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KARST GEOLOGY, RADON FLUCTUATIONS, AND IMPLICATIONS FOR MEASUREMENT AND MITIGATION

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ABSTRACT

Starting in December, 1996 and continuing through April, 1998, the Tennessee Radon Program, USEPA Region 4 Office, the Southern Regional Radon Training Center, and USEPA Headquarters conducted an investigation of several houses in Livingston, TN in which homeowners had discovered indoor radon concentrations far in excess of their original post-mitigation test levels. The investigation team conducted intensive diagnostic procedures and deployed equipment to provide long-term data on indoor radon concentrations and several other building and environmental parameters. Analyses of these data indicated extraordinary fluctuations in soil gas and indoor radon concentrations primarily related to outdoor temperature. Other investigators had previously described the same phenomena in geologically similar areas characterized by extreme karst development. It is probable that the extensive network of solution cavities provides pathways for significant bulk flow of soil gas over great horizontal and vertical distances, and in areas with elevation differences, enables pressure-driven flow through these pathways caused by stack effect developed due to temperature differences between the ground and outdoor air. Limitations of standard measurement and mitigation procedures in light of the magnitude of the radon concentration fluctuations are discussed, along with recommendations for measurement, diagnostic and mitigation procedures based on analysis of the long-term data and the efficacy of various system configurations.

INTRODUCTION

Livingston, TN is the county seat of Overton County in northeast central Tennessee, about halfway between Nashville and Knoxville. On the steeply sloping sides of Schoolhouse Mountain, an elevated area of about 250 acres, are located approximately 100 houses, including all those involved in this study. The geological unit on which the study houses sit is the Monteagle

Limestone. This unit is characterized by extreme karst development, which extends in some places into the upper part of the next lower unit, the St. Louis Limestone. Most of the numerous caves in the region have developed in these units, including Mammoth Cave in Kentucky. This karst development is primarily the product of water dissolving the limestone, and the openings thus produced are more properly termed solution cavities. In addition to the cavities large enough to have names, there are countless other smaller ones, often forming networks of great extent and complexity, providing pathways for movement of enormous quantities of soil gas. Livingston is located in one of the larger and more intensely developed karst regions in the country, but there are many others. (Figure 1)

PROJECT HISTORY

The impetus for the Tennessee House Investigation Project was the radon measurement data obtained by independent post-mitigation testing of several of the houses in Livingston which had mitigation systems installed in the fall of 1995. These measurements, conducted in the winter of 1995-1996, indicated that, in at least some of the houses, the mitigation systems were not maintaining indoor radon concentrations equivalent to those measured immediately post-mitigation. Some of the houses which had tested below the EPA action level of 4.0 pCi/L were well above that level on the later tests. (It should be noted that all post-mitigation radon tests in all of the houses yielded results below their initial pre-mitigation levels, indicating that the mitigations systems were producing significant radon reductions.) Concerned homeowners contacted Tennessee Radon Program personnel, who, in cooperation with the USEPA Region 4 radon program, initiated efforts to provide investigative resources to address the public concerns regarding apparently intractable radon problems.

The sustained efforts of these individuals resulted in the formation of an investigation team consisting of personnel from the Tennessee Radon Program, USEPA Region 4 office, the Southern Regional Radon Training Center, and USEPA headquarters. Team members arrived in Livingston in December, 1996 and began their investigation. Nine houses were visited, homeowners interviewed, and continuous radon monitors deployed. Of these nine houses, three were selected for intensive study, designated TN01, TN02, and TN09. (Figures 2, 3 & 4 are floorplans of the basements of these houses, showing both the original mitigation system suction point locations and those installed during the project, as well as test holes in floor and walls.) Relevant structural features shared by all the houses include: full basements with slabs throughout; block exterior basement walls; crushed rock of varying depth under the slabs; lack of sumps or any indication of footer drains. TN01 and TN02 were among those with mitigation systems previously installed, and were selected because the post-mitigation radon concentrations were running as high as 35 pCi/L. Measurement data from TN09 indicated higher concentrations (150-175 pCi/L) than had been encountered in any of the other houses, and the homeowners were very concerned. (Figures 5-18 show continuous radon monitor data for these three houses under various weather and mitigation system operating conditions. Figures 19-23 show the outside temperature for the same time periods.) The mitigation contractor who had installed the systems was very cooperative, and supplied descriptions of the original systems as well as information about the houses and procedures he had employed.

Initial visual inspection of the systems provided no indication of discrepancies. All the systems included single or multiple slab suction points and were well laid out and neatly installed. Sub-slab pressure field extension (PFE) measurements revealed what the investigators considered to be good to excellent pressure field extension in most cases. The overall initial impression was that the systems appeared to have characteristics of what are usually effective installations. However, data from continuous radon monitors deployed at the beginning of the site visit indicated that some of the houses were averaging well above the action level of 4.0 pCi/L. All except one of these houses had tested below 4.0 pCi/L on their first post-mitigation tests. Several sets of procedures were initiated in selected houses, including: extensive 'sniffing' measurements to produce radon concentration maps; system performance evaluation; and installation of equipment to monitor and record data on several house and environmental parameters (e.g., pressure differences in-house/outside and in-house/sub-slab, radon concentrations inside block walls and under slabs, outside temperature and pressure, wind speed and direction). Intensive diagnostic procedures were employed to further examine PFE potential and other performance characteristics of several proposed additions and modifications to existing systems, including the installation of temporary sub-slab depressurization (referred to as ASD in this paper) and block wall depressurization (WD) systems.

Review of data from previous investigations of indoor radon concentrations in other karst areas, and consultations with local geologists and cave experts indicated the probability of a significant influence by geological and environmental factors on soil gas movement over great vertical and horizontal distances, whereby the solution cavities can act as very effective conduits for radon, whether the radon originates in the karst units or not. The variability in magnitude and direction of this soil gas movement can result in drastic fluctuations in radon concentrations both in soil gas adjacent to building shells and indoors.

Data acquisition from the monitoring equipment installed during the initial visit continued until the team's return to Livingston in November, 1997. Analysis of the periodic downloads of these data had confirmed the extreme variability of radon concentrations over both short and long time periods, including extended periods during which the indoor concentrations averaged well above the initial post-mitigation test levels.

The purpose of the November, 1997 visit was to complete diagnostic work and to design mitigation systems with some excess capacity in order to determine the optimal installed system capacities and configurations required to maintain indoor radon concentrations below 4.0 pCi/L under these conditions. Additional monitoring equipment was deployed to permit more complete system performance evaluation. The systems were installed in January, 1998, and cycled through various operational configurations, with the selected parameters continuously monitored, and PFE profiles taken when the systems were re-configured. This operational/monitoring regime continued through the third week of April, 1998.

During the week of May 11-15, 1998, the Tennessee Radon Program, EPA Region 4 office and the SRRTC presented two 2-day training courses for radon contractors using the subject houses as demonstration sites. A presentation by geologist Francis Fitzgerald of nearby Cookeville, TN included a summation of his radon work in Livingston, which started in 1994 (Officer, et al. 1995), and a briefing on the local geology including a tour of a local limestone quarry to observe the karst development in the exposed profile. David Wilson of ORNL reviewed the findings of studies he and his co-workers undertook in karst areas in Tennessee and Alabama starting in the late 1980's. The course also included a review of long-term radon and environmental parameter data, demonstrations and exercises using the diagnostic and system design procedures employed in the study including 'sniffing', and demonstration and review of the operation of various mitigation system configurations and their effect on PFE profiles and indoor radon concentrations.

The training sessions ended with a class discussion of the study's methods and findings, and their implications regarding the adequacy of standard radon measurement and mitigation procedures in areas with similar geology or otherwise difficult situations. Class members expressed concern that the phenomena operative in the study houses may be more common than generally realized, with the result that many houses with potentially serious radon problems are judged not to need mitigation on the basis of measurements taken when the indoor concentrations are at their low ebb. Further, several of the experienced mitigators in the class, some from areas with considerable karst development, expressed doubts about the reliability of evaluating the efficacy of their mitigation systems by means of standard post-mitigation test procedures, and how that question could impact their businesses in terms of guarantees and other contractual considerations.

STUDY RESULTS:
INFLUENCING FACTORS AND DATA RELATIONSHIPS

While this project is focused on an area with anomalous radon behavior related to the underlying geology, other contributory factors are also at work in a variety of regions. Earlier studies (Dudney, et al., 1988, 1990, 1992; Gammage, et al., 1992; Wilson, et al., 1991) and results of this project strongly suggest that buoyancy effects, caused by temperature differences between the air outdoors and the air in underground caverns and fissures, acting over a topographical gradient, drives flow of radon-laden soil gas through openings that occasionally intersect with building substructures.

Temperature Differences

Use of standard engineering formulas yields estimates of the pressures caused by this 'stack' effect of 5 to 12 Pascals for Schoolhouse Mountain under common winter temperature conditions. Using a temperature difference of 3 degrees C., the pressure is 8.6 Pascals.(Figure 28). Constant ground temperature in this area is approximately 16 degrees C. (57-58 degree F.). These large pressures may have significant impact on soil gas entry into structures. In TN02, a large void was discovered running under the basement wall footer. A strong flow of soil gas was exiting from this void, and the radon concentration in the soil gas was measured at approximately 1000 pCi/L. Pressure measurements taken inside the wall cavities adjacent to this area before removal of the slab and discovery of the void indicated higher wall interior pressures than at other locations in the house. It is important to remember during this discussion that the building continues to be an active participant in drawing radon from the soil. When falling outdoor temperatures enhance the transport of radon through openings in the ground, they also increase the stack effect in buildings, boosting negative pressures in the substructure.

The overall effects of outdoor temperature on indoor radon levels are apparent in the data. Under baseline conditions (all mitigation systems off) at all three houses, indoor radon was inversely related to outdoor temperatures (i.e., falling temperatures = increasing radon) -- upwards of 50% of the variation in indoor radon levels can be explained by changes in outdoor temperature. Operation of effective radon control systems decoupled this relationship.

A particularly striking example of the magnitude of the effect of outdoor temperature is seen in Figures 16-18, which show the radon concentration in two adjacent basement rooms in TN09. Note the difference in test results which would have been obtained with standard 48-hour deployment of devices for the two periods March 22-23 and March 26-27. Under identical mitigation system operating conditions, the average for March 26-27 was less than 4.0 pCi/L in both rooms, while the average for March 22-23 was 70-80 pCi/L, with one room consistently higher than the other. Also, the average concentration for the period March 28-31 with all systems off was only a fraction of the average concentration for March 21-25 with ASD (slab-suction) system #4 operating. Figures 21-23 show the outside temperature during the same period, and when compared with the radon concentrations, provide a vivid illustration of this phenomenon. Figures 24 & 25 show another example of the same relationship in TN01, reflecting the same consequences of measurement timing and duration. Figure 27 shows seasonal and annual average concentrations with the original mitigation systems operating in TN01 and TN02, and for baseline (all systems off) in TN09.

Siting and Construction

Local siting and construction preferences can have a large impact on radon entry by altering the substructure's interface with pathways for radon movement. Constructing houses with basements blasted out of near-surface rock on hillsides above valley bottoms may make seasonal radon increases more likely. The fact that virtually all basements in this area have block walls is also significant regarding radon entry.

Thoron

In some houses, the resulting entry rate can be large, and be a significant fraction of the total ventilation air. At rapid entry rates, such as may occur in these study houses, it is possible that short-lived thoron gas (radon-220, with a half-life of approximately 55 sec) could survive long enough to enter a building and cause additional risk of exposure to inhaled radioactive progeny. Thoron measurements were not conducted as part of this study.

Other Soil Gas Pollutants

Anecdotal observations by the study homeowners suggest that substantial moisture and/or airborne biocontaminants may also be entering with soil air, since when mitigation systems are operated, 'musty' odors are diminished. Data collected on basement relative humidity levels at two of the houses are equivocal.

Other Environmental Factors

Data from this study also hint that, on occasion, large and rapid changes in barometric pressure, wind from certain directions , and possibly precipitation events may also enhance radon entry into the study houses. For example, a wind direction of approximately 180^0 may cause unexpected 'spikes' in indoor radon concentrations at TN01, while wind from approximately 300^0 may have the same effect at TN02. This could be caused by connection of these two house with subterranean passages that open to the atmosphere at different locations on the mountain. Thus, strong and persistent winds could, for a short time, become the dominant mechanism creating pressure-driven flow of soil gas.

Changes in atmospheric pressure can create significant pressure gradients across some soils, resulting in exhalation of soil gas to the atmosphere during periods of falling atmospheric pressure (producing high indoor radon levels), and inhalation of ambient air during periods of increasing atmospheric pressure (low indoor radon). With a few exceptions in this study, indoor radon levels generally did not respond in this fashion to changes in barometric pressure. Instead, indoor radon and barometric pressure were often weakly correlated (increasing barometric pressure = increasing indoor radon), probably because an increasing barometric pressure signified colder outdoor temperatures. Figure 5 shows the TN01 basement radon concentrations for the last half of February, 1997. Figure 26 shows the barometric pressure for the same period. Notice that several of the major upward fluctuations in the radon concentration during this period occurred simultaneously with a rising barometer.

Radon in Walls

Data from this study show that indoor radon levels correlate well with radon in wall cavities and, to a lesser extent, subslab radon. This finding highlights the importance of walls as a significant source of radon indoors, and remediation efforts that treat walls. During some test periods (including baseline) at TN01 and TN02, radon concentrations in the wall cavities were higher than below the slab. Results from various ASD and WD configurations suggest that wall and subslab radon levels may increase because the mitigation systems are 'mining' radon from a nearby source.

IDENTIFICATION OF RADON HOT SPOTS

In buildings with difficult-to-solve indoor radon problems, diagnostic techniques to identify those areas where radon concentrations are highest can be helpful in isolating possible radon sources and entry locations. In simplest form, radon levels in different rooms or zones are measured and compared to locate those areas, if any, where radon entry is greatest (or perhaps ventilation rates are lowest). The accuracy of the measurement device is not critical since the assessment is relative; i.e. to find the strongest radon 'signal'. However, the device's ability to provide consistent or repeatable measurement results (precision) is important.

