TECHNICAL PUBLICATION NO. 71

Study of Mitigative Techniques in Existing Houses to Control Indoor Radon Exposure in Alachua and Marion Counties in Florida

This research project was sponsored by the
Building Construction Industry Advisory Committee

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School of Building Construction
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1991

STUDY OF MITIGATIVE TECHNIQUES IN EXISTING HOUSES TO CONTROL INDOOR RADON EXPOSURE IN ALACHUA AND MARION COUNTIES IN FLORIDA

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July 12, 1990

This research project was sponsored by the
Building Construction Industry Advisory Committee
under a grant from the State of Florida
Department of Education

EXECUTIVE SUMMARY

The primary purpose of this research project was to investigate the effectiveness of various radon mitigation strategies on atypical, existing Florida homes. This project was conducted in conjunction with the United States Environmental Protection Agency (EPA) funded Radon Mitigation Demonstration Project - Phase II. The research project was designed to look beyond the standard radon mitigation problems found with typical Florida home construction and to provide guidance to the citizens of Florida and its construction industry on radon abatement practice.

Exposure to indoor radon gas has been recognized by EPA as the second most significant health and environmental hazard resulting in lung cancer, smoking being first. EPA has estimated that as many as eight million, or ten percent of the eighty million homes in the United States, presently have elevated levels of radon.

The concern with radon is with its associated health risk; lung cancer. These damaging health effects are not believed to develop immediately, therefore, years may pass before any damage ever becomes evident, if at all.

Radon mitigation is a relatively new issue of concern for the construction industry. In 1988, the Florida Legislature passed legislation which directed the Department of Health and Rehabilitative Services (HRS) to develop and implement a training and certification program for any party conducting radon testing or mitigation. This act has effectively created a new and regulated profession. Building contractors, unless certified, can not lawfully engage in radon mitigation activity. However, a good understanding of the radon problem and those effective solutions that have been developed to date will aid the general construction industry in being more capable in responding to their clients concerns.

The Florida Legislature also, in the 1988 legislative session, directed the Department of Community Affairs (DCA) to develop a radon resistant building code for new construction. The researchers involved in this project performed an instrumental role in conducting the necessary research for the development of the draft code. It is expected that DCA will initiate the code adoption process for this new code some time during the 1990 calendar year.

The four homes discussed in this report were selected from a list of over 300 homes, in Alachua and Marion Counties, having elevated levels of radon. This list was developed through a previous contract with EPA. Following selection, agreements were developed and executed for each homeowner and diagnostic testing was commenced. After the diagnostic testing program had been completed, two homes dropped out of the program. Mitigation plans were developed for the remaining two homes and were successfully implemented. A phased mitigation approach was utilized in order to extend the knowledge of the various mitigation practices employed. The strategies, or techniques, utilized in the successful mitigation of the two homes included; sub-slab depressurization, increased ventilation with heat recovery, and sub-barrier depressurization of crawlspaces.

Case studies have been developed for each of the four houses. The case studies, prepared for the two houses that dropped out of the project, will present and discuss the recommended mitigation plans for informational purposes.

The mitigation techniques utilized in this study are in conformance with the draft building code for new construction developed by the State University System/Radon Advisory Board. Much of the knowledge gained through the research conducted for the SUS/RAB was used to refine and extend the effectiveness of the mitigation systems studied in the project.

Local contractors in both Alachua and Marion counties were invited to participate in the research project, however, only one was actually willing to participate in the submission of bids. This is due in part to the implementation of the State's regulation of this activity through HRS's certification program. This certification requirement has effectively eliminated the homebuilding industry from participating in the designing and installing radon mitigation systems.

A copy of this report may be obtained by contacting the Executive Secretary, Building Construction Industry Advisory Committee at the following address:

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ACKNOWLEDGEMENTS

This research effort was conducted by specialists representing many different agencies, both public and private, from around the United States. The cooperative pooling of knowledge and resources resulted in the State of Florida taking an aggressive posture towards effectively dealing with a public health concern. The willingness of federal, state and private agencies to contribute and participate in the development of an extensive radon mitigation research program has resulted in the development and testing of numerous approaches to effectively control indoor radon.

The researchers wish to thank the Building Construction Industry Advisory Committee for funding this study. This investment has yielded to date approximately 30 times its dollar value in additional funded research. Special thanks are given to Dr. Brisbane H. Brown, Jr., Executive Secretary, and Ms. Patty Wood for their many hours of guidance and assistance in the development of this project.

The United States Environmental Protection Agency's Air and Energy Engineering Research Laboratory contributed many hours of consultation, diagnostic and analysis time. Appreciation is expressed to Mr. A.B. (Chick) Craig, Mr. David Sanchez, Mr. Bruce Harris, Mr. Michael Osborne and Mr. Ron Mosley.

Major contributions were made by the following personnel during the initial diagnostic phase of the research program. Thanks are extended to Dr. Ashley Williamson, Dr. Charles Fowler and Dr. Bobby Pyle from the Southern Research Institute, Birmingham, Alabama and to Mr. Ken Gadsby, Princeton University Center for Energy and Environmental Studies.

Several students made significant contributions during the course of the research project and deserve special recognition; Ms. Pamela Guevarra, Mr. Donald Dollar, Mr. Tim Thomas, Mr. Tim Kelly and Mr. Frank Roessler.

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INTRODUCTION

FOREWORD

Exposure to radon gas in residential homes is now recognized as a significant health and environmental hazard (PD8, 1988). As more and more investigations of this hazard are being conducted throughout the country, people are beginning to realize the seriousness of this problem. The United States Environmental Protection Agency has speculated that as many as eight million, or ten percent of the eighty million homes in the United States presently have elevated levels of radon (T1, 1986). As a result of their investigations and studies, the radon issue is starting to get the attention it has long deserved by homeowners, environmentalists, and legislative bodies.

The major concerns about radon are the health risks associated with it. Recently, the United States Environmental Protection Agency (EPA) has named radon to be the number one cause of lung cancer in non-smoking lung cancer victims (N1, 1988). Adverse health effects from the exposure to radon may not develop immediately, if at all, and it may be years before these effects ever become evident.

Radon mitigation is a relatively new issue for the construction industry. It consists of detecting the radon, controlling its infiltration and reducing concentrations by installing radon mitigation systems. Consequently, many contractors have been in this particular field for a very short time resulting in significant variations in experience. As of yet, no organization certifies mitigation contractors on a national basis as being qualified or experienced, however, some states have or are developing contractor certification programs. Thus, the responsibility for evaluating candidate contractors presently falls on the homeowner (PD5, 1988).

Radon is a colorless, odorless, tasteless, radioactive gas that is produced by radioactive decay from uranium in the Earth's crust. Radioactive decay is the disintegration of the nucleus of atoms in a radioactive element. This disintegration takes place through the emission of charged particles, and as these particles are released, new elements are formed. The radioactive decay chain for radon starts with uranium, which through a series of elements, produces radium, which in turn ultimately produces radon, a chemically inert gas. (PD8, 1988)

As radon is formed it begins to migrate to the Earth's surface. If it emerges under a house, it may seep through the foundation, become trapped inside, and accumulate to potentially elevated levels. An elevated level, according to the EPA, is defined as being at or above 4 pico curies per liter (pCi/l) or 0.02 Working Level (WL), (PD4, 1987).

Methods of detection to determine whether a structure has elevated levels of the gas are categorized as either "passive" methods or "active" methods.

"Passive" methods are simple and relatively inexpensive for homeowners to use themselves. These methods also have the advantage of providing averaged or integrated measurements over a period of time, and thus provide a meaningful measure of the concentration to which homeowners are exposed. "Active" methods require an experienced sampling team to visit the house with specialized equipment. These measurements are relatively expensive and are less commonly used for initial radon measurements in a house. However, their most beneficial applications are in pre-mitigation diagnostic testing, and in evaluation of the performance of installed radon mitigation systems.

If a house does contain elevated levels of radon, a number of mitigation systems can be considered for reducing and/or preventing radon contamination. The mitigative approaches consist of one or more approaches. One strategy is aimed at preventing the radon from entering the house, and another is aimed at removing radon or its decay products after entry (PD5 1988).

Radon mitigation systems are also dependent upon the particular construction characteristics of the type of substructure. Typical Florida substructure types are monolithic slab, floating slab, slab-in-stemwall, and wood floor with crawlspace. However, houses with basements and any combination of these types are also found. The design and effectiveness of the mitigative techniques will vary greatly upon the unique characteristics of each substructure type, level of radon, routes of entry, and the effectiveness of the mitigation plan.

Once a technique or a combination of techniques has been installed, it is important to follow-up with post-mitigation diagnostic testing in order to determine the effectiveness of the mitigation plan. If the radon levels are subsequently found to be unsatisfactory, alternative mitigative techniques may have to be examined and implemented. The post-mitigation measurements should attempt to duplicate in every aspect the pre-mitigation measurement process so as to eliminate any factors or variables which may distort the results of the post-mitigation tests.

SCOPE AND GOALS OF RESEARCH PROJECT

The Public Health Service and the U.S. Environmental Protection Agency recently advised all homeowners and renters, in light of new findings showing high concentrations in seven states, to test their homes for dangerous levels of radon gas (N1, 1988). As a result of this recommendation, the scope of this report shall examine a case study of a typical Florida residence by providing the necessary background information on radon as a basis for examining the causes and solutions of radon contamination.

Because many homeowners already face the problem of radon migrating into their home, the emphasis of this report is to educate the homeowner on all essential characteristics of radon and to introduce mitigation methods to facilitate its removal and/or minimize its entry.

Below is the basic information needed to produce an informed homeowner:

- What is radon and where does it come from?
- How does it enter a home?
- What are the health risks?
- How do different types of construction affect radon entry?
- How is radon detected and what kind of tests and equipment are required?

Following a discussion of these issues, this report shall examine a case study of a typical Florida residence. This case study should assist the homeowner in developing a mitigation plan for their home. It should be noted that this mitigation plan is representative of a specific type of construction. The scope of this case study will consist of the following:

- House characterization
- Identification of entry routes
- Pre-mitigation monitoring
- Diagnostic process and test results
- Proposed mitigation plan
- Alternative mitigative techniques

It is the goal of this report to establish a comprehensive analysis of the radon problem in a typical home that will be aimed toward educating homeowners and/or contractors. To accomplish this goal, this report shall diagnose and evaluate the case study home based on the findings of the University of Florida School of Building Construction's Study of Mitigative Techniques in Existing Houses to Control Indoor Radon Exposure in Alachua and Marion Counties in Florida. Future related studies are being planned with the U.S. Environmental Protection Agency in conjunction with the University of Florida and will be utilized as information becomes available.

CHAPTER 2

RADON

WHAT IS IT?

Radon is a colorless, odorless, tasteless, radioactive gas that occurs naturally in most soils and rocks. It is a noble gas, which means it is inert or very stable chemically and, therefore, does not react with other elements (O1, 1982). By being a noble gas, it can travel relatively freely through most materials.

WHERE DOES IT COME FROM?

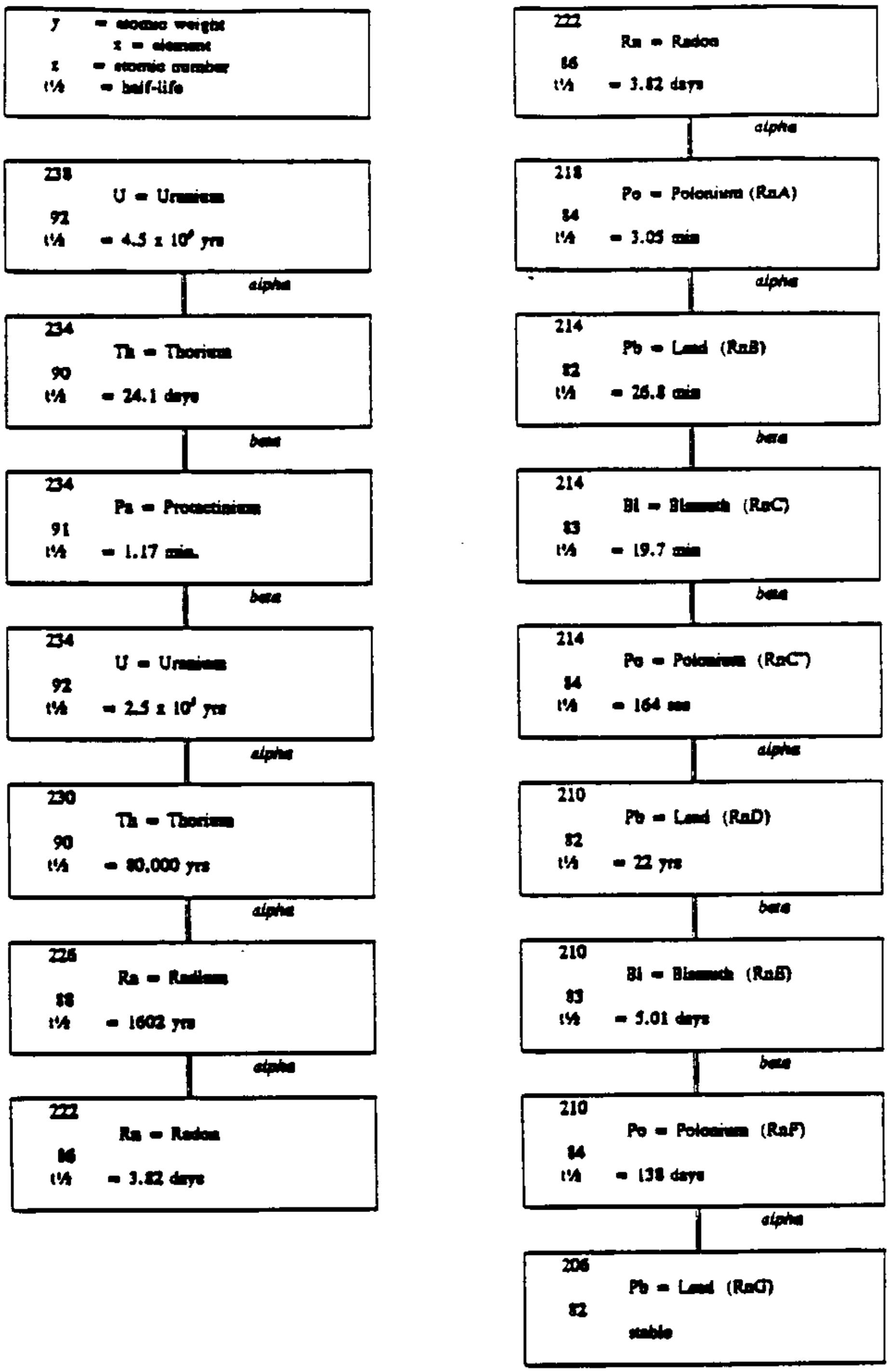
Radon is produced by the radioactive decay (natural breakdown) of uranium-238 (PD2, 1986). Uranium itself can be found in varying amounts in almost all soils and rocks within the Earth's crust. Of particular concern for Florida homeowners is the high level of uranium present in Florida's phosphate enriched soils (PD1, 1979). Some of these highly mineralized soils are being mined, primarily in Central and Southcentral Florida. Uranium, however, is not the primary problem. It is several of uranium's radioactive decay products that produce high levels of indoor radiation sufficient to prompt concern.

The basic elements associated with the natural decay of uranium-238 are radium-226, radon-222 (radon gas), and the decay products of radon gas, commonly referred to as "radon daughters" or "radon progeny." More specifically, uranium-238 is the parent of radium-226, radium-226 is the parent of radon-222 (radon gas), and radon gas is the parent of the radon daughter chain.

The uranium-238 decay chain extends from uranium-238 to lead-206. At each point in the chain, radioactive particles and/or electromagnetic radiation are released, resulting in a new element being created. This process continues until the original parent uranium-238 has decayed to a stable isotope of lead, lead-206 (See Figure 1).

The atom consists of a nucleus, which is made of protons and neutrons, and electrons which orbit the nucleus. Since certain types of nuclei are unstable by nature, they attempt to achieve stability by altering the nuclear structure. When this nuclear alteration occurs various types of radiation are emitted. The three types of radiation resulting from this radioactive decay process are gamma, beta, and alpha energies.

Gamma rays are high frequency electromagnetic radiation which displace more energy than beta or alpha radiation. These rays have a strong penetrating power similar to man-made x-rays (PD7, 1986). It is because of this relatively high penetrating power, that the rays can travel deeper into objects than beta or alpha particles. This higher energy level allows these rays to pass through the human body.



RADON DECAY CHAIN

(T1, 1986)

FIGURE 1

Beta radiation is a very small energized particle discharged from the nucleus of a radioactive atom. These particles have medium penetrating power, and can penetrate up to approximately 0.5 inches of surface tissue. This type of radiation is much easier to shield than a gamma ray.

Alpha radiation is a particle greater in size than a beta particle. Alpha radiation occurs when alpha particles are discharged from the nucleus of atoms during radioactive decay. These particles are low in penetrating power, and are stopped by the first layer of skin. However, these large particles deposit energy quickly, and present a greater risk of damaging tissue cells while passing through them. As a result, alpha radiation produces the greatest risk to lung tissue of the three types of radiation ingested into the lungs.

The number "222" in "radon-222" is the atomic weight of the element. The atomic weight is the sum of the protons and neutrons in the nucleus. The number of protons, which determines the makeup of an element, is called the atomic number. For example, during radioactive decay, radon-222 loses two of its 86 protons and two of its 136 neutrons to become polonium-218.

Each of these radioactive elements has a different "half-life." The term "half-life" is the time required for half of the atoms to decay into the next element in the decay chain. For instance, radon gas has a half-life of 3.8 days. This half-life is sufficiently long that a percentage of the radon produced below ground will be mobile long enough to reach the surface of the ground and possibly enter a home.

At room temperature all elements in the uranium-238 decay chain are solids except for radon-222, which is a gas. In order to become an indoor health threat, a radon atom must first escape from the rock or soil in which its immediate parent (radium-226) is embedded. The atom must then be transported through the voids between the rock or soil particles until it reaches the surface of the ground. Radon is found in trace amounts in "soil gas" (PD5, 1988). This is a composite gas which continuously moves through the soil, and contains other major components such as nitrogen, oxygen, carbon dioxide, and other trace elements. The movement of soil gas through the soil matrix is a function of changing pressures. As atmospheric pressure changes in relation to the soil gas pressure movement of the soil gas will follow the basic laws of fluid dynamics. That is, fluids and gases flow from areas of high pressure to areas of low pressure. This aspect of the radon phenomenon is of great importance since buildings can generate negative pressure conditions relative to the soil gas pressure.

Radon gas produced from rock and soil particles can also pass through underground aquifers which may supply water for municipal and/or private wells. Since radon is somewhat soluble in water, significant amounts can accumulate in these underground aquifers and be transported into buildings. The radon can then be released when the water is used, especially when aerated through showering or mechanical dishwashing. However, despite this contribution to airborne radon concentrations, soil gas entry into the home poses a far more significant source of indoor radon than does water usage. Although some levels of radon have been measured in Florida ground water the levels are not felt to be of significant concern.

To further understand the effects of radon gas and its process of radioactive decay, basic units of measure must be defined. The primary measurement for all naturally occurring radiation is the Curie. It was named after Madame Curie for discovering radiation quantities while working with radium (PD7, 1986). Her research found that a given quantity of radium decayed at a given rate. Thus, defining a Curie as "that quantity of radioactive material having associated with it 3.7×10^{10} disintegrations per second (DPS), or 2.22×10^{8} disintegrations per minute (dpm)" (PD7, 1986). Figure 2 provides a comprehensive table for the various units of measure commonly used.

