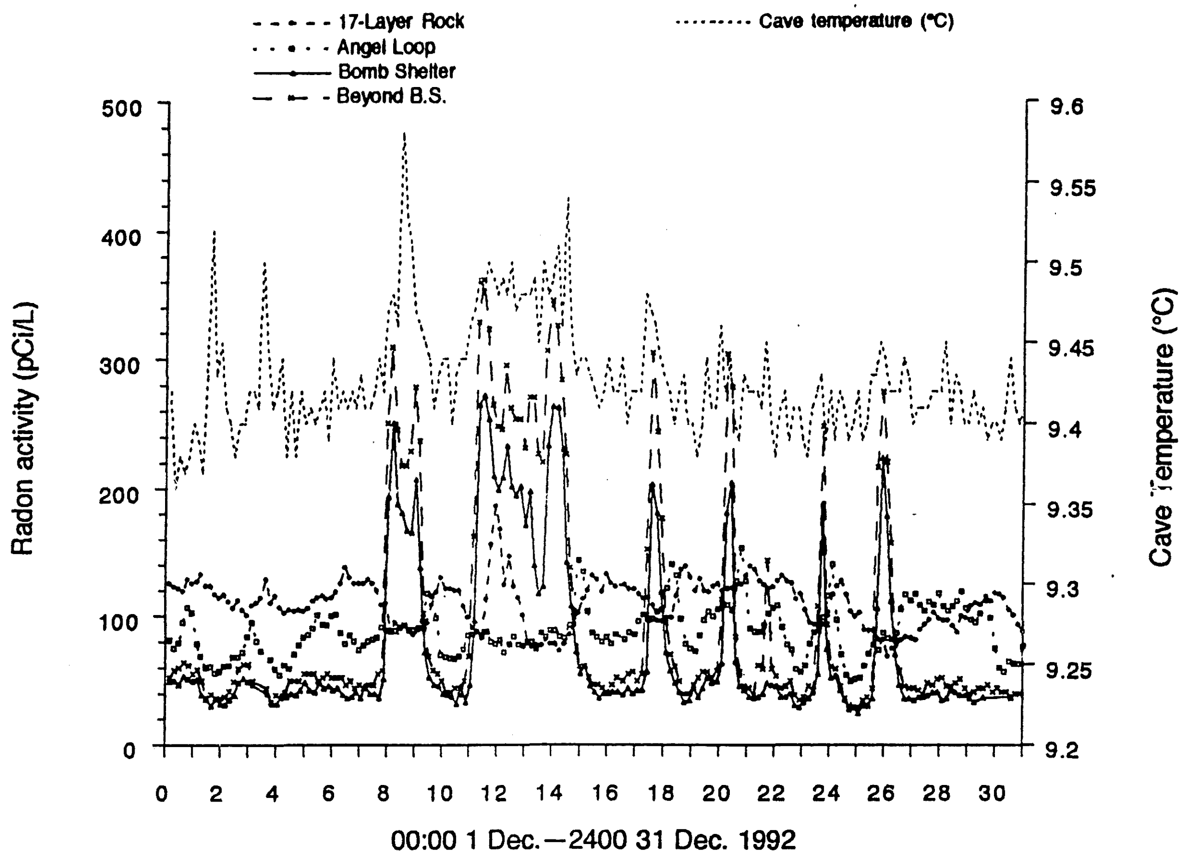


Figure F-29. The relationship between 4 hour air temperatures at Bomb Shelter and radon concentrations in Mystery I and II, October-November 1992.



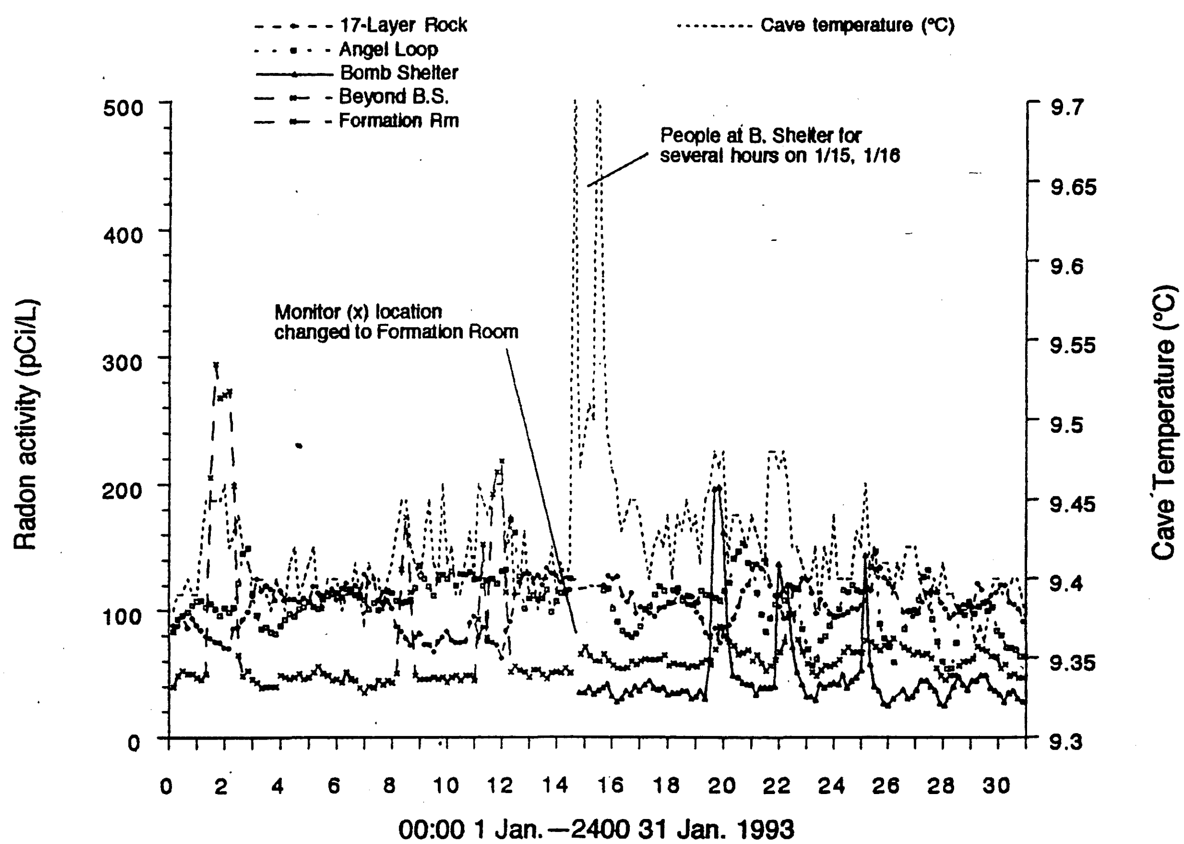


Figure F-30. The relationship between 4 hour air temperatures at Bomb Shelter and radon concentrations in Mystery I and II, December 1992-January 1993.

APPENDIX G. RADON PROGENY MONITORS AND RESULTS

Two monitors for measuring activities of radon decay products (A Pylon AB-5 with a 0.5 micron PTFE membrane filter for attached and unattached radon progeny (Figure G-1a); a 1" alpha counter and Ludlum Model 2000 rate meter for unattached progeny collected on a 40 mesh wire screen (Figure G-1b) were installed at Bomb Shelter in Mystery I (Figure 3). The airflow rate through the grid was 1.42 cfm and through the filter 7.06 x 10^{-3} cfm. Both the Pylon and Ludlum counter performance were checked with radioactive sources of known activity, however, neither was calibrated to calculate absolute concentrations. The configuration of the Pylon system (Figure G-1a) collected radon progeny on the exterior of the filter causing the alpha particles to pass through the filter to reach the detector. Laboratory testing indicated that the PTFE filter material used would only allow a small fraction of high energy alpha particles to reach the detector, reducing the efficiency to about 2% from a more usual 14% with polycarbonate filters. However given the high activity levels in the cave the lower efficiency was not considered a problem as the activity accumulated provided good counting statistics. In addition to lowering the count rate, the PTFE filter by screening out alpha particles below 6 Mev, prevented the unit from directly measuring ^{218}Po activity, the isotope associated with the unattached fraction. It would measure any ^{214}Po collected from the air and any ^{214}Po resulting from decay of collected ^{218}Po. The extent to which this affected the record of progeny variation, if at all, is unclear and would require more detailed experimentation in the cave atmosphere.

Radon progeny attaching to the grid are known as 'free' or 'unattached'. That is, they are charged particles with high diffusion rates relative to large aerosol particles. They may be associated with <0.1 micron size particles and are nominally the first radon decay product, ^{218}Po. Progeny that are 'attached', no longer carry a charge, and become part of aerosol particles >0.1 microns in size and have slower diffusion rates. These attached progeny were not collected by the grid. Air flowing through the filter had both the attached and unattached fractions removed and trapped on the filter surface. These decayed through ^{214}Po (the isotope with the high energy alpha capable of penetrating the filter) and provide an indication of the total concentration of progeny in the air.

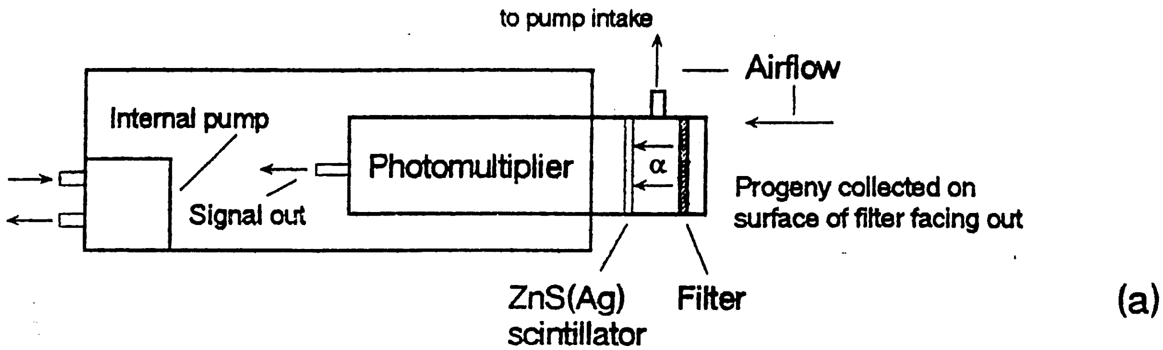
The results from measurements of radon decay products are shown in Figures G-2 to G-8, for February 1992 to March 1993. The activity collected on the grid were adjusted for the difference in flow rates and detector areas between the two monitors (Grid flow rate 201 times that of Pylon and detector area 1.076 times larger). The monitors were not calibrated to measure progeny concentrations, but were able to track the progeny on the same time scale as the radon and meteorological variations. Plots show the total counts accumulated in each 4 hour interval, along with the radon concentration measured in the same interval. Between March and June 1992, there was a large gap in progeny data due to equipment failure as a result of condensation. This problem was fixed when the equipment was reinstalled in June. Also note that the first four graphs of progeny activity were measurements taken at Angel Loop, Mystery II, while the remaining were collected at Bomb Shelter, Mystery I.

Major increases or decreases in radon were usually accompanied by similar changes in both the attached and unattached radon progeny concentrations. However, the correlations of progeny variations to radon variations were better during colder months than during the warmer summer months. This is illustrated by the data from July or August 1992 (Figure G-4, G-5) and November or December 1992 (Figures G-6, G-7). The response of the progeny to changes in radon concentration occurred over approximately the same time intervals and at the same rates. There were also numerous intervals where the grid and filter activities were anti-correlated and showed little if any correlation with the radon concentration (see July 22, 1992, Figure G-4, or August 7, 1992, Figure G-5). At other intervals, the grid would correlate well with the radon, but the filter activity behaved independently (see August 19 - September 1992, Figure G-5). There were also instances where the relative magnitude of the variations were similar and others where they were not. Over the course of the monitoring, the progeny activity collected on the grid (^{218}Po) showed a much better correlation with the radon than did the activity on the filter. One reason for this was that ^{218}Po immediately follows radon in the decay chain and has a short half-life, whereas the other alpha emitter, ^{214}Po is separated from radon by two decay products with half-lives of about 30 minutes. The behavior of the decay products will be influenced by rates of attachment to aerosols, plateout and removal by ventilation.

Working levels

Plots showing the working level measurements collected by Park staff along with either Angel Loop or Bomb Shelter radon concentrations are shown in Figures G-9 to G-13 for the period February 1992 - November 1992. A plot of the average working levels between October 1991 to March 1993 is shown in Figure G-14. Because working levels were measured weekly or less often, the data cannot be reliably correlated with the radon, however, several observations can be made. The average plot shows a pattern broadly similar to that of the annual average radon. Highest values occurred in the summer and lowest values in the winter, with the spring and fall showing large variations. The individual monthly records also showed a general correlation to radon levels. Working levels measured during periods when radon was elevated were somewhat higher than during periods with low radon. When radon levels in Mystery II were higher than in Mystery I this was reflected in the working levels. A point to keep in mind is that the frequency of working level measurements was far lower than the frequency of radon variations and cannot be used to accurately track radon variability. In addition, the working level measurements may not accurately reflect exposure for any given period because of the rapid and large radon fluctuations that occur during different parts of the year.

The equilibrium ratio of radon to radon progeny appears to fluctuate around 50%, that is, only about half of the daughter products produced by radon decay were in the air at any one time. The relationship of the working level measurements to the radon progeny measurements was similar to that of radon, but not as good. The reason for this was because the radon progeny can be altered by rapid changes in aerosol concentrations. During the short span of the WL measurements it is unlikely that these fluctuations would have been observed. For instance, the working level measured on July 22, 1992 (Figure G-11) and a marked change in the activities of the decay products shown by the grid and filter (Figure G-4) were made 5 hours apart and show no correlation with each other.



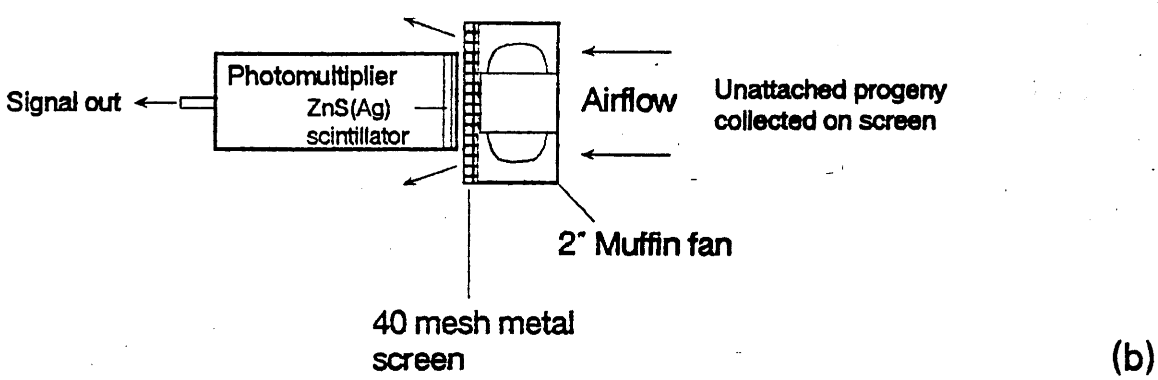


Figure G-1. Schematic diagram showing collection of radon decay products using a filter and Pylon AB-5 (a) and a wire mesh and Ludlum 1" NaI detector (b).