Radon 'Sniffing'

This approach has also been applied to 'sniff' the locations of radon 'hot spots' below slabs, within block walls and exterior to substructure walls. Using a variety of passive and active sampling techniques, radon (and thoron) activity at each location can be determined and compared with other locations. Identification of these 'hot spots' implies the presence of relatively stronger radon sources due to: a) localized enrichment of the soil in radionuclides; b) transport mechanisms delivering radon to these locations, or c) conversely, trapping/retention of radon by physical barriers (e.g., slabs) and/or low-permeability materials. Transferring these data to a simple floor plan of the building, can assist in visualizing the areas where active soil depressurization and/or wall depressurization might be most effectively applied. Experience has shown that placement of sub-surface depressurization at radon 'hot spots' often is very effective in lowering radon levels, without the need for robust PFE over the entire subsurface.

Although the presence of hot spots suggests that greater radon entry occurs at these locations, other factors are also important in determining actual entry of radon into a building. Most significant are:

(1) the relationship of the resistance to flow of soil gas of the nearby sub-surface soil and materials and substructure surfaces (caused by floor or wall gaps, cracks and other openings); and

(2) the magnitude of the pressures that drive entry in different zones of the building.

Advanced diagnostic techniques are required to perform measurements at the resistances in #1. In lieu of performing more time-consuming diagnostics, it is usually preferable, in combination with a map of radon hot spots, to employ qualitative criteria, such as a visual assessment of the likelihood for radon or soil gas to enter at a location. Particularly susceptible are sites near wall/floor joints, gaps, cracks and other openings, and block wall surfaces.

Even these simplified procedures are more time- and instrumentation intensive than is ordinarily required for most radon mitigation system designs. However, in difficult-to-mitigate houses, this approach may save time and money -- while local experience may be the best substitute.

Limitations

The 'sniffing' procedure is vulnerable to the same factors causing variability in indoor radon levels. Seasonal differences, along with short-term effects caused by

- wind,
- indoor-outdoor temperature differences,
- barometric pressure,
- precipitation,
- operation of air handling equipment, and
- occupant activities

can have a complicating impact on measurements and interpretation (especially in block walls).

Some instruments are not suitable for sniffing, because lengthy response times can make this procedure very time-consuming. In addition, sampling instrumentation can become contaminated by high radon levels at a particular test location -- which may temporarily render the device unusable for subsequent sampling at low-radon locations. Therefore, a good 'sniffing' strategy would have sampling begin at those locations expected to have the lowest concentrations, moving on to locations with higher expected levels. After sampling a high radon location, the device may need to be flushed with low radon air, or fitted with a new sample media (e.g., alpha scintillation cell). The background activity in the instrument should also be periodically measured during sampling so that corrections to the strategy or data can be made.

TN01

Because of the numerous test holes at TN01, extensive identification of 'hot spots' for radon mapping was possible. With the original ASD system off, the highest radon levels were found in two general locations:

1.) along the uphill wall (F4, F18, F19, F7, F8) that is capped by a patio slab, and
2.) the wall facing the garage (with the capping garage slab).

The excavation (and more likely interception of fissures) on the uphill wall and the capping slabs are probably the primary reasons for the elevated levels in these locations.

TN02

The highest radon concentrations sniffed at TN02 coincided with the large void and significant soil gas movement discovered under the footer near F13. Comparatively higher levels also extended along the uphill wall (F13, F15, W9) and the side wall (F4 and F6). Although radon concentrations at other test holes were quite low, they could make important contributions to indoor levels if sizeable soil gas flows were present. Note that significant, additional reductions in indoor radon were finally achieved after ASD suction points (ASD #B2 and D1) were installed at the observed hot spots. The structural characteristics of this house made it particularly demanding. Most of the interior walls in the basement are cinder block construction, with sub-slab footers which effectively limit PFE from a slab suction point to the 'cell' within which the suction point is located. Also, sub-slab communication is not as good as at either of the other two houses, even within a 'cell'.

TN09

Radon sniffing found, as in the other houses, that those test holes with the highest radon concentrations were located along the uphill wall (F2, F11, F4, F5 to F7) which is capped by a patio slab. Other locations, including the remaining two walls of the shelter room and the floor drain in the storage room, also had elevated levels.

MEASUREMENT IMPLICATIONS

It is difficult to perform accurate measurements of radon or related variables in buildings that are strongly influenced by environmental or operational factors. These buildings and circumstances are not limited to the situation described in this study. EPA protocols for measurement of indoor radon levels were developed to address the variations encountered in most houses and schools. But in more 'sensitive' buildings, the protocols may result in a greater number of false positive measurements (leading to unnecessary mitigation), or worse, a greater number of false negative measurements (problem buildings are not remediated).

Initial Measurements

Continuous monitoring of radon in the three Tennessee project houses shows that large variations (factors of 10) in indoor concentrations can occur over rather short time periods (hours to days), especially under baseline conditions. Further compounding the problem, seasonal differences in average radon levels tend to be larger in these houses (except for TN09). For some houses in this region (e.g., Huntsville, Alabama) with low siting on hillsides, the seasonal effects may be reversed from what is commonly encountered in other parts of the country: average radon levels in summer are higher than in winter.

Therefore, at a minimum, it is preferable to perform longer-term initial measurements than is currently recommended in EPA measurement guidance. However, data from this study strongly suggest that there may be periods of days or even weeks during which average radon concentrations are very unrepresentative of annual averages. It may be necessary to perform seasonal testing, year-long testing, or a combination of these strategies to ensure that the test results are an accurate indication of occupant exposure potential. It would also be advisable to consider siting factors that may cause seasonal differences. Other environmental factors, such as barometric pressure, precipitation, and wind speed and direction, may also impact the measurements, as they do in other regions of the country with different soil/geologic conditions.

Diagnostic Measurements

Measurements performed during investigation of a radon problem and design of radon mitigation systems can also be influenced by existing environmental conditions. For example, radon levels in wall cavities and below slabs have been observed to vary even more widely than indoor levels. If radon sniffing of 'hot spots' occurs during periods of unusual conditions, it is possible that locations will be mis-identified. However, the long-term data collected at these three houses suggest that radon levels at most locations usually rise and fall in unison. The exception is during windy periods where pressure differentials and radon concentrations at windward and leeward surfaces can be affected differently. Hot spot identification during the summer can also present a problem, since indoor and substructure radon levels are often very low and difficult to measure, even though they can be much higher during the winter.

Post-Mitigation Monitoring

Determining when a radon problem is fixed can be more difficult than performing accurate screening measurements. First, criteria have to be established that describe successful mitigation (perhaps written into mitigation contracts). In most houses, it is impractical to install a mitigation system to overcome all conditions that might lead to short-term radon spikes. Since EPA's action level of 4.0 pCi/L is based on an annual average, brief periods at high concentrations can be tolerated. Therefore (and secondly), post-mitigation radon measurements must be of sufficient length to 'average out' spikes of short duration and meet the established criteria.

Probably more vexing is attempting to avoid post-mitigation testing during periods that do not sufficiently challenge mitigation systems and can lead to the incorrect conclusion that the system is providing effective radon control. This implies (for these houses) that follow-up monitoring should not be performed during the summer or other periods of warm weather.

MITIGATION IMPLICATIONS

Design of cost-effective soil or wall depressurization systems depends on the mitigator's ability to determine what areas of soil in contact with the building shell, or areas of the walls, need to be addressed and to what degree. So long as the cost of diagnostics sufficient to enable design of initially effective systems does not exceed the cost of installing and operating ineffective or superfluous systems, adequate diagnostic procedures save money, and more importantly, expedite the reduction of radon exposure.

Timing of Mitigation Activities

While probably less critical than the timing of initial, confirmatory and post-mitigation measurements, the timing of mitigation activities, especially diagnostic radon measurements, may influence the mitigator's ability to determine the areas of greatest radon entry potential, and thus impair the design of effective systems. Careful evaluation of previous radon test data, especially if such data are available from multiple tests conducted at different times of the year, may be helpful in determining when radon entry potential is likely to be greatest and allow most accurate diagnostic measurements. Non-availability of such data and work scheduling demands are probable obstacles to this approach in many cases. This fact was immediately obvious to the class members in the training sessions, and was recognized by them as potentially very problematic.

Diagnostic Measurements

Considerable effort was expended in this project to locate 'hot spots' both under the basement slabs and inside the block walls. The rationale for this effort was the assumption that the failure of some of the previously installed systems to maintain their initial radon reductions was due at least in part to their lack of sufficient pressure fields in areas of high entry potential. Thus, extensive 'sniffing' was performed with the intent of locating suction points as close as practically possible to the 'hot spots.' Generally, and not unexpectedly, most of the 'hot spots' were located in those areas where the building shell is in proximity to the most undisturbed soil/rock which in these houses is the uphill side. The presence of 'capping' slabs may play a role as well. It should be emphasized, however, that building construction details and other factors play an important role in determining whether suction points located only at 'hot spots' will be capable of extending adequate pressure fields to all areas which have sufficient radon entry potential to cause elevated indoor concentrations. Data from the operation of the various system configurations installed in the houses seem to confirm the greater efficacy of locating suction points near 'hot spots.'

Pressure Field Extension

The original systems in these houses produced relatively good pressure fields under most or all of the slabs, yet were unable to maintain their initial indoor radon reductions. While probably sufficient to significantly reduce or preclude radon entry through most slab openings, the pressure fields were not robust enough to adequately impact the block wall interiors, or to extend into the soil on the exterior of the walls. When pressure fields strong enough to have that impact were generated, indoor concentrations were much more favorably affected. Sub-slab obstacles to PFE, including footers or other construction features as well as natural barriers, must be located and their effect determined. Assuming adequate PFE from a very few measurements is risky when the entry potential is as large and variable as demonstrated in this situation.

Prediction of System Mechanical Performance

Installation of systems which do not perform mechanically as required is no more effective than installing them with poorly located suction points. Diagnostic/system design methods which do not enable accurate prediction of system mechanical performance in terms of pressure, flow rates and extent and strength of PFE can result in unexpectedly poor system performance, or the installation of excessively powerful or overly extensive systems. In difficult-to-mitigate buildings, accurate diagnostic/system design techniques are especially desirable.

Block Wall vs. Sub-slab Depressurization

A fairly consistent relationship exists between the block wall interior radon concentration and the concentration indoors in these houses. Sub-slab depressurization systems with suction points located next to exterior walls and sufficient fan capacity to impact the wall interiors were more effective at controlling both wall interior and indoor concentrations than were block wall depressurization systems. The sub-slab systems generated more evenly distributed pressure fields in the walls, and did so with lower airflows than the wall systems. It is reasonable to assume that this results in less energy penalty (loss of conditioned air) from system operation. All the wall depressurization systems installed during this study were single suction point systems. Multi-suction point (manifold-type) systems may have been equally able to produce the well-distributed pressure fields created by the slab suction systems, but almost certainly would have been more obtrusive and expensive to install. There are situations in which no reasonably achievable sub-slab pressure field will adequately impact block walls, but that was not the case here.

Through-wall Depressurization

Two attempts were made to install suction points through the basement walls into the soil outside. One installation was completed, but the clay fill at that point was so compacted as to be virtually impermeable, and the suction point proved ineffective. In the other attempt, water-saturated clay fill was encountered, and the exterior wall of the block had to be re-sealed. This suction point was converted for use as wall depressurization. One additional suction point was installed through the garage slab in TN01. This slab is at finished grade on the downhill side of the house, and sits largely on fill. Sniffing measurements indicated high concentrations in the adjacent basement wall, and the suction point was installed through the slab next to the wall. It was assumed that such an arrangement would generate a pressure field similar to a through-wall suction point in the loose fill material, and it in fact proved to be effective.

Long-term Considerations

Creation of new and changes to existing openings in rock and soil in this type of geological situation are ongoing processes. Further, excavation for a basement, which often entails blasting, and the presence of the basement structure itself represent disruptions to the natural processes. Over the life of a house, there may be significant changes in the radon entry potential which could render existing mitigation systems ineffective. The EPA recommendation for periodic retesting of mitigated houses would be particularly applicable under these conditions.

SUMMARY

Data from this study and others indicate that, in areas of extensive karst development, the potential exists for fluctuations in indoor radon concentrations which are extraordinary in magnitude, duration and seasonal occurrence. Here, as in other locations, many factors may influence indoor concentrations, but the dominant factor appears to be outside temperature and the consequent pressure-driven movement of radon-bearing soil gas through the solution cavities of the karst formations.

The nature of these fluctuations creates considerable difficulty in arriving at a reasonably accurate radon profile of a house on the basis of very short duration measurements, whether they are initial, confirmatory or post-mitigation tests. It is possible that a larger percentage of 'false negatives' and 'false positives' will occur under these conditions than where fluctuations in radon concentrations exhibit more 'normal' characteristics. Alternative measurement strategies may be needed to enable homeowners and technicians to have reasonable confidence in their test results. These strategies might include longer-duration measurements, multiple measurements during different seasons, or year-long measurements.

The efficacy of standard mitigation procedures may also be influenced by these phenomena. Beyond the obvious problems with location of 'hot spots , other diagnostic radon measurements and post-mitigation measurements, the large variations in radon entry potential make the design of effective mitigation systems more demanding in terms of identification of potential entry points and driving forces, and accurate prediction of system mechanical performance characteristics like magnitude and extent of pressure fields.

ADDITIONAL DATA

The body of data derived thus far from this study is much larger than could be presented in the context of this paper. Readers with a serious interest in the topics discussed here are encouraged to contact the SRRTC or one of the authors for more information. We also request that persons with radon experience in karst areas share that experience with us.