HOW DOES RADON AFFECT US AND WHAT ARE THE RISKS?

The only known health risk associated with exposure to radon and its decay products is an increased chance of developing lung cancer. The American Lung Cancer Society estimated that about 130,000 people would die of lung cancer in 1986 (PD2, 1986). Of this estimate, the Surgeon General and the EPA cite that approximately 5000 to 20,000 lung cancer deaths could be attributed to exposure from elevated levels of radon (N2, 1988). An elevated level is defined as being at or above the EPA suggested guidelines of 4 pCi/l or 0.02 WL for average annual indoor radon concentrations.

Not everyone exposed to elevated levels of radon will ultimately develop lung cancer. The cancer risk associated with exposure to radon gas depends upon both the airborne radon concentration and exposure duration. Exposure from slightly elevated radon levels over extended durations may result in an increase in the chance of developing lung cancer as compared with exposure from a high radon level for a short period of time. Medical studies have shown that

UNIT	DEFINITION
pico-Curie per (pCi/l)	A common unit of measurement of the liter concentration of radioactivity in a gas. pico-Curie is one trillionth or 10^{-12} of Curie or 0.037 dps in every liter of air.
Working Level (WL)	Any combination of radon daughters in one liter of air that will ultimately release .3 x 10^{5} MeV of alpha energy during its decay to Lead-210.
Working Level Month (WLM)	One WLM corresponds to 1.0 WL for a duration of 170 hours, or the number of working hours in one month.
Million electron Volt (MeV)	An electron volt is energy emitted from radiation. Since the electron volt is an extremely small unit, the energy associated with radiation is expressed in millionths for practical purposes.
Microrem per (μrem or μR)	A unit of measure of "dose quivalence", which hour reflects the rate of health risk resulting from a given absorbed dose of radiation. A microrem (μrem) is one millionth or 10^{-6} of a rem (roentgen equivalent man).

COMMON RADIATION UNITS OF MEASURE

FIGURE 2

the body's ability to repair damage to tissues is very effective when the damage causing agent (radon) is not a continuing problem. Nevertheless, the greater the exposure to radon, the greater the chances are for developing lung cancer.

The U.S. EPA has formulated a Radon Risk Evaluation Chart to help individuals estimate their risk to radon exposure (see Figure 3). The figures assume a person spends 75% of his time indoors over a lifetime of seventy years at a fifty percent equilibrium. Equilibrium is defined as the total concentration of radon daughters (decay products) present divided by the concentration that would exist if the daughters were in radioactive equilibrium with the radon gas concentration which is present. At equilibrium (i.e., an equilibrium ratio of 1.0), one WL of radon daughters would be present when the radon concentration was 100 pCi/l. In general, equilibrium does not occur in homes because ventilation removes both radon and its daughters. A commonly assumed equilibrium ratio is 0.5, which corresponds to 200 pCi/l (PD5, 1988).

The values from the EPA Radon Risk Evaluation Chart for determining the lung cancer risk associated with long-term exposure to radon have been based on animal studies and on health studies conducted on uranium miners. The animal studies were implemented since the results can show possible effects on mammal tissues and organs, which are similar to those found in humans without directly exposing humans to the potential dangers of radon. This scientific research using dogs, mice, and rats has shown a definite connection between lung cancer and exposure to radon and its short-lived decay products (PD8, 1987).

pCi/l	WL	Estimated Number of lung cancer deaths due to radon (out of 1000 people)	Comparable Exposure Levels		Comparable Risk
				>	More than
200	1	440 - 770	1000 times		60 times
			average	<	non-smoker
			outdoor		risk
			level		
100	0.5	270 - 630		>	4 pack-a-day
			100 times		smoker
			average	<	
			indoor		20,000
40	0.2	12 - 380	level	>	chest x-rays
					per year
20	.1	60 - 120	100 times	>	2 pack-a-day
			average		smoker
			outdoor	<	
			level	>	1 pack-a-day
10	0.05	30 - 120			smoker
			10 times	<	
			average	>	5 times non-
			indoor		smoker risk
			level		
4	0.02	13 - 50		>	200 chest
			10 times	<	x-rays per
			average		year
			outdoor		
2	0.01	7 - 30	level	>	Non-smoker
					dying from
			Average	<	lung cancer
1	0.005	3 - 13	indoor		
			level		20 chest
				>	x-rays per
			Average	<	year
0.2	0.001	1 - 3	outdoor		
			level		

EPA RADON RISK EVALUATION CHART

(PD8, 1987)

FIGURE 3

The health studies conducted on uranium miners and other miners were beneficial in assessing the correlation between lung cancer occurrence and radon exposure. The analysis used experimental and control groups as a basis for comparison. The experimental group were underground miners of uranium, iron, tin and other hard rock materials, who had high exposure to radon and radon progeny. These rock mines have the highest concentrations of the uranium decay series. The miners in the control group consisted of coal and gold miners with no radon exposure. Both groups had the same exposure to fumes, tobacco smoke, and particulates that are standard in mining operations. Every study based on these populations found higher lung cancer rates in the experimental group than in the control group. In addition, the lung cancer rate of the miners in the control group did not show a greater lung cancer rate than that of the general public. Furthermore, the lung cancers observed in these studies did not emerge until five to 10 years after exposure, and occurred only in persons over the age of forty (PD1, 1979). As a result of these findings, the Occupational Safety and Health Administration (OSHA) established standard limits of exposure to radon and radon progeny. This standard limits the miner to four working level months (WLM) per year (PD5, 1988).

Some doubts have arisen regarding the use of health data from miners when estimating the risks faced by the homeowner. One concern is that the mining environment differs from the home environment, i.e. dust and fume levels are higher. Another concern is that the radon concentrations were much greater for the miners than for homeowners, except for extremely high concentrations found in some homes.

To defend these uncertainties, the estimated deaths shown in Figure 3, for the lower WL values assume that the health effects of radon are based on the cumulative dose (the total WLM), and not on the rate at which the dose is incurred. For instance, a homeowner in a low level radon house could receive a cumulative dose over seventy years that a miner might receive in just a few years (PD5, 1988). Even though more data on the effect of dose rates is needed, the existing miner health studies do cover the cumulative, or lifetime doses estimated for many homeowners as well. The results show a definite increase in lung cancer risk at these cumulative exposures.

Several agencies such as the U.S. Mine Safety and Health Administration, the EPA, ASHRAE, and others, have prepared guidelines to show people the recommended levels for homes and buildings (See Figure 4). Though these guidelines are not enforced nationwide at this time, the EPA believes that radon levels should be permanently reduced as much as possible. This position was taken following Congress passing the Radon Reduction Act in 1988 which established the reduction of indoor radon to levels comparable to those found outdoors as a national goal.

HOW DOES RADON CAUSE LUNG CANCER?

The alpha particles that are released by radon and the radon progeny are the primary agents creating the health hazard for individuals. These alpha particles can be stopped by an inch of air, or by the external dead layers of skin without causing any damage to the living skin tissue which lies underneath. However, lung tissue has no protective covering and is therefore susceptible to severe damage if radon is inhaled (T1, 1986).

ORGANIZATION	RECOMMENDED MAXIMUM RADON LEVEL		COMMENTS
U.S. Mine Safety & Health Admin.	0.08 WL	16 pCi/l	Regulation for Miners
National Council on Radiation, Protection, and Measurement	0.04 WL	8 pCi/l	Recommended Action level for general population
BPA	0.025 WL	5 pCi/l	Action level for residential weatherization program
U.S. Environmental Protection Agency (EPA)	0.02 WL	4 pCi/l	Indoor radon in homes built on sites contaminated by uranium processing
American Society of Heating, Refrigeration, and Air Conditioning (ASHRAE)	0.01 WL	2 pCi/l	Recommended exposure level in commercial buildings and residences
Sweden	0.11 WL	22 pCi/l	Existing buildings
	0.05 WL	11 pCi/l	Houses undergoing remodeling
	0.02 WL	4 pCi/l	New houses

RADON STANDARDS AND GUIDELINES

(PD8, 1987)

FIGURE 4

A very important aspect of the health hazard associated with radon is the time duration in which the alpha energies are released. Radon-222, a gas, has a half life of 3.8 days. Following the decay of radon the following isotopes are formed:

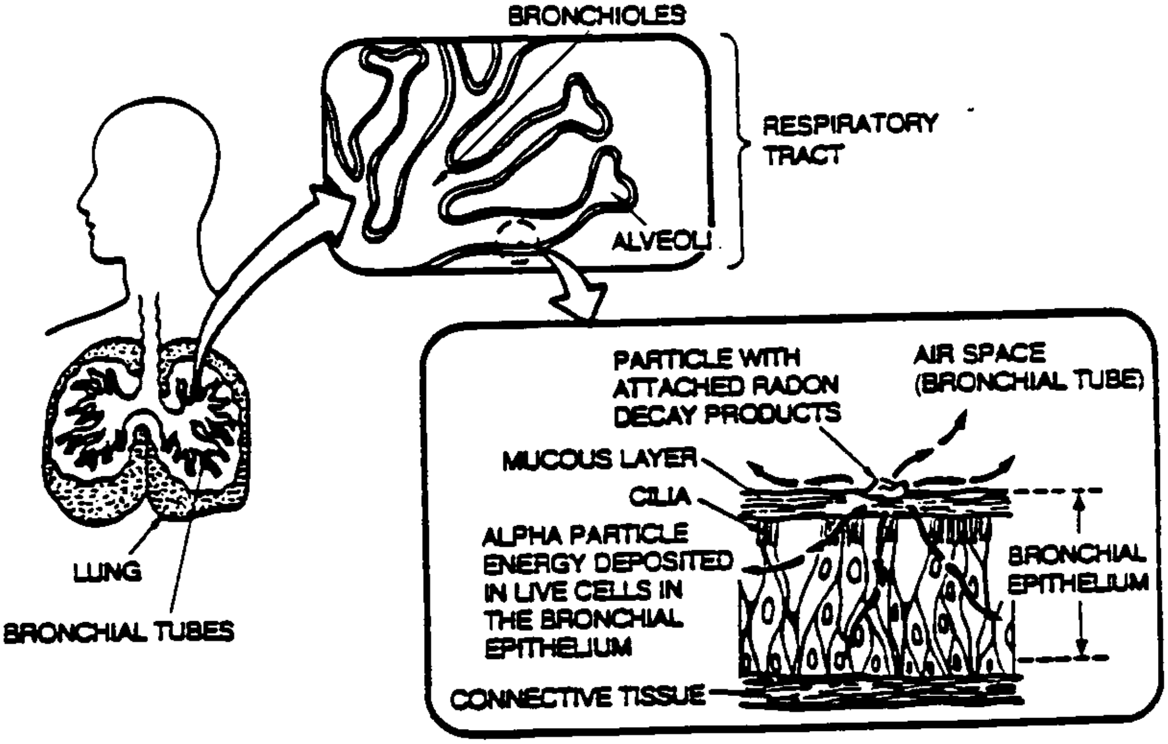
Isotope	Half-life
Polonium-218	3.0 minutes
Lead-214	26.8 minutes
Bismuth-214	19.7 minutes
Polonium-214	.00016 seconds

It is clear that within just over 50 minutes the lung tissues surrounding a filtered out particle would be subjected to an average of four energy bursts. Again, it is this repeated exposure to these energy releases that creates the elevated lung cancer risk.

These four progeny of radon have high electrostatic charges which increases their ability to stick to what they come in contact with, or "plate out." When these progeny attach themselves to airborne dust, or other particles that can be inhaled, they are more easily filtered out by the respiratory system. Since the progeny are atomic in size they substantially increase their ability to be filtered out in the upper portion of the bronchial system by attaching themselves to much larger airborne particles. However, some of the progeny will not become attached to any airborne particles and if inhaled pose the risk of being drawn deeper into the bronchial system. Insufficient studies have been conducted, at this time, to conclusively determine if there is an elevated risk associated with the unattached fraction versus the attached fraction. Those radon progeny which have become attached to other airborne particles (smoke, dust, etc.) are referred to as the attached fraction. Therefore, the unattached fraction is that portion of the total radon progeny that are not influenced in their movement by the characteristics of the attached particle. The general feeling of those researchers currently working in the radon field is that logically it would seem that there would be an increased risk if the atmosphere had a higher concentration of unattached particles than attached. This is important in that its impact on air filtration systems, as a potential radon mitigation device, is currently considered of questionable value.

Two of the radon progeny, the isotopes polonium-218 and polonium-214 release harmful alpha particles when they radioactively decay. These isotopes themselves are highly energized particles which attach readily to whatever they come in contact with: dust, pollen, smoke, etc. These particles, whether attached or not, can be inhaled with ambient air and when filtered out by the respiratory track, can subject sensitive lung tissues to repeated bombardment of these large Alpha particles. It is this repeated exposure over a small duration of time that greatly increases the risk of the tissue cells being damaged, most especially the DNA structure of the chromosomes. The resulting damage to the DNA can cause the cells to mutate which manifests itself as lung cancer (see Figure 5). This repeated bombardment of unprotected lung tissue by these alpha particles can significantly increase the risk of developing lung cancer.

Because radon itself is a noble gas, it does not chemically combine with tissue when it is inhaled. As a result, radon by itself is not considered a significant health hazard since most of it is exhaled before it decays (PD5, 1988).



FATE OF ATTACHED PARTICLES

(PD9)

FIGURE 5

CHAPTER 3

DETECTION AND MONITORING EQUIPMENT

In order to determine whether a home has a high concentration of radon and/or radon progeny requires the use of detection and monitoring equipment. This equipment is used for measuring existing radon and progeny levels and may assist in diagnosing the location of specific radon entry conditions (PD5, 1988).

Today, there are several different measurement systems available to the general public and the professional radon investigator for determining indoor radon levels. These measurement devices are categorized into two basic types of systems: "active" and "passive." Passive techniques do not require pumps or specialized equipment that active methods do, and are used primarily as screening measurements. These passive measurement devices are typically low cost, convenient to use, and some manufacturers have made them readily available to the general public. Screening measurements differ from diagnostic measurements in that they are utilized to determine _if_ a radon reduction program should be implemented, whereas diagnostic measurements are used mainly for mitigation system design purposes. The screening measurement is normally a short-term measurement made under worst case conditions in order to determine the highest risk to which the occupant is exposed. The Environmental Protection

Agency (EPA) has established an action level for indoor radon at an annual average concentration of 4 pCi/l. This means that, while the radon concentration may fluctuate from day to day and season to season, its yearly average should not exceed 4 pCi/l. If annual average levels exceed 4 pCi/l then EPA recommends a radon reduction program be implemented within the following time frames.

If levels are:

>4 but <20 pCi/l	Additional testing should be made over a longer time frame in order to establish a more accurate annual average. If, after further study, the annual average is confirmed to be in this range, a radon reduction program should be implemented within a few years.
>20 but <200 pCi/l	Additional testing should be made to confirm the screening measurement and if these levels exist, remedial action should be implemented within several months.
>200 pCi/l	Confirmation measurements should be expedited and a reduction program initiated within several weeks.

It must be understood that screening measurements are made over a short time-span and when used for determining compliance to the annual average guideline of 4 pCi/l care must be taken to assure accuracy. Frequently, single measurements at levels <20 pCi/l are improperly used in determining if mitigation is necessary. When using short-term measurements to establish compliance with an annual average level one must be cautious to not misinterpret or misrepresent the results.

SCREENING MEASUREMENT DEVICES

Three screening devices are in common use today: the charcoal canister, the alpha track detector and the Electret-Passive Environmental Radon Monitor (E-PERM).

CHARCOAL CANISTERS

Charcoal canister devices are manufactured in several different configurations including metal canisters and foil lined paper pouches. The container or package contains a measured amount of activated charcoal which when exposed to radon contaminated air will absorb radon. The device is normally exposed for time intervals ranging from two to seven days. The manufacturer will recommend the appropriate time interval for the amount of activated charcoal contained in the device. Humidity adversely effects charcoal canister type tests since it also is absorbed by the charcoal thereby reducing the amount of radon absorbed. Following exposure the device must be resealed and shipped to a laboratory for analysis. Normally it takes several weeks to receive results from the laboratory for this type of test.

ALPHA TRACK DETECTORS

Alpha track detectors (ATD's) are small containers containing a sensitive plastic insert which is physically damaged when struck by alpha particles. A laboratory etching process produces a permanent "track" in the plastic for each alpha particle encountered. Following the etching process these "tracks" can be counted and an average radon concentration determined for the exposure period. As with the charcoal canister devices, the laboratory processing time may run into several weeks. Since alpha track detectors are not affected by humidity they can be exposed for periods up to a year. However, these devices are normally used for making 30 to 90 day measurements. One manufacturer has recently introduced a short term alpha track device which can be used for exposure times as short as two weeks.

ELECTRET-PASSIVE ENVIRONMENTAL RADON MONITOR (E-PERM)

The E-PERM device is a non-homeowner type screening system which is gaining popularity in the professional radon testing community. This device utilizes an electret, a membrane having a electrostatic charge, which is affected by the exposure to radon gas. When radon encounters the charged electret a voltage reduction is caused by radon ions satisfying part of the electrostatic charge. This voltage drop is conveniently measured with a portable instrument making on site analysis possible. This feature, along with the ability of the E-PERM to withstand the effects of humidity, is making this device a system of choice with professional radon testers. Depending upon the electret's charge, exposure durations can be as short as hours and as long as a year.

Charcoal canister and alpha track devices are the most common homeowner employed measurement systems. Costs are generally less than $50.00 for the test device and the laboratory analysis. Due to the cost of the entire system, the E-PERM is predominantly used by professional mitigators and testing firms. Professional testers, as a rule, utilize all three measurement systems.

SCREENING MEASUREMENT TESTING PROTOCOL

Following the selection of the measurement device proper exposure protocols must be employed to achieve an acceptable level of accuracy. The EPA recommends the following procedures.

- Locate the testing device in the lowest accessible space (not necessarily a living space; ex. basement.)
- Place in area of lowest ventilation.
- Test under closed-house conditions. (All doors and windows closed for duration of test except for normal entry and exit of house.)
- Place the testing device where it will not be disturbed during the measurement period.
- Avoid drafts from heating and air conditioning systems, doors, and windows.
- Place the device at least eight inches below the ceiling and twenty inches above the floor.
- Keep objects that could interfere with air movement around the device a minimum of four inches away. Since convective drafts frequently occur at the exterior wall the device should be located away from these areas.

FOLLOW-UP MEASUREMENT TESTING PROTOCOL

Post-screening follow-up measurements should be made under normal house operating conditions. These measurements are intended to determine the actual living exposures rather than the worst case condition. The location criteria for the testing device remains the same as described in the screening protocol.

DIAGNOSTIC MEASUREMENT DEVICES

If screening and follow-up measurements determine that mitigation is warranted, then diagnostic measurements should be performed to specifically identify the elevated radon locations and entry conditions. The testing devices utilized for these measurements are highly sophisticated and expensive pieces of equipment. The Florida Legislature, in 1988, directed the Department of Health and Rehabilitative Services (HRS) to develop and implement a training and certification program for radon testers and mitigators. EPA also has a program to certify various types of radon testing equipment and test protocols. These actions by the governmental agencies are intended to provide the consumer with a way to ensure that technically competent personnel are performing these services and that they are using approved testing devices and procedures.

The following is a description of testing processes rather than specific testing devices.