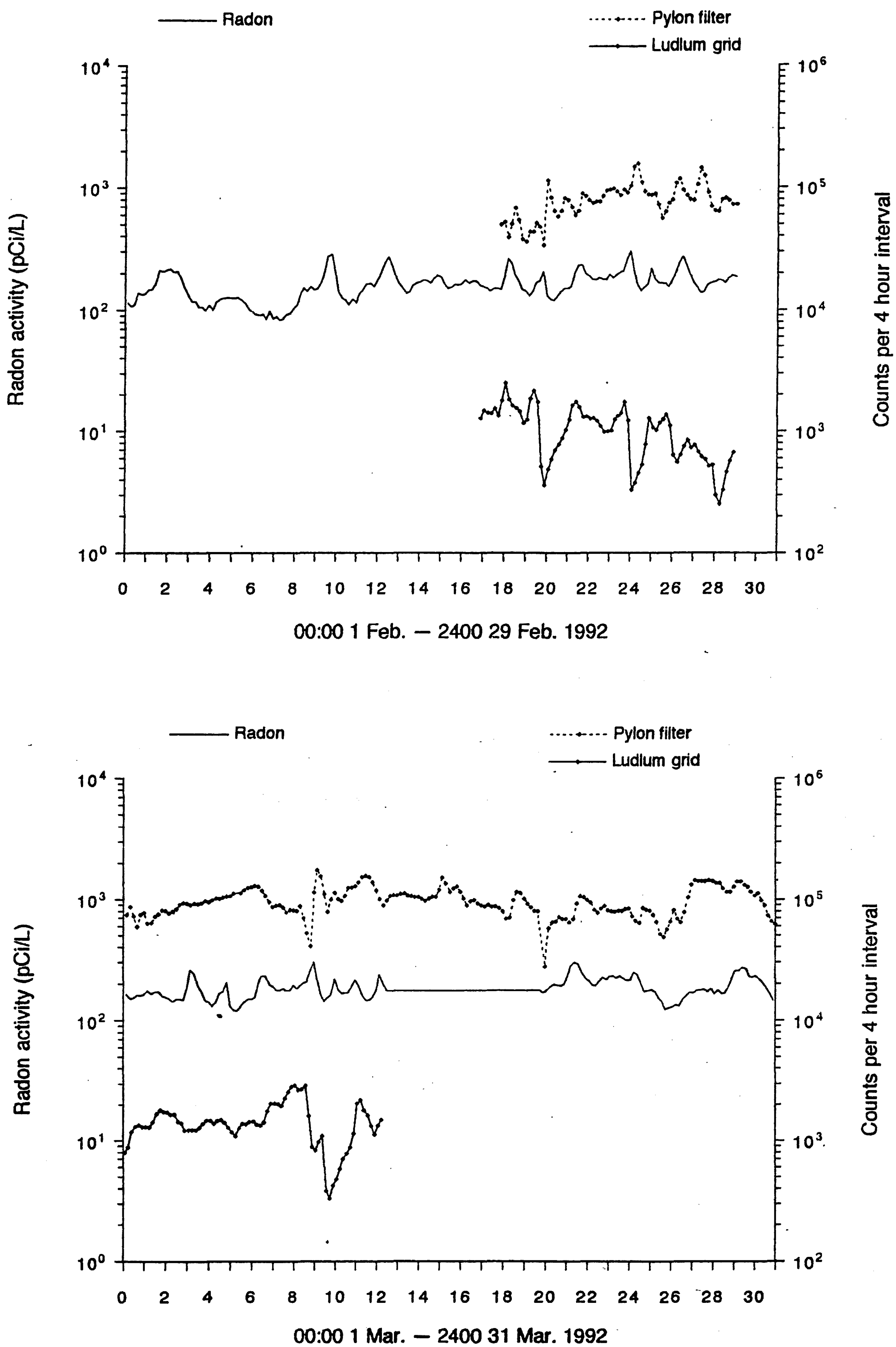


Figure G-2. Measured activities on the Pylon filter and wire grid relative to measured radon concentrations, February-March 1992.

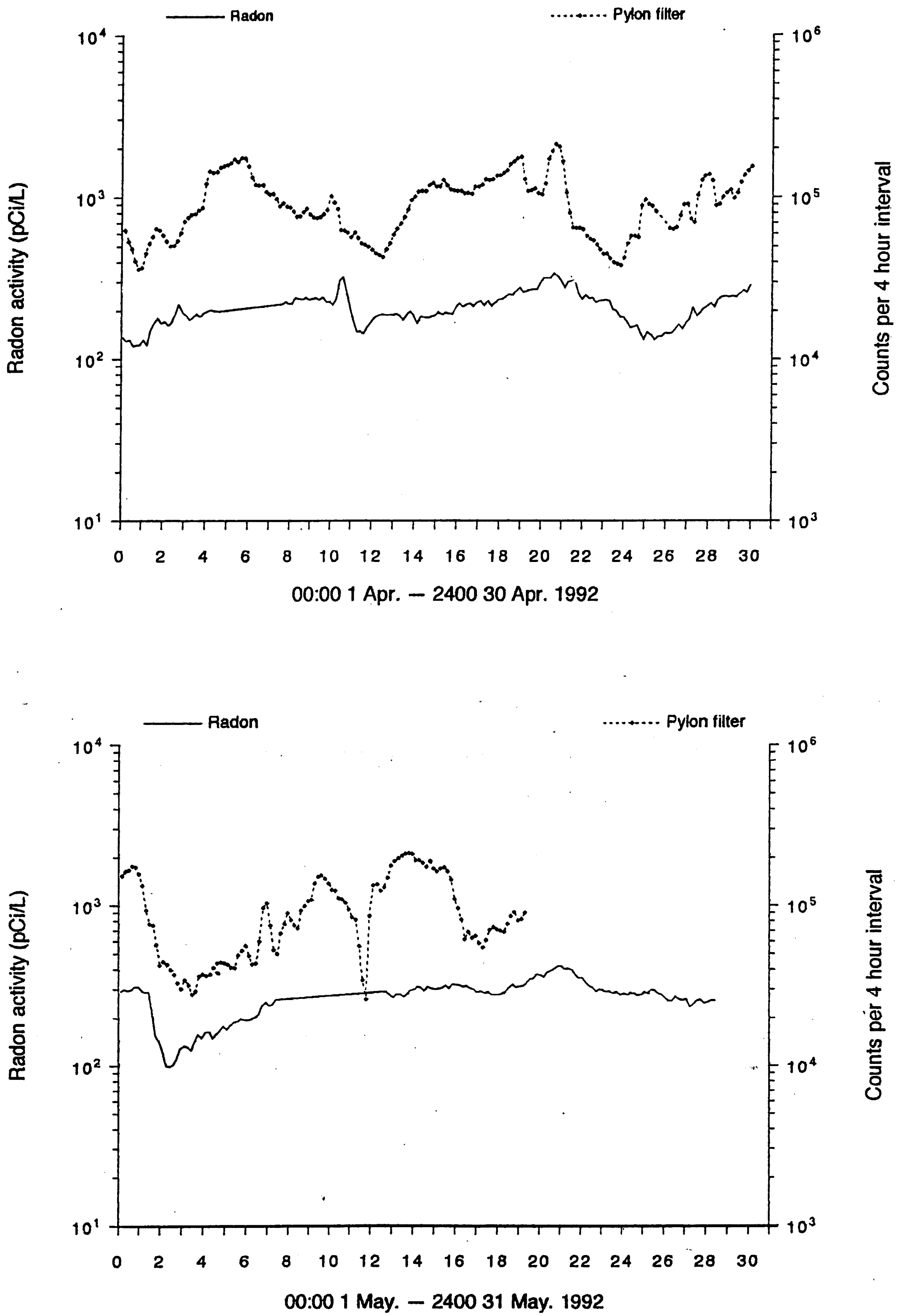
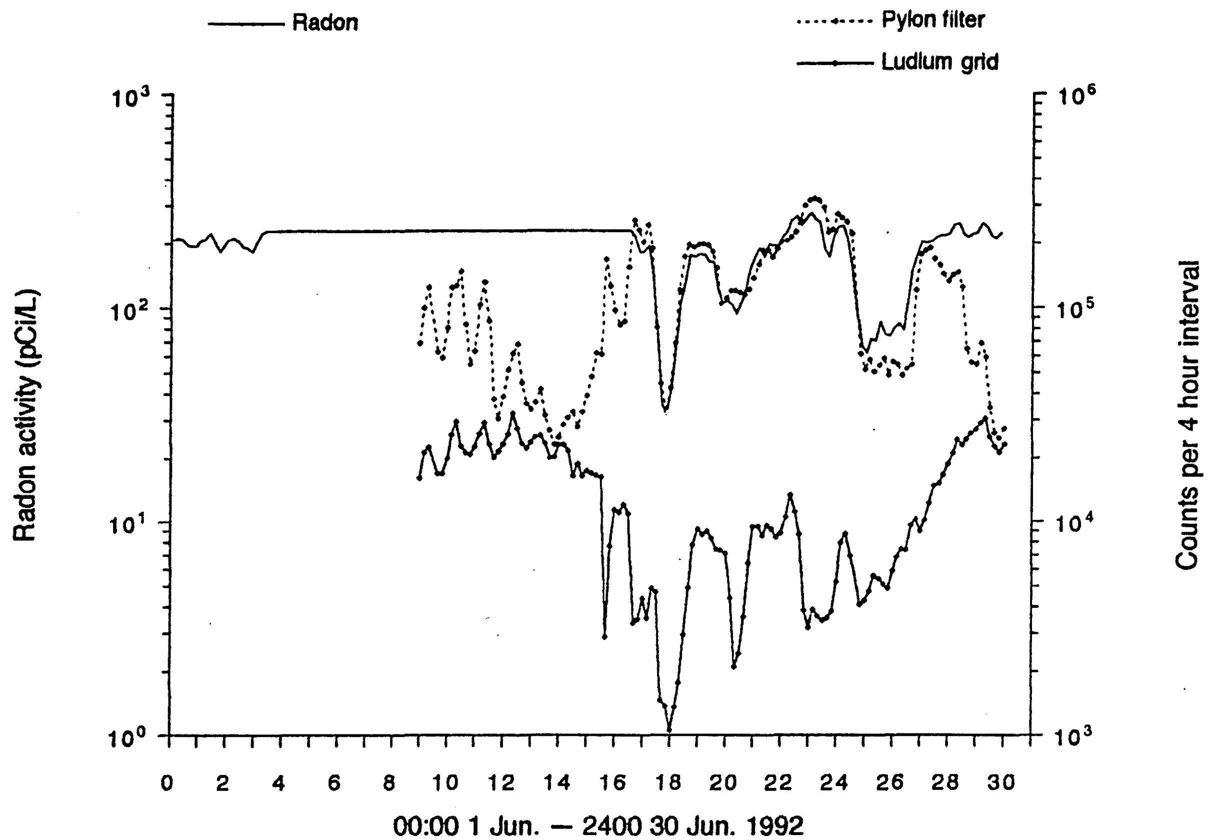


Figure G-3. **Measured activities on the Pylon filter and wire grid relative to measured radon concentrations, April-May 1992.**



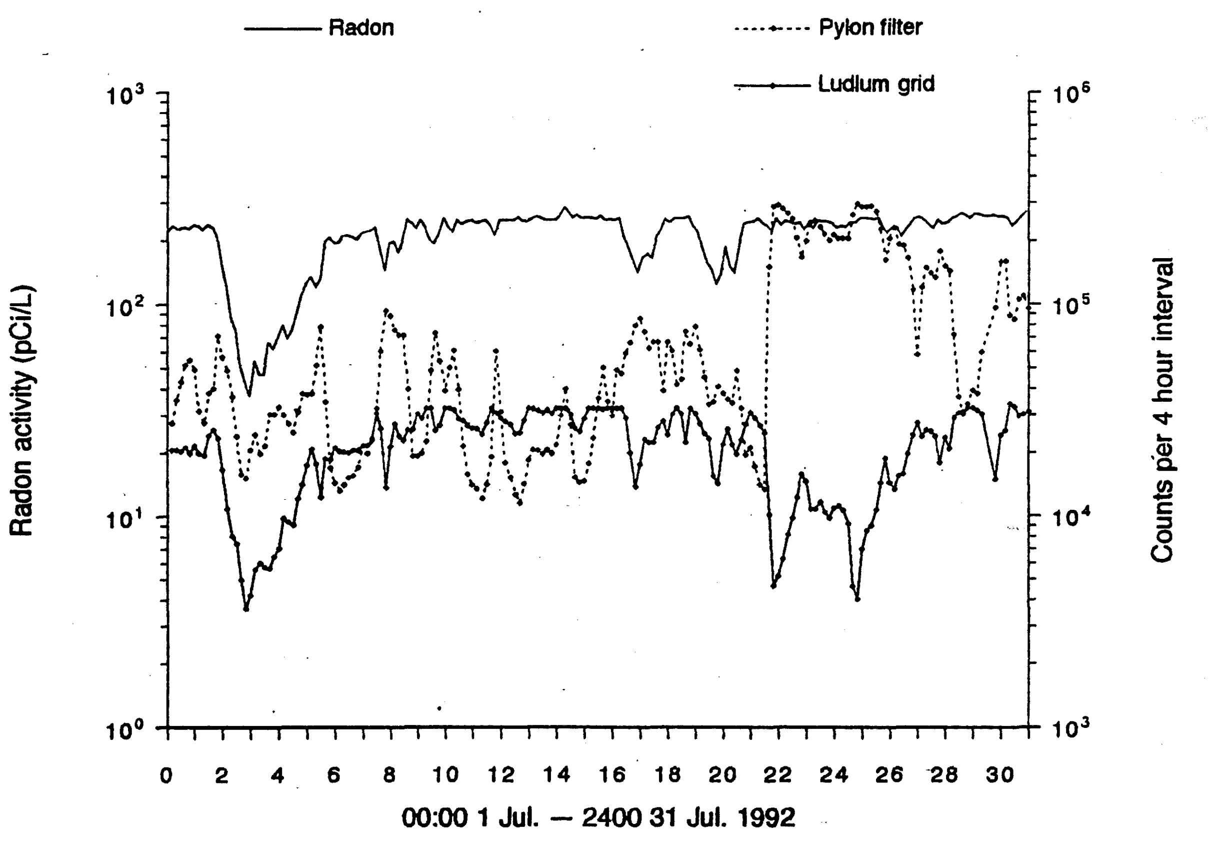
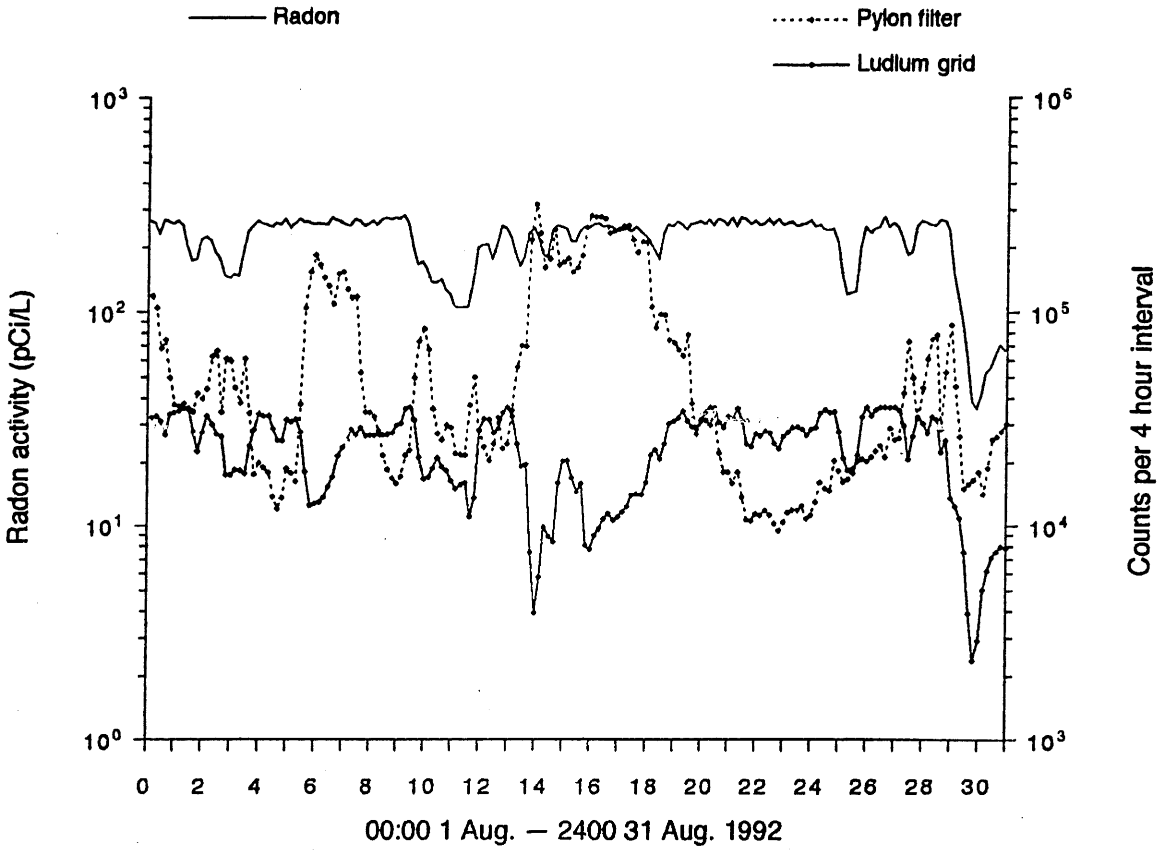