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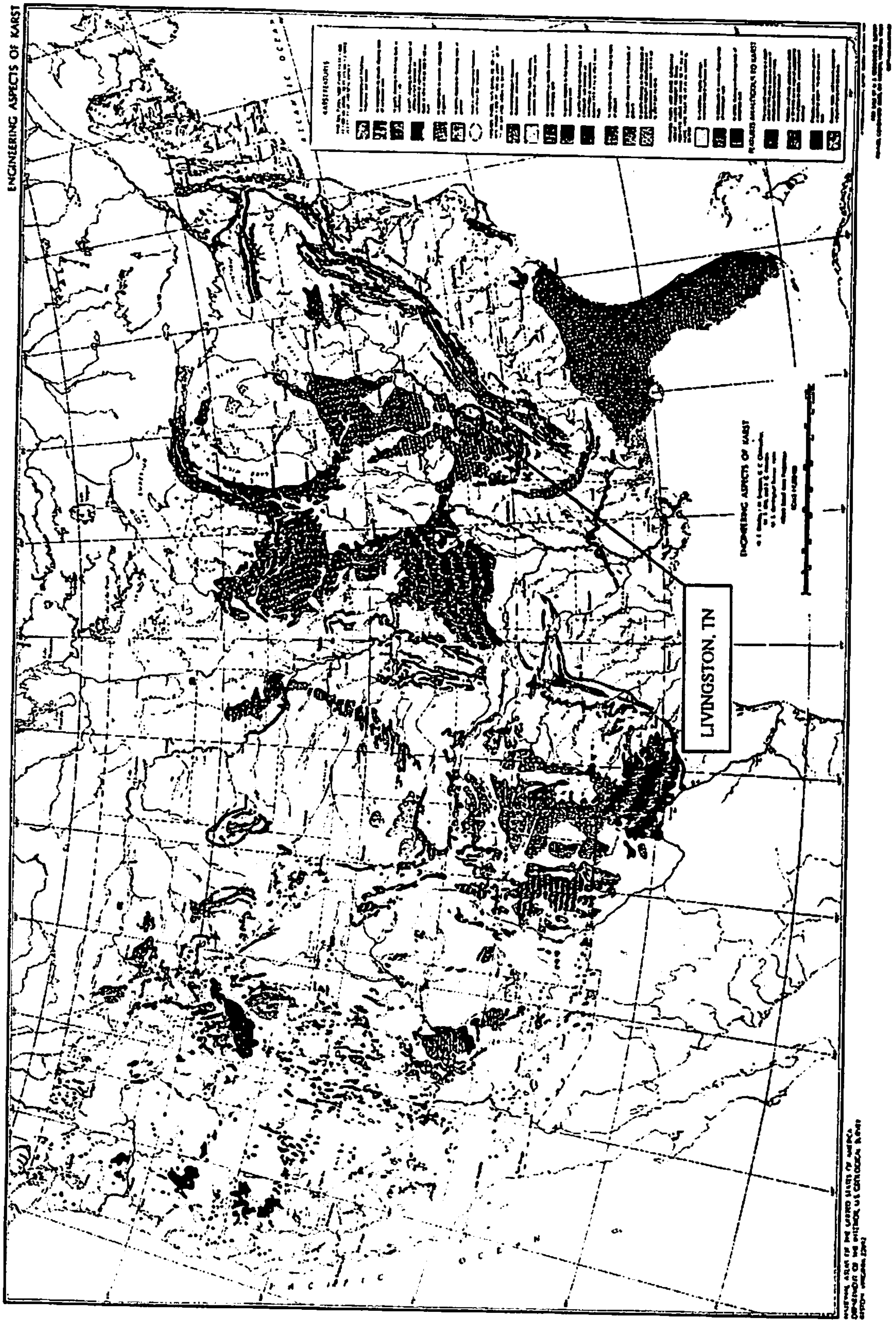
Figure 1



Karst Areas in US

Figure 2

(ASD #1 is original system)

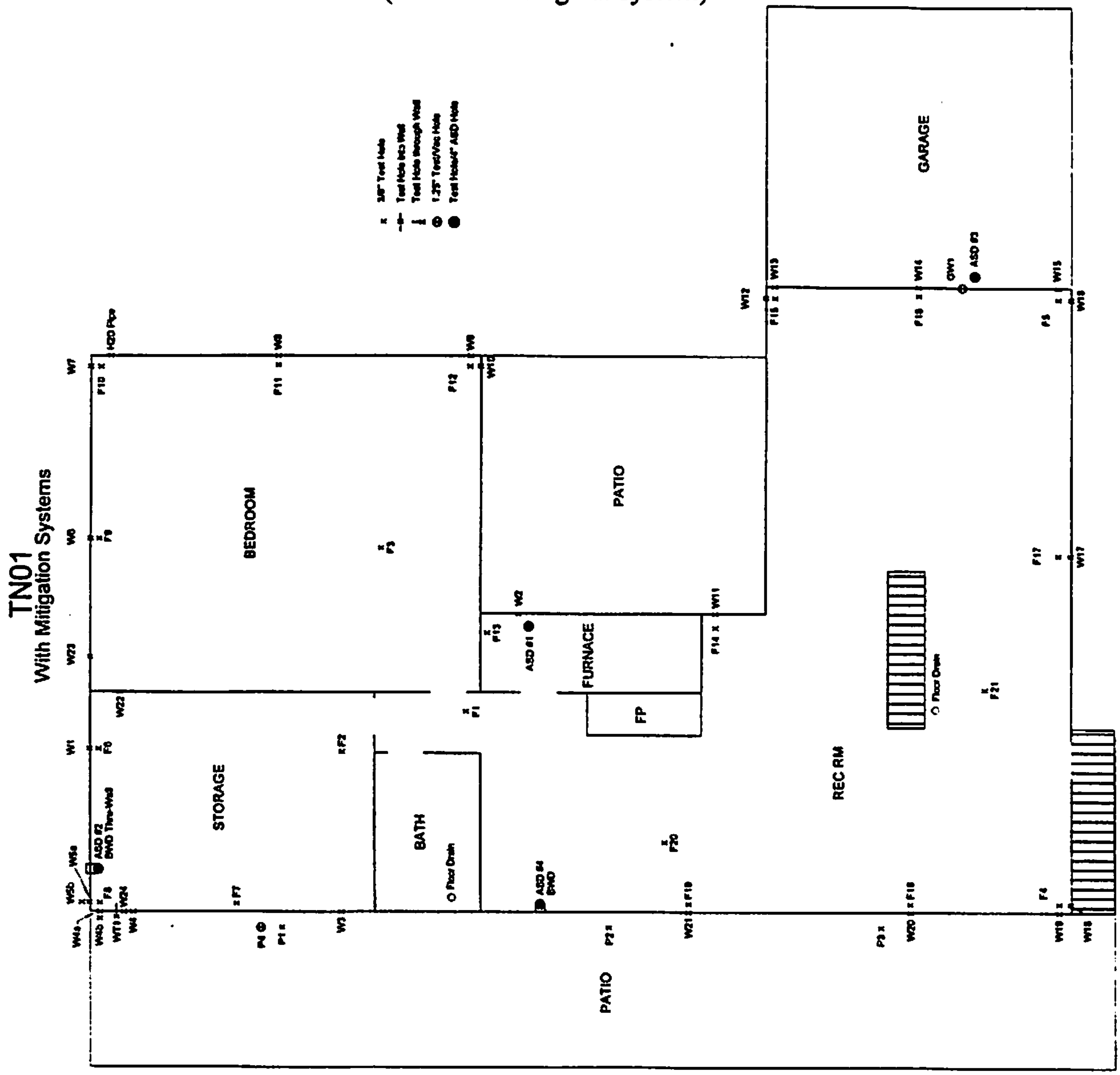


Figure 3
(ASD # A1, A2, B1, C1 & C2 are original systems)

TN02
With Mitigation Systems

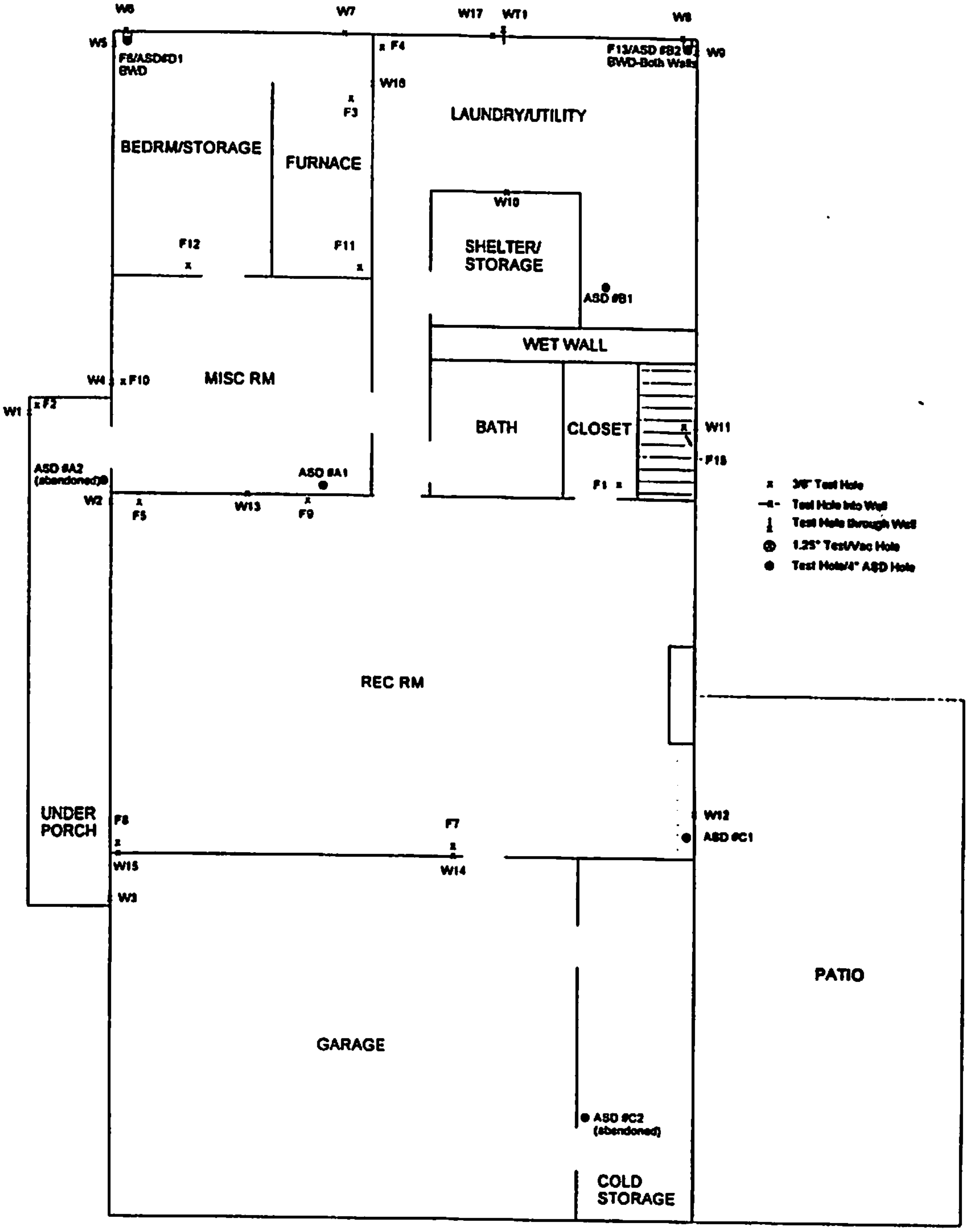


Figure 4
(No original systems)