GRAB SAMPLING

Grab sampling is a process where radon and radon progeny concentrations are determined. Radon concentrations are measured in pCi/l and radon progeny concentrations are measured in working levels (WL). These samples can be taken from various locations inside or outside the home and are short-term (i.e. 5-10 minutes in duration). Grab sampling assists in identifying the predominant locations of radon in the home.

A grab sample device which measures radon concentrations consists of a scintillation flask or cell. The cell, which has a zinc sulfide phosphor coating on the inside, is used to collect samples of air (T1, 1986). A filter is attached to prevent dust particulates from entering the container.

A grab sample device which measures radon daughters uses a similar scintillation system with the addition of an air pump. This system also uses a filter for collecting alpha particles. The cells for both devices are then analyzed by counting the light pulses (scintillations) with a photomultiplier tube through a clear window. These scintillations are generated by alpha disintegrations interacting with the zinc sulfide coating (PD3, 1987). Appropriate correction factors for both devices are applied to the measured results to account for elapsed time between collection and counting, and for decay during counting. A calibration factor is applied to the grab sample device for measuring radon daughters to convert the counts collected into WL.

Grab sampling can allow several samples to be taken in a day and can also allow radon and radon daughters to be evaluated simultaneously. The results can be quick, utilizing portable or laboratory analysis. However, house conditions must be controlled 12 hours prior to sampling, cost is relatively expensive, and a professional sampling team is necessary (PD8, 1987).

CONTINUOUS SAMPLING

Continuous sampling produces a series of short-term averages of radon and radon daughter concentrations. These samples can allow correlations with other measured or observed variations such as ventilation rate, seasonal variations, or radon source strength (PD7, 1986). The most common devices used in continuous sampling are the continuous radon monitor (CRM), and the continuous WL monitor (CWLM).

Continuous Radon Monitor (CRM)

A CRM is similar to the grab sample scintillation system, with the addition of a microprocessor. It totals the number of counts for a fixed interval, stores the count in memory or is printed out, and then begins a new count for the next time interval (PD8, 1987). The CRM may be either a flow-through or periodic-fill device. In the flow-through type, sample air is continuously pumped through the scintillation cell. In the periodic fill type, the cell is filled with sample air, sealed, counted for a fixed interval, flushed and then filled again (PD6, 1988). Counting for the fixed interval is usually done where the air sample is accumulated for 30 or 60 minute periods. The level of accuracy is dependent upon the counting rate and proper calibration and maintenance of the nominal flow rate for flow-through devices.

The CRM can also be used to make comparative measurements in an attempt to determine points of high radon concentration. This process is referred to as "sniffing" and is a highly effective diagnostic technique for locating entry points. A device, such as a Pylon AB-5 Continuous Radon Monitor can be equipped with a length of tubing which will allow technicians to detect radon concentrations in virtually inaccessible spaces.

Continuous Working Level Monitor (CWLM)

The CWLM is similar to the flow-through scintillation device. The radon progeny are collected on a filter by the use of an air pump. As the alpha particles decay, they are counted on a silicon-surface barrier detector preset to detect two to eight MeV for a fixed time interval (TI, 1986). The count rate is then stored and converted to WL by way of a calibration factor.

Continuous sampling by either CRM or CWLM devices permit relatively short measurement times, on-site results, and portable equipment capabilities. However, the devices are expensive, a professional sampling team is needed, and the devices require regular calibration.

CHAPTER 4

EVALUATION OF RADON TRANSPORT AND ENTRY

Radon, being a noble gas, is a highly mobile substance. Its ability to move relatively freely through the soil means that it also has the ability to move easily through openings in the foundation/floor systems of buildings. Entry into occupied spaces of buildings can result in excessive levels of radon gas being accumulated with significant health risks resulting. Therefore, it is vitally important to understand the transport mechanisms and where the most likely entry conditions occur in order that preventative or mitigative efforts can be taken.

Before proceeding, a brief review of some important radon facts is warranted. First, radon is an atomic sized element, in other words, infinitesimally small. Second, radon's inert characteristic provides it with an ability to move virtually unimpeded through any porous medium. Third, its fluid nature means it will move in response to pressure gradients, either naturally or mechanically induced.

TRANSPORT MECHANISMS

The various types of transport mechanisms by which radon can enter a home include airflow, well water, and diffusion. Pressure differentials, with the exception of radon entry by diffusion or well water sources, are the driving forces that power these mechanisms and influence the rate of entry.

AIRFLOW

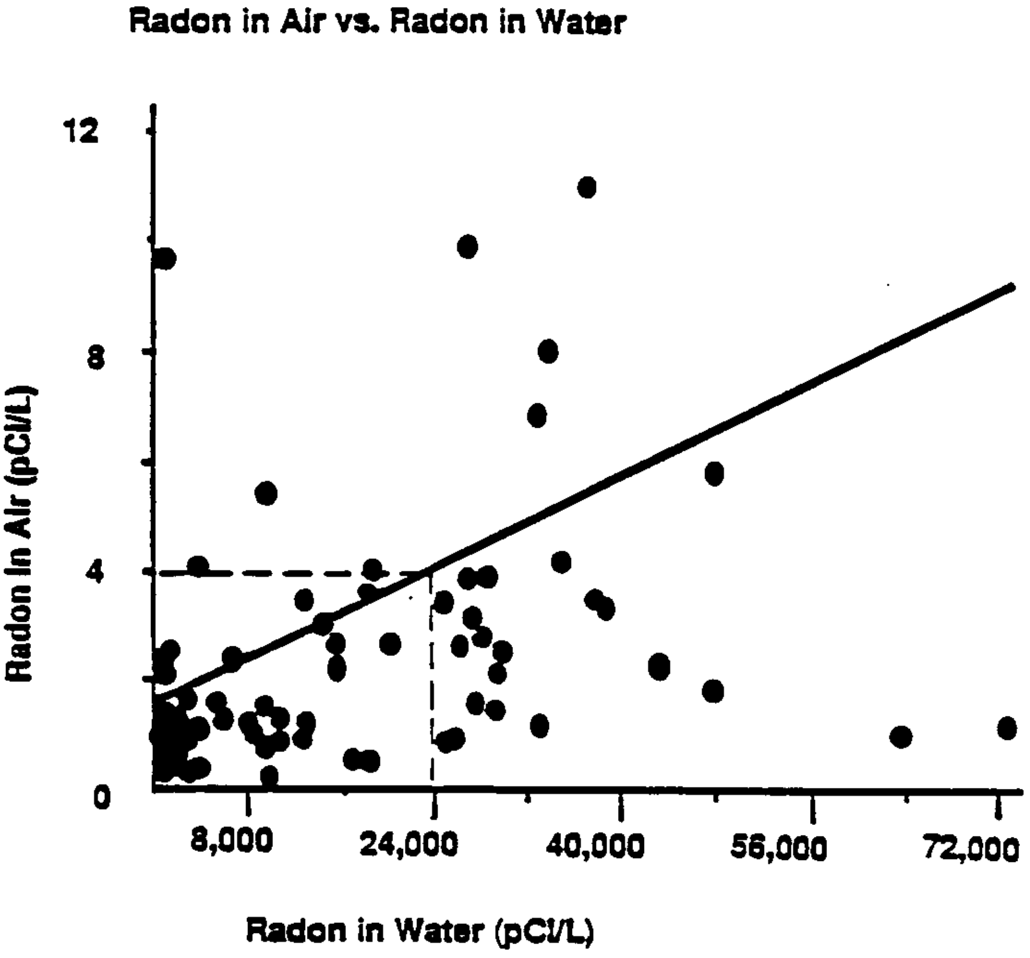
Air from the atmosphere constantly flows in and out of the soil due to the pressure difference between the atmosphere and the soil gas. These pressure differences are influenced by temperature, wind, and soil permeability (M2, 1983). As air flows through radium-bearing soil, it can carry or transport radon to the surface and into the structure.

WELL WATER

When radon is produced in a water-bearing strata of soil or rock, a portion of the gas will diffuse into the water and be transported by it. When the water is used, especially in ways which aerate (i.e., washing machines, dishwashers, cooking, or showers), some of the radon is released into the atmosphere. Radon can quickly transfer to air with efficiencies of thirty to ninety percent (M2, 1983). However, for waterborne radon to become a significant airborne problem, it takes high radon concentrations in the water to equal similar air concentrations. For example, it takes approximately 24,000 pCi/l of radon in water to produce a 4 pCi/l concentration in the air. (See Figure 6)

DIFFUSION

Diffusion is defined as the random movement of atoms or molecules independent of pressure-driven gas flow (PD5, 1988). Diffusion occurs when a gas travels from a higher concentration to a lower one. With radon, the highest concentration is at the source, or the radium. Permeable soils will allow radon to diffuse quickly and will result in a uniform soil gas concentration. Soils that are less permeable will hold the high concentrations closer to the



RADON IN AIR vs. RADON IN WATER

(PD8, 1987)

FIGURE 6

radium source. In both cases, the radon concentrations dilute as they near the surface due to atmospheric air mixing in the near surface soil. Radon transport by diffusion means it can enter a structure through hairline cracks in the foundation/floor system (molecular diffusion of a gas through a mixture of gases), or through solid concrete walls or slabs (molecular diffusion through a porous solid) (PD8, 1987). The significance of this mechanism is that radon can become trapped beneath concrete slabs, or other barriers, and accumulate to very high concentrations. These high concentrations can result in radon being transported into the structure through diffusion.

PRESSURE DIFFERENTIALS

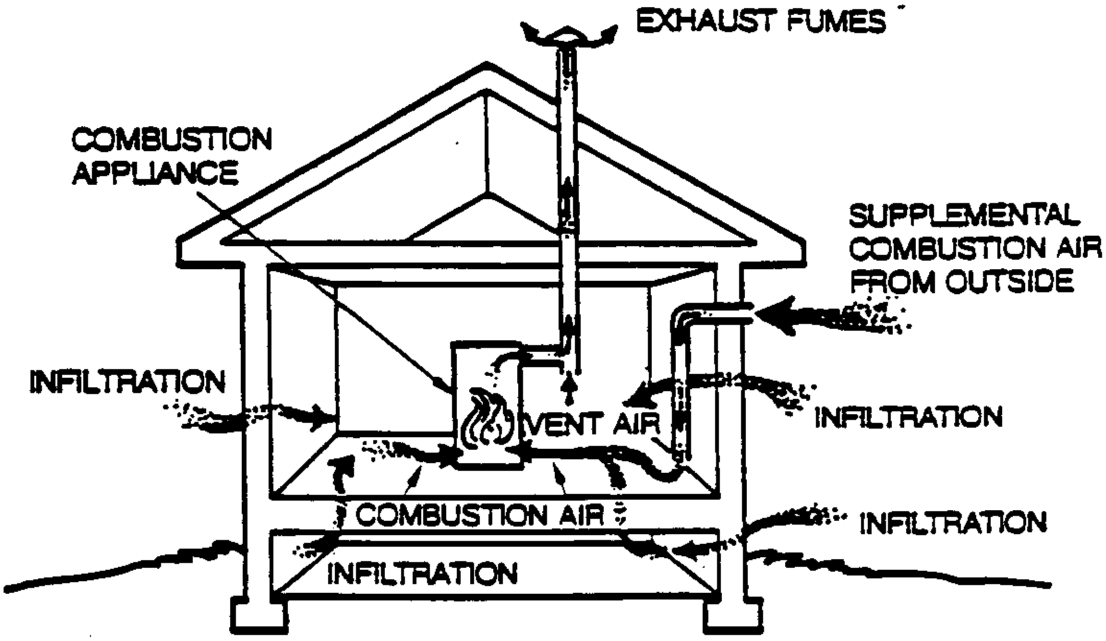
The primary force that powers the transportation of radon is the pressure differential. A pressure differential is simply the difference in pressure from one area to another. It is influenced by mechanical systems such as heating, ventilation and air-conditioning (HVAC) system, as well as by natural environmental factors. Of particular interest to homeowners are the pressure differentials which can exist between soil gas and indoor air. Differentials occur when air is extracted from the home, resulting in house depressurization or a reduced (negative) indoor air pressure. A suction effect results from this reduced pressure, increasing soil gas transport into the home (PD5, 1988).

Pressure differentials between soil gas and indoor air can be affected by mechanical devices such as ceiling or window fans, kitchen or bathroom exhaust fans, attic exhaust fans, clothes driers and all other devices which exhaust air outdoors. These devices can cause a vacuum effect by sucking air out of the home (PD3, 1987).

Combustion devices such as fireplaces, wood stoves, gas and water heaters, furnaces or boilers (if located inside the inhabitable space) can also move air outdoors (see Figure 7). The extent to which these mechanical and combustion devices cause depressurization is dependent upon the tightness of the home and the amount of air extracted by these devices.

Another factor influencing these pressure differentials is the air exchange or infiltration rate. This rate is the measure of the amount of airflow through a structure by means of infiltration, and is influenced by mechanical systems. Infiltration is dependent upon weather conditions, use of mechanical or combustion devices, and the tightness of the home. The infiltration rate for most homes with the windows closed is between 0.5 to 1.0 air changes per hour (M2, 1983) (One air change per hour is the volume of air indoors replaced in one hour).

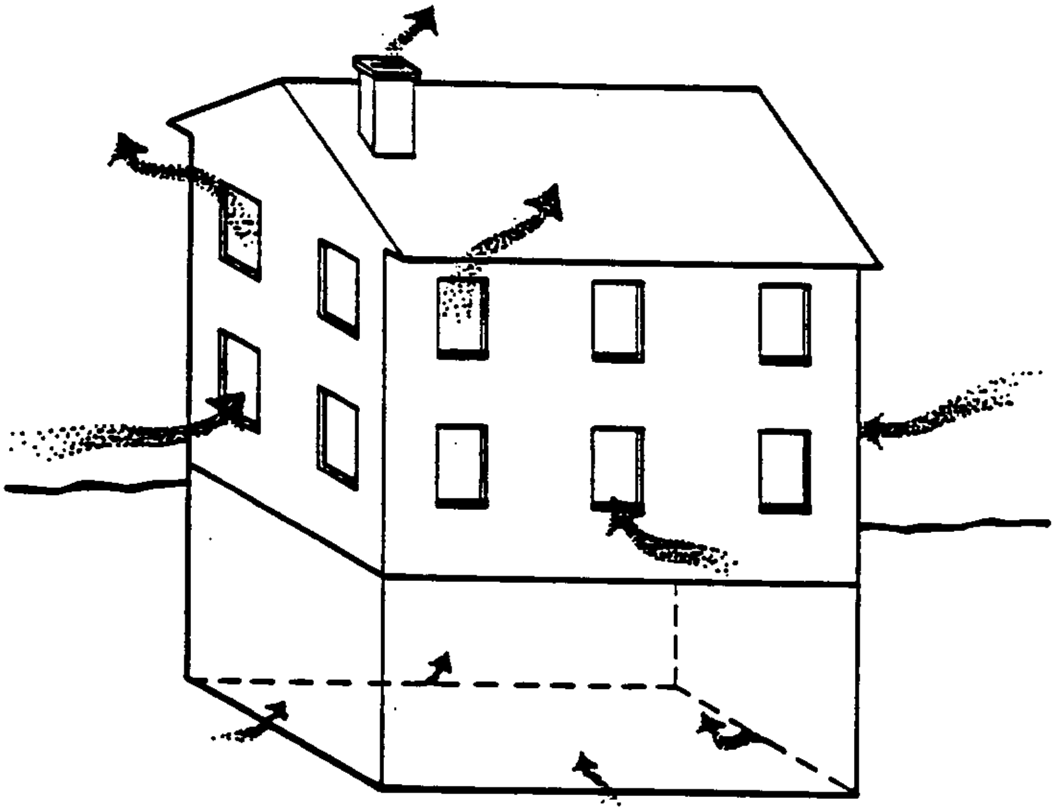
Environmental conditions can greatly influence pressure differentials which can lead to house depressurization. A phenomenon known as the "thermal stack effect" can occur when the outdoor temperature is colder than the indoor temperature. The buoyancy of the warmer indoor air will tend to rise and seep through openings at the top of the structure. This creates a lower pressure or suction effect at the lower level of the house, thus drawing in air and possibly radon. Once inside, the infiltrating air and radon become heated, rise, and seep out. This process causes the house to function like a chimney or smokestack, hence, creating a thermal stack effect (see Figure 8). This phenomenon is more prevalent in multi-story structures that in single-story structures. Since Florida homes are predominantly single-story structures, this condition is not considered to be of major significance. However, coupled with other sources of pressure modification, it certainly needs to be addressed.



COMBUSTION AIR CONCEPTS

(PD9)

FIGURE 7



TEMPERATURE DIFFERENCE DRIVEN INFILTRATION

THERMAL STACK EFFECT

(PD9)

FIGURE 8

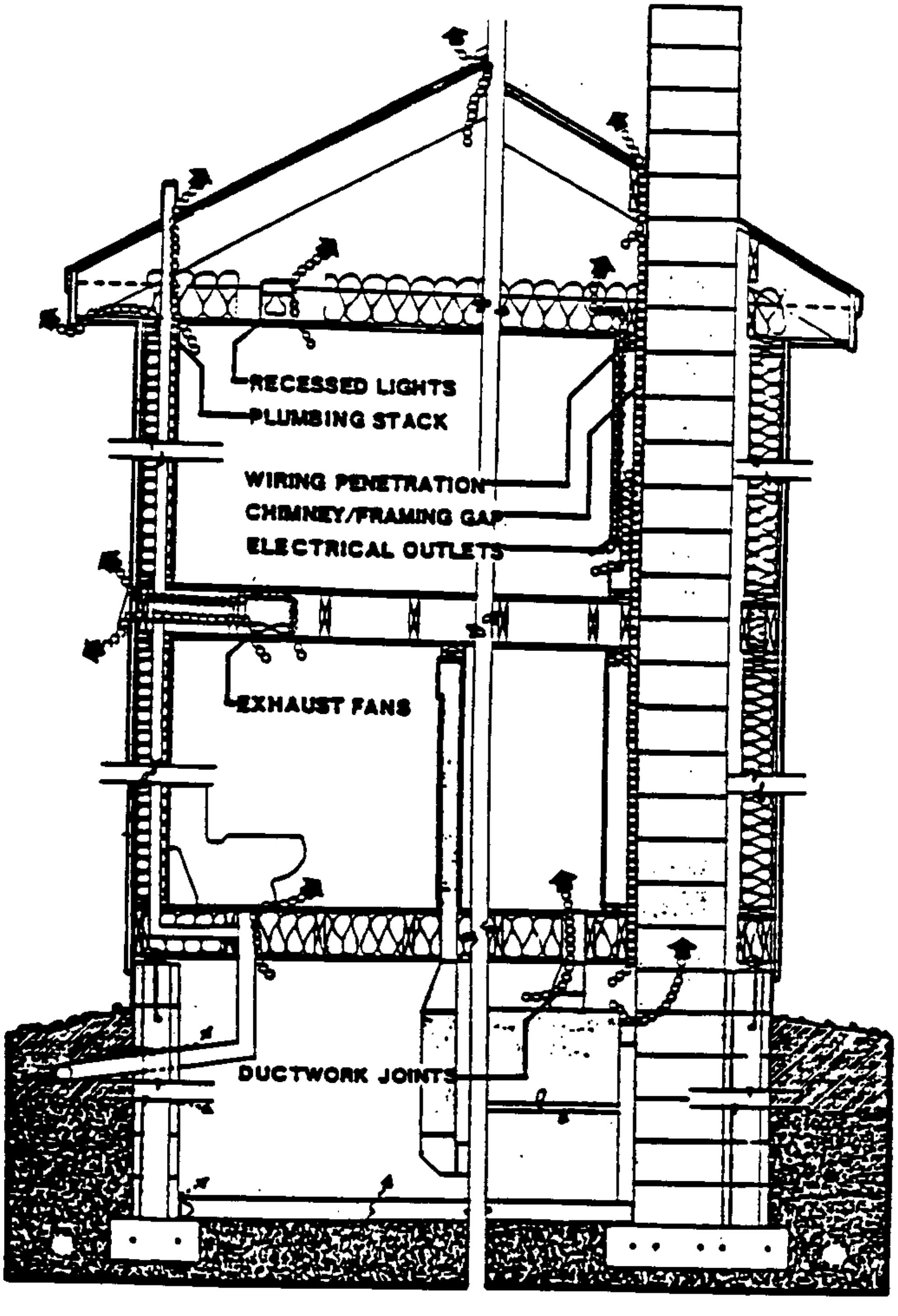
The openings that allow inside air to flow to the attic or outside are known as "thermal bypasses". These penetrations can contribute to house depressurization (negative pressures) by allowing the warm air inside to move up through these channels (see Figure 9). If major thermal bypasses were to be closed, the upward airflow would be reduced, and the exfiltration of warm air along with the infiltration of radon could also be reduced (See Figure 10).