Figure G-4. **Measured activities on the Pylon filter and wire grid relative to measured radon concentrations, June-July 1992.**



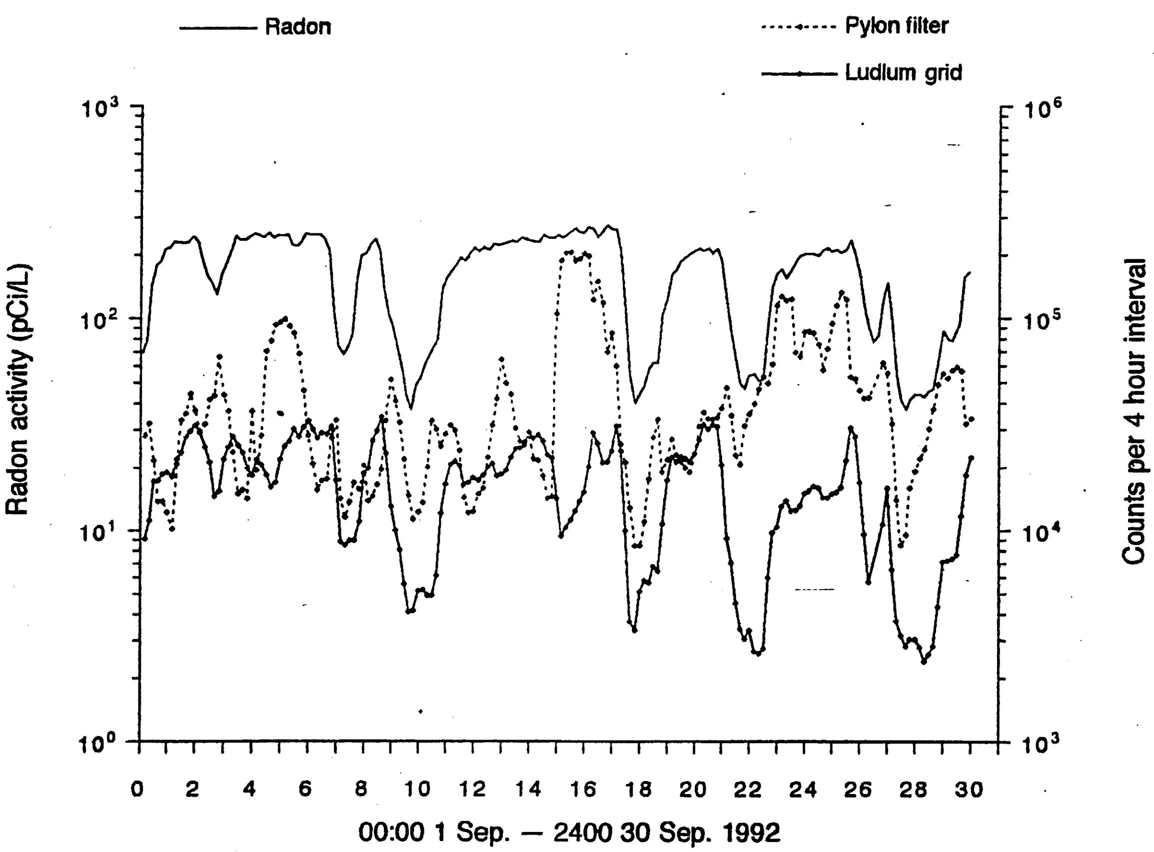
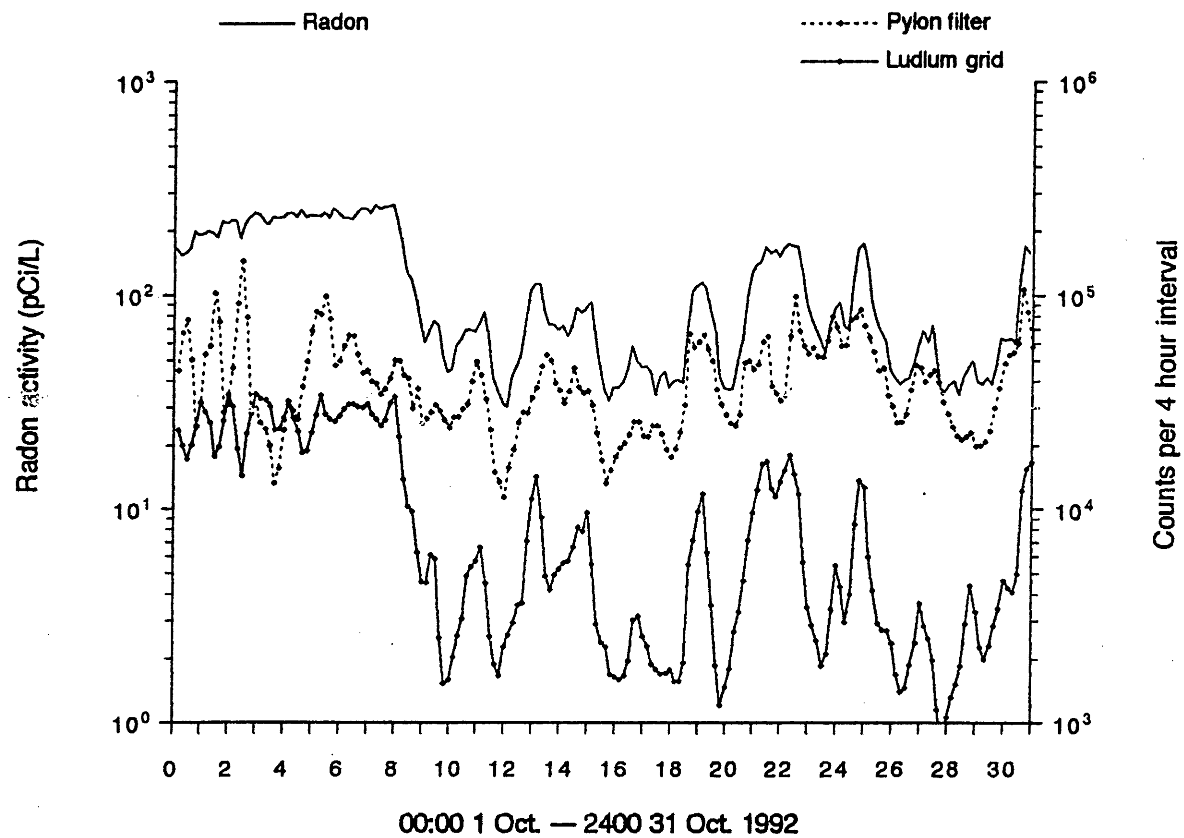


Figure G-5. Measured activities on the Pylon filter and wire grid relative to measured radon concentrations, August-September 1992.



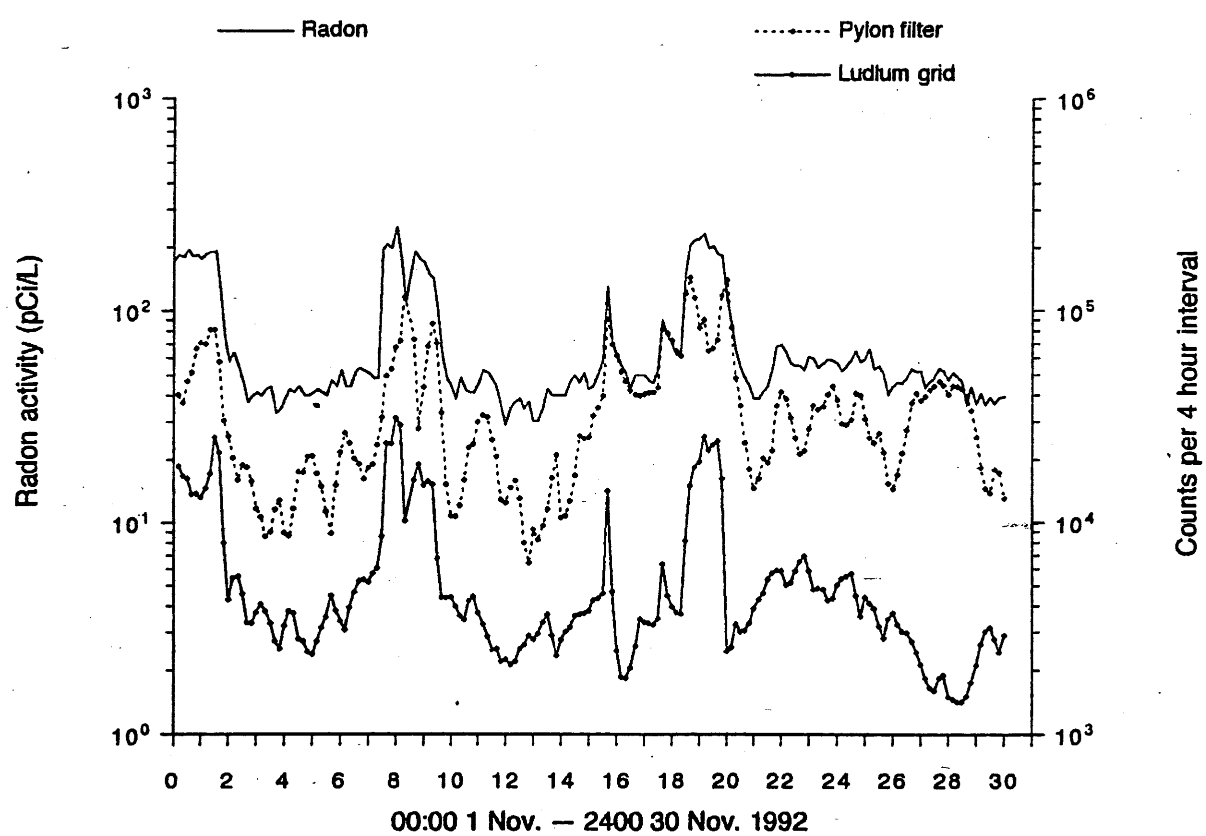


Figure G-6. Measured activities on the Pylon filter and wire grid relative to measured radon concentrations, October-November 1992.

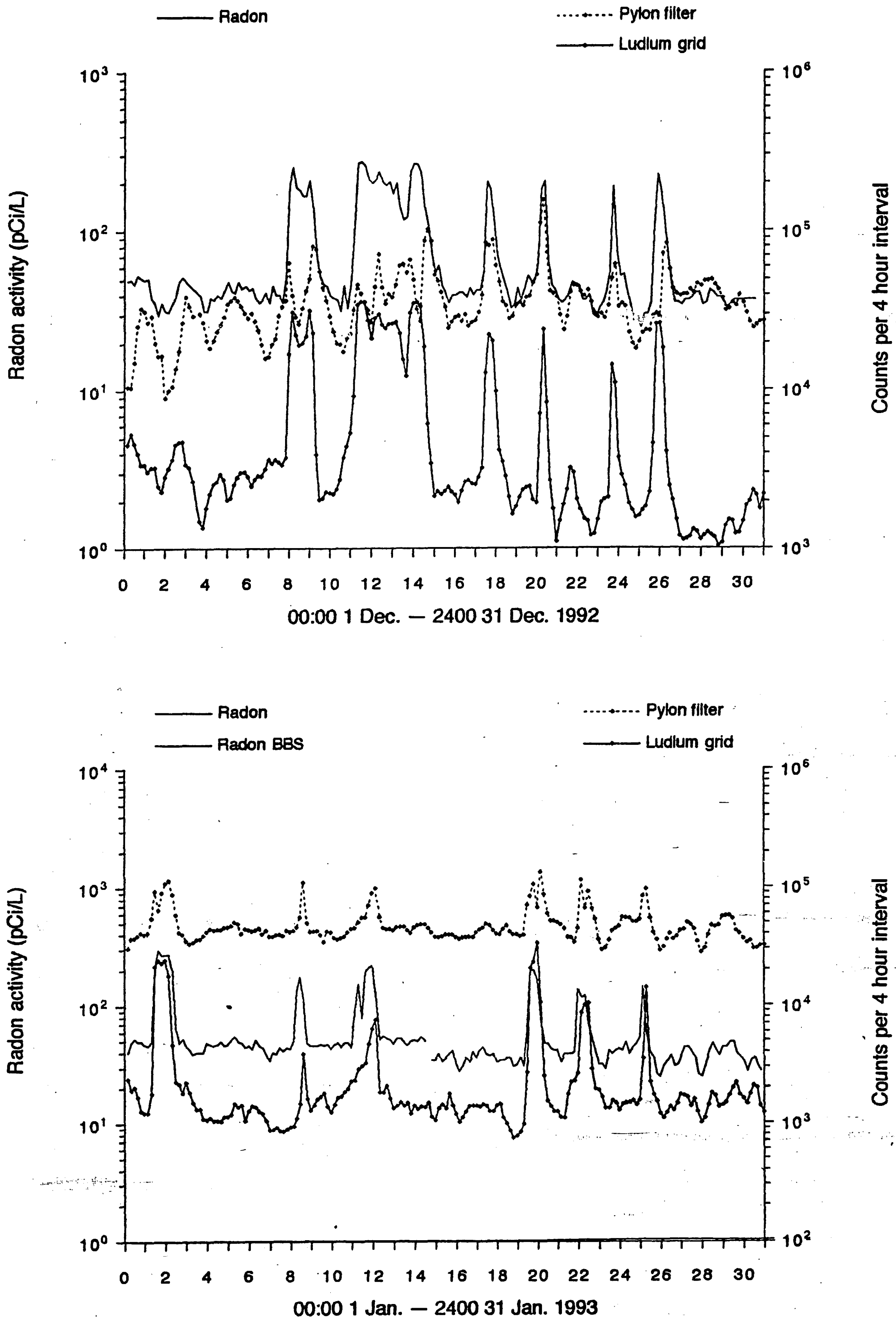


Figure G-7. **Measured activities on the Pylon filter and wire grid relative to measured radon concentrations, December 1992- January 1993.**