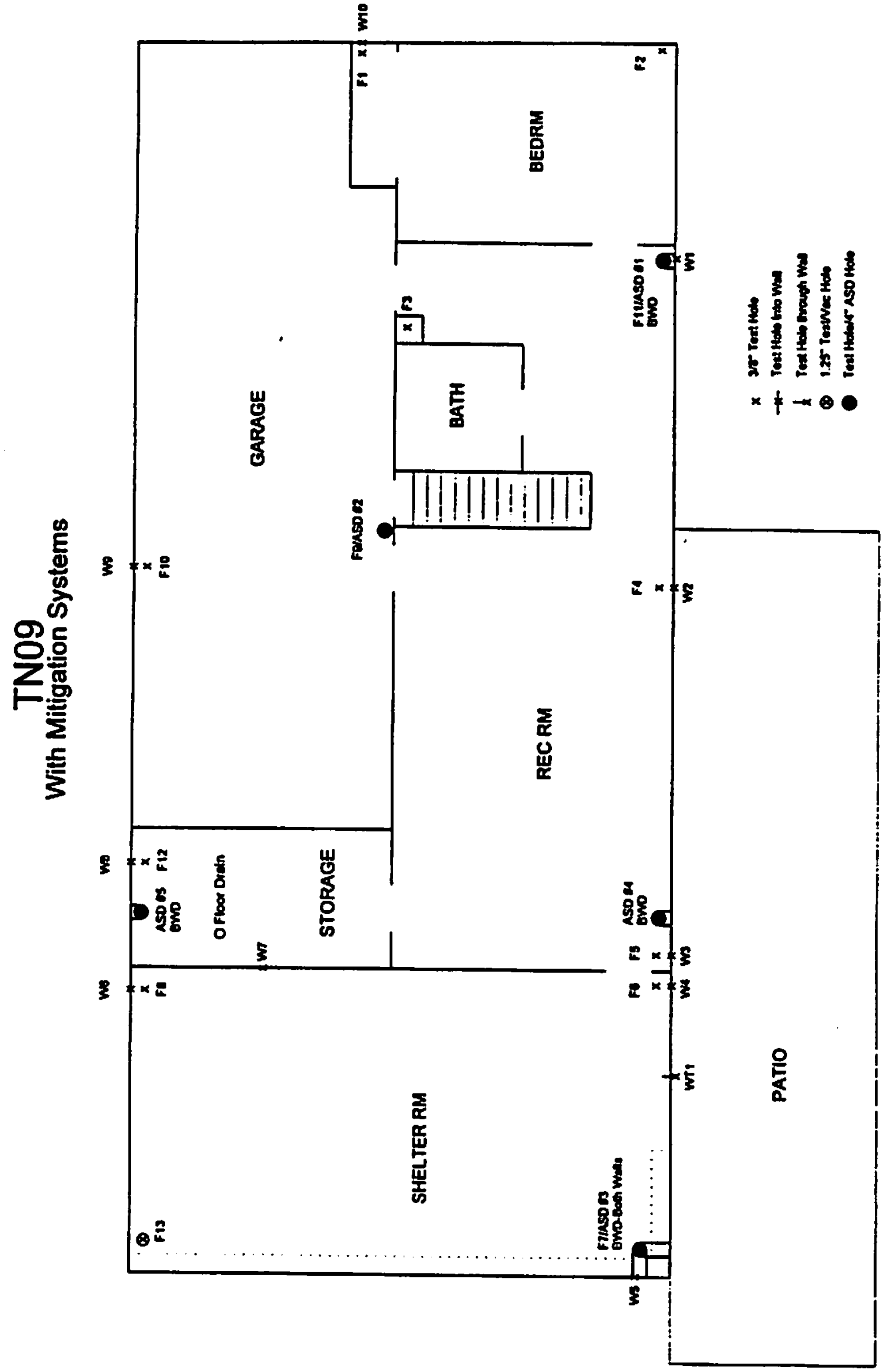


Figure 5

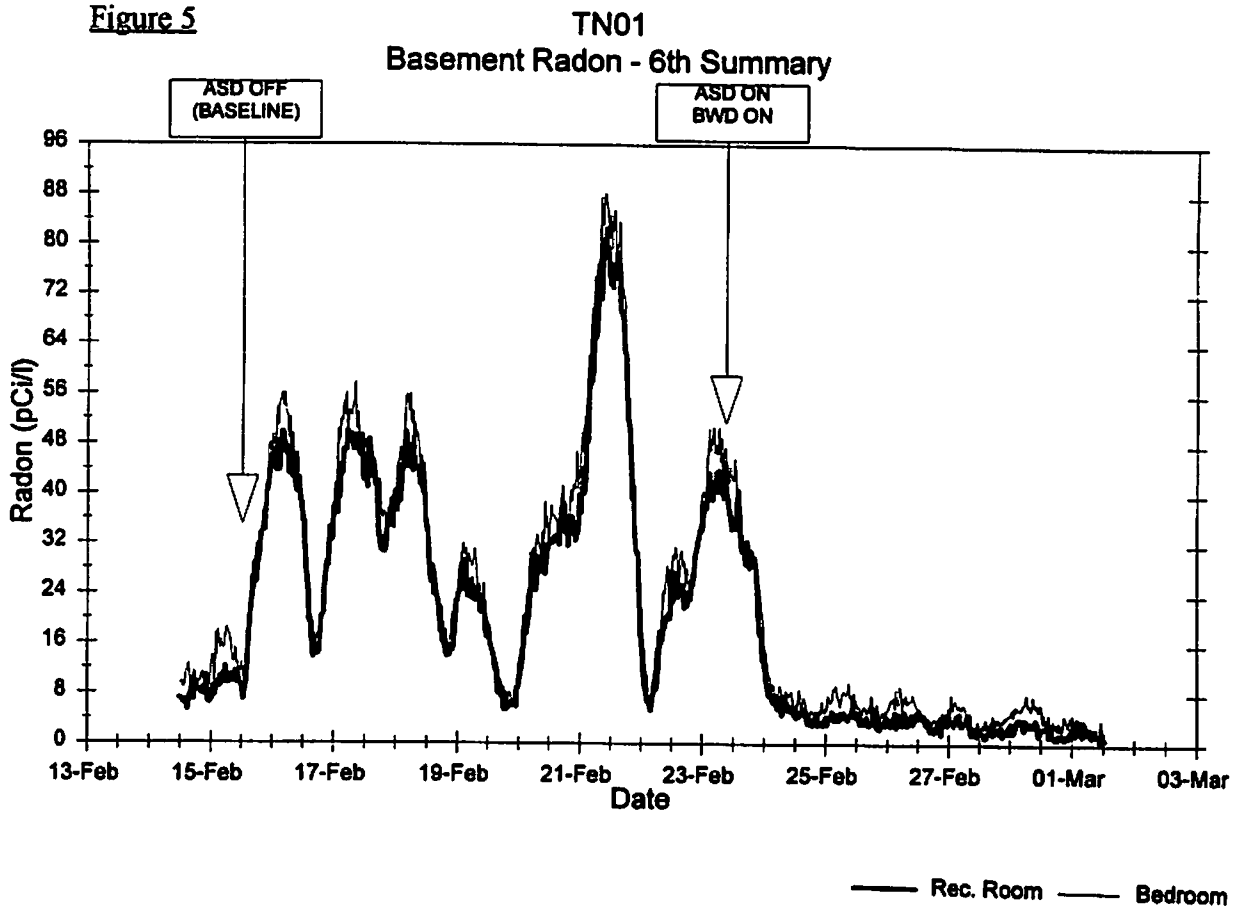


Figure 6

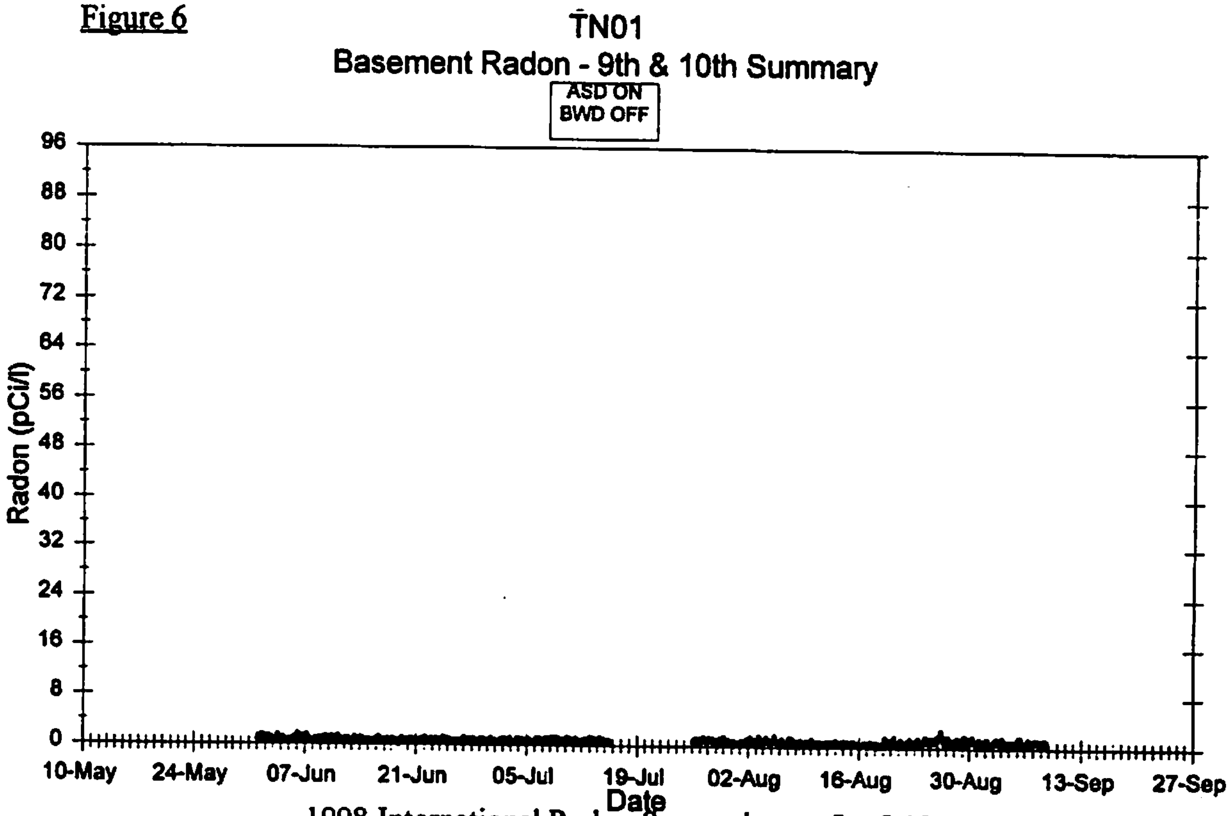


Figure 7

TN01
Basement Radon - 19th Summary

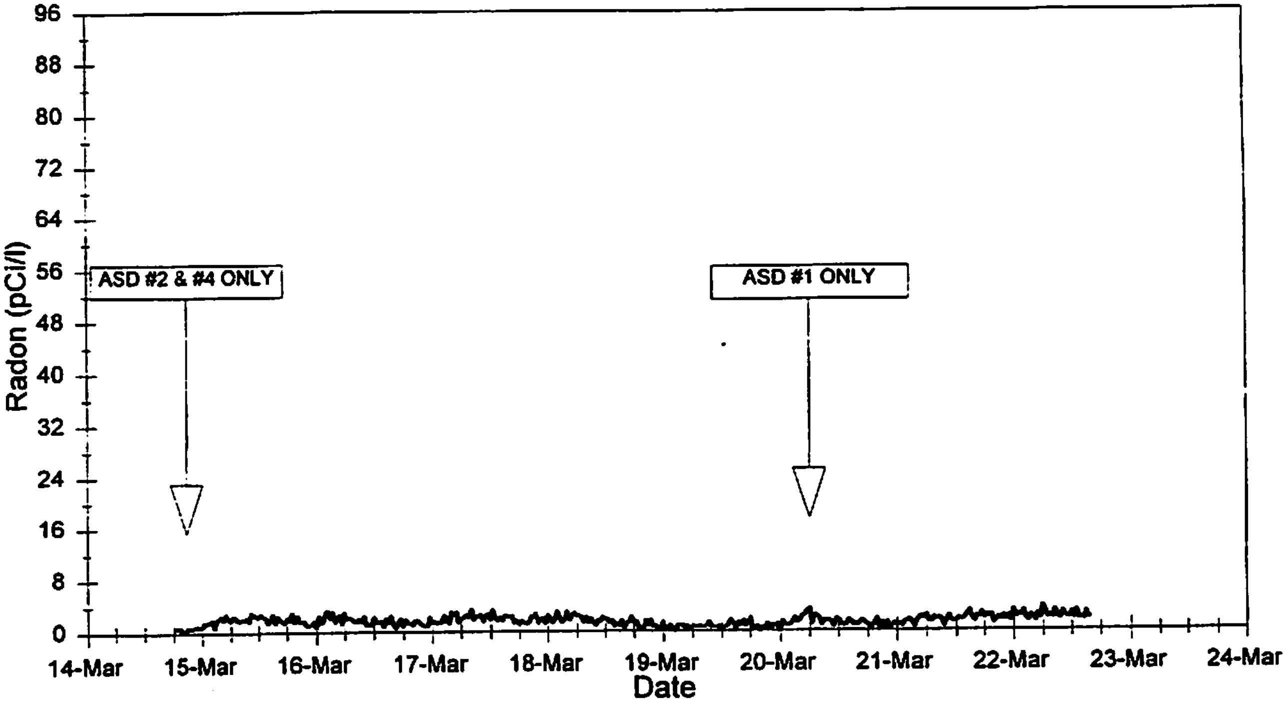


Figure 8

TN01
Basement Radon - 20th Summary

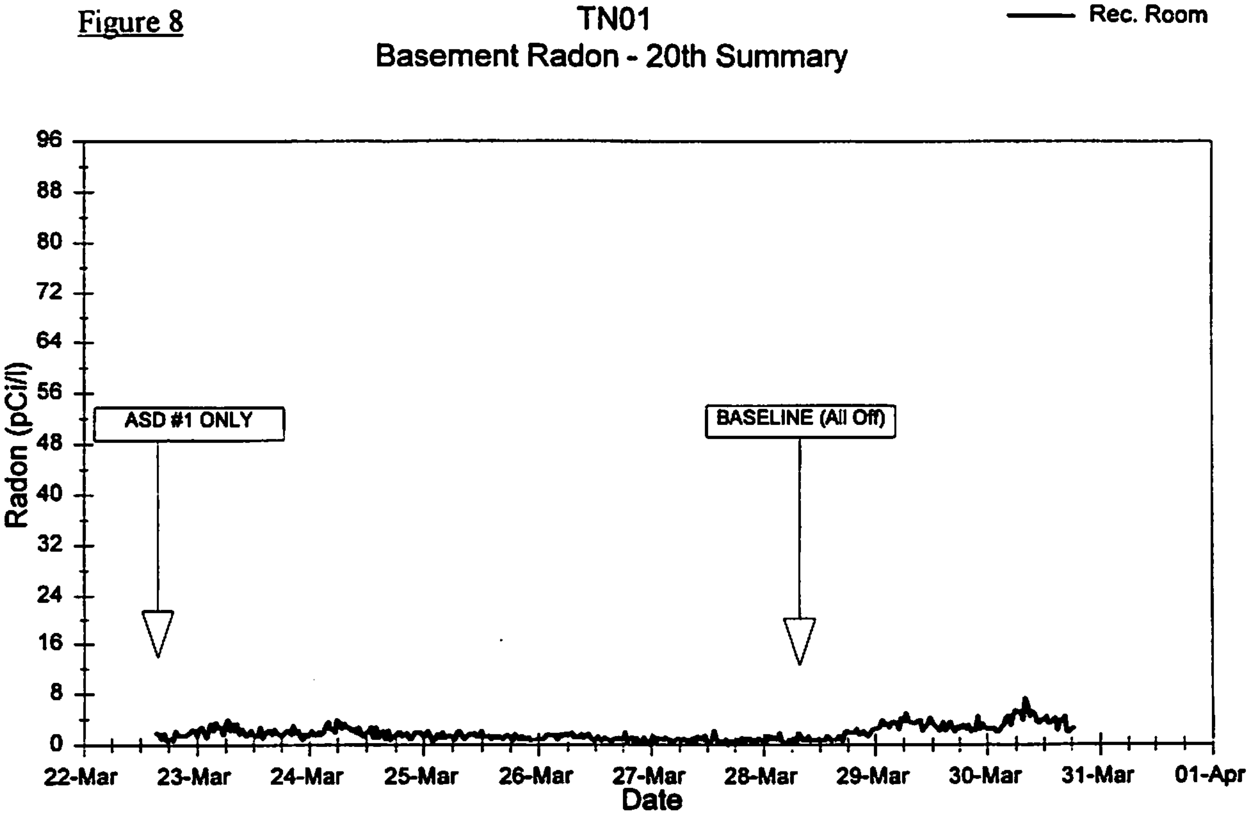


Figure 9

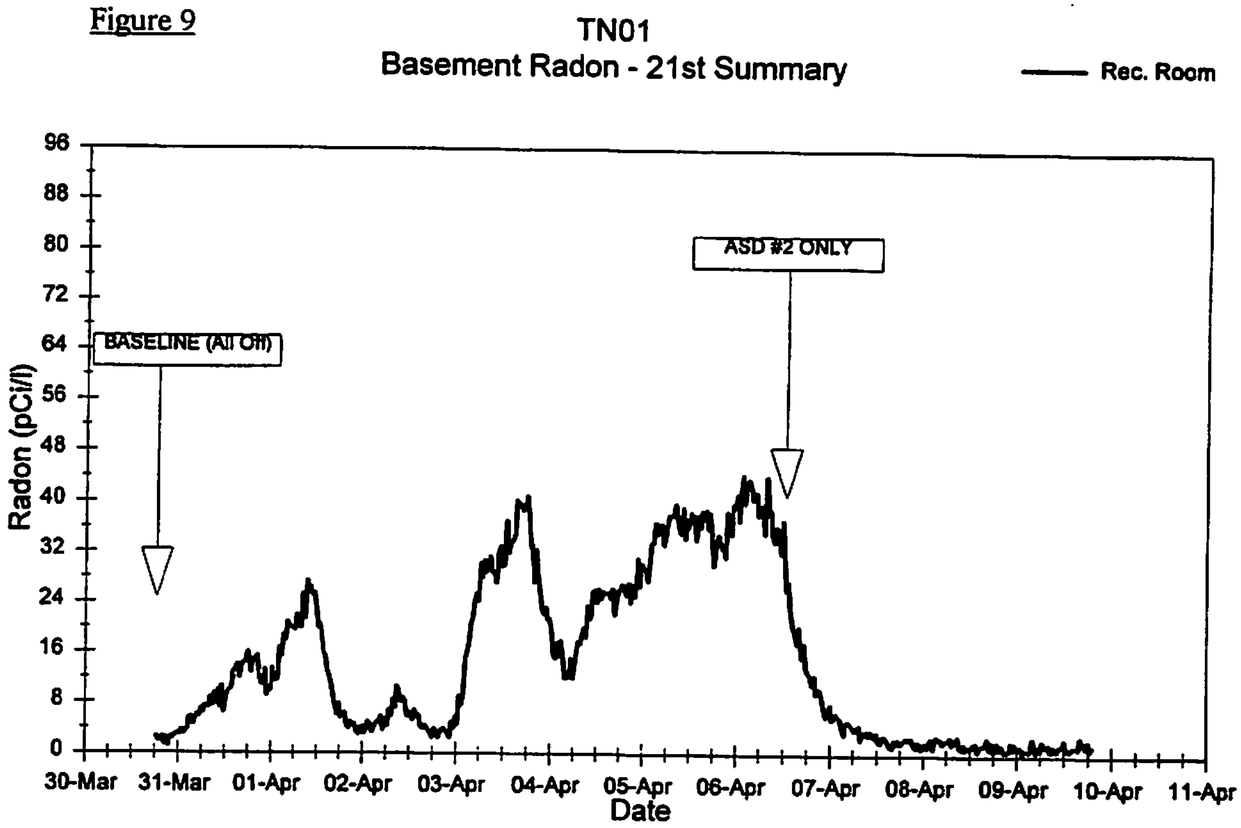


Figure 10

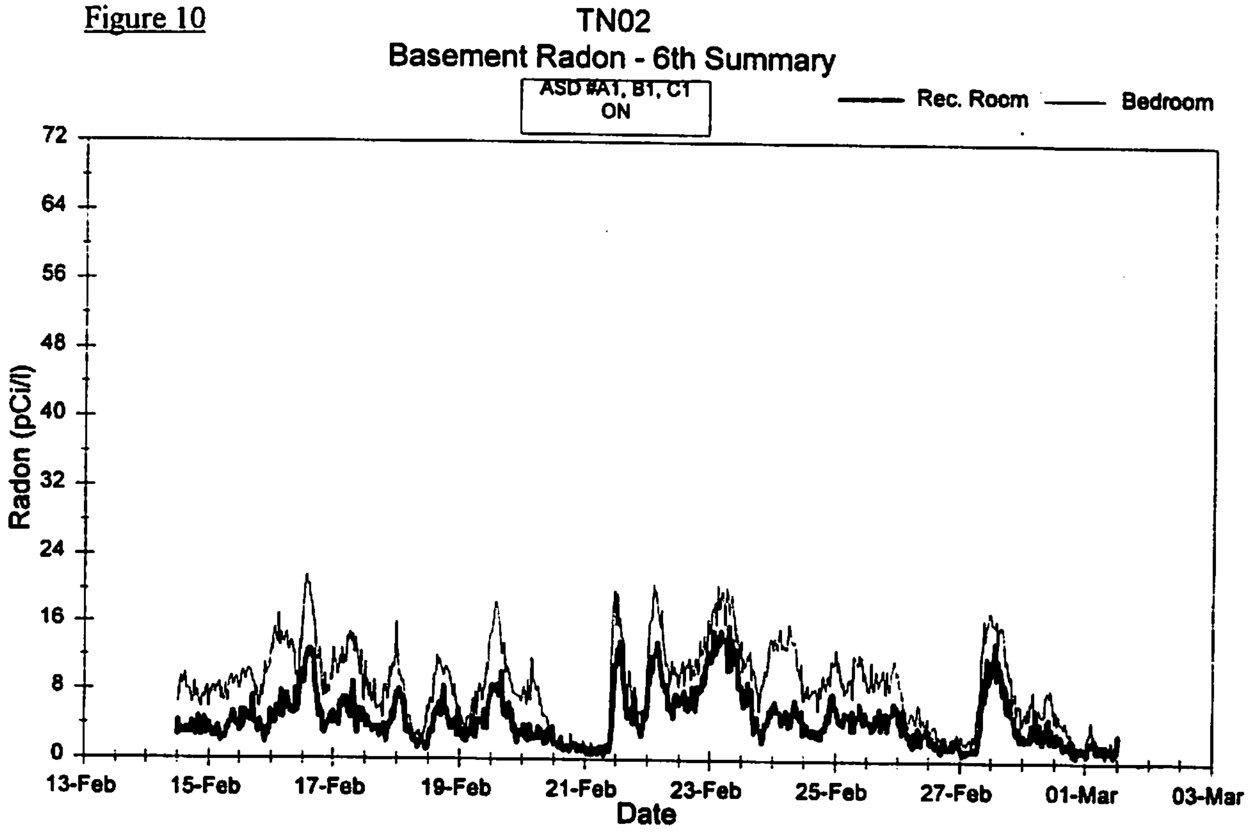


Figure 11

TN02