In addition to thermal factors, wind induced airflows create another pressure condition which can contribute to indoor radon entry. Winds create low pressure areas on the leeward side of the house inducing indoor air to exfiltrate, thereby resulting in an indoor negative pressure condition. This condition is enhanced when there are more openings on the leeward side (i.e., more windows open on the leeward side versus the windward side).

SITE SPECIFIC VARIABLES

The degree to which radon and its daughters can enter and accumulate in a home is dependent upon site specific conditions. One of the variables is the amount of radium-226 present in the soil near the surface. Soil throughout the U.S. typically contains between 0.2 to 3.0 pCi/g of radium-226 (PD1, 1979). However, several areas throughout Florida including Central Florida's phosphate mining lands have significantly higher concentrations.

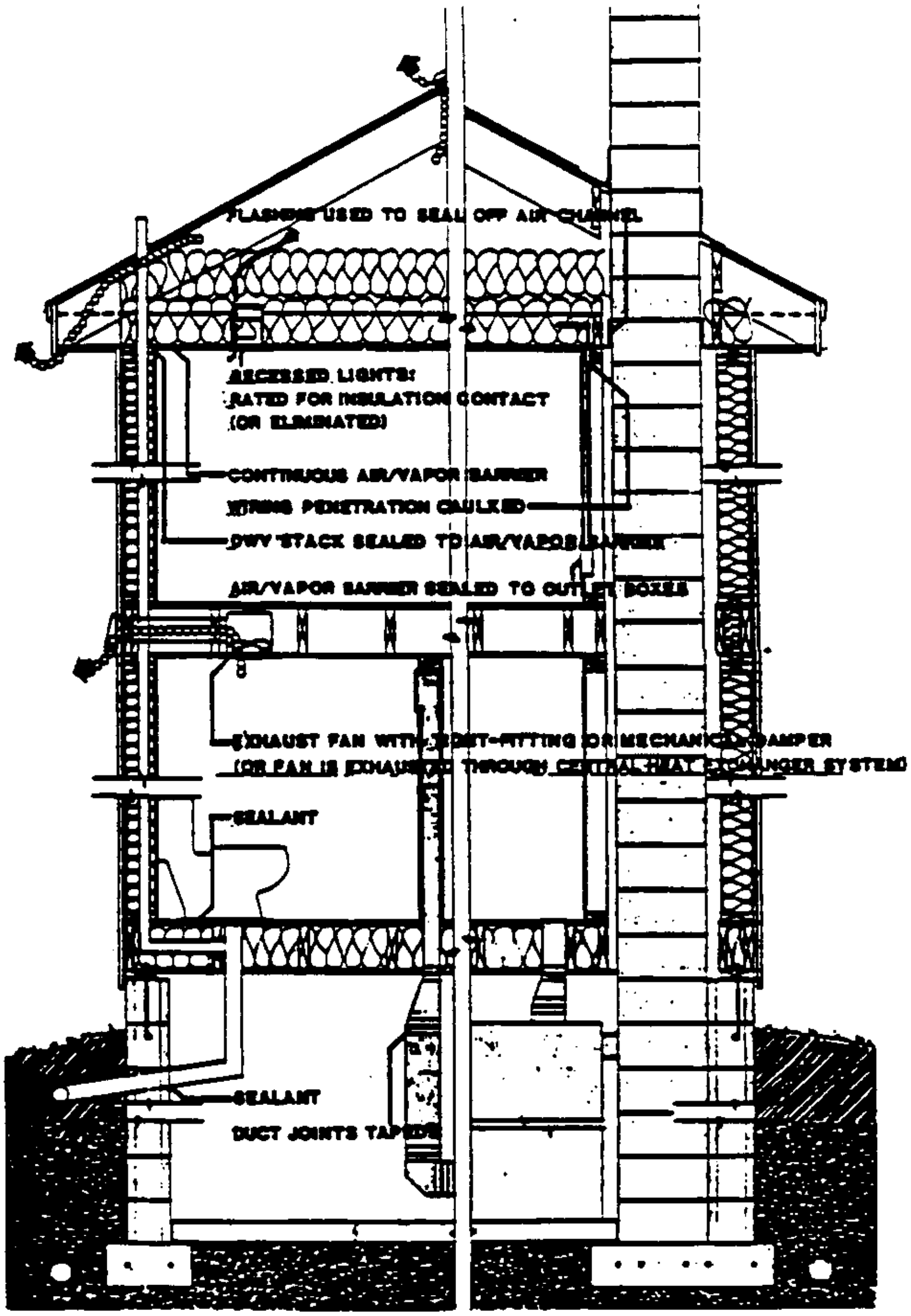
Radon can be transported from hundreds of feet below the surface through soil or rock. However, due to its relatively short half-life (3.8 days), and the time it takes to migrate to the surface, the first twenty feet of soil (when containing radium) is considered to be the major source of airborne radon (PD1, 1979). Studies have shown that radon can enter structures built



NEGATIVE PRESSURE SOURCES

(PD9)

FIGURE 9



BLOCKING THERMAL BYPASSES

(PD9)

FIGURE 10

over radium-bearing soil and this path represents the primary radon entry route (M3, 1983). When a structure is placed over radon producing soil, the building functions as a container once radon enters the living environment. (M1, 1983)

Another site specific variable influencing indoor radon is the permeability of the soil, as well as the degree of fissure of sub-surface rock. A key factor in the migration of radon to the surface is its ability to travel through soil or rock in a short time. Soils that are relatively permeable, such as sandy soils or rocks that are highly fissured, as in loose sands or fractured shales, will allow the radon to travel easily to the surface with only minor losses due to half-life decay (PD5, 1988). Other factors such as soil density and moisture content will modify the effective permeability of soil.

It should be noted that the previous discussion has dealt solely with variables associated with the soil. There are other site specific variables that intermingle with the entire evaluation of entry routes and shall be discussed throughout this chapter.

CONSTRUCTION VARIABLES

Florida's sub-tropical climate and high precipitation levels significantly influence the construction techniques used in the Sunbelt region. One of the most significant construction characteristics is the type of media used under the slab. Where in colder climates and areas of low rain fall sub-grade construction is common, in Florida basement construction is rare. Gravels, used primarily in sub-grade construction to facilitate water removal, have substantially higher permeabilities than the sand fills used in the Sunbelt region. The permeability of these base materials coupled with the effective leakage of the confining construction are of major importance in the effectiveness of the radon control systems.

To facilitate the construction of concrete slabs on grade, Florida's abundant supplies of clean construction-grade sands are normally used as compactible fill material. Fill sands are frequently relocated from one area of the project site to another or may be transported in from distant borrow pits. Some of these sands have been identified as having moderate to high radium content thereby raising the possibility of transporting radon contamination from one locale to another.

These common construction practices have been utilized for many years in Florida and with minor modifications are still being used today. During the past 30 years the trend of the homebuilding industry has been toward a higher use of concrete slabs-on-grade and away from raised wood floor systems over a crawlspace. During the transition era many builders utilized construction techniques traditionally employed on crawlspace structures on slab-on-grade systems. The worst condition identified has been the placement of return-air ducting under the slabs. Specific entry conditions for radon gas will be discussed by type of foundation floor system.

SLAB CONSTRUCTION CATEGORIES

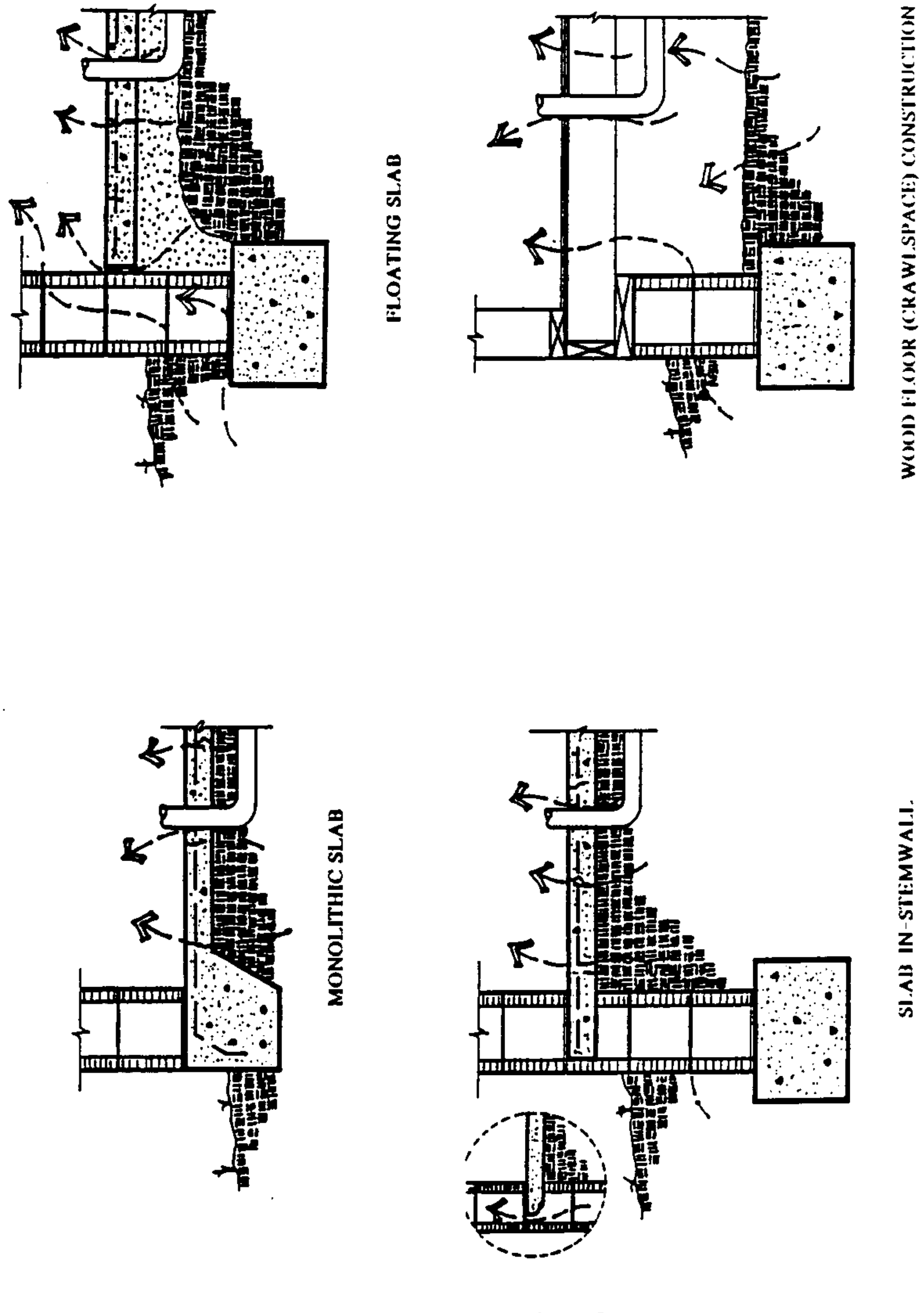
Concrete floor slabs used in Florida typically represent one of the following three slab construction categories: Monolithic Slabs, Floating Slabs or Slab-in-Stemwall Slabs.

Monolithic Slabs

Slabs constructed on near level ground, in areas not subject to flooding, are most cost effectively constructed as monolithic slabs. When site modifications to create a level building area are more cost effective than the construction of foundation walls, monolithic slabs will also be found in areas of irregular terrain. Monolithic slabs are characterized as having the footing and the slab cast as one integral unit with the foundation depth minimized. Potential radon entry routes through the slab are usually confined to cracks (planned or not) and penetrations for the plumbing, electrical, HVAC, etc (See Figure 11). Monolithic slabs present fewer entry conditions to radon than either of the two other categories.

Floating Slabs

Where terrain features, water considerations and/or other conditions demand the use of foundation walls to elevate the slab some distance above natural grade, floating slabs are one of two construction techniques commonly employed. Floating slabs are floor slabs that are cast against, not into, the foundation wall. Expansion joint materials are normally used to separate the slab from the inside face of the foundation wall, resulting in a continuous entry condition along the perimeter of the slab. Along with the typical entry conditions associated with slab cracking and mechanical penetrations, foundation wall conduction of radon from below the floor slab into the superstructure wall is also common (See Figure 11). Most superstructure walls using floating slabs are constructed of masonry block. The thickness of the masonry block wall is such that the baseboard will conceal the perimeter crack, thus making it virtually inaccessible after construction. The continuous perimeter crack and the foundation/superstructure wall conduction are the most significant entry conditions associated with this slab system.



FLOATING SLAB

WOOD FLOOR (CRAWLSPACE) CONSTRUCTION

MONOLITHIC SLAB

SLAB IN-STEMWALL

TYPICAL FOUNDATION SYSTEMS

FIGURE 11

Slab-in-Stemwall Slabs

Many contractors prefer a frame superstructure wall to a masonry one. By employing a four inch thick wall with a floating slab floor system the perimeter crack along the foundation wall would be exposed. To eliminate this condition the slab-in-stemwall technique was developed. This process utilizes one of two types of masonry block to function as a form for the edge of the slab. A lintel block can be used where only the outer face shell remains as the slab form, resulting in a hairline crack approximately one inch in from the outside face of the stemwall. When a header block is used the web partitions which extend half way across the block add to the overall crack length but most importantly, can keep the concrete from coming into contact with the inside face of the block. When contractors use a header block and drape their vapor barrier over the stemwall, rather than cutting it to lay flat, the concrete when placed will be held away from the outside face shell of the block. The importance of this is that entry conditions can result and radon from below the slab can migrate up and into the superstructure. If the contractor is careful in how he places his vapor barrier he can produce a slab that eliminates the foundation wall superstructure conduction problem.

When the slab-in-stemwall technique is used and good contact between the slab and the stemwall are made, then an effective seal against sub-structure/superstructure conduction can be achieved. At this point radon entry conditions are usually those associated with mechanical penetrations and cracks (See Figure 11).

CRAWLSPACE CONSTRUCTION

Today, crawlspace construction accounts for less than 5% of the total number of homes built in Florida. Prior to the 1950's however, this type of construction was the predominant type of foundation/floor system for residential structures. For this reason, a general understanding of raised wood floor systems is necessary. Radon gas, as discussed earlier, can accumulate in high concentrations in the crawlspace and enter the structure through many routes.

Older wood floor systems primarily used diagonal planking as the sub-flooring material. Spaces were intentionally left between each board to allow for moisture related swelling and shrinking. Building papers were used between the sub-floor material and the finish floor material to reduce squeaking and to partially control air migration through the floor. This assembly does very little to reduce radon transport. Penetrations through the floor system for plumbing and electrical lines frequently are found to be very large in comparison to the size of the pipe or wire passing through them. Homes with elevated indoor radon problems which have this type of floor system have extremely little chance of improving the barrier capabilities of the floor system.

Homes constructed since the development of plywood sheeting have far fewer joints in the sub-flooring which produces a better floor system barrier. Sealing the edges of the plywood sub-floor during assembly, as required by the Florida Model Energy Efficiency Code, will significantly reduce the number of entry routes for radon. During new construction and, when accessible on existing homes with plywood sub-flooring, if all other penetrations through the plywood is kept to a minimum and sealed, a moderate level of barrier effectiveness can be realized. However, over time the constant movement of wood floor systems may cause some of the seals to break down and allow radon to enter the house.

Wood floor systems in general are not considered to be, by themselves, very effective barrier systems against radon for extended periods of time.

CHAPTER 5

RADON MITIGATION

Reduction of elevated radon levels in existing structures is far more complex and costly than the provision of an equally effective mitigation system installed during the course of construction. Difficulties of access and cosmetic concerns can significantly influence the overall effectiveness of the mitigation system. In some instances homeowner concerns over the appearance of the installed mitigation system precludes more effective approaches being taken. In new construction it is possible to optimize the effectiveness of the mitigation system by being able to access all parts of the structure before they are covered or closed in. The degree of accessibility usually results in all components of the mitigation system being concealed from view and operation and effectiveness being optimized.

MITIGATION APPROACHES

Radon control in either new or existing construction is generally accomplished by applying one or more of the following mitigative concepts:

1. Block it, with a barrier.
2. Divert it, before it can enter the structure.
3. Dilute it, after it enters the occupied space.
4. Eliminate interior negative pressure conditions.

The effectiveness of each of these approaches is extremely dependent upon the particular construction characteristics of the structure being mitigated. It is common to employ more than one approach in order that specific conditions present in a particular structure can be effectively dealt with.

BARRIER SYSTEMS

The concept of the barrier system is simply to prevent radon gas from traveling across the barrier and gaining access into the occupied space. Barriers can be created with pressure fields or by the construction of a physical barrier system. The applicability of the physical barrier approach is much greater in new construction than in existing construction. This, once again, is due to the opportunity that is afforded during the construction process to install system components in locations that are effectively inaccessible after the structure is finished. The type of foundation/floor system utilized, either slab-on-grade or raised floor systems with a crawlspace, is the primary determinant of what type of barrier will be utilized. Blocking radon transport with a barrier system can be effective if the installation and operation of the mitigation system is very carefully monitored.

Slab Construction - Physical Barrier Systems

In new slab-on-grade construction, a combination of the concrete slab and the vapor barrier is considered to be a moderately effective barrier, if penetrations through either component are minimized. Exceptional care in placing, sealing around penetrations, and protection from inadvertent puncture must be taken. However, even when the utmost care has been taken, inadvertent puncture or barrier failure may result from post-construction activity or environmental influences, such as cracking resulting from movement.

Due to the inaccessibility of the barrier components - vapor barrier under 4" of concrete and the slab under framing and finished flooring materials - effective repair or sealing of penetrations in existing structures is felt to be limited. Considering the cost and inconvenience of removing and replacing finished flooring materials, in order to access the slab for inspection and sealing purposes, physical barrier systems are not deemed to be the most cost effective approach for total radon control. However, any mitigation strategy should include improving the existing barrier (floor system) by sealing any and all reasonably accessible penetrations.

The overall level of confidence of the long-term effectiveness of physical barrier systems is considered to be marginal. Again, this is due to compromises of the barrier system that occur during or after installation and go unnoticed or uncorrected.