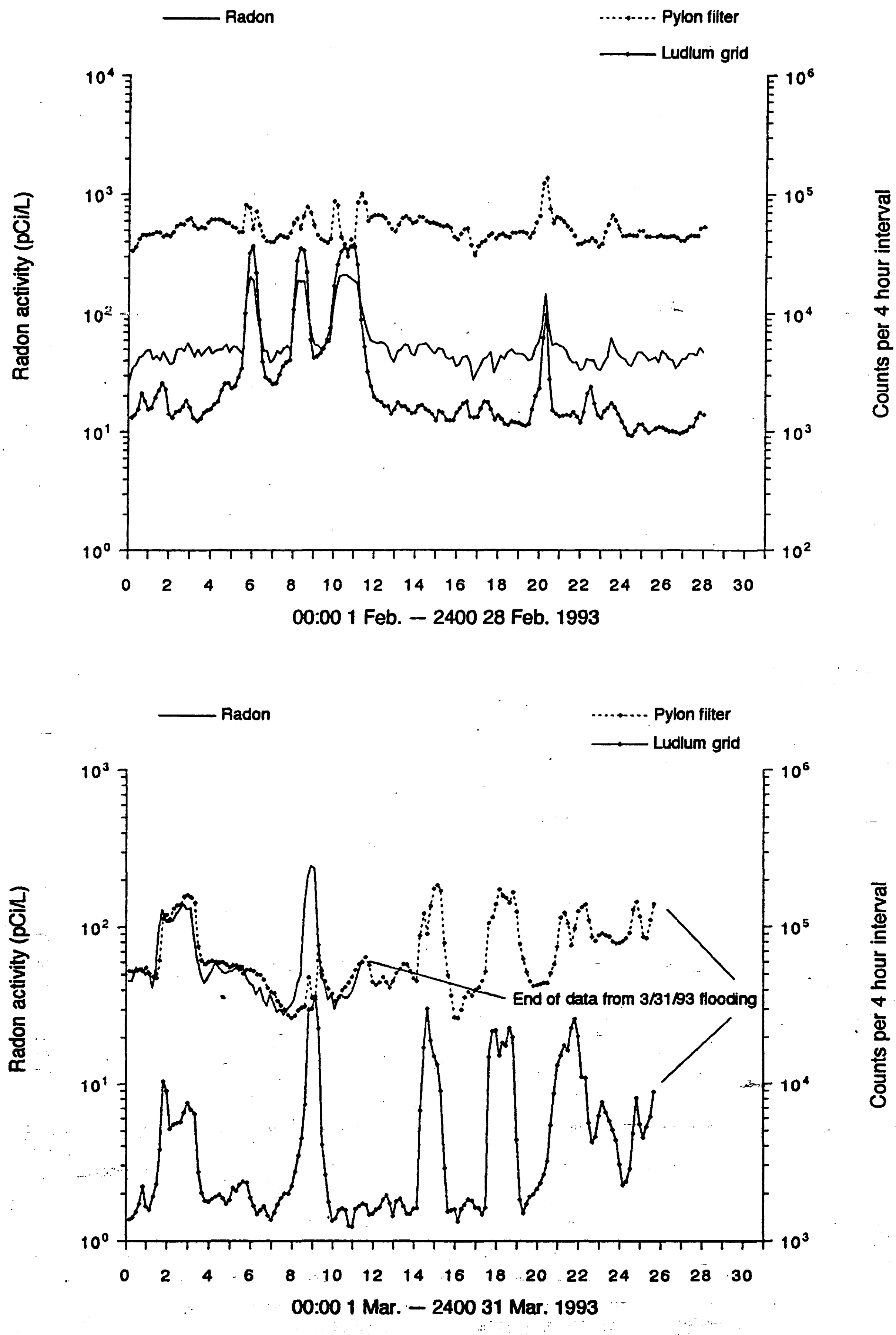


Figure G-8. Measured activities on the Pylon filter and wire grid relative to measured radon concentrations, February-March 1993.

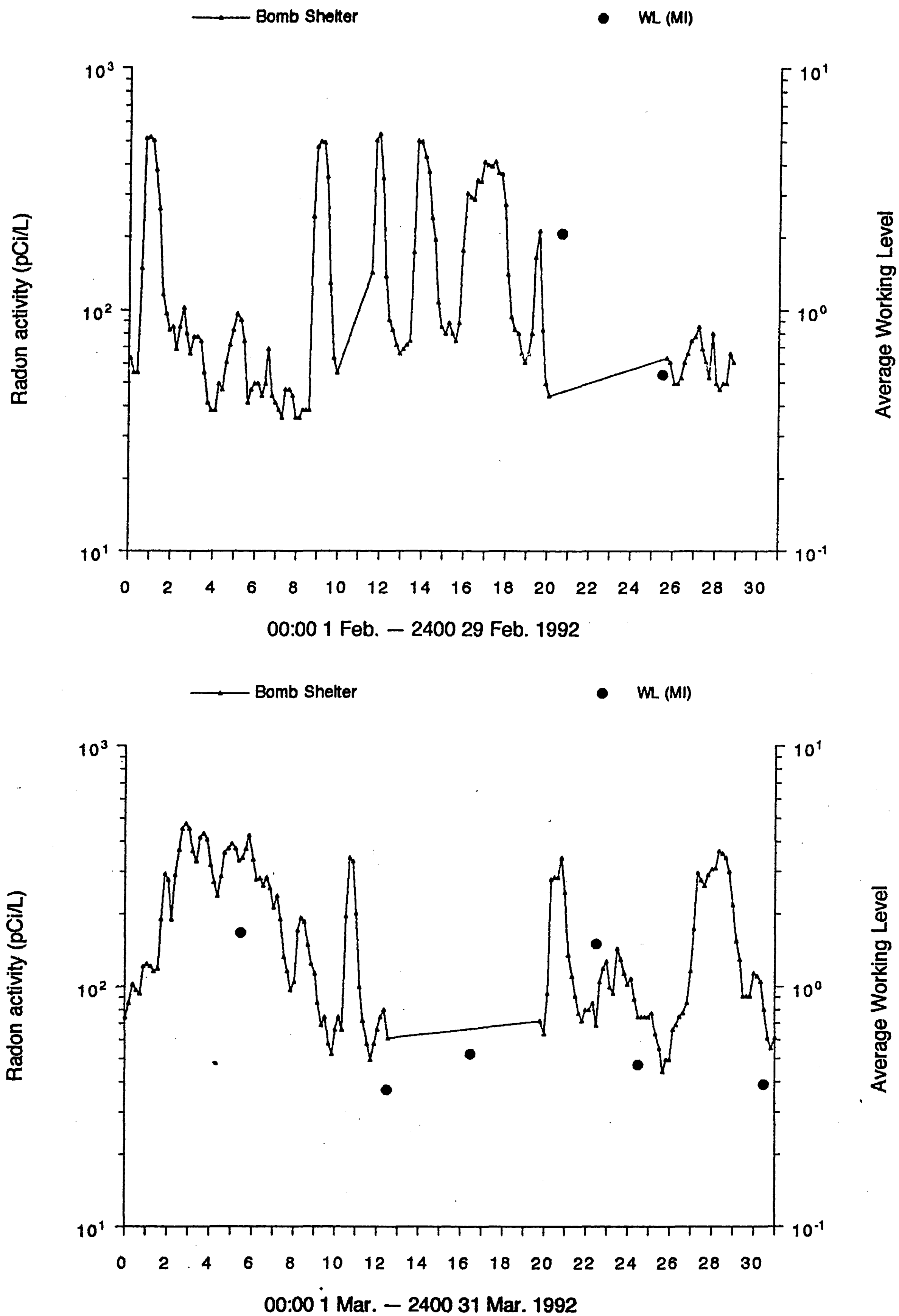
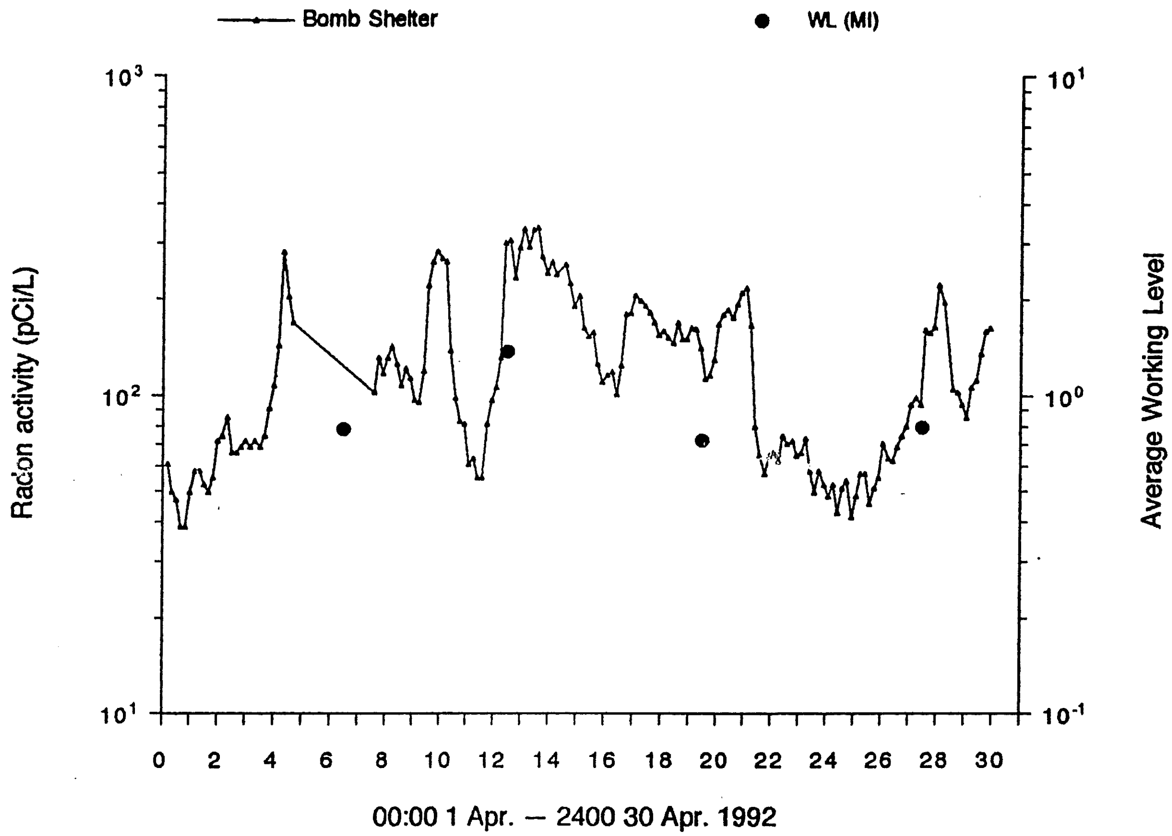


Figure G-9. Radon concentrations at Bomb Shelter with average working levels in Mystery I, February-March 1992.



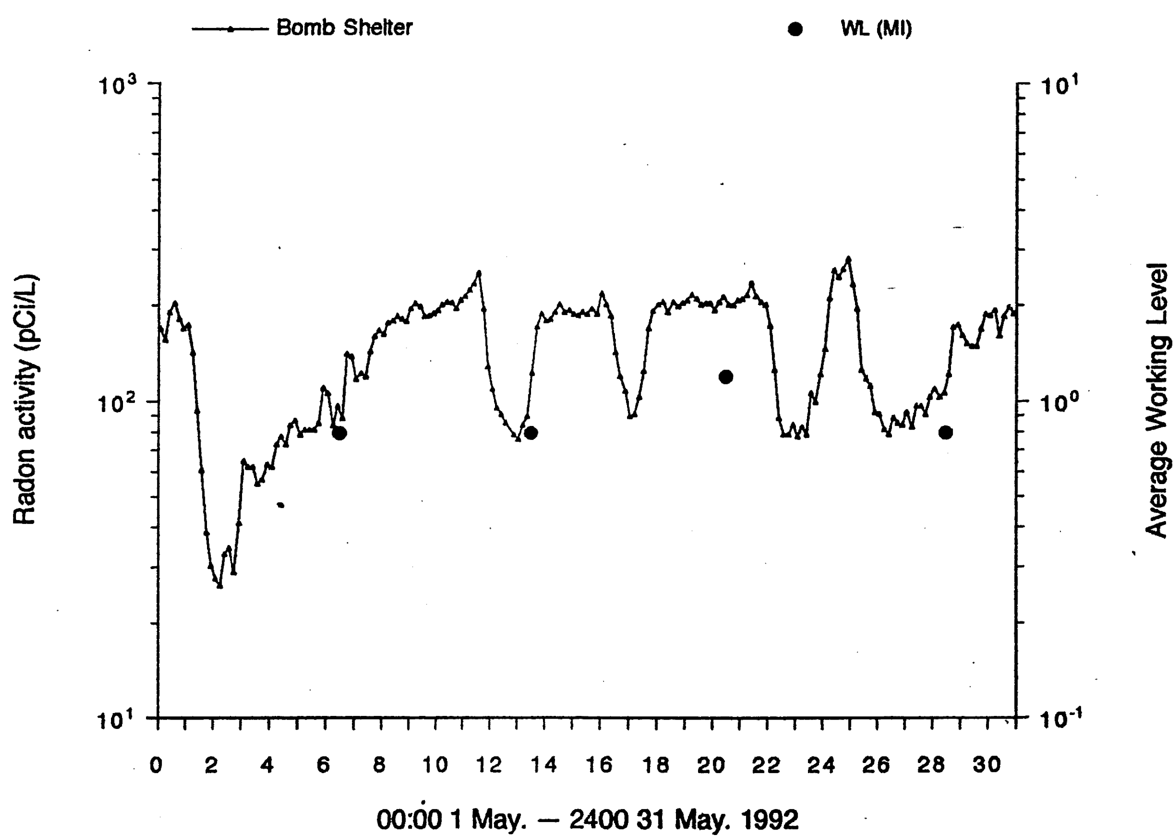
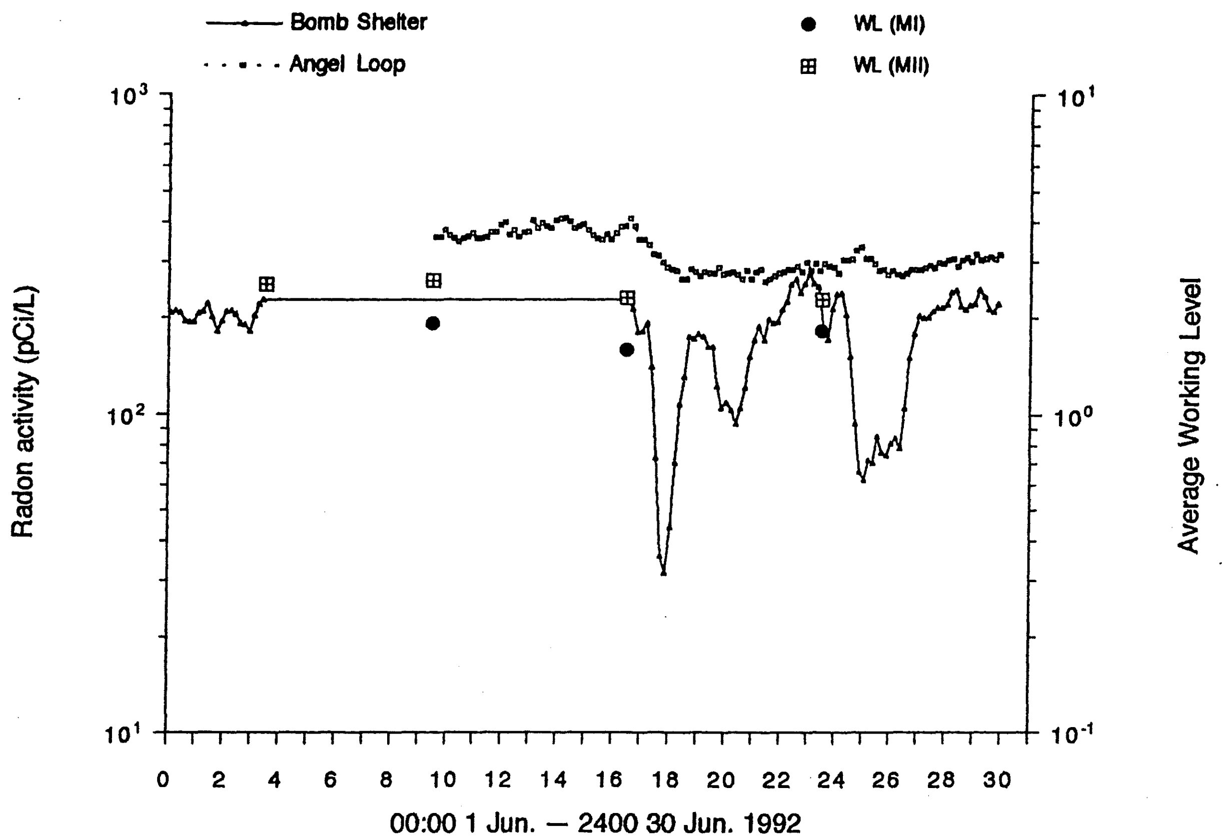


Figure G-10. Radon concentrations at Bomb Shelter with average working levels in Mystery I, April-May 1992.