Basement Radon - 9th & 10th Summary

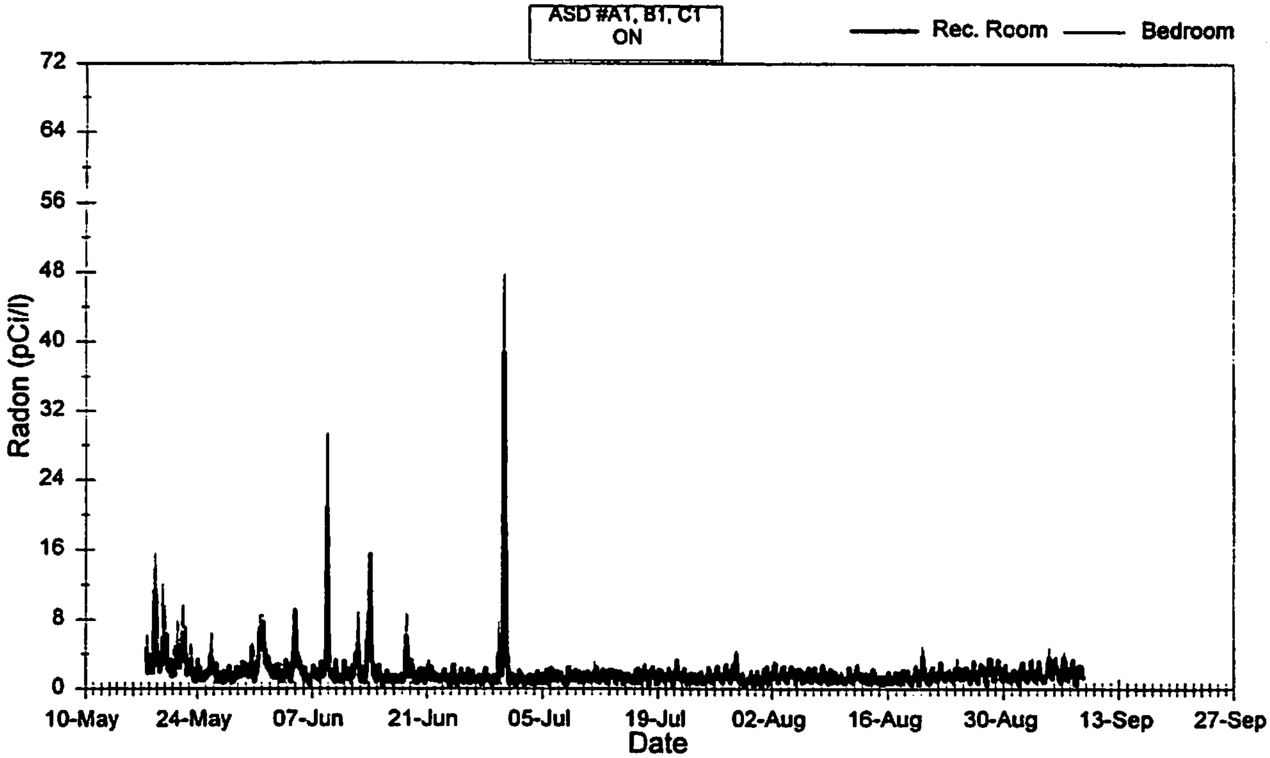


Figure 12

TN02
Basement Radon - 19th Summary

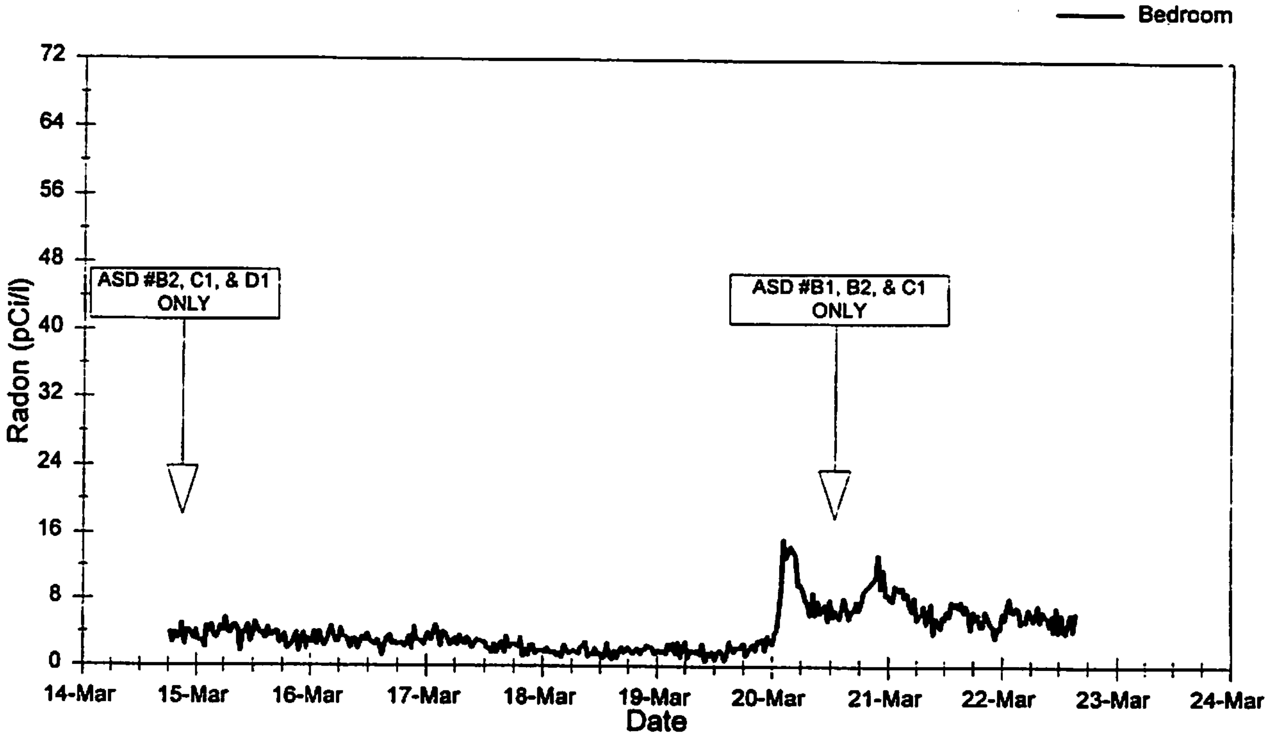


Figure 13

TN02
Basement Radon - 20th Summary

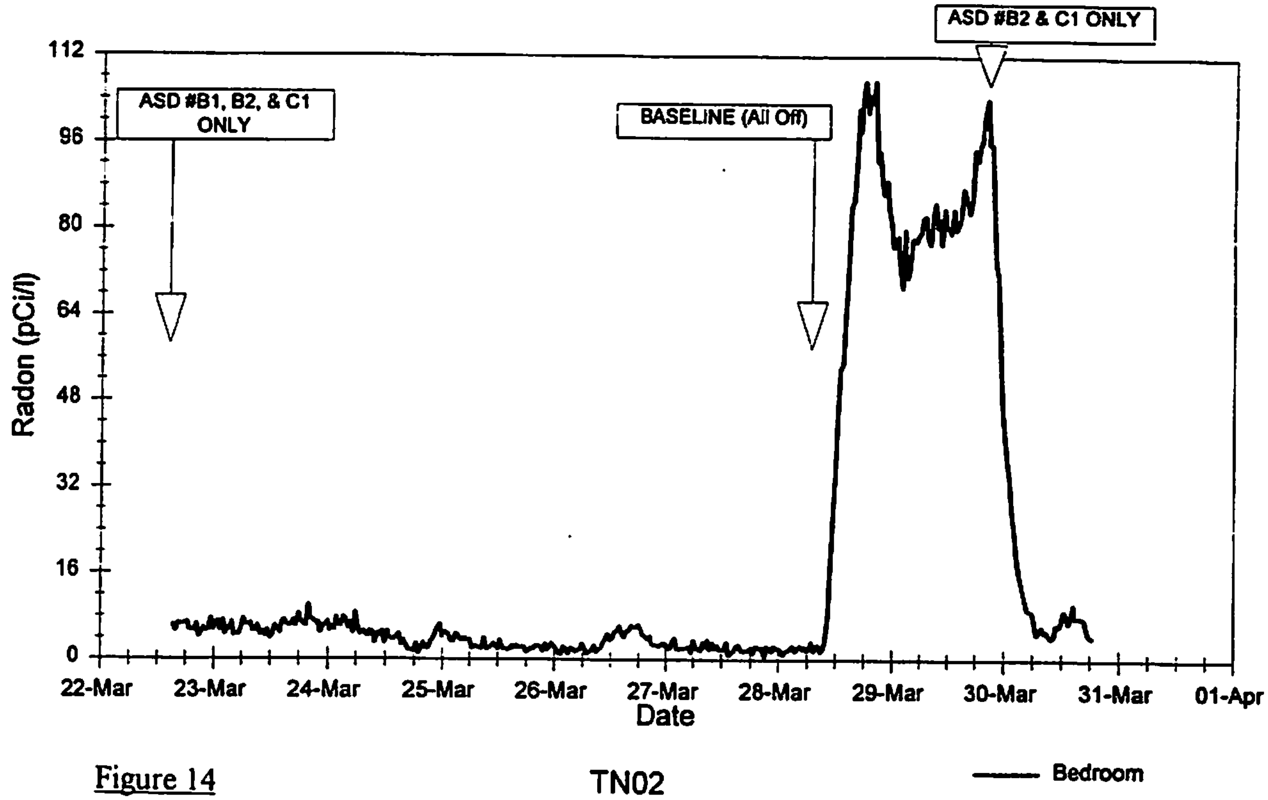


Figure 14

TN02
Basement Radon - 21st Summary

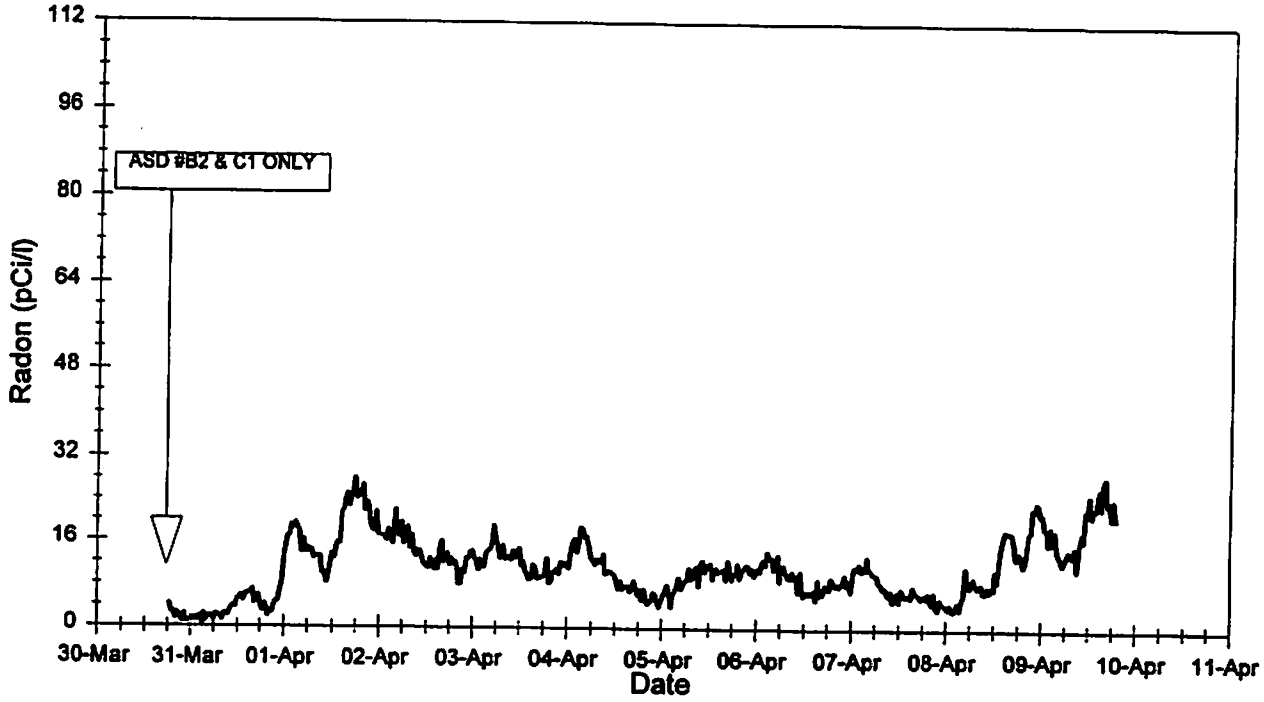


Figure15

TN09
Basement Radon - 6th Summary

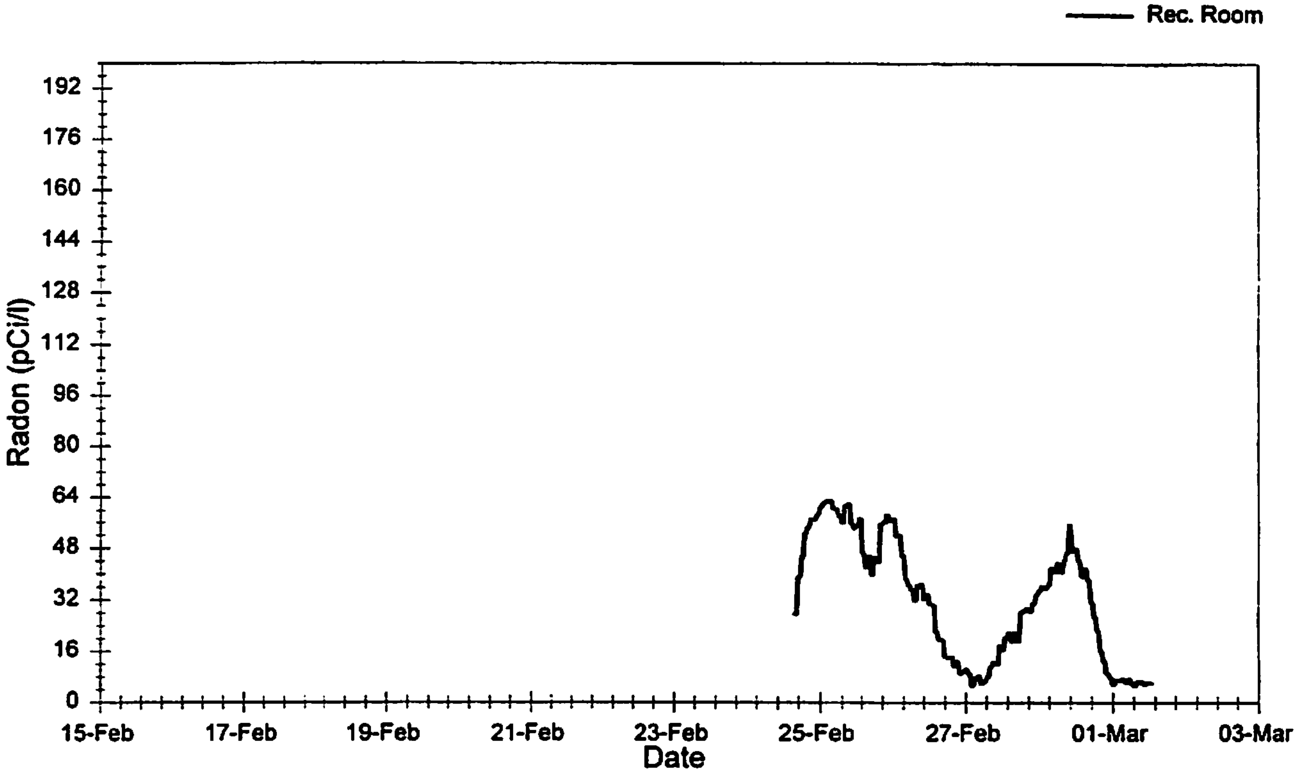


Figure 16

TN09