Slab Construction - Pressure Barrier Systems

A pressurization barrier is a control technique that functions primarily because of the fluid properties of radon gas . Radon, being a gas and responding to the laws of fluid dynamics, will alter its path of migration when it encounters an area of higher pressure. When indoor pressures are lower than the soil gas pressure, the radon laden soil gas will flow toward the area of least pressure. If indoor atmospheric pressures are lower than the sub-floor gas pressure, the radon laden gas will seek any penetration in the floor system to gain access into the indoor space. When the movement of soil gas is restricted by a building component then high concentrations can occur on the soil side of the restriction. Even small penetrations with a low indoor pressure will result in radon contaminated air being drawn into the house. The important concept to understand is that all gasses, including radon, will always move from a higher pressure state to a lower pressure state. By developing indoor pressures higher than the sub-floor gas pressure, no flow will occur from the sub-floor area into the structure. In fact, the reverse will happen - the indoor air will actually flow down through the floor into the soil. This counter or reverse flow through the floor will not allow the radon laden gas to enter the structure since it would have to "flow up-stream." With minor modification, standard HVAC equipment can produce elevated indoor pressures sufficient to prevent radon from entering the structure. These modifications normally involve introducing outdoor air into the return-air side of the air handler. This technique effectively compensates for any air lost through leaks in the supply ducting which allows the air handler to satisfy its intake demand without creating indoor negative pressures.

Several other factors must be considered prior to selecting this technique. Elevated pressures can only be achieved if the supply into the structure is greater than the exfiltration. Therefore, the house must be reasonably tight or well sealed and weatherized. If the structure has a high level of infiltration then it may be impossible, or at least impractical, to over pressurize the structure. There are also two energy considerations to be considered. In order for the pressurization state to be maintained the HVAC fan must be operational all the time. This results in additional energy consumption or expense. Also, the outdoor air is likely to be high in humidity, especially in Florida. By inducting quantities of humidity laden air into the house the amount of dehumidification the HVAC system must control is substantially increased. This results in the air-conditioning system having to work for longer periods of time or in shorter cycles in order to maintain a satisfactory level of comfort. Some reduction in the energy penalty can be achieved by installing a heat pipe heat exchanger between the return-air and supply ducts. These units do not require any electricity to operate but can increase the HVAC systems dehumidification efficiency by upwards of 30%. This boost in dehumidification efficiency can result in an equal level of comfort being achieved at a lower cost.

Overall effectiveness of the pressure barrier system is considered to be marginal, especially when used by itself. However, in some applications it may be the only acceptable technique available.

Crawlspace Construction - Physical Barrier Systems

Physical barrier systems used in crawlspaces have, in some instances, produced significant reductions in indoor radon levels. However, many problems exist in achieving and maintaining consistent levels of effectiveness of this type of system. Most of these barriers are constructed from membrane type materials such as polyethylene sheeting. Applying a membrane - or other type material - barrier to the underside of the floor system is virtually impossible. Piping and ducting, along with many other construction components, interfere with and restrict the installation of any type of barrier attached to the underside of the floor system. Therefore, most physical barriers used in crawlspaces are applied to the ground surface. Installation is normally a simple process of deploying the membrane material and sealing it around any pipe or structural component that must pass through the barrier. Careful attention must be paid to ensuring that a complete seal is achieved to prevent leakage of the sub-barrier soil gas into the crawlspace cavity above the barrier. This sealing process is often difficult to achieve and maintain. Also, the membrane is subject to damage when and if persons need to access areas under the house. Any rupture in the membrane or failure of a seal will substantially degrade the performance of the barrier.

Problems have been encountered in some parts of the country where membrane barriers were surface applied to the ground surface in the crawlspace. When atmospheric barometric conditions produced lower pressure conditions in the crawlspace above the membrane compared to the soil gas pressure under the membrane, ballooning of the membrane has occurred. Since this condition can exist in any area it becomes important to consider some type of barrier hold down system. Covering the membrane barrier with several inches of clean sand or a thin layer of concrete would keep the barrier from ballooning off the ground, as well as protecting it against traffic damage. Although this solution seems simple enough, it is not an easy or inexpensive task to accomplish.

The long-term confidence in crawlspace barrier effectiveness is marginal when applied without a protective covering. With a protective covering of sand or concrete the long-term operational confidence in increased, but the cost-effectiveness of the system as a whole is considered to be minimal.

Crawlspace Construction - Pressure Barrier Systems

Pressurization of crawlspaces has been utilized with varying degrees of success by researchers across the country. When considering the porosity of older wood floor systems what usually results is a forced infiltration of crawlspace air into the structure. If the pressure levels in the crawlspace are less than the soil gas pressure at any time, the influx of radon could be forced into the home by the pressure barrier system. Developing a uniform high pressure condition through out the crawlspace can sometimes prove difficult. This pressure variation may effectively result in higher soil gas pressures literally pumping radon into the crawlspace.

Negative pressure barriers have been attempted in some crawlspaces by researchers around the country with, again, a varying level of success. If air is drawn out of the crawlspace at a faster rate than it can flow in, then a low pressure zone can be produced. When soil gas emanates from the ground it will move to the point of least pressure and be exhausted away from the house. If however, localized negative pressure conditions occur around return-air ducting or other floor openings then radon laden air can be drawn into the house.

In designing a crawlspace pressurization or depressurization system it is important to ensure that uniform pressures and air flows are created. In most homes with crawlspaces, significant portions of the exterior foundation wall are not constructed with ventilation ports. This usually is due to the construction of other portions of the structure that are built on concrete slabs - porches and garage slabs. In these instances, ducting may be the only way to create the uniform air movement through these "dead spots" in the crawlspace. In order to move the volume of air necessary to either pressurize or depressurize a crawlspace of any reasonable size a high CFM fan would be required. These fans are relatively expensive and noisy. The sound attenuation problems associated with these large fan units can prove to be expensive and difficult. Homeowner complaints of being able to hear fan noise have been encountered numerous times even with very small capacity fan units.

Long-term confidence in crawlspace pressure barrier systems as the sole radon control strategy is marginal at best.

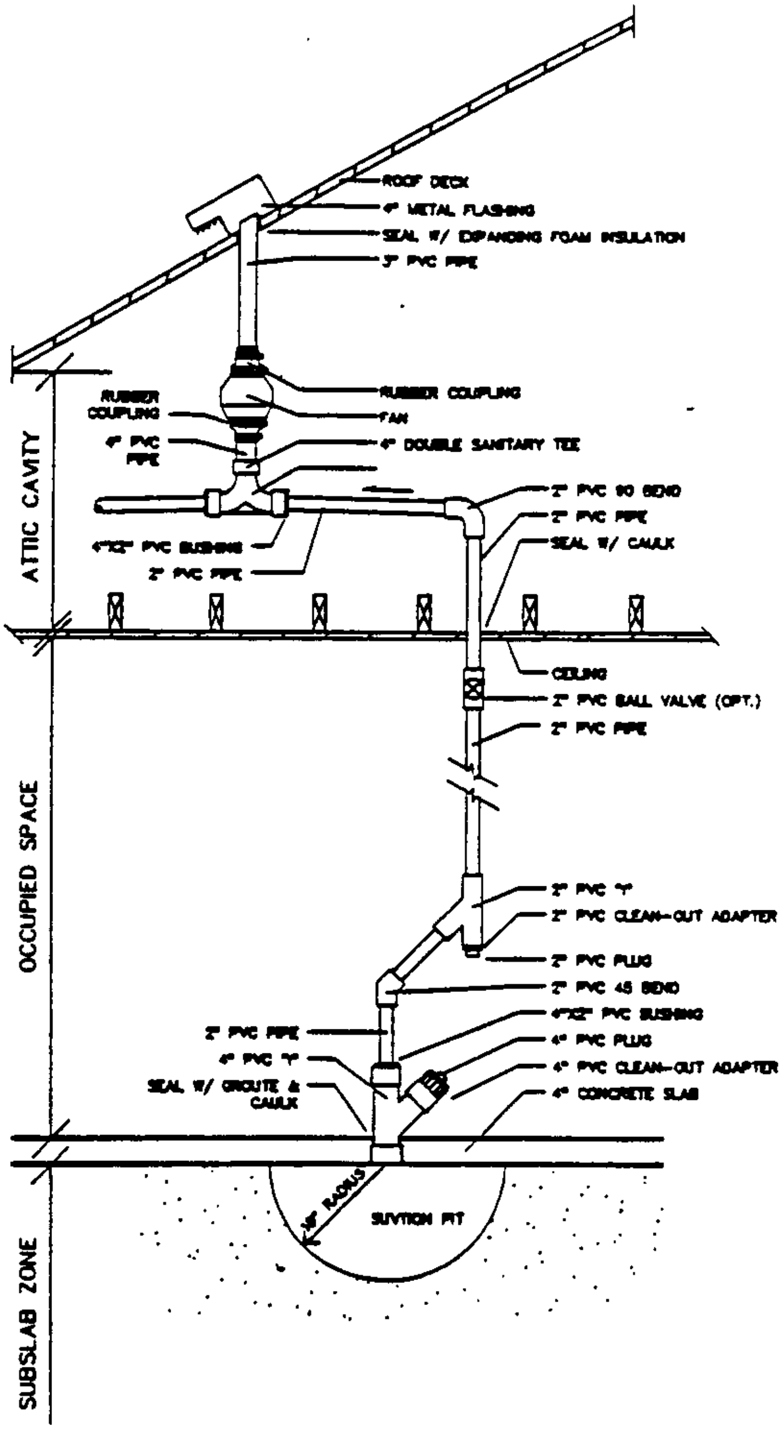
DIVERSION SYSTEMS

The most effective radon control system demonstrated to date on existing structures is the sub-barrier radon diversion system. These systems work on the principle of fluid dynamics where a fluid, or gas, will migrate from an area of higher pressure to an area of lower pressure. When a low pressure zone can be created between the radon source and the occupied space, interception and diversion of the radon bearing soil gas can be effected. These systems are quite simple in concept and construction for both new and existing structures. Also, this process is equally applicable to crawlspace structures as it is to slab-on-grade construction.

Slab-on-Grade Construction

Sub-slab depressurization/diversion systems work on the principal of developing a low pressure zone under the entire slab. In new construction it is quite easy and cost effective to install a system that will result in a complete sub-slab pressure field extension. In existing structures however, the opportunity to locate a suction point is normally determined by the floor plan. Since these systems involve the installation of a PVC piping system extending from the slab, to the attic, and through the roof, the location becomes very important. Normally these systems are installed in a closet or pantry since these spaces are not usually considered to be cosmetically critical. Using only closet locations for suction point determination generally does not result in the optimum placement of the suction pit. System performance can be severely degraded if the suction point is located too close to an exterior foundation wall. Short circuiting of the depressurization system can occur when sufficient quantities of air are drawn through the foundation wall or under the footing by the high suction pressures. For this reason it is important to attempt to locate the suction points as close to the center line of the slab and at least six feet from any exterior foundation wall.

The installation of the sub-slab depressurization system commences with the identification of the suction pit locations. It is important to ensure, before drilling a 5" diameter hole in the slab, that the PVC suction piping will not encounter any obstacles in the attic when penetrating the ceiling. The holes drilled through the slab must be large enough to allow the installer to excavate a 36" diameter hemispherical pit (18" radius) in the fill material immediately under the slab (Figure 12). Using an industrial vacuum cleaner to aid in the removal of the excavated fill sands has still resulted in several hours being taken to complete one excavation. Following the excavation process the PVC piping is assembled loose in order to ensure proper routing into the attic space. The system diagramed in Figure 12 provides access to the suction pit using a 4" PVC "Y" fitting at the bottom of the pipe system. Either branch of the "Y" fitting can be used for access. Two inch diameter PVC piping is then used to connect the suction pit with the attic mounted fan unit. Just above the suction pit however, is a condensate trap. This functions to keep any condensate which forms in the vertical run of piping from draining back down into the suction pit and saturating the soil. Severe system degradation might result if this condensate is allowed to saturate the soil around the suction pit. Just below the ceiling is a PVC ball valve which can be used to balance the airflows and/or suction pressures in multiple suction point systems. Inside the attic cavity, the horizontal piping is constructed with a slight slope to allow the condensate to drain back to the trap. The attic piping terminates with a 4" PVC double sanitary tee which supports the fan unit. The fan is mounted with rubber couplings in an attempt to control vibration and noise. A 3" PVC pipe was used to penetrate the roof deck and terminate in a weather proof flashing. The flashings used in this research project were of a configuration



TYPICAL SUB-SLAB DEPRESSURIZATION SYSTEM

FIGURE 12

that a 4" pipe would not fit into the flashing when mounted at the angle of the roof slope. Expanding foam insulation was used to seal between the pipe and the roof deck to ensure that the exhaust would not be drawn back into the attic. The location of the termination point should be as close to the ridge of the roof as possible in order to allow for the best dispersion of the radon enriched exhaust.

After the piping is test assembled final solvent welding is completed at all joints making sure that those joints in the occupied space are completely sealed. The 4" PVC "Y" is then anchored into the slab with grout and caulk. It is recommended that a dedicated electrical circuit be installed to power the fan unit.

When the system is complete and the fan is activated, the suction created in the piping and the pit is extended into the soil under the slab. The strength of the negative pressure field created in the sub-slab fill is related to slab geometry and distance from the suction pit. Therefore, on large or irregularly shaped slabs, several suction points may be necessary in order to achieve satisfactory pressure field development. The technique of joining two suction points to one fan in the attic has been successfully demonstrated on multiple occasions.

A major advantage of the sub-slab depressurization system is the induced effect of reverse, or counter flow. This phenomenon occurs when indoor air, also responding to the laws of fluid dynamics, flows from the indoor space through any penetration in the floor into the low pressure zone under the slab. This results in an additional level of protection against radon migration and effectively eliminates the need to seal all the floor system penetrations. A significant benefit of this condition is that future cracks or penetrations will not result in increased radon entry.

New structures under construction can take advantage of the building process to optimize the effectiveness of a sub-slab depressurization system. Various techniques can be utilized at this point - during the construction process - to maximize pressure field development with the fewest number of fans. Multiple suction pits, located in the most optimum locations, can be joined together below the slab and then routed to a fan in the attic through a wall cavity. Higher levels of effectiveness and system confidence are achieved when the installer is not limited to locating the suction points only where the floor plan allows. Very high levels of effectiveness have been achieved by installing lengths of drainage-type matting in a configuration which allows the suction pressures to be more efficiently distributed under the slab. EnkaVent, a trademarked product of AGZO Industries, has been field tested by the UF Indoor Radon Task Force in a test slab program and has shown this type of product to be very effective in increasing the size and strength of the sub-slab pressure field.

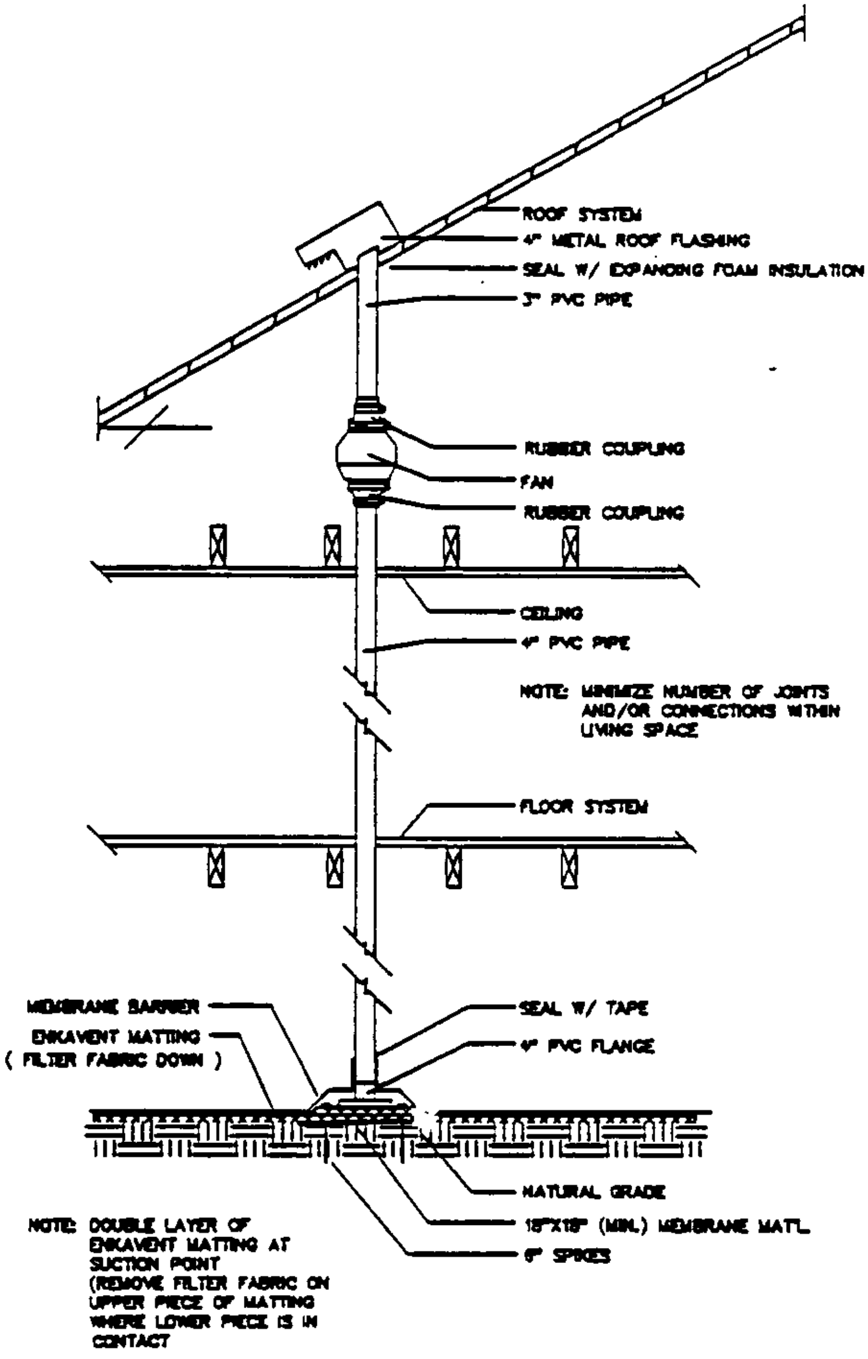
Crawlspace Construction

Sub-barrier depressurization/diversion systems are highly effective at controlling radon in crawlspace type construction. By applying suction under a membrane barrier, a low-pressure, or diversion, zone can be created. Radon bearing soil gas will migrate to the point of least pressure and be piped to a preferred discharge point.

These systems function the same way as a sub-slab depressurization system except that a polyethylene membrane is the only barrier component. High levels of efficiency have been achieved by utilizing a drainage matting material, such as EnkaVent, as a pressure distribution manifold. This matting was installed with the filter fabric down in a connected pattern and covered with the polyethylene sheeting (Figure 13). At the suction point, a double layer of drainage matting is provided by placing an 18" square piece of drainage matting, with the filter fabric removed, on top of the length of matting installed as the manifold grid. To minimize the movement of fine soil particles through the filter fabric at the suction point it is recommended that an 18" square piece of polyethylene sheeting be installed under the suction point. Centered on the double matting, a 4" PVC pipe flange is spiked to the ground and connected to a 4" PVC pipe. This pipe is then routed to the attic where it is connected to a fan unit. The discharge of the fan is exhausted through a free-flow weatherproof flashing located as close to the ridge as possible.