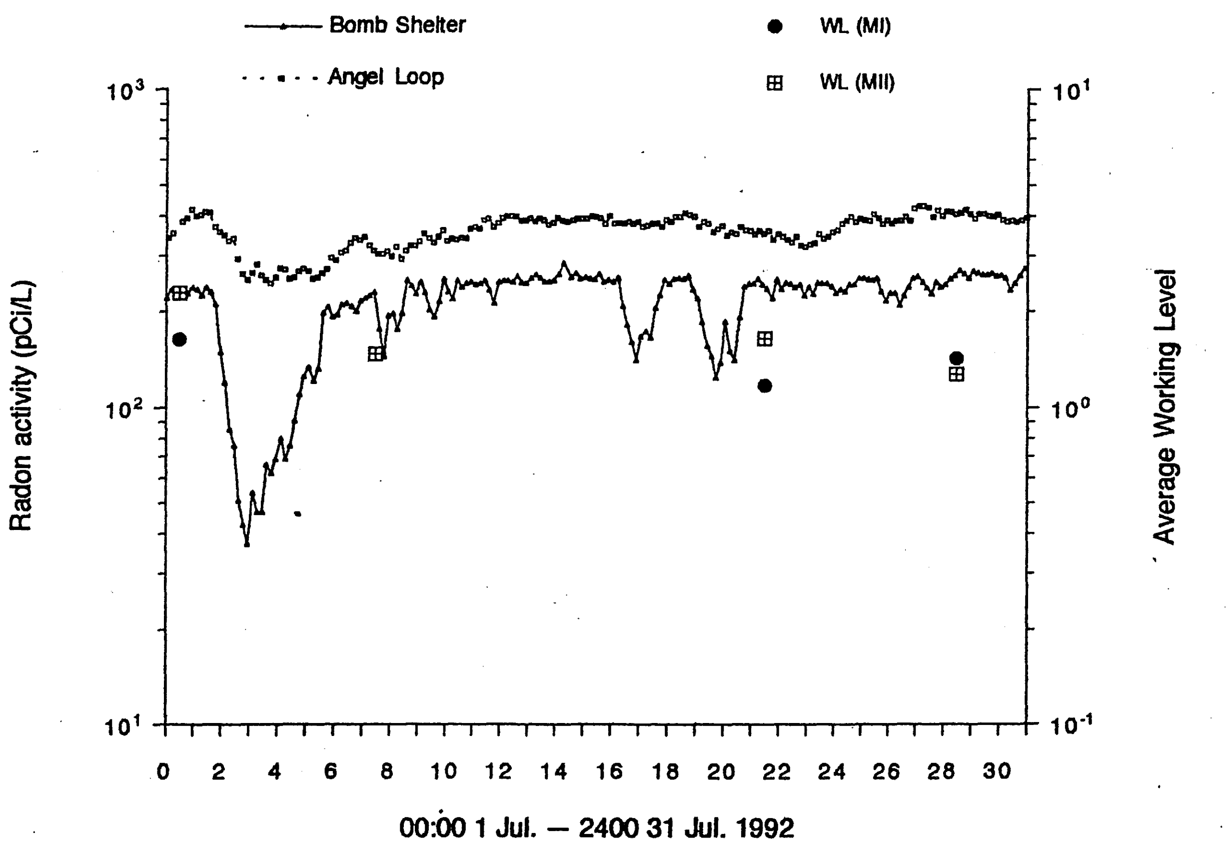
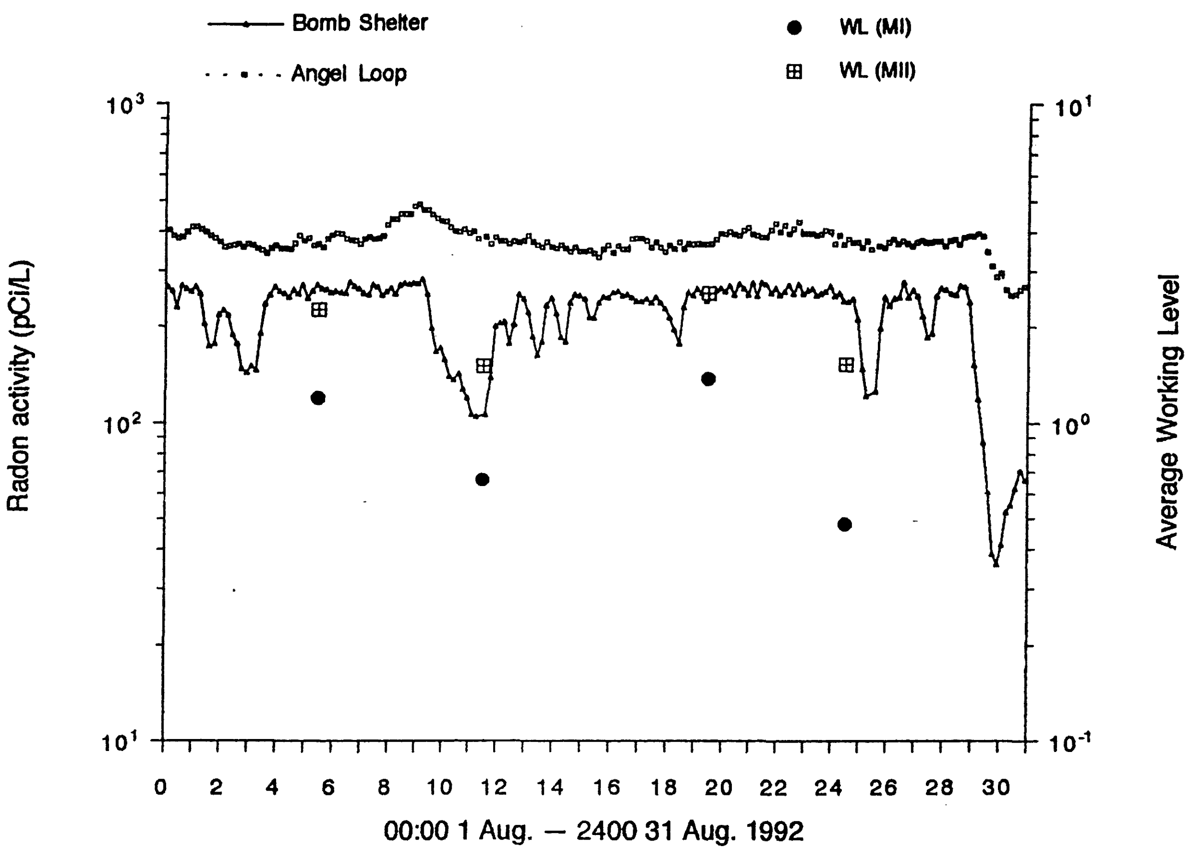


Figure G-11. Radon concentrations at Bomb Shelter and Angel Loop with average working levels in Mystery I and Mystery II, June-July 1992.



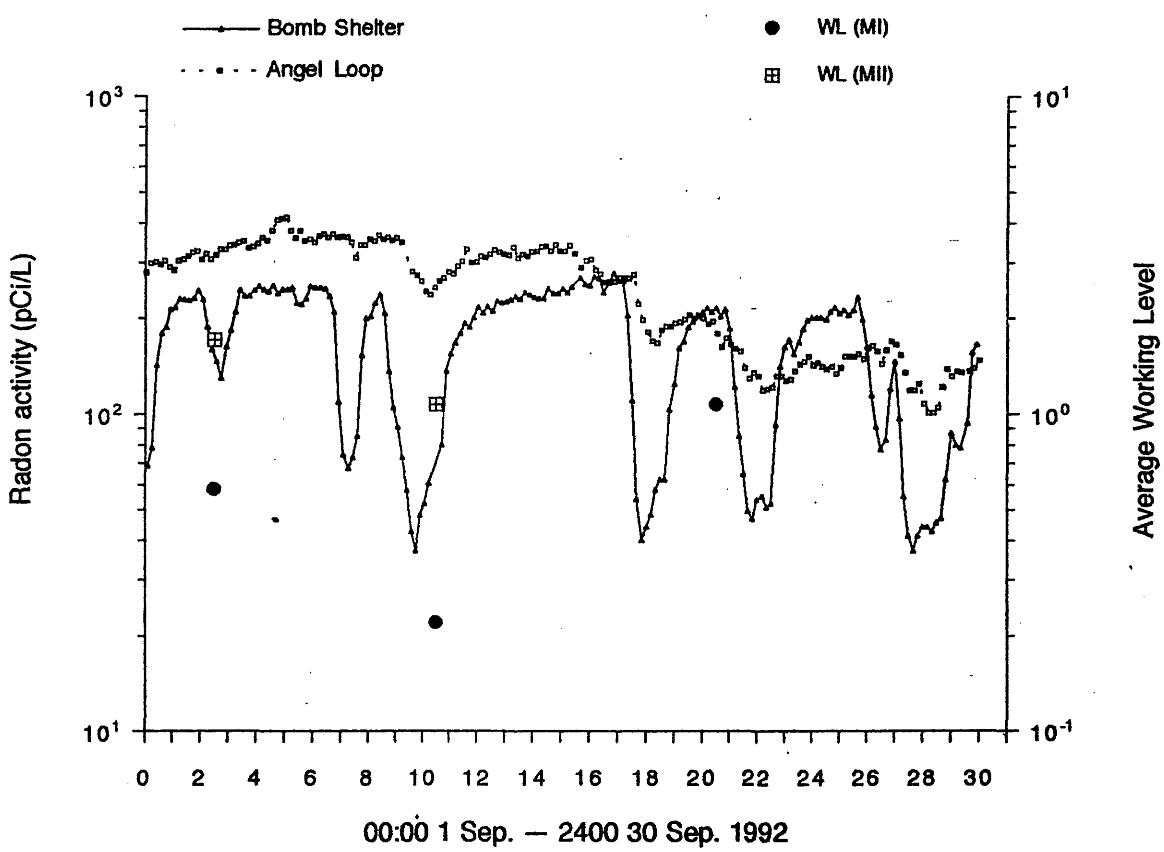
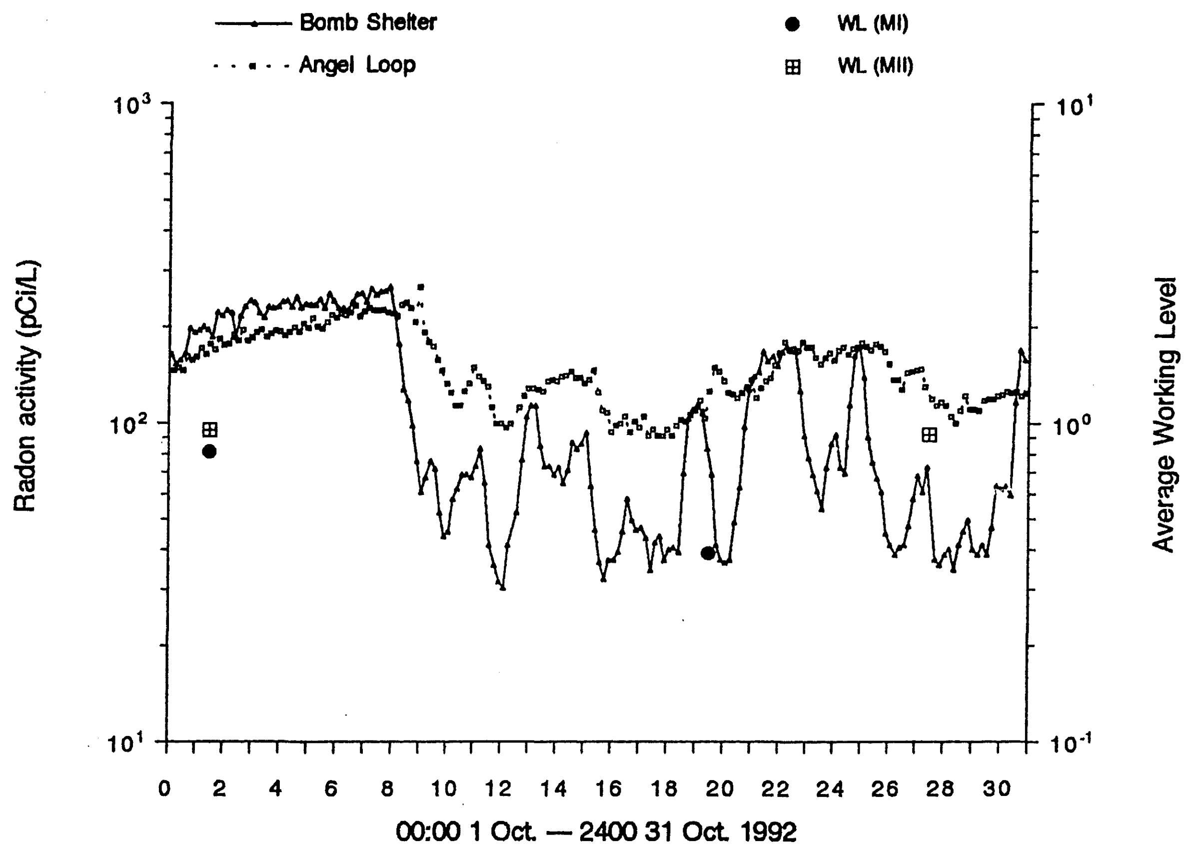


Figure G-12. Radon concentrations at Bomb Shelter and Angel Loop with average working levels in Mystery I and Mystery II, August-September 1992.