Basement Radon - 19th Summary

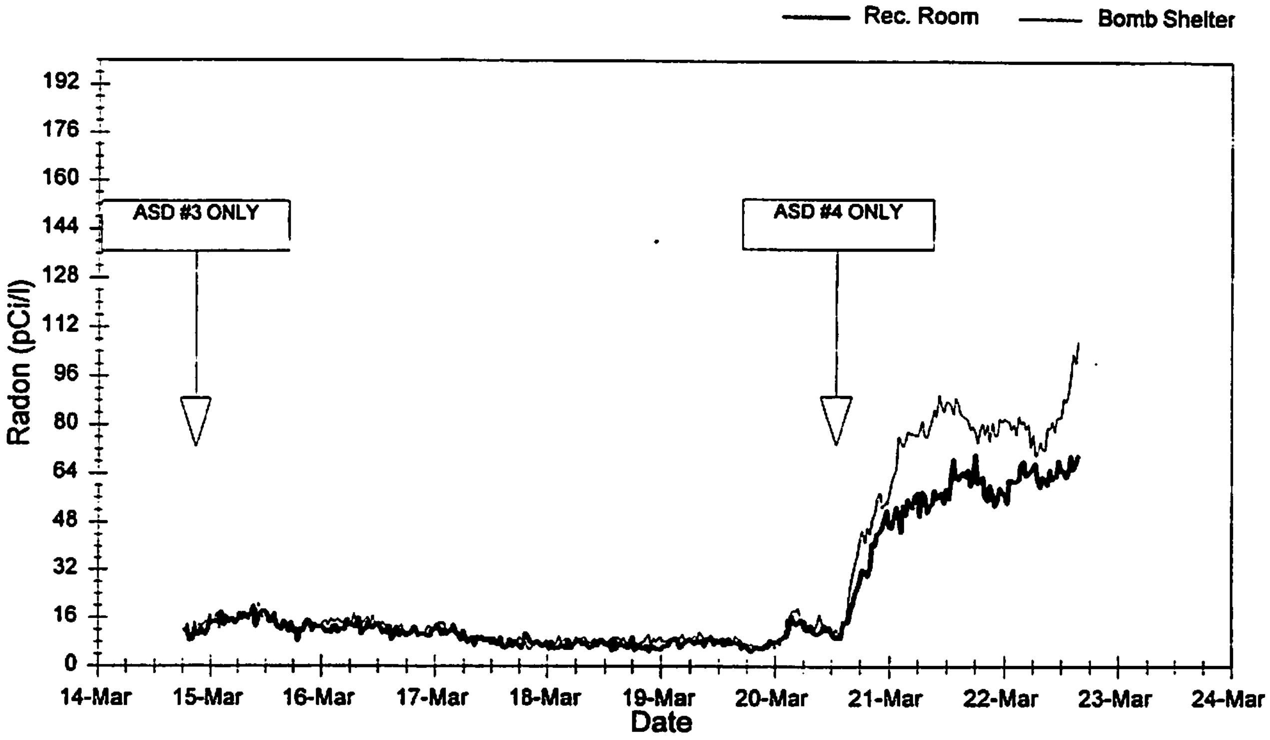


Figure 17

TN09
Basement Radon - 20th Summary

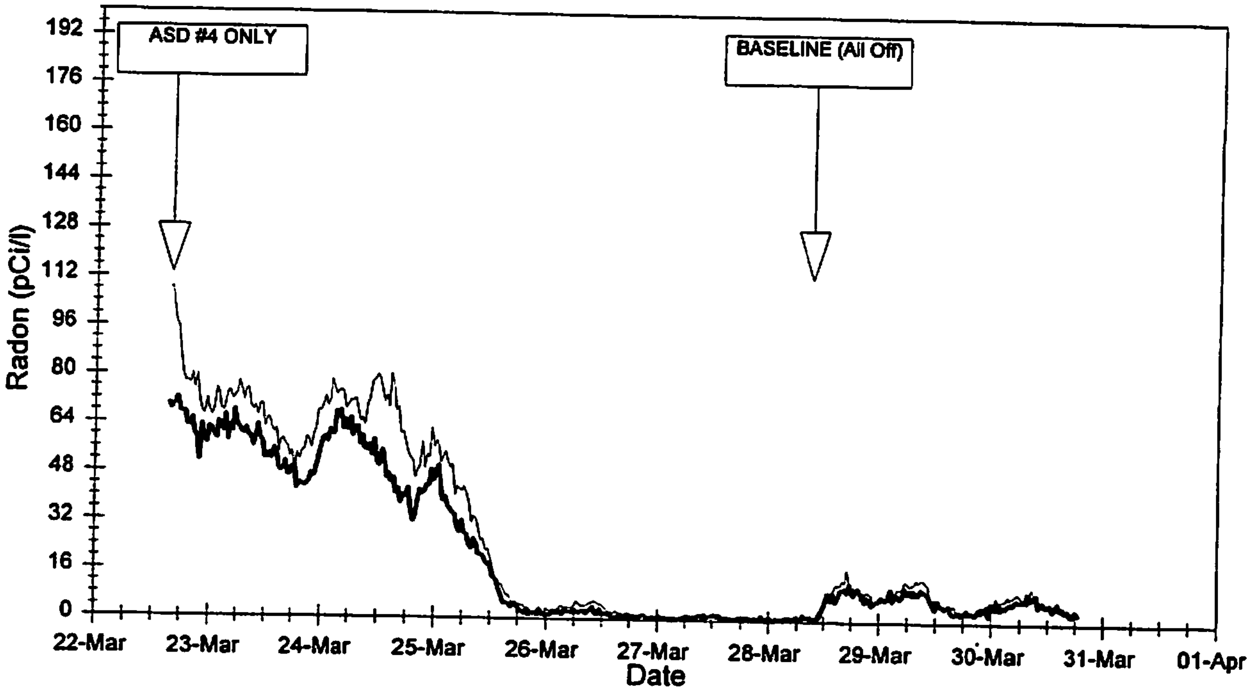


Figure 18

TN09
Basement Radon - 21st Summary

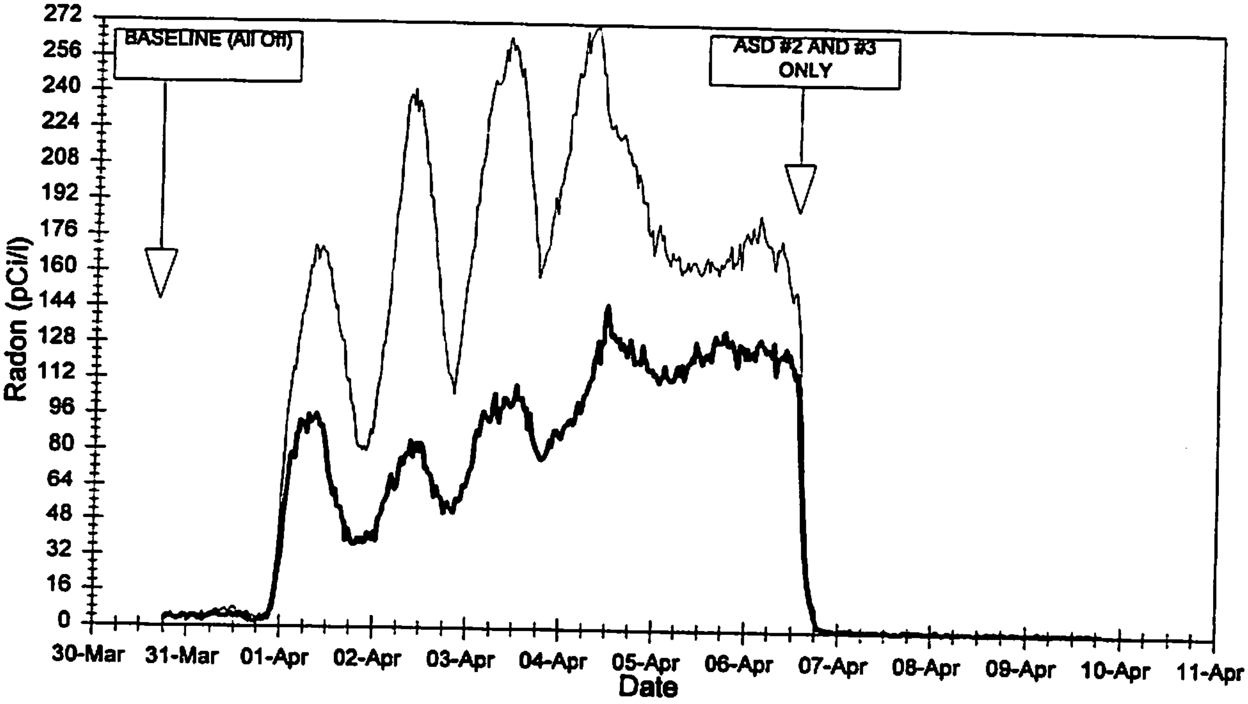


Figure 19

ENVIRONMENTAL DATA (TN01)
Outdoor Temperature - 6th Summary

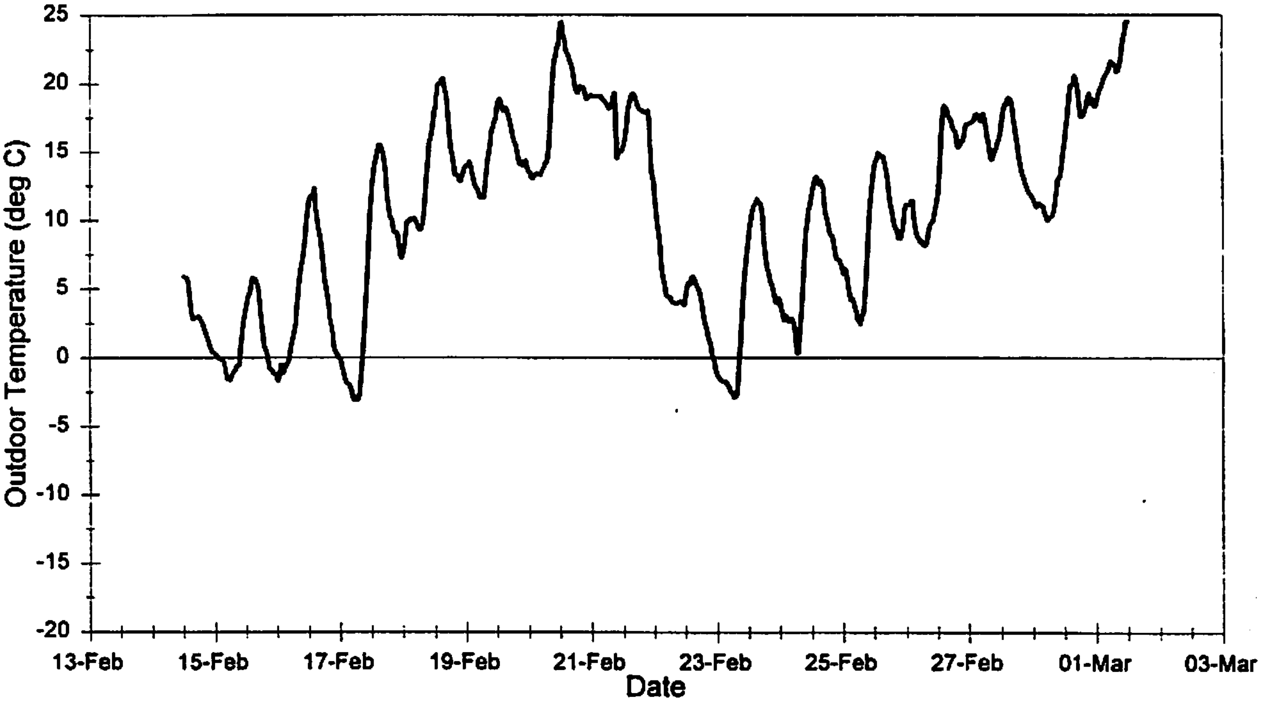


Figure 20

ENVIRONMENTAL DATA (TN01)
Out. Temperature - 9th & 10th Summary