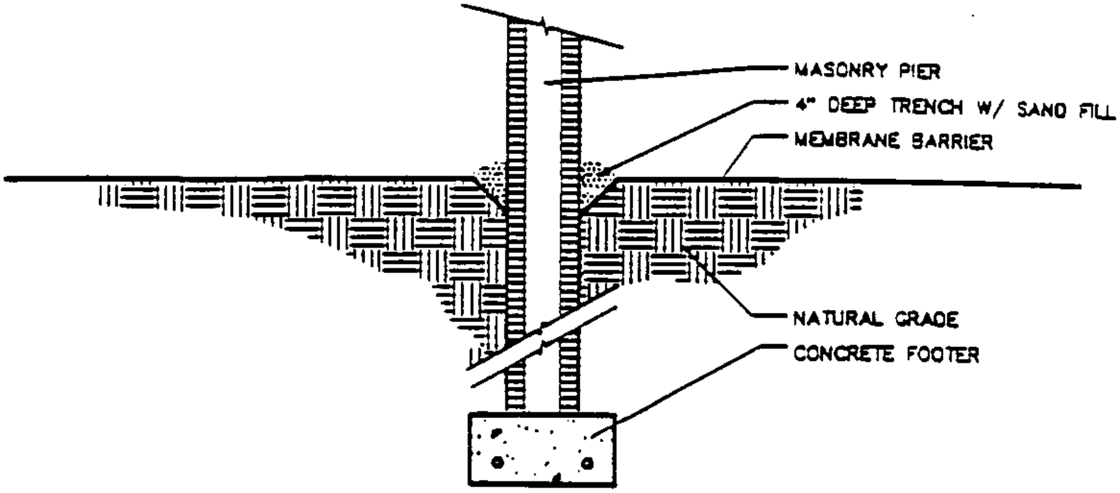
The polyethylene membrane barrier is installed over the drainage matting grid once the suction point is assembled. All laps, punctures, tears, etc. will be sealed with an appropriate tape. Figures 14-A & 14-B illustrate a cost effective way of terminating the edge of the membrane barrier. It is not necessary to attain a perfectly sealed barrier with the sub-barrier depressurization system. Once the fan is activated the leaks in the barrier will be in a reverse direction, ie. from the crawlspace air to the sub-barrier zone.

With the fan operating, the high suction pressure quickly develops throughout the network of drainage matting and results in a larger area of influence being achieved than that produced by a single suction point without the highly permeable matting. Tears, punctures or compromised boundary seals are not as significant a concern with the sub-barrier depressurization

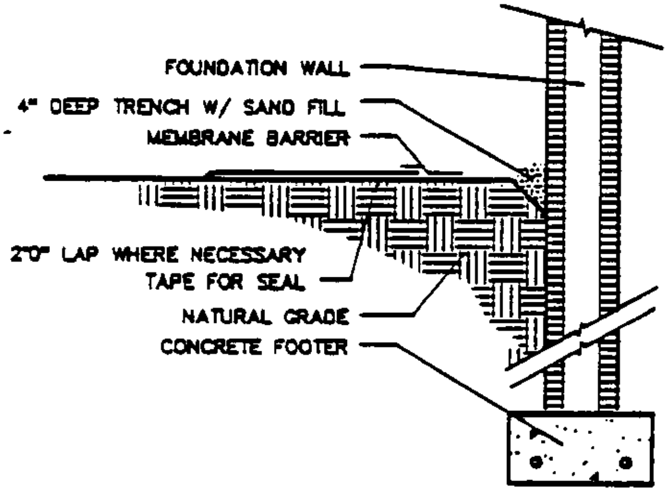


TYPICAL SUB-BARRIER DEPRESSURIZATION SYSTEM

FIGURE 13



A - TERMINATION AT PIER



B - TERMINATION AT PERIMETER FOUNDATION WALL

MEMBRANE BARRIER TERMINATION DETAILS

FIGURE 14

system due to the counter flow effect. Also, HVAC induced pressure effects are minimized or eliminated.

Crawlspace sub-barrier depressurization systems are easily and cost effectively installed in either new or existing structures. In new construction, however, the piping can usually be routed through a wall cavity instead of through closets or living spaces, eliminating any cosmetic difficulties.

DILUTION SYSTEMS

Of all the radon mitigation approaches, the dilution technique may be the one best reserved as the system of last resort. If radon can not be prevented from getting into the structure then there is little else to do but minimize its effects through dilution.

Dilution is achieved by increasing the air exchange rate of the structure, thereby ventilating the space with outside air. In some parts of the country where humidity is not a problem, simple air-to-air heat exchangers can lessen the energy penalty associated with the induction of unconditioned air. However, in sub-tropical climates like Florida, both sensible and latent heat must be managed. Hot and humid air being used to ventilate an air conditioned space, for purposes of diluting the radon concentration, places two burdens on the HVAC system. Simply lowering the temperature (sensible heat) is not sufficient to achieve comfort. Therefore, removing the excess humidity (latent heat) must also be accomplished. Very few air-to-air heat exchange systems can manage both tasks. Heat pipe heat exchange units, installed between the supply and return-air ducts, near the evaporator coil can increase the system's dehumidification efficiency by as much as 30%. With the humidity reduced at no energy burden, comfort can be achieved at higher temperatures. This results in the air conditioning system having to operate less frequently in order to maintain the desired level of comfort. Of course, the dehumidification only occurs when the air conditioning system is operating. When the A/C is off and the air handler is providing the necessary dilution air, no thermal or humidity modification is being effected.

Utilizing this technique in existing construction is probably best reserved for those occasions where other techniques have failed to successfully reduce indoor radon levels and/or the structure doesn't lend itself to the application of the other techniques. The energy penalties associated with a dilution approach are considerable and must be understood before choosing this approach.

New construction should never have to utilize the dilution approach for radon control. However, if for some reason this technique was chosen, the entire HVAC system should be designed for the additional sensible and latent heat loads.

PRESSURE CONTROL SYSTEMS

In virtually all structures some mechanical system is creating a negative pressure condition within the occupied space. The worst conditions are usually produced by the HVAC system and/or clothes dryer. When negative pressure conditions are created then a pressure differential or driving force results and radon bearing soil gas is effectively drawn into the structure. Any mechanical or thermal appliance can produce localized depressurization conditions. In many instances, simply providing replacement air for that air which is exhausted will reduce or eliminate the negative pressure condition. This replacement or make-up air must be supplied from a source outside the indoor pressure envelope.

HVAC Systems

Heating and air conditioning systems are usually forced air type systems. Whenever fans are used to move air there exists a low pressure zone and a high pressure zone. The supply ducting is of course under high pressure, and if located outside of the conditioned space and not completely sealed, can leak and cause an unbalanced condition. If supply air is lost a negative pressure condition is created as the fan attempts to satisfy its demand. On the other hand, if the return-air ducts are leaky and are located in a radon contaminated environment, the radon will be inducted into the duct system and distributed throughout the house.

Improperly constructed box plenums that utilize the concrete slab or wood floor as the bottom of the plenum can induce great quantities of soil gas to flow through any penetrations that are present in that area. All box plenums constructed on the floor should be examined and sealed against any outside air intrusion. Paticular attention should be given to sealing any cracks or joints in the slab under the box plenum.

In houses where one or two centralized return-air grills are used, negative pressure conditions can result when doors are closed to rooms being supplied with air but not provided with a return-air duct. High pressure conditions result in these rooms as the air is restricted from freely returning to the return-air grill. As the supply air is being restricted the fan is attempting to satisfy its demand and localized depressurization results. If this condition exists in rooms that have numerous penetrations through the floor, increased radon flow can result.

Clothes Dryers

Most clothes dryers utilize indoor conditioned air as the air source for the drying operation. Of course, the heated and high humidity laden air is then discharged outside. Without any resupply of air into the room negative pressure conditions result. Laundry rooms are one of the areas with the greatest number of floor penetrations. Therefore, localized depressurization of this space can result in significant radon entry.

Mitigating this condition is relatively simple. By installing a duct to the outside and terminating it, preferably behind the dryer, air will be drawn in from the outside, thus eliminating or minimizing the indoor negative pressure condition.

Fireplaces

Older, conventional fireplaces that are not equipped with an outside combustion air source and doors separating the firebox from the room can cause significant room depressurization when operating. In this type of fireplace, when the fire is burning, conditioned room air is used for combustion and exhausted up the chimney. Vast quantities of indoor air are also drawn up the chimney during the process. Anytime indoor air is exhausted to the outside without make-up air being provided, localized negative pressure conditions result. Since conventional masonry fireplaces are usually constructed on a separate footing and isolated from the floor slab by expansion joints, major entry conditions exist in very close proximity to the point of lowest pressure.

If the installation of a dedicated combustion air supply into the firebox is impracticable, the homeowner should at least partially open a window in the same general area. This will allow make-up air to be readily available to the fireplace. Even though discomfort may result from cold drafts, a significant radon problem can be mitigated.

Down-flow Vented Cooktops

Modern cooktop units equipped with high capacity down-flow type fans can cause localized negative pressure conditions in the kitchen area. If the kitchen is closed off from the rest of the house, the resulting low pressure zone can induce radon to enter through the multiple floor penetrations common to kitchens.

Mitigation of this condition can also be achieved either by ducting a make-up air supply in close proximity to the unit or by partially opening a window.

In conclusion, when considering all the various mitigation techniques and strategies available, it will be rare that any single technique will be employed as the total radon abatement system. In selecting the most appropriate radon control system for existing structures, many issues must be considered, including the construction specific variables and the homeowners acceptance of those techniques. Because each structure is unique, the appropriateness of any mitigation plan must be evaluated with the homeowner in mind. Even though general mitigation principles may be applicable, the homeowner may or may not allow certain modifications to be employed.

CHAPTER 6

CASE STUDY 1

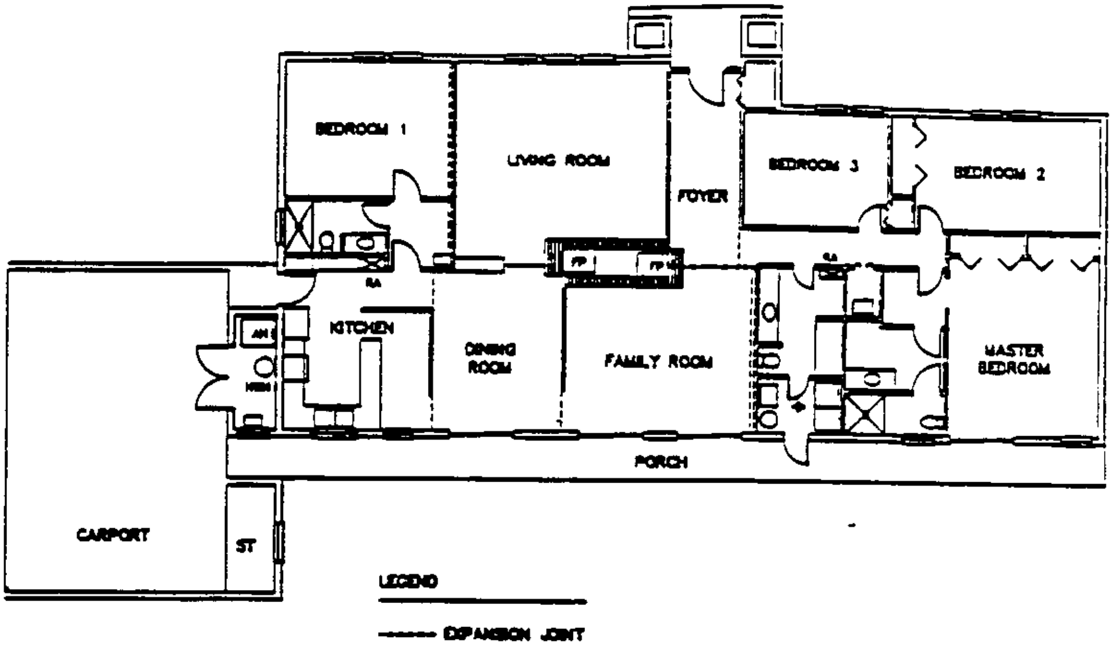
CONSTRUCTION CHARACTERIZATION

GENERAL

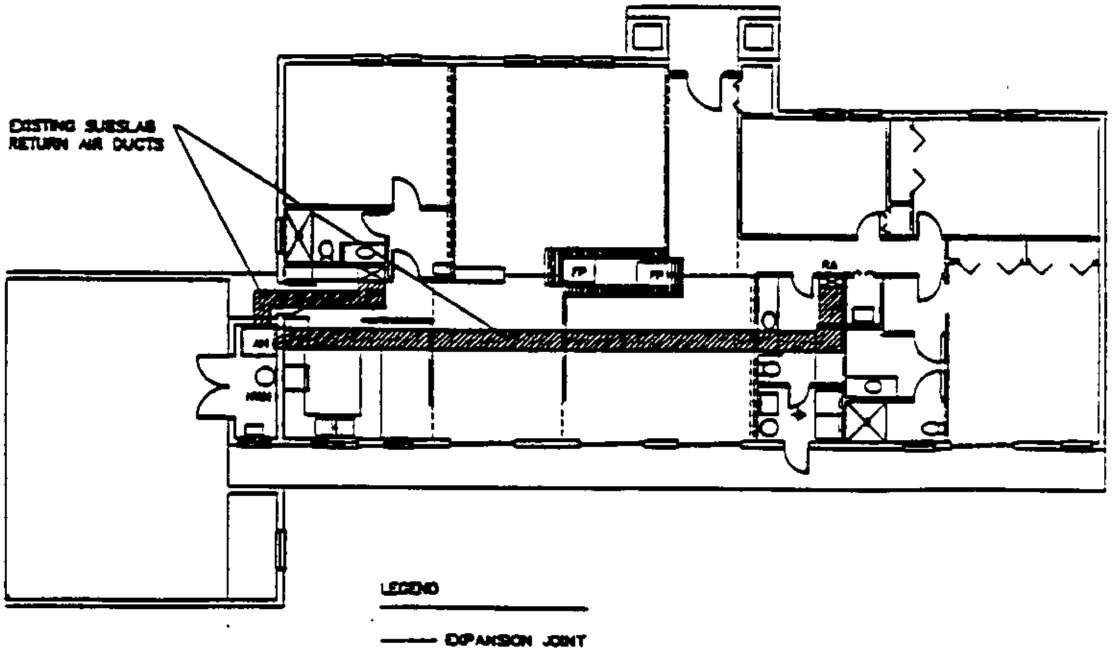
The house investigated as Case Study #1 is a four bedroom, three bath structure (Figure 15) which was constructed in 1967 on a slight to moderately sloping site. The site has been classified as a high risk radon producing site by the UF Indoor Radon Task Force from previous research conducted for the US Environmental Protection Agency. This house was one of more than 300 homes tested in Alachua and Marion Counties for elevated levels of radon under the U.S. EPA study. Case Study #1 had the highest indoor radon level (128 pCi/L) of all homes in the screening test program tested with charcoal canisters. The homeowners were very willing to participate in this research effort in hopes that a satisfactory reduction of the radon levels could be achieved.

STRUCTURAL SYSTEM

The house was constructed of 4" high, natural finish yellow masonry block. This block, locally referred to as "Ocala" block, does not have any exterior coating applied. The natural finish of this block, while very attractive, also does not hide any blemishes very well. The exterior load bearing walls were supported by a continuous concrete spread footing. The interior



A - FLOOR PLAN



B - SUB-SLAB RETURN AIR DUCT LAYOUT

FLOOR PLAN AND SUB-SLAB RETURN AIR DUCT LAYOUT

FIGURE 15

load bearing walls were supported by thickened, reinforced areas of the concrete floor slab. A reinforced bond beam was cast at the top of the masonry exterior wall. Vertical reinforcing extended from the footing to the bond beam at the corners and at various other locations. No structural problems or abnormalities were observed.

FLOOR SYSTEM

The main floor slab was constructed as a "floating slab" and did not penetrate into the masonry wall, thereby producing a continuous joint between the wall and the slab around the entire slab perimeter. Two conventional masonry fireplaces were constructed on a separate pad footing and isolated from the main floor slab by expansion joints. Several control joints were constructed in the floor slab to minimize future cracking in the areas where slate flooring was utilized. The living room slab was recessed 4" from the main floor slab and curing type cracks were observed along the perimeter of the recessed area.

ROOF SYSTEM

The fiberglass shingle roof was constructed on plywood decking with conventional (non-truss) framing which provided minimal but accessible attic space. The supply ducting from the gas furnace and air conditioning system was installed in the attic cavity and consumed most of the usable space.

HVAC SYSTEM

This house was equipped with a natural gas furnace and gas air conditioning system. The furnace and air handler are located in a ventilated storage closet in the carport. The return-air ducting was located below the floor slab in the sand fill. This ducting was constructed of 16" diameter spiral metal piping with the sub-slab concrete plenum cast under the airhandler. Two separate runs of piping connected the plenum to two individual air return points, both located in the hall (see Figure 15).

PLUMBING SYSTEM

Three full bathrooms and an interior laundry room resulted in many plumbing penetrations through the slab. The laundry room was also provided with a floor drain for washer overflow protection. The outlet to this drain was not determined. The hot water heater was located in the same storage closet that the HVAC unit was located in.

OTHER PERTINENT CHARACTERISTICS

The two masonry fireplaces were not equipped with glass doors or an outside combustion air source. When operating, these fireplaces consume large amounts of conditioned air and exhaust it up the chimney creating negative pressure conditions inside. This is also true of the clothes dryer which was located inside the conditioned space.

IDENTIFICATION OF POTENTIAL ENTRY ROUTES

Radon entry conditions identified in this structure included many of the worst conditions ever encountered. The primary entry route was judged to be the sub-slab return-air duct system. The spiral piping used to construct over 75 feet of buried ducting provided numerous opportunities for radon to be drawn, or mined, from the sub-slab soils by the high suction pressures created by the air handler. Once the radon was drawn into the duct system it was distributed throughout the entire house.