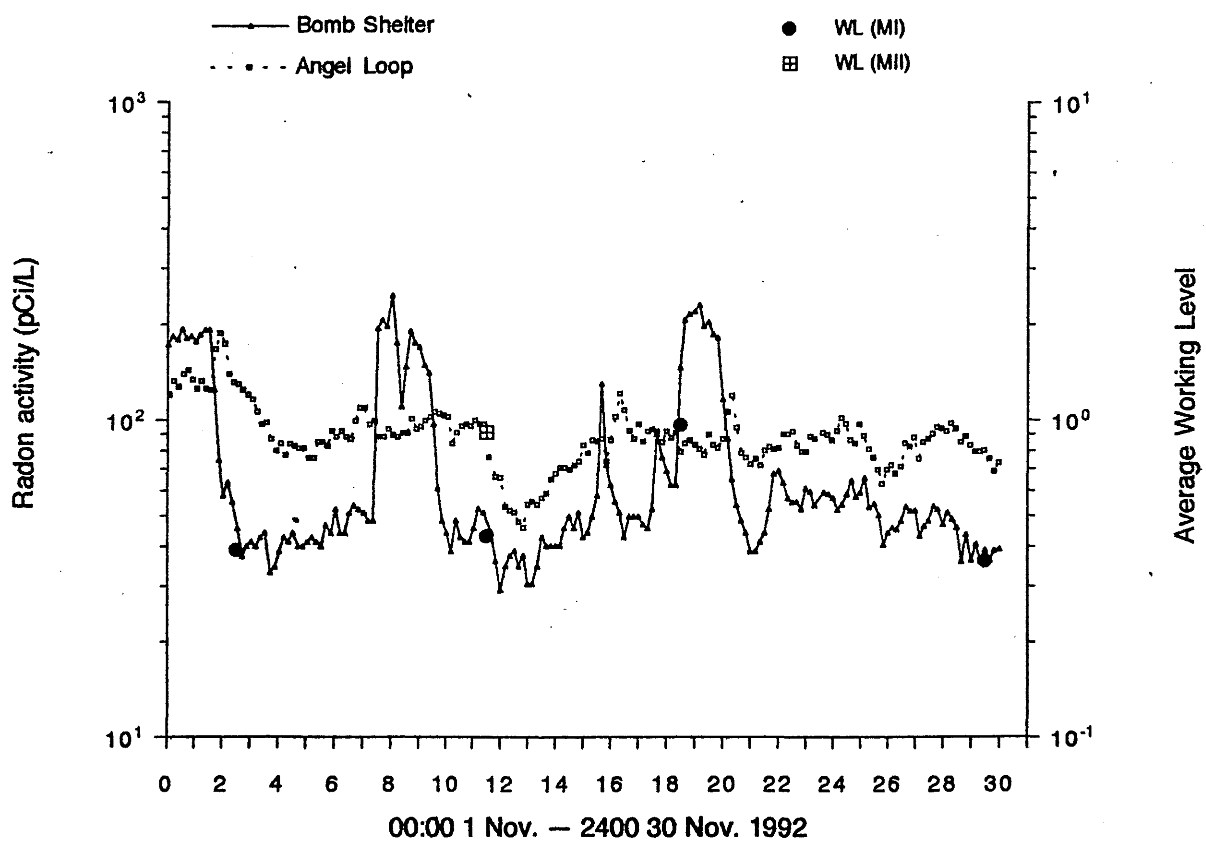


Figure G-13. Radon concentrations at Bomb Shelter and Angel Loop with average working levels in Mystery I and Mystery II, October-November 1992.

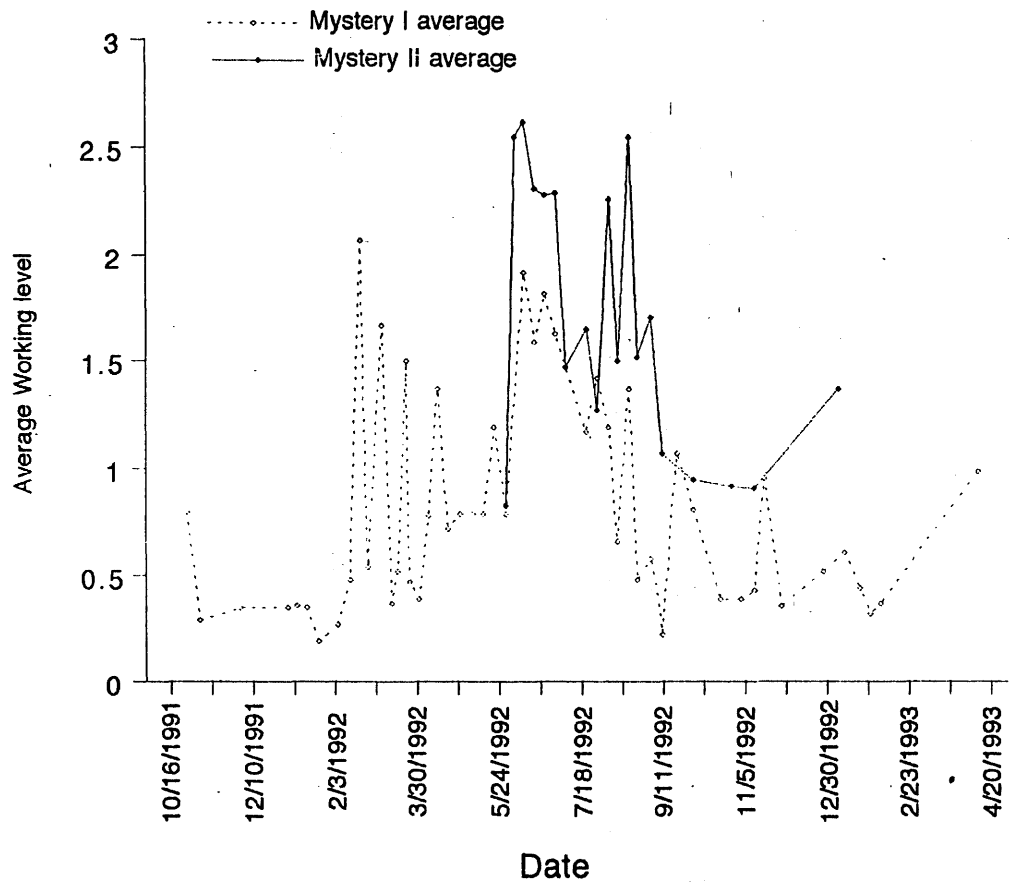


Figure G-14 Average measured working levels in Mystery I and Mystery II from October 1991 - April 1992. Some months only have a single measurement.

APPENDIX H. PARTICLE MONITORING AND RESULTS

Particle concentrations and size distributions in the cave air were measured using a Royco Model 225 light scattering particle counter with a lower size limit of 0.3 microns. This was coupled with an optical detection device to allow time series measurements to be made of the size distributions. Measurements involved pumping air, containing particles, through a white light region and measuring the scattered light reflected by the particles. Calibration was accomplished with polystyrene latex beads of different sizes to obtain the correct operating voltages for the scattered light.

Particle measurements in the cave were made over four seasons (Table H-1). The equipment was not capable of operating for extended period within the cool, humid cave environment and had to be transported for each trial. The equipment was allowed to come to thermal equilibrium for several hours prior to beginning measurements. Measurements lasted from 4-6 hours to about 24 hours over a two day period. The analyses were made more to characterize the particles in the cave atmosphere than to do continuous monitoring for correlation with the radon measurements. In all instances we were able to track the change in particles from a people influenced environment to the undisturbed system.

Results from the particle concentrations and size distribution measurements in 1992 are shown in Figures H-1 to H-8 for three sets of measurements between June 1992 and January 1993. The two and three dimensional plots show the change in particle concentration for each size range over time. In all tests, initial particle concentrations were relatively high (1-10 particles cm^{-3}) due to the presence of the people in the area setting up the equipment. The high initial levels gradually decreased over 1-2 hours to an equilibrium concentration of about 0.01 to 0.1 particles cm^{-3}. These remained relatively constant during the remainder of each test interval.

For comparison purposes, homes and commercial buildings have around 10,000 particles cm^{-3}. Class 100 clean rooms are built to have concentrations less than 0.0035 particles cm^{-3} at 0.3 microns. Thus Mystery Cave had many fewer particles than typical buildings. As with other intermittent measurements, long-term variations may be different than those measured, or other parts of the cave may have different size distributions.

Using the June 10th data at Bomb Shelter (Figure H-1), the decrease in particle concentrations over time was used to calculate a representative air exchange rate at Bomb Shelter. The exchange rate was calculated under the assumption that excess particles due to people at the measurement site would decrease by ventilation (once the source is removed) until an equilibrium was established between supply and removal:

Air changes per hour = $\ln(C_i/C_{i_2})/(t_i-t_{i_2})$

where C is a particle size concentration at times i and i_2 and t is the time in hours

The calculated air exchange rate on June 10th was 2.75 air changes per hour at the Bomb Shelter. The rate calculated on November 10th from data collected at Turquoise Lake (Figure H-3) gave 2.1 air changes per hour and the January 16, 1993 data (Figure H-7) at Bomb Shelter resulted in a rate of 1.4 air exchanges per hour. These air exchange rates are only applicable to the area where the particle concentrations were measured and do not necessarily apply to air exchange between the cave and outside or with other areas in the cave. These air exchange rates of between 1-3 air exchanges per hour were in relatively good agreement with estimates of air velocities through the constricted tunnel connecting Bomb Shelter with Door to Door route. These ranged from 2-80 ft min^{-1} through an opening roughly 9 ft^2, giving volume flows of 18 to 720 ft^3 min^{-1}. Estimating the volume of the Bomb Shelter to be approximately 4,500 ft^2 the turn-over rate could range from 0.25 per hour to 10 times per hour. A linear flow rate of about 20 ft min^{-1} would be consistent with 2-3 air exchanges per hour.

The 3-d figures show the changes in particle concentration with the particle size distribution, allowing for comparisons between different particle diameters. For the June 10th data, particles of highest concentration were in the 0.5-1.3 micron range. On November 10th, the majority of particles were in the 0.3 and 0.5 size ranges.

The particle data taken on January 15-16, 1993 at the Bomb Shelter is shown in Figures H-5 to H-8 and represents the longest measurement interval. The data has been divided into that acquired on the 15th and that on the 16th. The particle monitor on the 16th was modified to measure a smaller set of particle diameters than on the 15th (0.3 to 10 microns on the 15th and 0.3 to 2.0 microns on the 16th). This allowed a better characterization of the smaller particles since particles larger than 2 microns settled out much faster. Although particle concentrations on the 15th decreased within a couple of hours after setup was completed, several hours later, at about 4:00 AM there was a significant increase in the concentration of smaller particles that, to our knowledge, was not associated with anyone near the monitor. The high concentrations at noon on the 16th were due to the researchers near the monitor. Levels dropped off after we left and started to go up again when we reentered to pick up the equipment. During both runs, once equilibrium was established, the majority of the particles were below 1 micron in diameter. It is likely that there were significant particle concentrations below the detection limit of 0.3 microns.

The measurements indicated that significant concentrations of particles could be generated by occupants of the cave system, either singly or in groups. The results also indicated that the particles were removed from the area within which they were generated within about 3 hours after the source was removed. They either settled out on surfaces in the area or were carried by air currents to different locations before settling out. Particles that remained in the cave air under undisturbed equilibrium conditions were very small, less than 1.0 microns and usually less than 0.5 microns in diameter.

The relationship of particle concentration and size distribution to radon decay products was investigated for the period January 15-16, 1993, as this was the only measurement for an extended duration. As can be observed in Figure H-9 (note the scale difference), there was no significant change in the decay product distributions, even though there were several changes in particle concentrations and distributions associated with people at Bomb Shelter. Changes in the decay products did occur before and after the particle monitoring period, but we have no data on particulates at those times. It is not clear how these results should be interpreted. One possibility is that two few particles in the larger size ranges were created or the that the particles created by people were not of a variety that seriously affected the radon decay products.

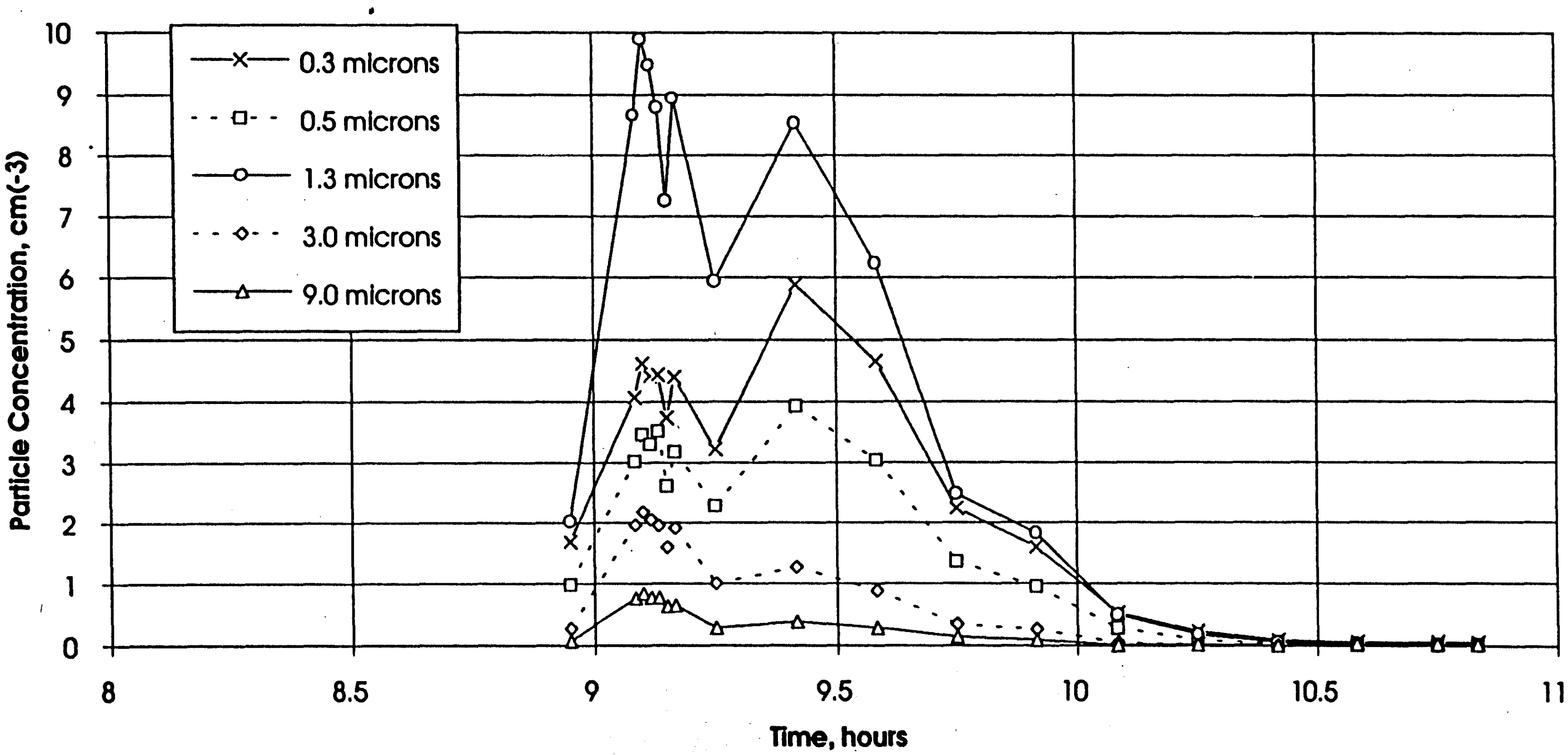


Figure H-1. Particle concentrations June 10, 1992 at Bomb Shelter.