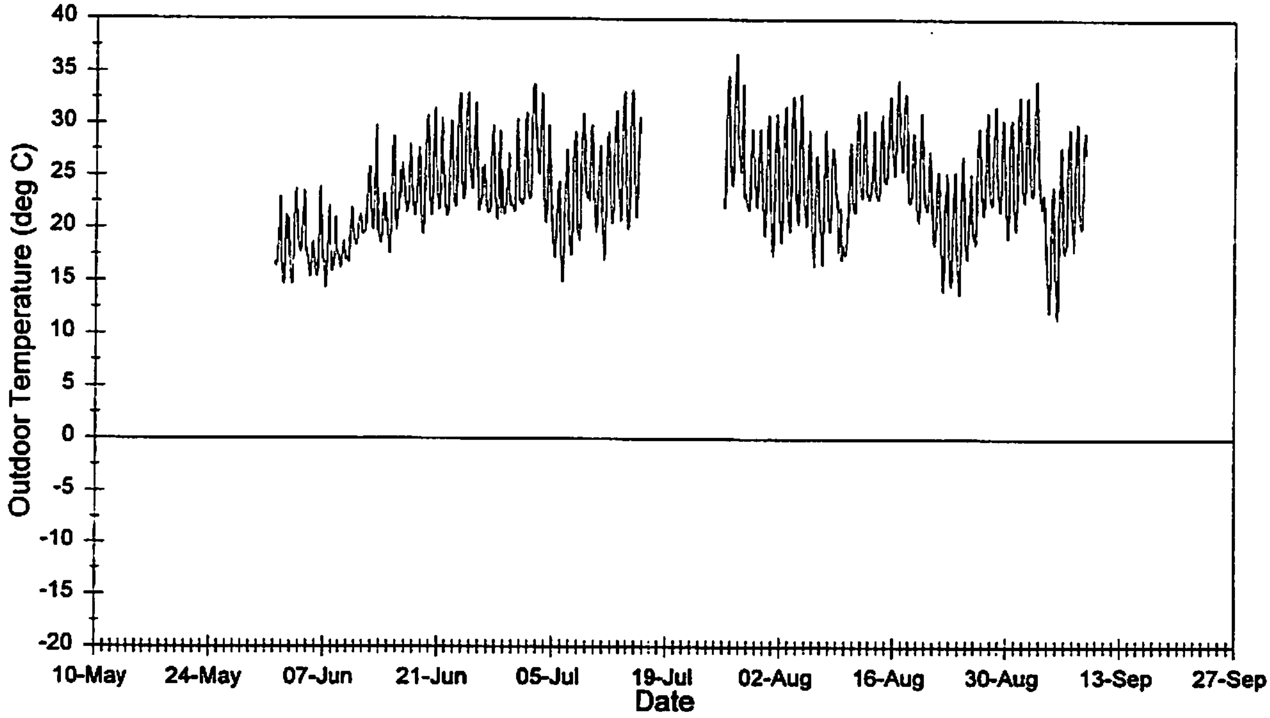


Figure 21

ENVIRONMENTAL DATA (TN01)
Out. Temperature - 19th Summary

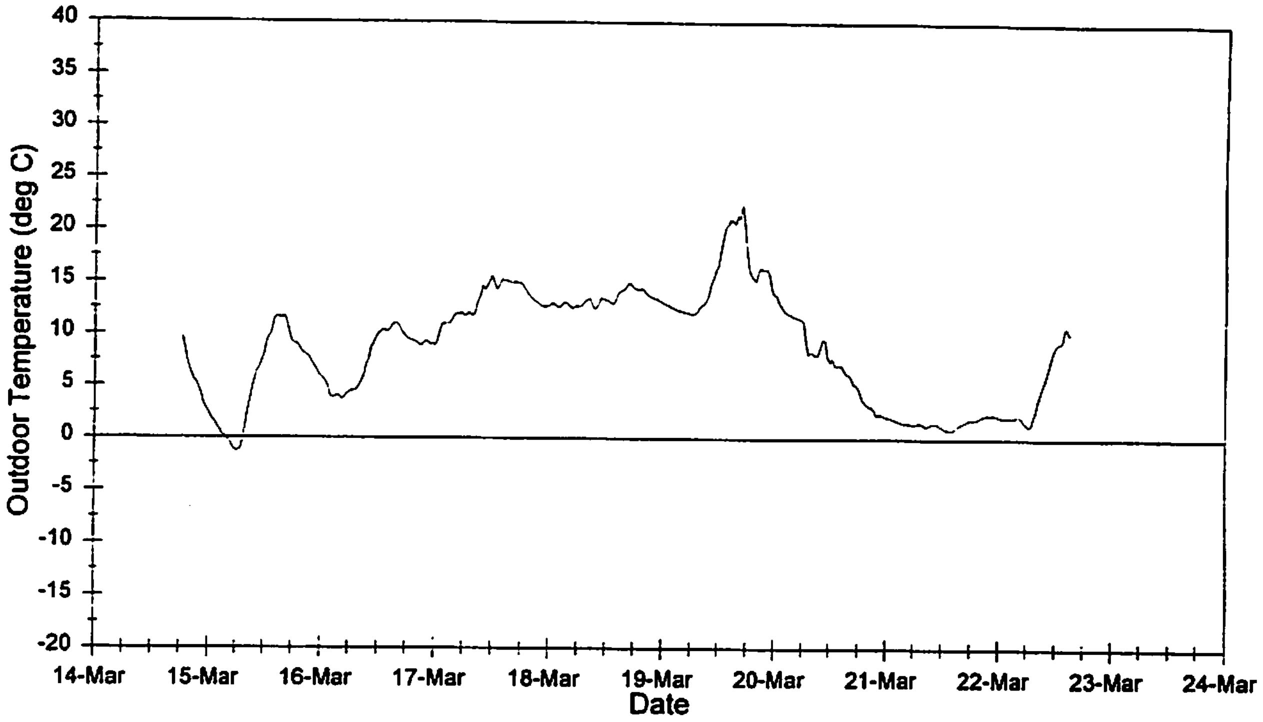


Figure 22

ENVIRONMENTAL DATA (TN01)
Out. Temperature - 20th Summary

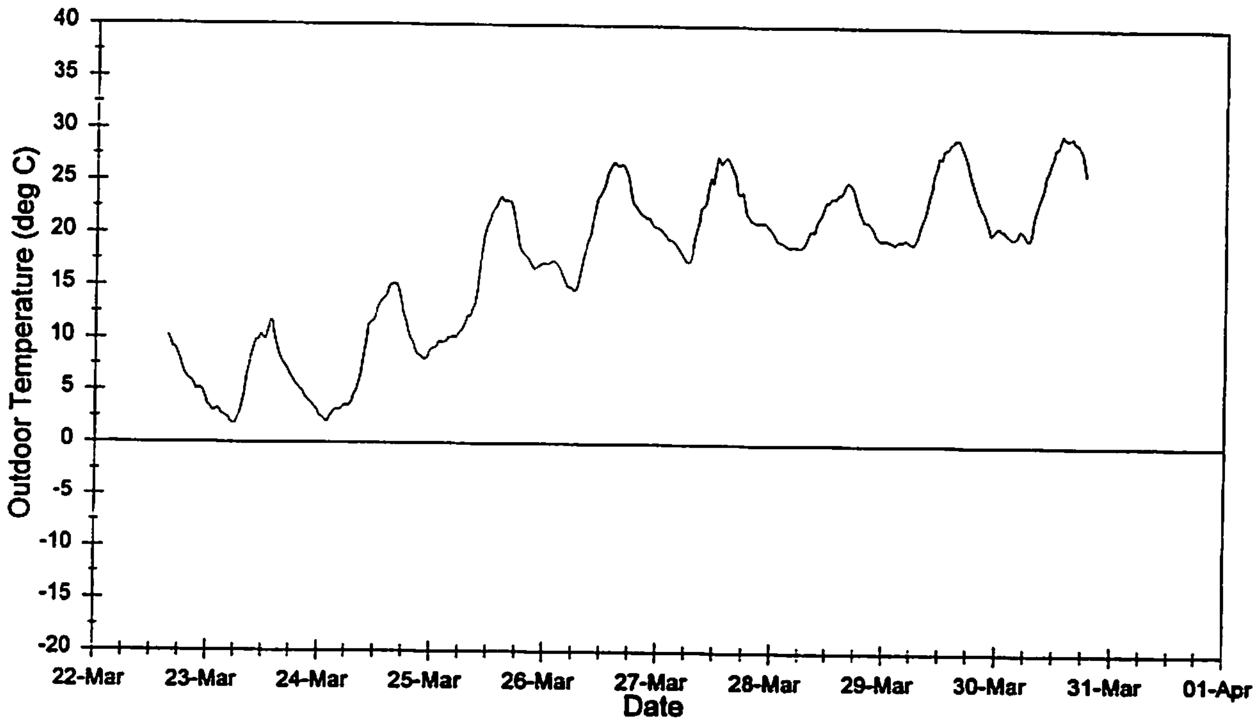


Figure 23

ENVIRONMENTAL DATA (TN01)
Out. Temperature - 21st Summary

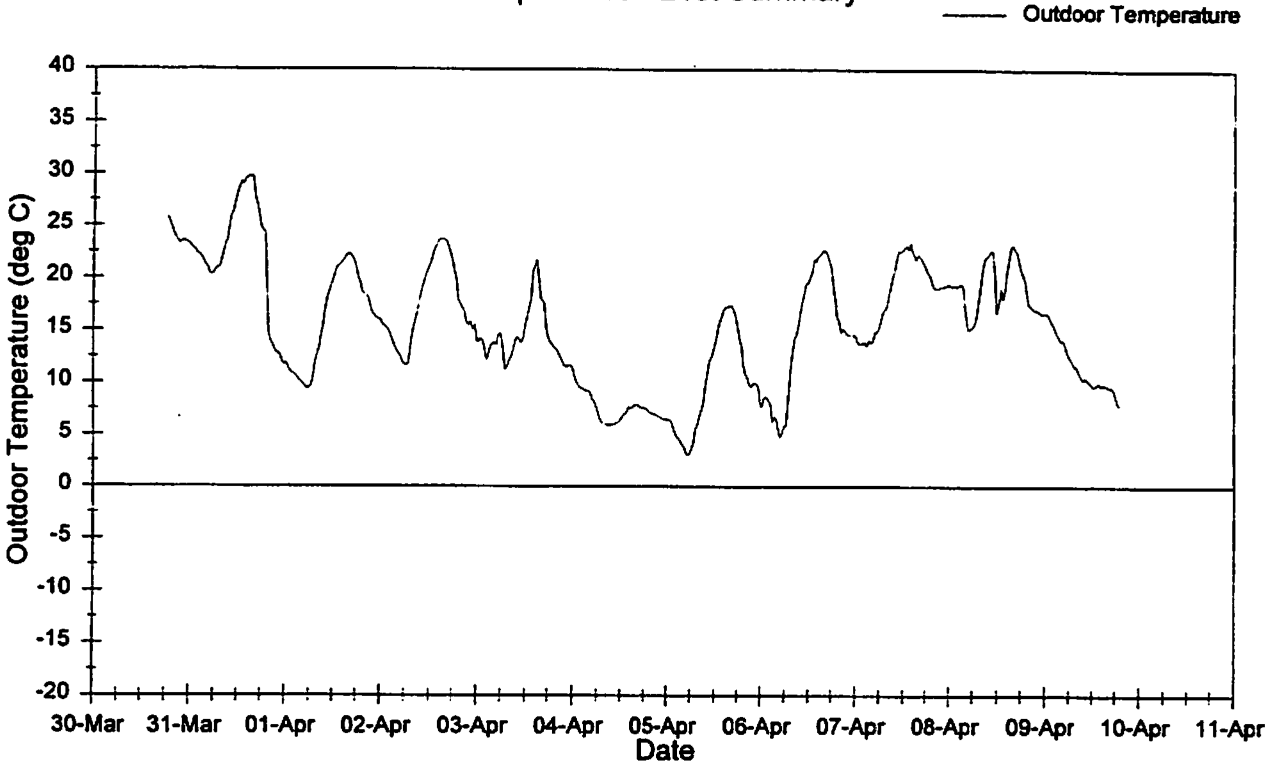


Figure 24

TN01
Basement Radon - 18th Summary

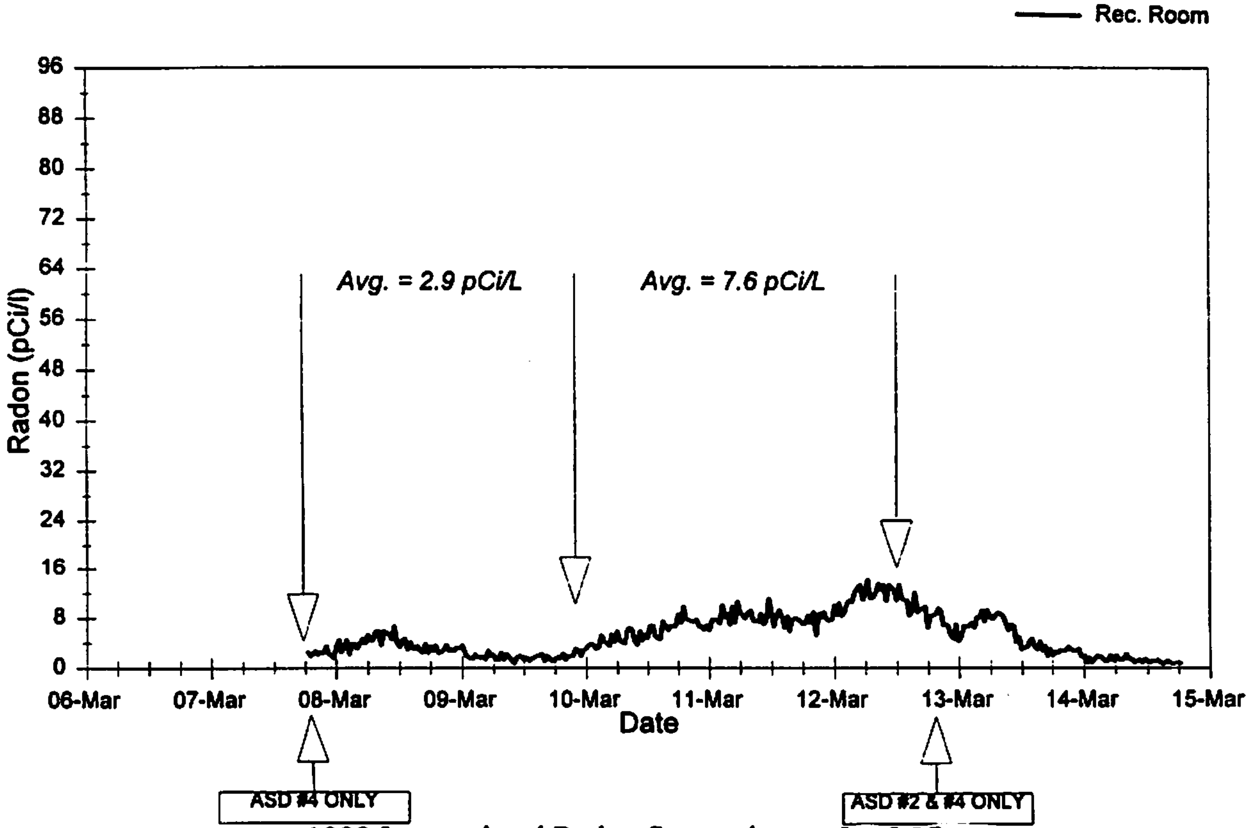