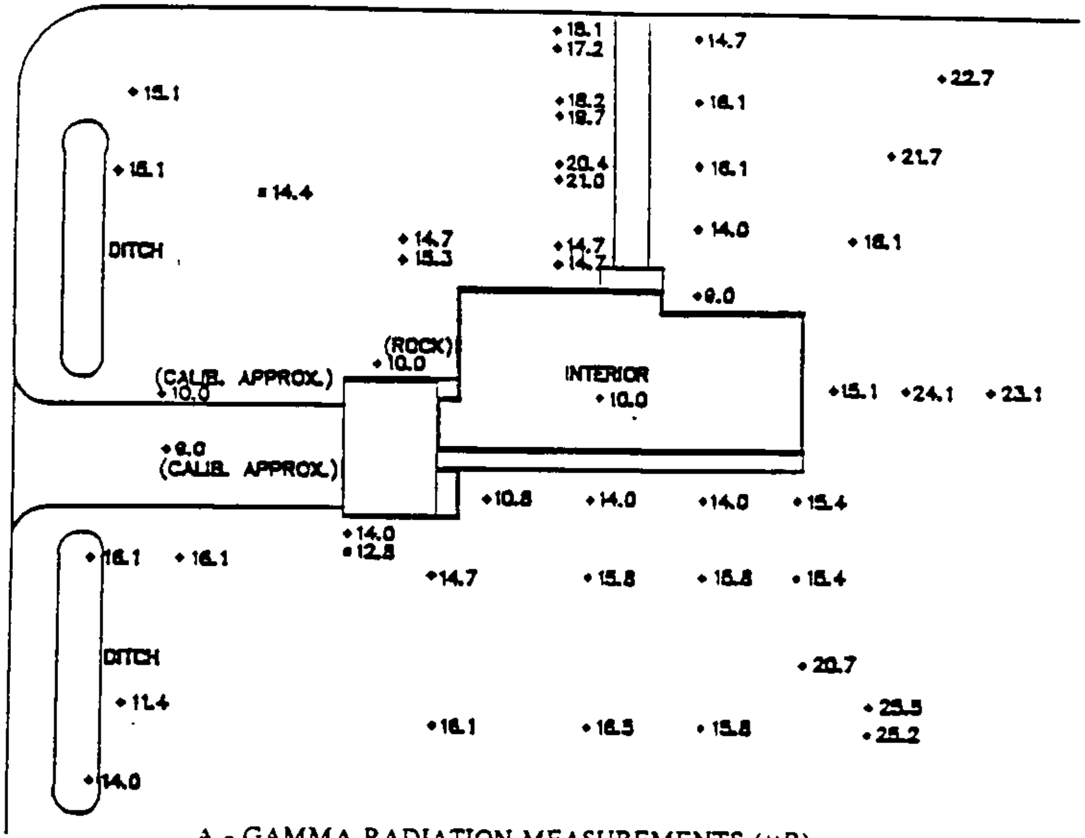
Other significant entry conditions were determined to be associated with the masonry wall construction in conjunction with the floating slab. The slab/foundation technique used on this house, the floating slab technique, does not provide a cavity seal between the sub-grade masonry and the above-grade masonry. By not having this cavity sealed, radon entering the masonry wall is allowed to migrate quickly and easily throughout the entire wall cavity. When electrical switch and receptacle boxes are installed a hole is usually broken into the masonry wall to allow the box to be sufficiently recessed so the face of the box is flush with the finish wall. When interior pressure conditions are caused to be lower than the pressure in the wall cavity, the radon laden air is drawn through the many penetrations in the masonry wall into the occupied space. Also, as the expansion joint material used to form the perimeter expansion joint between the slab and the masonry foundation wall, decays over time it produces a major entry path for radon. An expansion joint was also created between the floor slab and the fireplace structure. Although this provided isolation of the fireplace structure from the floor slab, it also resulted in a major pathway for radon entry.

Numerous other penetrations through the floor slab were identified as radon entry routes. Plumbing penetrations, control joints and curing related cracks were also present in this structure. Cracks which completely penetrate the slab are usually confirmed to be radon entry points. Several control joints had been placed in the slab during construction to minimize future cracking of those floor areas where slate flooring was applied. These control joints produce a smaller cross sectional area of the slab, causing a weak point which induces the internal curing stresses to fracture the slab along the control joint. The resulting crack normally penetrates through the entire slab providing radon another entry route. The recessed floor area in the living room resulted in typical curing related cracks around the perimeter of the recess. Since plumbing penetrations through the slab are, for the most part, totally inaccessible, the entry conditions associated with them can not usually be visibly determined. However, diagnostic testing with a continuous radon monitor in the "sniffer" mode can confirm if elevated levels of radon are present in these inaccessible locations. All of these conditions, once identified, were later examined during the diagnostic testing program to confirm the presence of radon gas.

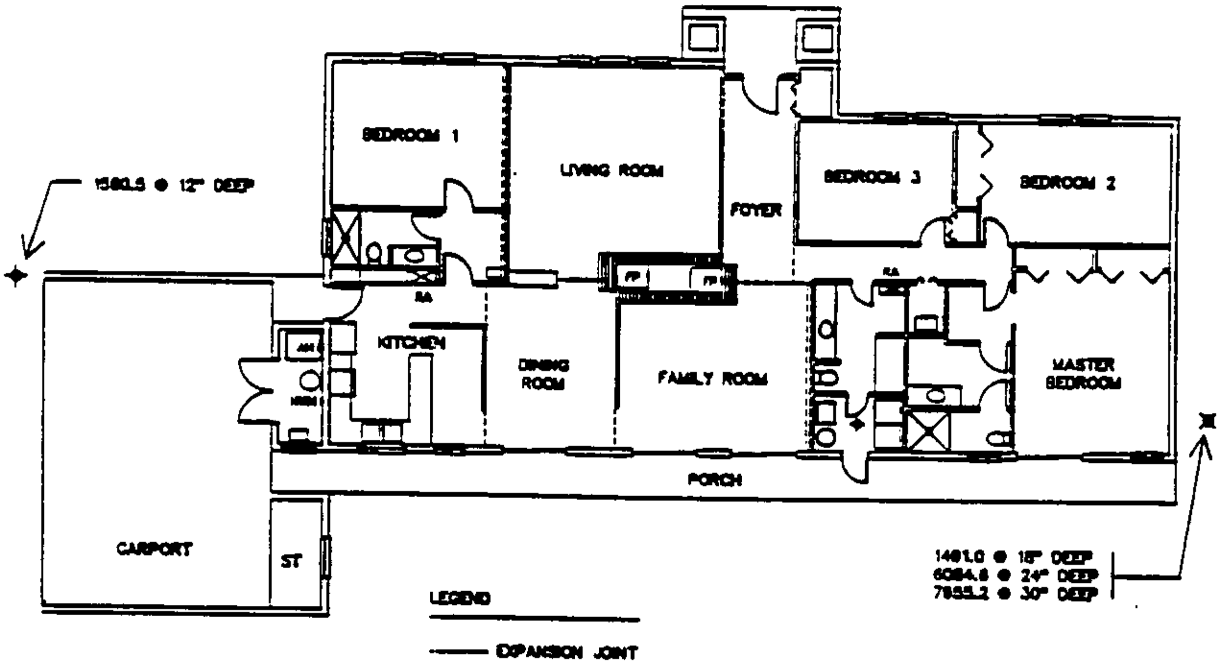
DIAGNOSTIC TESTING

A series of diagnostic tests were conducted on this structure in order to determine the magnitude of the radon problem and to confirm if radon was entering the house at those locations identified above.

The first test conducted upon arrival at the site was the outdoor gamma radiation test. The results of this test, illustrated in Figure 16-A, show moderate to very high soil radiation levels. The native soil on this site was found to be emitting higher levels of gamma radiation than most of the soils found around reclaimed phosphate mines in Southcentral Florida. Gamma emissions in the range measured on this site predict a very high radon source potential. Subsequent soil gas measurements for radon confirmed the presence of high levels of radon in



A - GAMMA RADIATION MEASUREMENTS (μR)



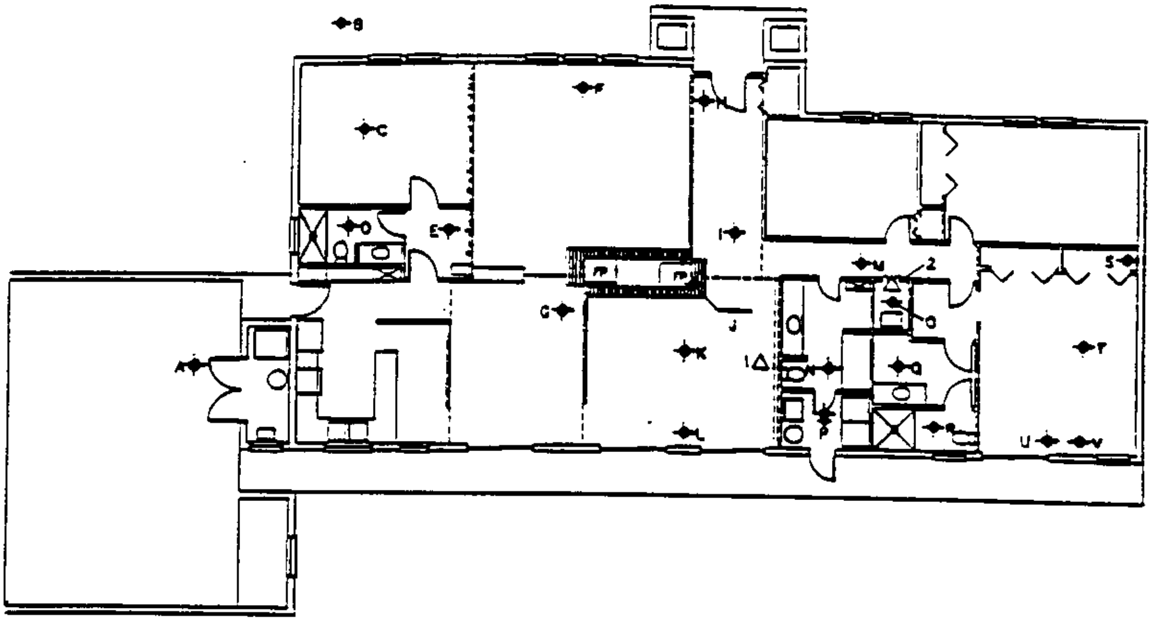
B - SOIL GAS RADON LEVELS (pCi/l)

GAMMA RADIATION AND SOIL GAS RADON MEASUREMENTS

FIGURE 16

the soil around the house (See Figure 16-B). Again, these two tests simply provided the researchers an indication of the magnitude of the problem they were working with.

Grab and sniffer sampling was then conducted to determine radon levels outdoors, inside the house and under the floor slab. See Figure 17 for the results of this testing. Sub-slab grab and sniffer measurements confirmed a very high radon source with levels exceeding 9000 pCi/L just four inches below the floor. With concentrations in this range, very little soil gas must enter the occupied space to make significant changes in the indoor radon level. Sniffer measurements confirmed that most of the suspected entry conditions were active radon pathways. The sub-slab return-air duct system was determined to be the primary entry route. Radon levels were monitored inside the return-air ducting while the air handler was cycled on and off. Elevated radon levels inside the masonry wall cavities, were confirmed as were radon levels at many of the slab penetrations. Small tents of plastic film were taped in place over the slab cracks and the air pumped through the radon monitor. This procedure for all practical purposes isolated the air inside the crack from the rest of the room air. The resulting radon levels were therefore representative of the gas migrating up through the crack from below the slab. Small holes were punched through the wall board just above the baseboard so that a small length of tubing could be inserted into the cavity for radon levels to be measured. This technique was especially useful for confirming suspected entry conditions associated with plumbing. In this house, no evidence was found that radon was entering through any openings under the bathtubs or shower stalls.



MARK	SAMPLE LOCATION	RADON LEVEL (pCi/l)
A	HVAC - RETURN AIR PLENUM - AMBIENT	103.1
	HVAC - RETURN AIR PLENUM - FAN ON	93.1
B	BEDROOM #1 - WALL RECEPTACLE	81.8
C	BEDROOM #1 - ROOM AIR	63.0
D	BEDROOM #1 BATH - TOILET BASE	132.7
	" - SHOWER HEAD/WALL PENETRATION	146.1
	" - TOILET WATER SUPPLY PENETRATION	120.6
E	BEDROOM #1 CLOSET - SUB-SLAB	9015.5
F	LIVING ROOM - ROOM AIR	165.4
	" - CABLE BOX	185.6
	" - ELECTRICAL RECEPTACLE	176.1
G	CRACKS AROUND FIREPLACE	115.9
H	LIGHT SWITCH AT FRONT DOOR	47.0
I	EXPANSION JOINT	70.5
J	FIREPLACE HEARTH EXPANSION JOINT	118.7
K	FAMILY ROOM - ROOM AIR	14.1
L	FAMILY ROOM - ROOM AIR	151.4
M	RETURN AIR GRILL - FAN ON	43.1
N	HALL BATH - TOILET BASE	168.2
	" - SHOWER HEAD/WALL PENETRATION	143.8
O	HALL CLOSET - SUB-SLAB	6753.8
P	UTILITY ROOM - FLOOR DRAIN	141.5
	" - WATER PIPE/WALL PENETRATION	164.8
	" - SINK DRAIN/WALL PENETRATION	166.2
Q	MASTER BATH - UNDER SINK PLUMBING PENETRATION	77.9
R	MASTER BATH - ROOM AIR - VENT FAN ON	95.5
S	MASTER BEDROOM CLOSET - SUB-SLAB	3046.2
T	MASTER BEDROOM - INSIDE WALL AT PHONE RECEPTA	70.7
U	MASTER BEDROOM - INSIDE WALL AT LIGHT SWITCH	200.0
V	MASTER BEDROOM - INSIDE WALL AT ELEC. RECEPTA	211.1
GRAB 1	FAMILY ROOM - ROOM AIR	36.7
GRAB 2	HALL CLOSET - SUB-SLAB	9047.0

GRAB SAMPLE AND SNIFFER MEASUREMENTS

FIGURE 17

MITIGATION STRATEGY

After the diagnostic testing was finished and the data examined, it was determined that the primary entry mechanism was the sub-slab duct system. The numerous slab penetrations and masonry wall cavity conduction conditions were also determined to be significant contributors to the indoor radon problem, but not to the same degree as the duct system.

Selecting the most appropriate mitigation strategy for this house had to be done with consideration for two other issues. First, the overall cosmetic/aesthetic condition of the house, both inside and out, was very high. The simplistic, clean design of the house meant that modifications to the house would be easily noticed. The exterior natural finish yellow block did not allow for penetrations, associated with some of the mitigation strategies, to be made and cosmetically concealed. Secondly, the homeowners did not want the installation of the mitigation system to significantly disrupt their daily routine or cause significant repairs or reconstruction to be needed. Considering these two factors, the number and variety of mitigative options that could have been utilized on this house were minimized.

The recommended mitigation plan was developed to be implemented in two phases.

PHASE 1 MITIGATION ACTIVITIES

The first phase would entail the following:

1. Terminate the existing return-air duct system and install a new return-air duct system in the attic cavity.

2. Depressurize the abandoned return-air duct with a small fan to create a sub-slab depressurization system.

These two activities could be accomplished without affecting the cosmetic/aesthetic condition of the house and at the same time eliminating the worst entry condition. Using the existing sub-slab ducting as a sub-slab depressurization system took advantage of an opportunity to create an intercept zone for the radon laden soil gas (Figure 18). It was predicted that if the pressure field could extend far enough it would provide adequate protection to those major slab penetrations. The depressurization system was not, however, expected to reduce the wall cavity radon levels.

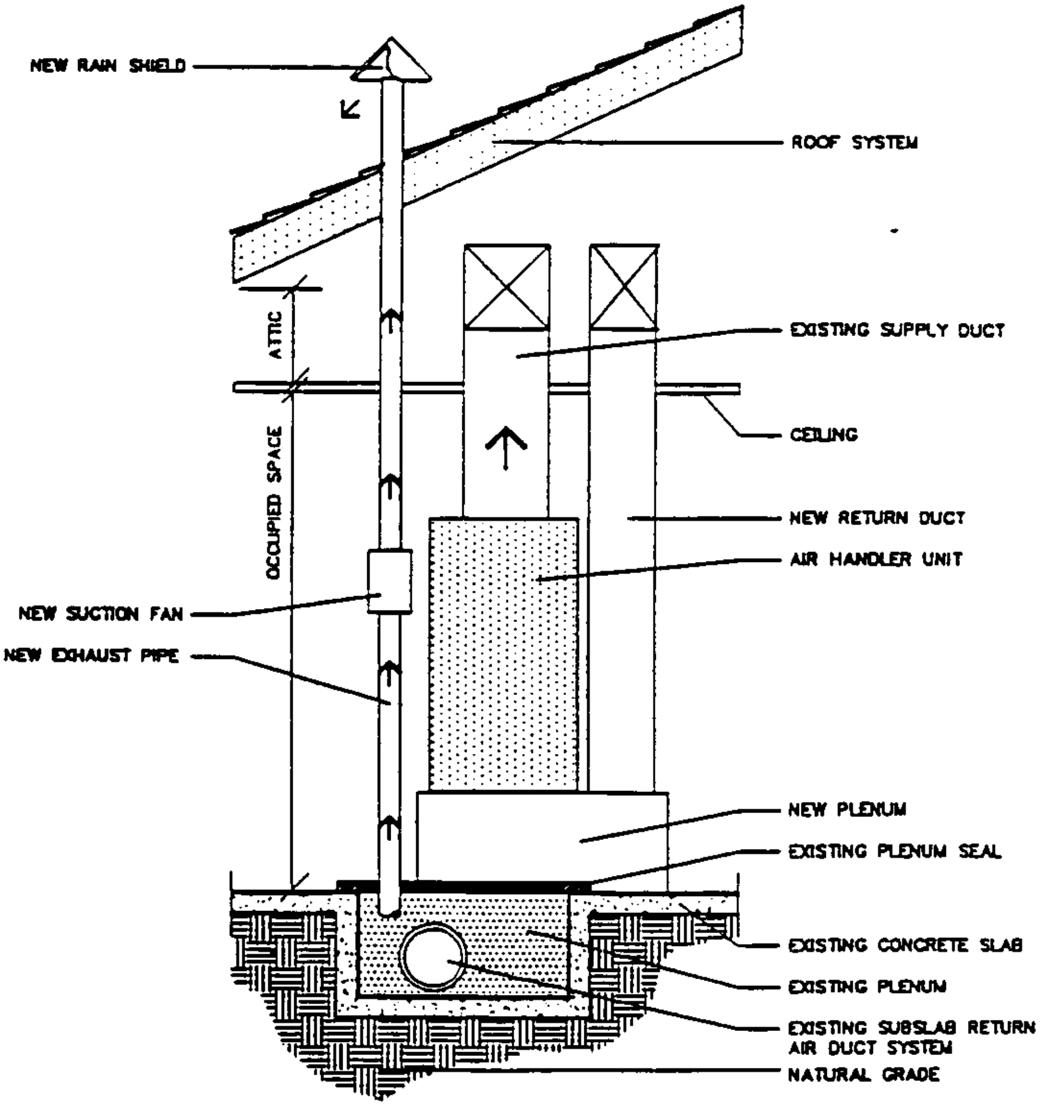
PHASE 2 MITIGATION ACTIVITIES

Phase two was designed to accomplish the following:

1. Create an indoor pressure barrier by inducting outside air into the return-air system.

2. Install a heat pipe heat exchange unit to offset the energy penalty created by the outside air.

The Phase 2 plan was selected in lieu of several other techniques that were felt to be more applicable to the particular entry conditions associated with this structure. However, in consideration of the cosmetic/aesthetic issue and the homeowner's reluctance to having the