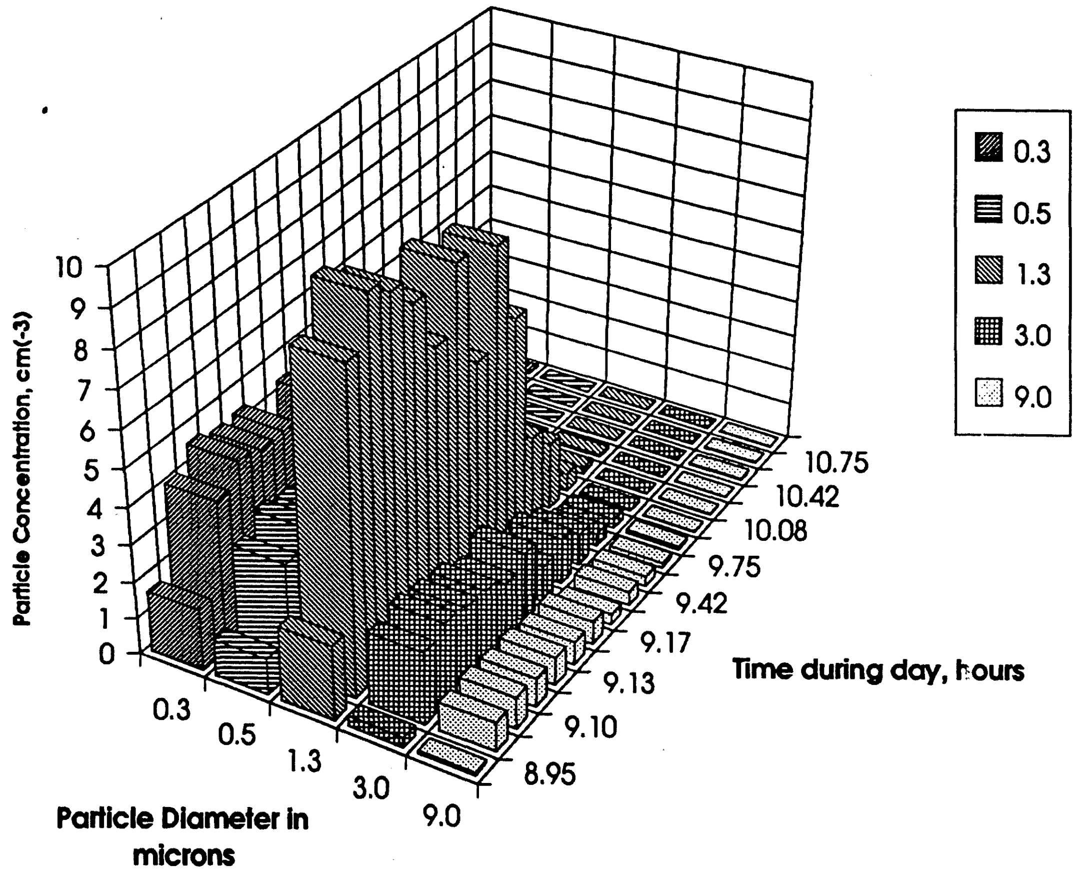


Figure H-2. Particle Size Distributions June 10, 1992 at Bomb Shelter

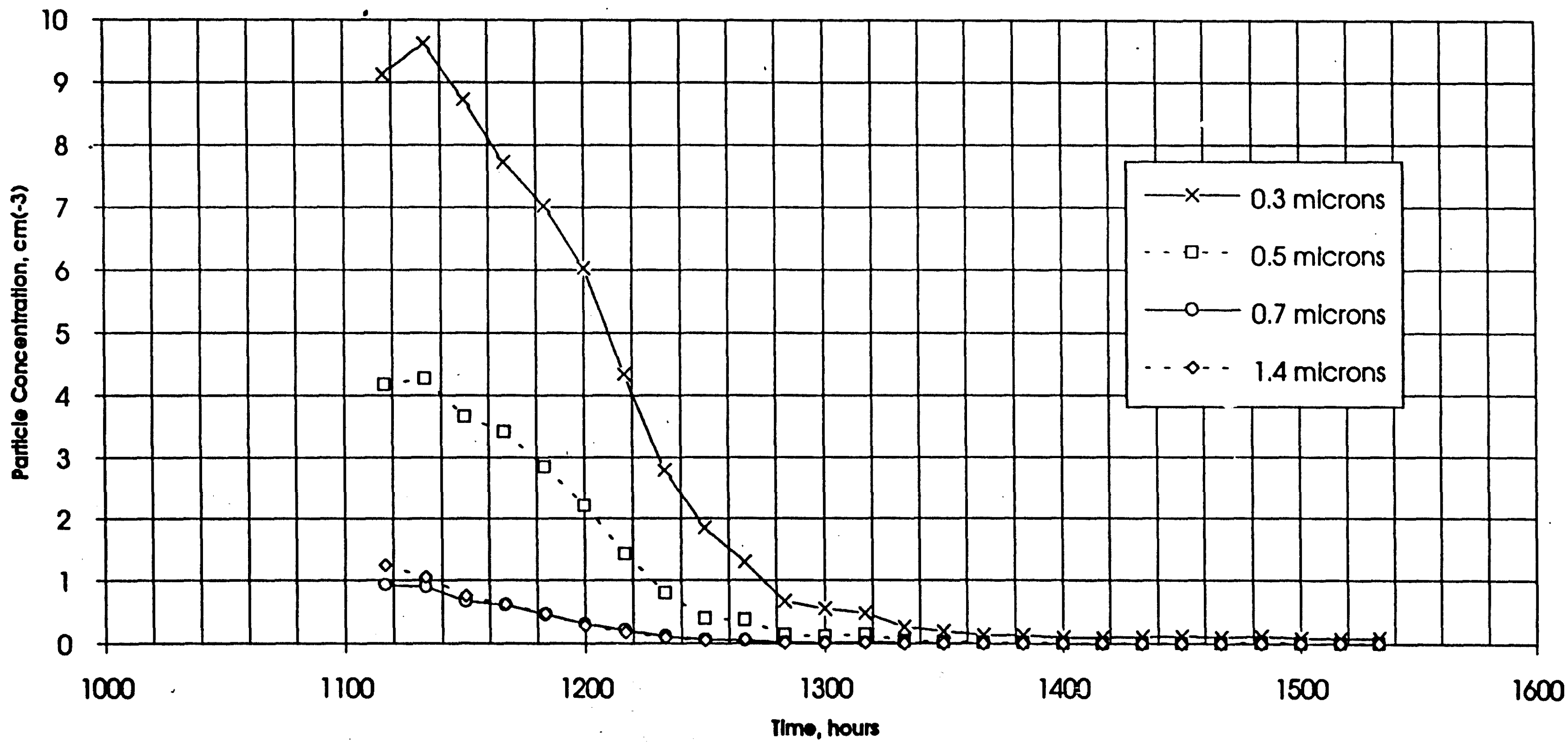


Figure H-3. Particle concentrations November 10, 1992 at Turquoise Lake, MI.