Figure 25

ENVIRONMENTAL DATA (TN01)
Out. Temperature - 18th Summary

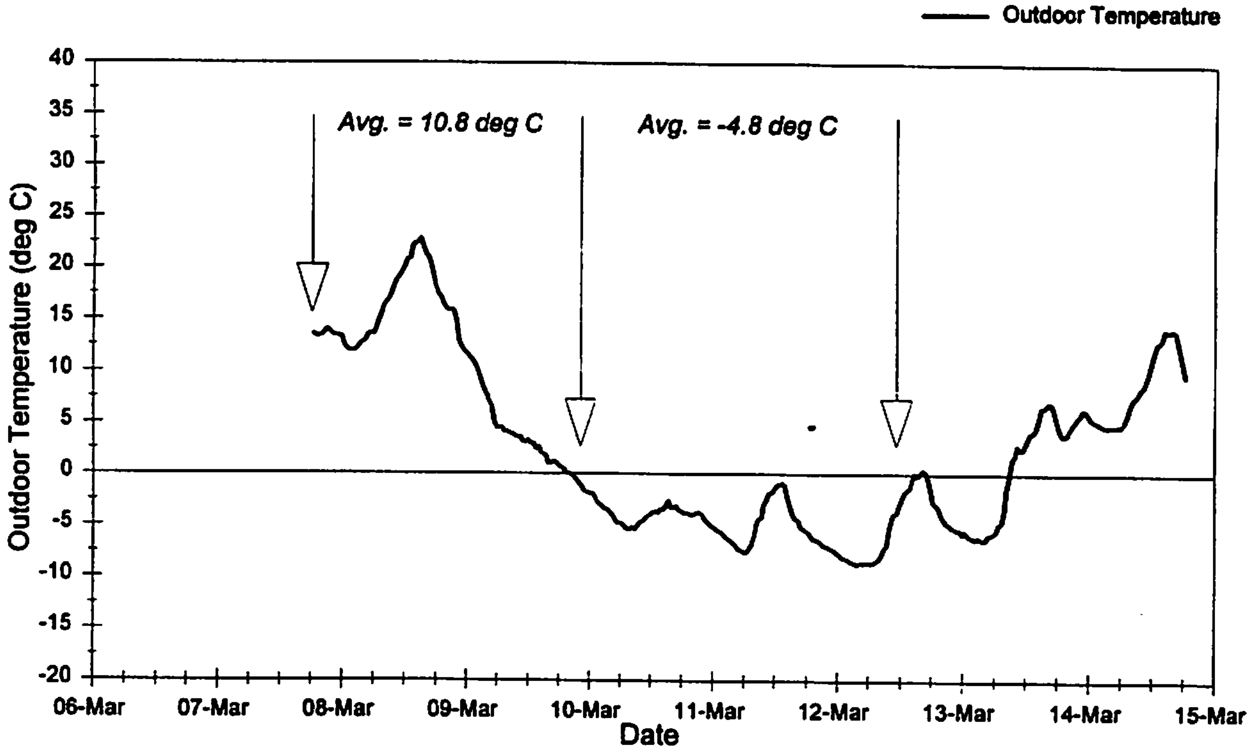


Figure 26

ENVIRONMENTAL DATA (TN01)
Barometric Pressure - 6th Summary

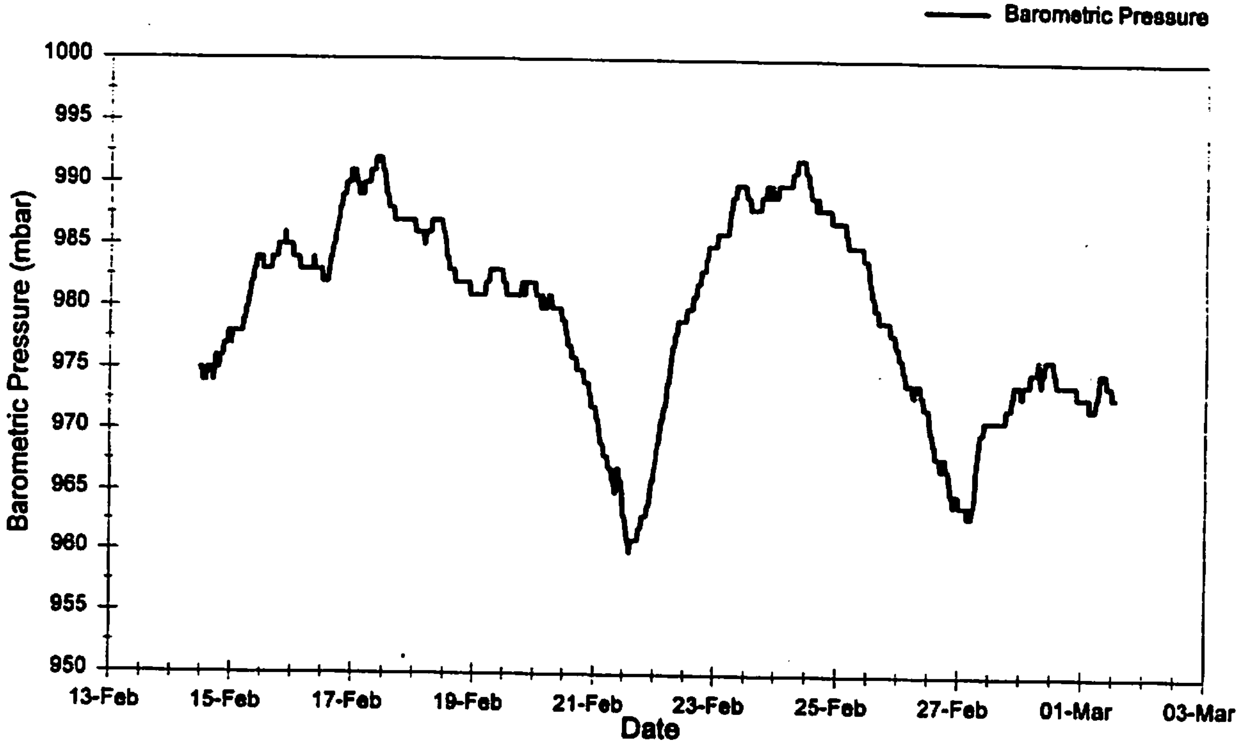
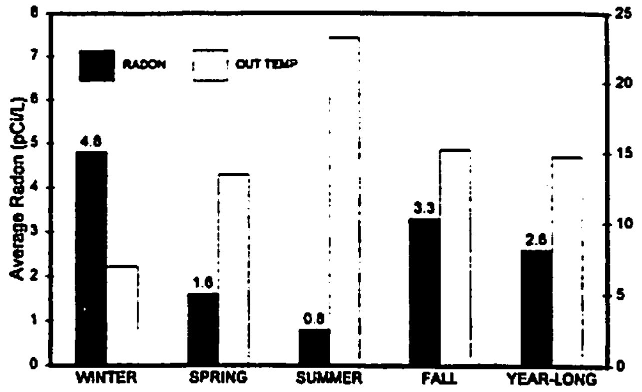
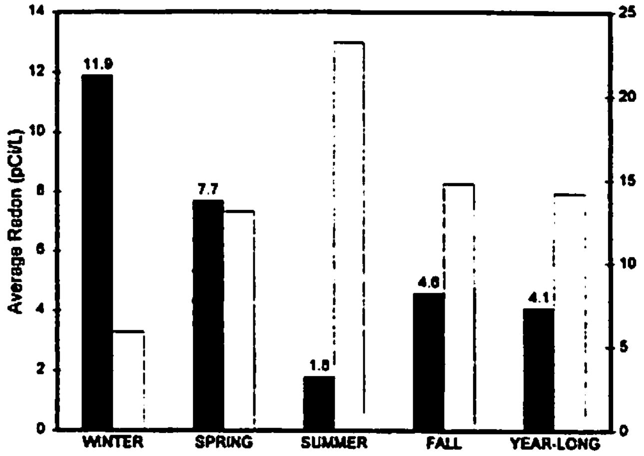


Figure 27

SEASONAL COMPARISON
TN01: Original 1-pipe ASD



TN02: 3-pipe ASD



TN09: Baseline

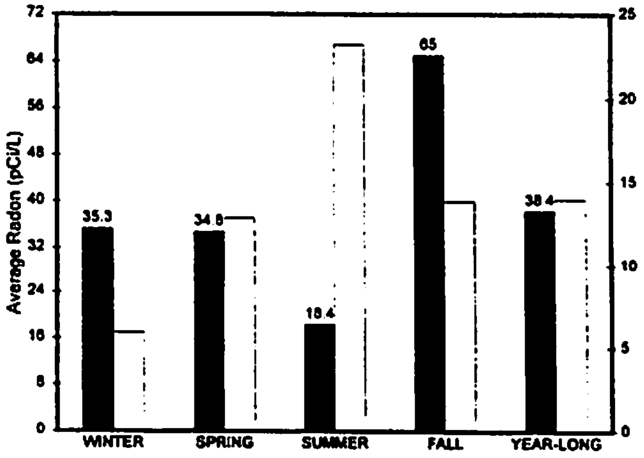


Figure 28