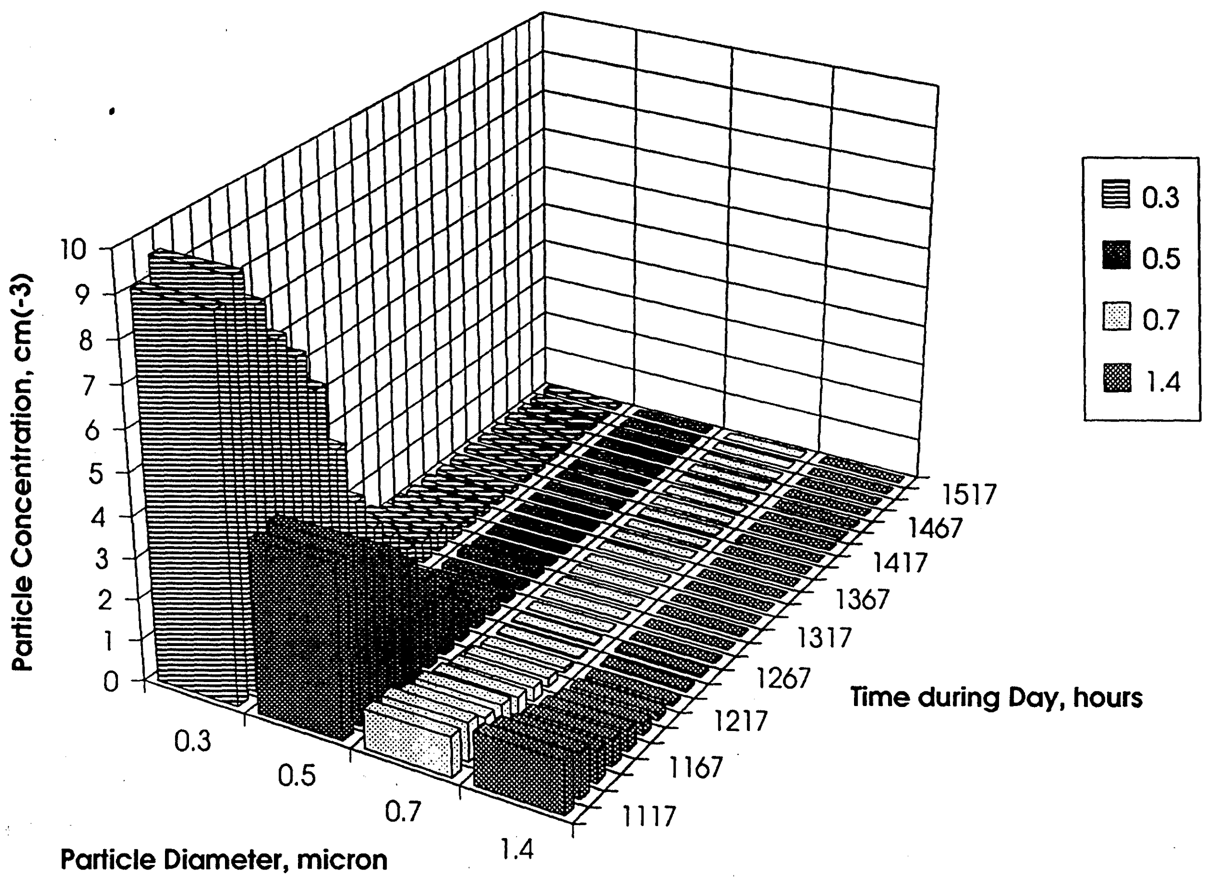


Figure H-4. Particle Size Distributions November 10, 1992 at Turquoise Lake

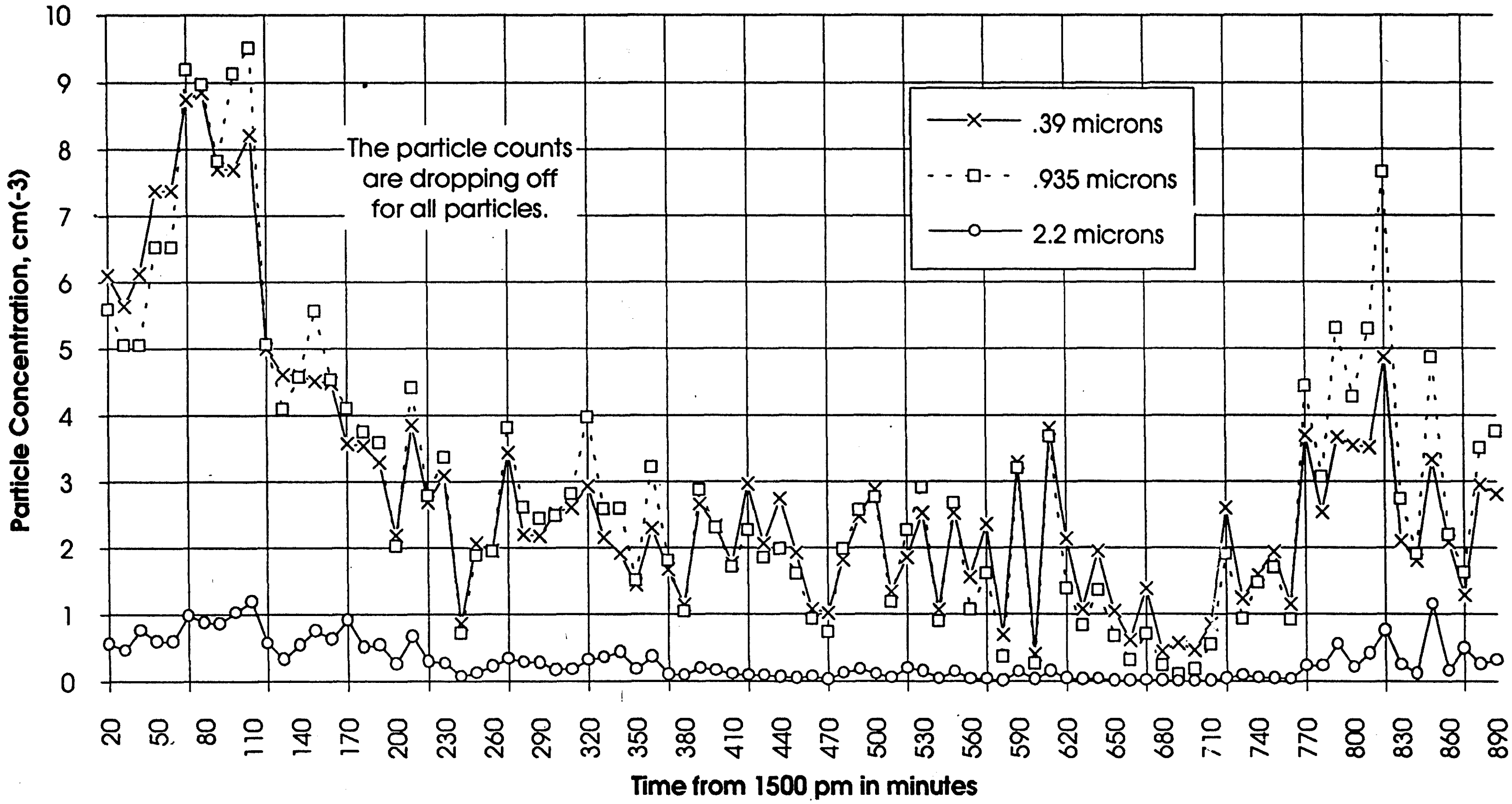


Figure H-5. Particle Concentrations January 15, 1993 at Bomb Shelter

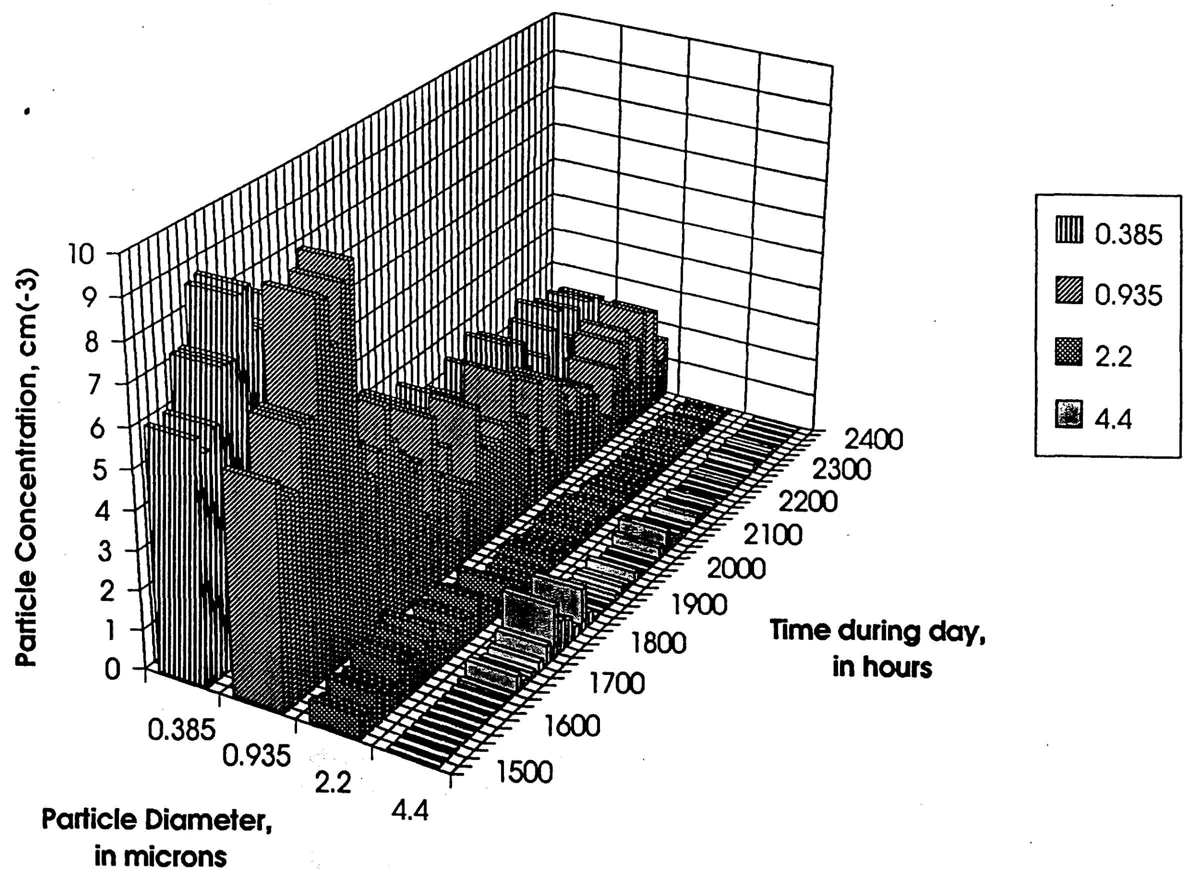


Figure H-6. Particle Size Distributions January 15, 1992 at Bomb Shelter

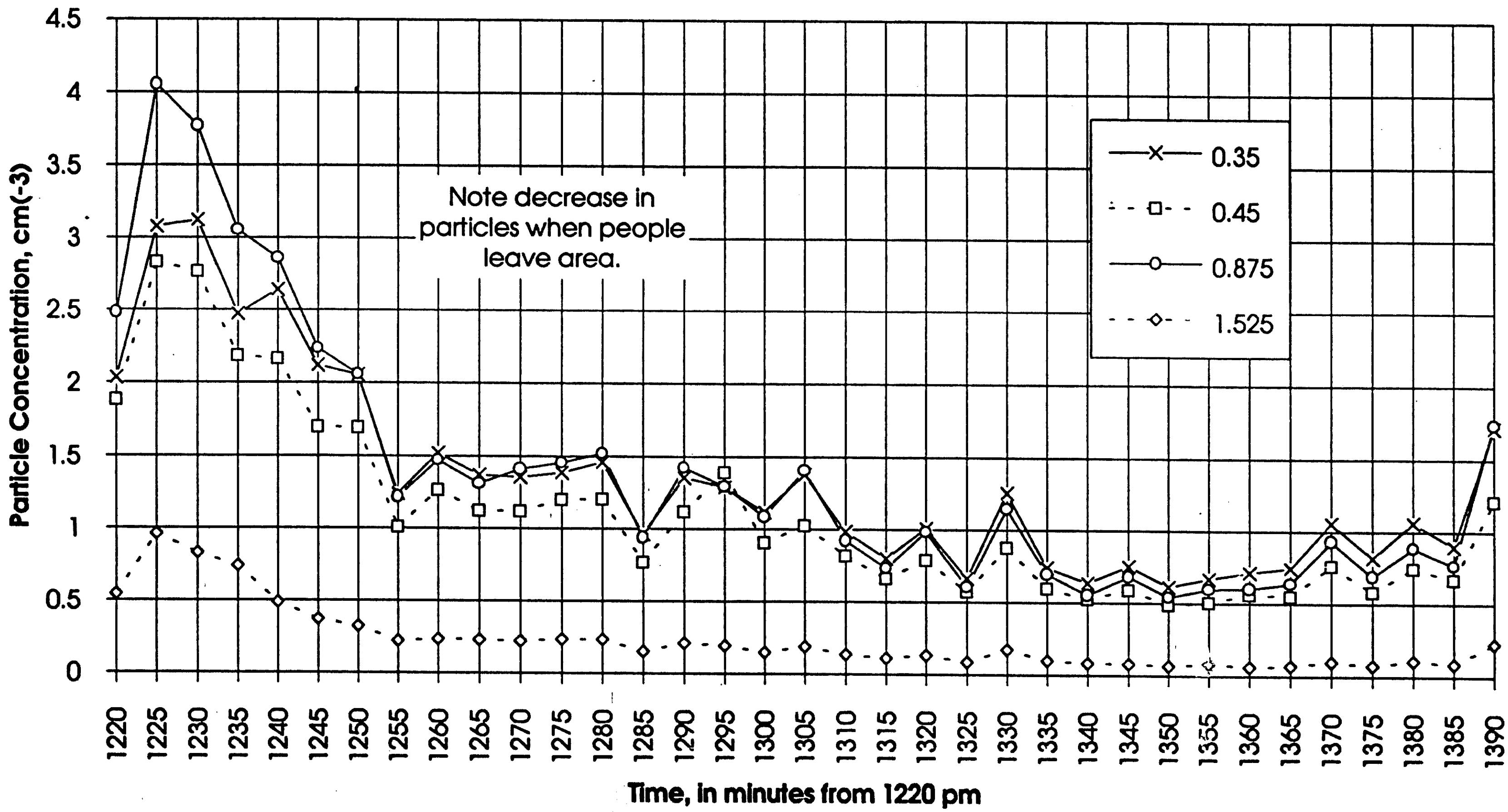


Figure H-7. Particle Concentrations January 16, 1993 at Bomb Shelter

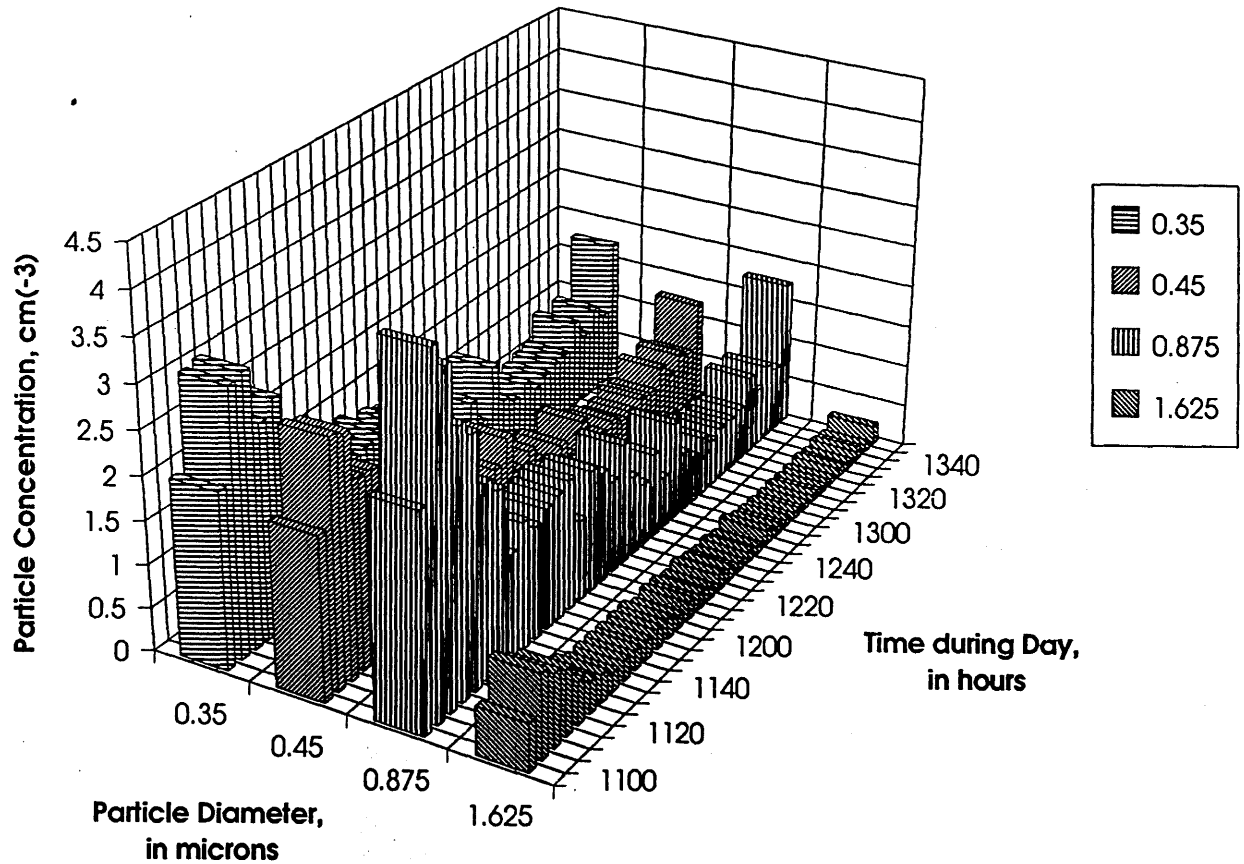
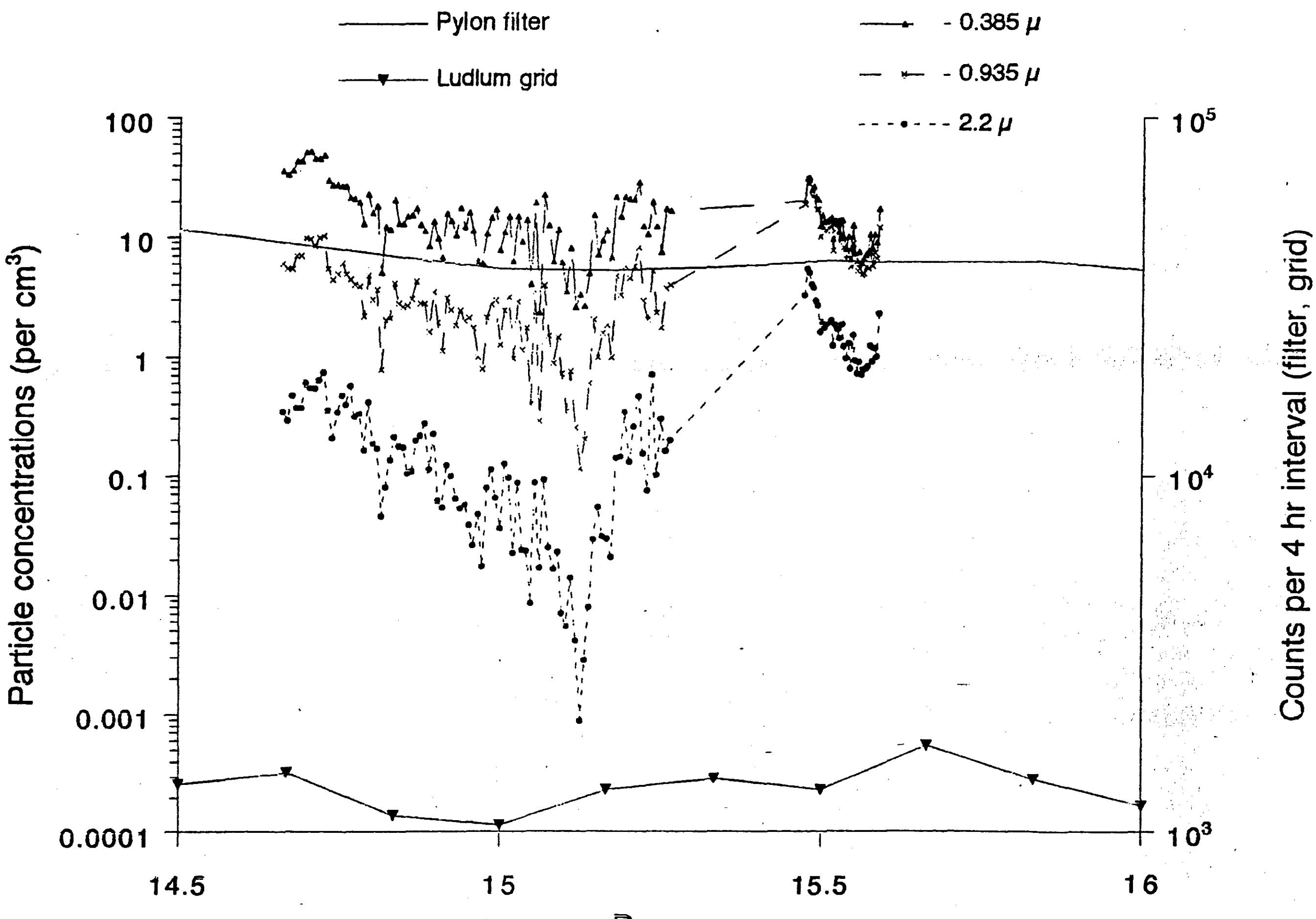


Figure H-8. Particle Size Distributions January 16, 1992 at Bomb Shelter



Particle size sampling interval = 10 Min. before 15.5 days, 5 minutes after.

Figure H-9. The relationship between radon progeny and aerosol concentrations January 15-16, 1993.

APPENDIX I. CO_2 MEASUREMENTS FROM 1991

Carbon dioxide (CO_2) concentrations were measured in May 1991 with a Riken portable CO_2 monitor. The monitor was used to sample the air at various locations along the commercial tour in Mystery II. The instrument could measure carbon dioxide concentrations between 0 and 10,000 ppm. Sampling locations and results are given in Table I-1.

Within the cave, levels were between 1700 to 1850 ppm. On the surface outside of the MII entrance, CO_2 was 1200 ppm. For comparison, CO_2 levels in Carlsbad Caverns, New Mexico varied between 345 to 490 ppm; Lehman Caves, Nevada, 1,040 ppm; Black Chasm Cave, California, 3,000 ppm, and as high as 4700 ppm in Altamira Cave, Santillana Del Mar, Spain.

The CO_2 levels in buildings normally range between 600 to 1,200 ppm and ASHRAE (ASHRAE, 1989) currently recommends levels of 1,000 ppm in commercial buildings. Because this was a one time measurement in late spring, we cannot say what variations could occur during other times of the year. The measured levels were in what could be considered a normal range for a limestone cave.

APPENDIX J. DEFINITIONS

Element – a substance that cannot be reduced to a simpler material by ordinary types of physical and chemical changes or unions.

Nuclide – a species of atom characterized by the number of protons (atomic number), and neutrons in the nucleus which together constitute the atomic mass.

Isotope – nuclides that have the same atomic number and therefore are the same element, but with different numbers of neutrons giving them a different atomic mass. Isotopes of a particular element have the same number of protons, but different numbers of neutrons.

Half-life – a measure of the rate of radioactive decay. The time it takes for a radioactive source to lose one half of its radioactivity. Radon-222 has a half-life of 3.82 days.

Radioactive decay mode the process by which a radioactive substance gives up energy and is transformed into a different element. Emission is by alpha particles, beta particles or gamma rays (electromagnetic radiation).

Working level – any combination of radon decay products in air that results in the ultimate emission of 1.3×10^5 MeV (million electron volts) of potential alpha energy. This is derived from the energy released by the decay of the radon progeny in equilibrium with 100 pCi/L of ^{222}Rn in air. Progeny are not usually in equilibrium with radon because they are removed from the air at a faster rate. Working levels based solely on radon concentrations with the assumption of equilibrium will be maximum values.

Working level month (WLM) - a working level month is equivalent to 100 pCi/L x 170 hr/month or 17,000 pCi hr/L. This assumes that all of the daughters are in equilibrium with ^{222}Rn.