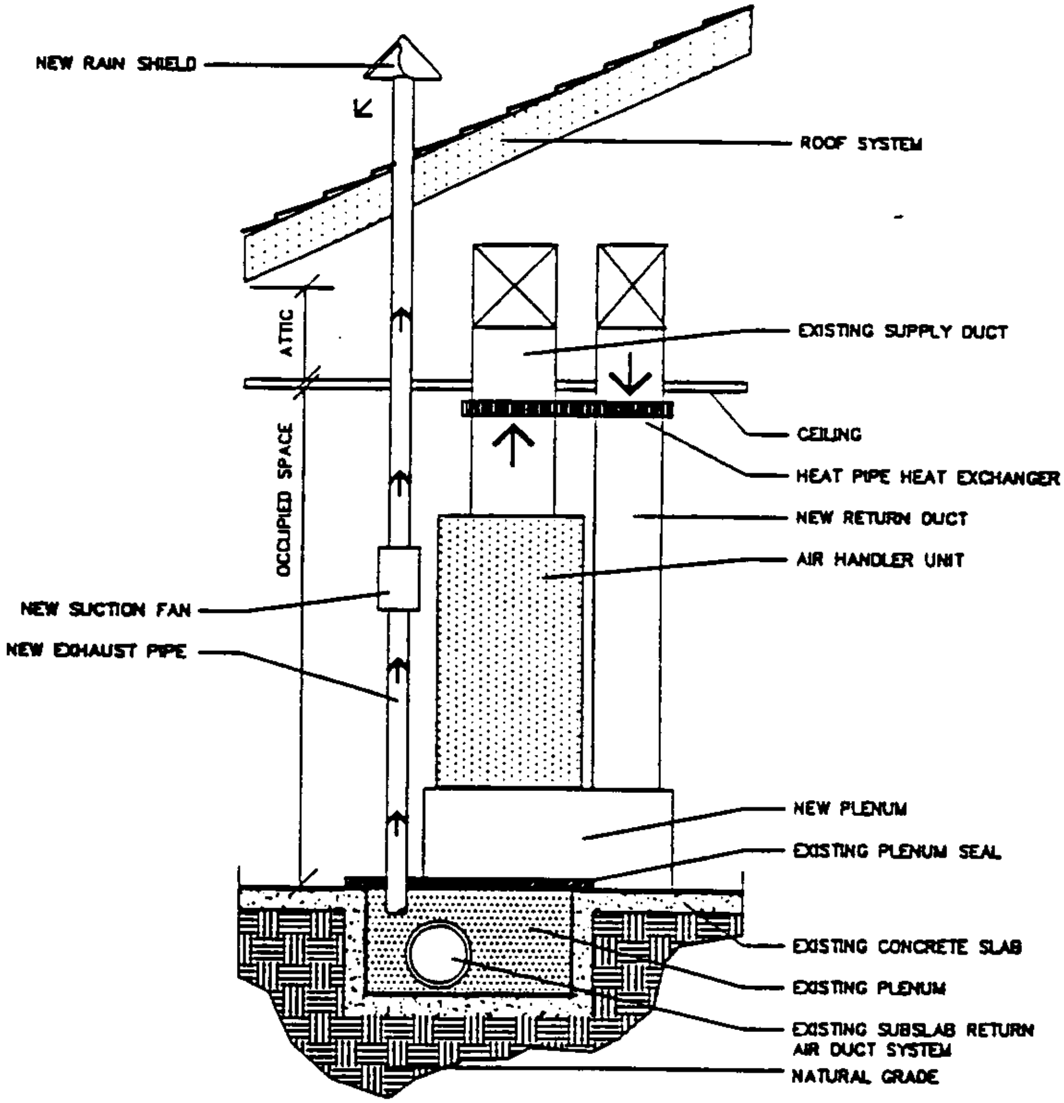


PHASE I MITIGATION PLAN

FIGURE 18

flooring and baseboards removed, this plan was recommended. The induction of outside air into the new return-air system effectively causes a high pressure condition to be developed inside the house (Figure 19). Of course, this pressure is only maintained while the airhandler is operating. For this reason it is necessary to operate the airhandler continuously resulting in warm, moisture laden outside air being drawn into the house. This results in higher indoor temperatures and humidity levels causing the air conditioning system to operate more frequently to maintain the desired comfort level. Increased energy consumption from operating the fan in a continuous mode and the more frequent cycling of the air conditioning system results in elevated utility bills. To reduce this energy penalty the heat pipe heat exchange unit was prescribed (Figure 19). Heat pipe heat exchangers are passive units, not requiring any energy to operate, which can increase the dehumidification efficiency of the air conditioning system by approximately 30%. By increasing the dehumidification efficiency of the HVAC system, comfort can effectively be achieved at a higher thermostat setting. This can reduce the frequency of air conditioner cycling and reduce the energy penalty.

Following the presentation of the mitigation plan, the homeowner contracted the work to a local HVAC contractor who also happened to be a state certified radon mitigation contractor. The HVAC contractor also is a manufacturer of heat pipe heat exchangers. The homeowner instructed the contractor to install both Phase 1 and Phase 2 systems at the same time. This decision by the homeowner did not affect the research program, but eliminated any opportunity to save the cost of the Phase 2 system if the Phase 1 plan proved sufficiently effective.



PHASE II MITIGATION PLAN

FIGURE 19

ALTERNATIVE MITIGATION STRATEGIES

These two mitigation plans did not specifically address two of the major entry conditions: the masonry wall conduction and the perimeter slab/wall joint. Both of these entry conditions would have required major construction efforts on both the interior and exterior of the house. If Phase 1 and 2 mitigation plans proved to be unsuccessful at lowering the indoor radon levels to an acceptable level, alternative strategies would have had to be considered. Two techniques under consideration were a baseboard suction system and a wall cavity depressurization system. These techniques were not recommended because of the amount of material removal and reconstruction necessary, not to mention the impact on the cosmetic/aesthetic condition of the house.

The baseboard suction system would have required the removal of all of the baseboard along the exterior wall. This would have exposed the slab/wall expansion joint and allowed a perforated PVC pipe to be installed to evacuate the radon as it migrated up through the joint. Difficulty in sealing the cavity behind the wallboard to prevent a loss of the suction field was expected. Also, routing the PVC piping behind intersecting interior walls and connecting the piping to a suction fan was expected to be very difficult and costly. The amount of demolition necessary to install this system was totally objectionable to the homeowner and therefore was not included in the recommended mitigation plan.

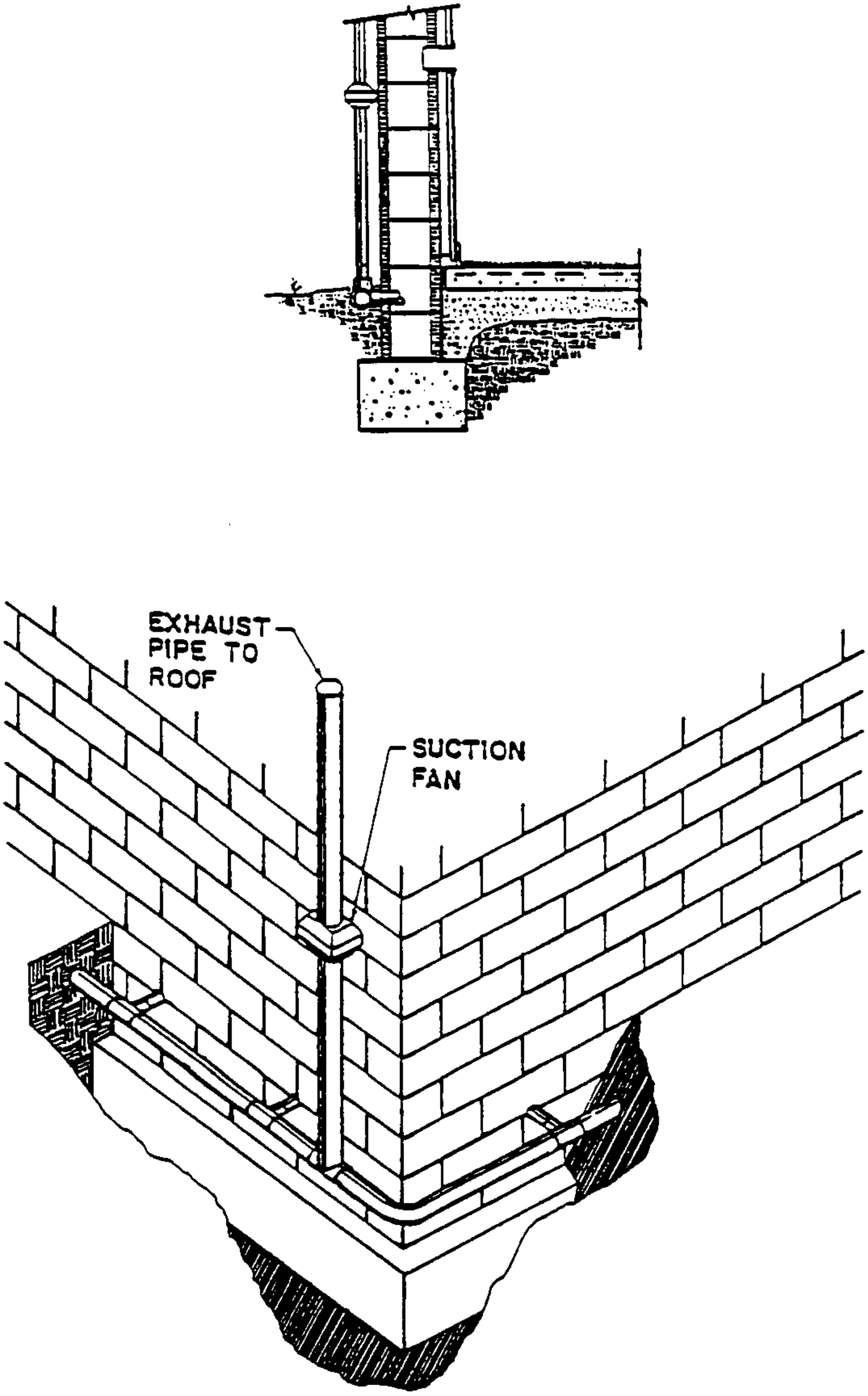
The wall cavity depressurization system would have required the exterior masonry wall to be tapped in multiple locations in order to create a negative pressure field inside all independent wall sections. Vertical reinforcing of masonry walls effectively separates the wall cavity into separate zones. Each of these zones would have to be accessed and tapped (see Figure 20). Exterior sidewalks adjacent to the building would have had to have been removed in order to access several of the wall cavities with the highest radon contaminations. Again, this amount of demolition and cosmetic damage was not acceptable to the homeowner. However, if Phase 1 and 2 did not prove effective at lowering the indoor radon to an acceptable level then these alternative strategies would have to be considered.

POST-MITIGATION EVALUATION

After the contractor had finished the installation of the Phase 1 and Phase 2 mitigation plans post-mitigation testing commenced. With both Phase 1 & 2 systems operating, indoor radon levels were reduced to the 2.8 to 3.2 pCi/L range (see Table 1). This degree of reduction was unexpected but very encouraging.

CASE STUDY #1		RADON MEASUREMENTS
PRE-MITIGATION LEVELS:	LIVING SPACE	
	Closed House	63.0 pCi/L
	Open House	15.0 pCi/L
	Average	45.0 pCi/L
	Spikes as high as:	190.0 pCi/L
POST-MITIGATION RADON LEVELS:	LIVING SPACE	
	Phase 1 & 2	2.8 pCi/L
	Phase 1 & 2	3.2 pCi/L
	Phase 1 only	3.0 pCi/L
	Phase 1 & 2	2.8 pCi/L

TABLE 1
Indoor Radon Measurements



WALL CAVITY DEPRESSURIZATION SYSTEM

FIGURE 20

Additional testing was conducted to determine the degree of effectiveness of each of the mitigation systems. The results proved to be very interesting. With the Phase 2 system disconnected the indoor radon levels were maintained at the 3.0 pCi/L level. When the Phase 2 system was reactivated the indoor radon levels only dropped an additional 0.2 pCi/L to 2.8 pCi/L. This meant that the sub-slab depressurization system was effectively reducing the level of radon by itself. The additional level of reduction achieved by the HVAC house pressurization system, 0.2 pCi/L, could be viewed as a beneficial effect, but based upon the cost of the systems, the Phase 2 installation was not judged to be very cost effective.

An additional advantage the Phase 1 installation provided was that no sealing of the numerous slab penetrations was necessary. Reverse, or counter, flow induced by the sub-slab low pressure field provided an additional level of protection of upward movement of the radon gas while not requiring costly caulking or sealing. When recognizing the cost and degree of difficulty in accessing cracks, control joints and plumbing penetrations, the advantages of the sub-slab depressurization system becomes clearly recognizable.

CHAPTER 7

CASE STUDY 2

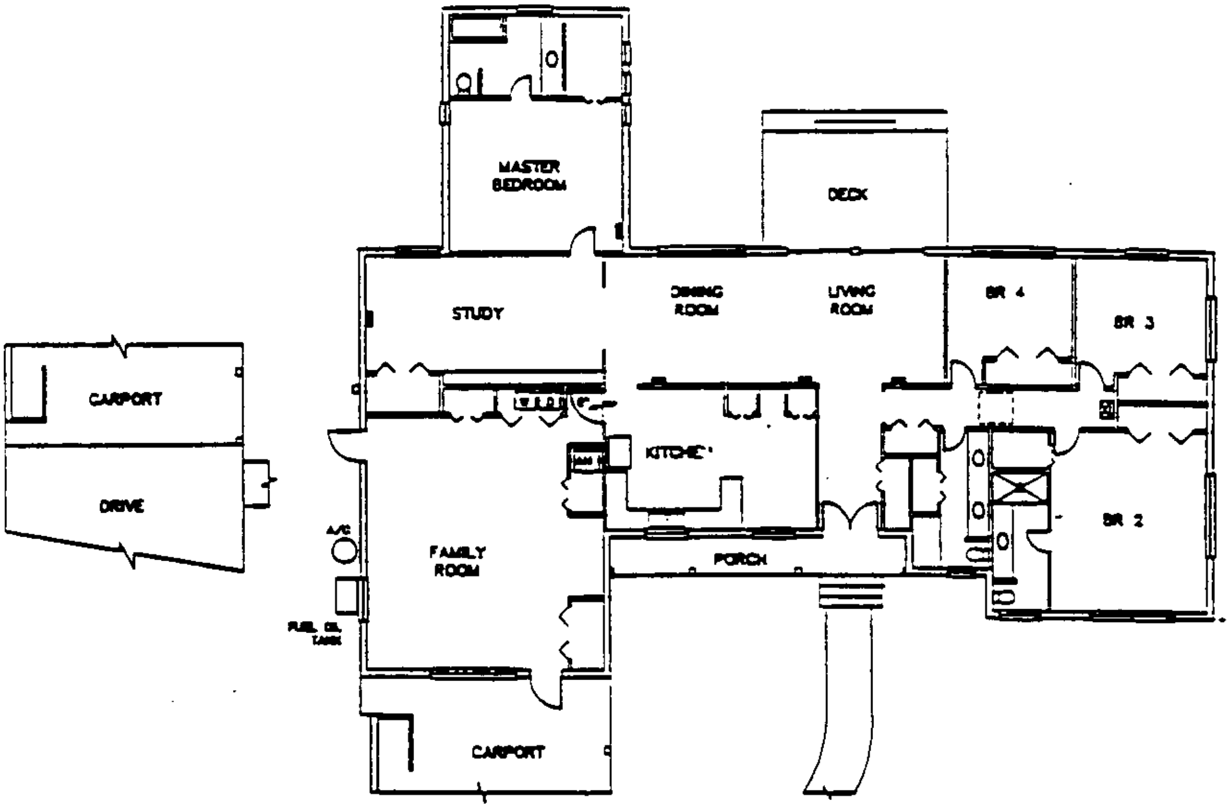
CONSTRUCTION CHARACTERIZATION

GENERAL

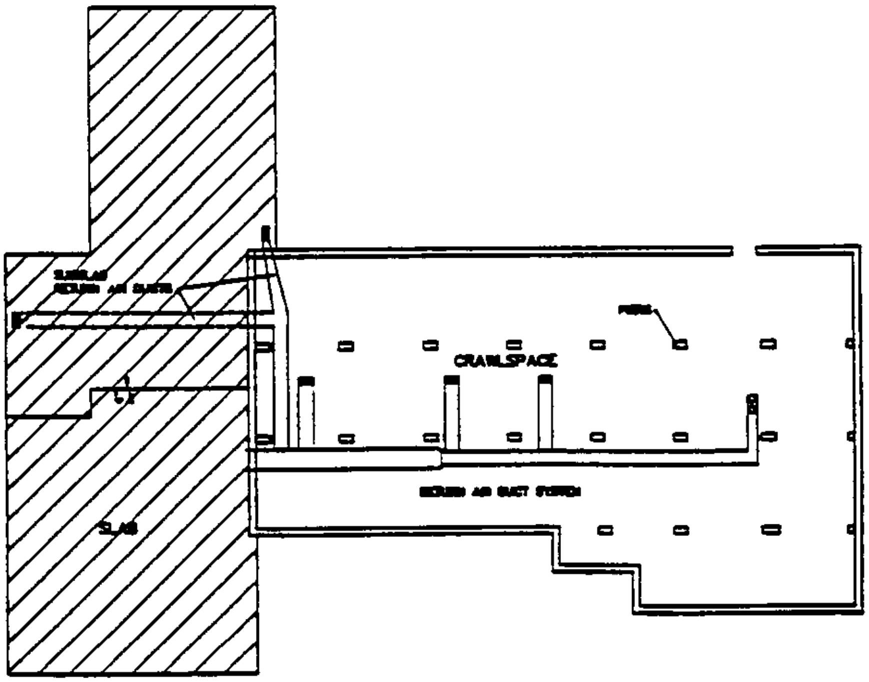
Case Study #2 is a four bedroom, three bath residence constructed on a moderately sloping site in Gainesville, Florida (Figure 21-A). The charcoal canister screening test conducted on this house reflected a radon level of 29.6 pCi/L.

This structure was built in 1960 and has had two additional spaces added-on since its original construction. A new master bedroom suite, including closet and full bath, was added to the rear of the house and a carport with storage room was built on the front, probably at the same time. The original garage was enclosed and is now being used as a family room. This room contains several closet spaces in which the laundry, washer and dryer, and the furnace/air handler are enclosed.

This house provided an opportunity to study a more complex structure having both concrete slab and a raised wood flooring systems (Figure 21-B). Additional areas of interest that this structure provided for study were those created by the addition of new areas of structure. The enclosing of a former garage and the addition of a new wing provided an opportunity to study a slab floor system with sub-slab partitioning. The partitioning of the sub-slab area was



A - FLOOR PLAN



B - FOUNDATION/FLOOR CONFIGURATION

FLOOR PLAN AND FOUNDATION/FLOOR CONFIGURATION

FIGURE 21

produced by the original foundation wall system, dividing one area of sub-slab fill from another.

STRUCTURAL SYSTEM

The exterior load bearing walls of this house are constructed of 8" high standard concrete masonry block. These walls are supported by a continuous reinforced concrete strip footing and terminated with a continuous reinforced concrete bond beam. The slab/wall connection was not determined but suspected to be a floating type slab system. The portion of the house constructed over a crawlspace had three rows of concrete pad footings, each supporting a wood beam on concrete masonry block piers.

FLOOR SYSTEM

The wood floor system was a traditional oak hardwood finish flooring over a subflooring supported by wood joists. The crawlspace was ventilated by 8"x 16" screened openings formed by a decorative block set on edge. Access to the crawlspace was through a 16"x 22" opening at the rear of the house. The vertical clearance in the crawlspace ranged from approximately 40 inches to 20 inches. All framing materials were in good condition and no unusual openings in the floor were observed.

That part of the house constructed with a concrete floor slab included the original study, the new master bedroom suite addition, and the enclosed former garage. The floor of the former garage was eight inches lower than the main floor. Foundation walls partitioned the fill of each of these three slab areas from one another. Portions of cracks were observed along the former garage slab perimeter where it abutted the foundation walls of the study and the adjoining wood floor system, but were found to be inaccessible without substantial demolition. The floor area in the study was covered with ceramic tile. The finish flooring used in the new master bedroom suite was carpet, while square vinyl tiles were used as the finish flooring in the family room or former garage.

ROOF SYSTEM

Fiberglass shingles were used on a plywood decking over a conventionally constructed roof framing system. The shingles were in serviceable condition but were starting to curl and get brittle. The roof was constructed on a 4:12 pitch and with a combination hip and gable design. Ample attic space for working and locating parts of the mitigation system was found for those areas over the original construction. The attic cavity over the new master bedroom addition was very limited and could not be accessed due to the opening between the original attic cavity and the new one being consumed by a HVAC supply duct.

HVAC SYSTEM

A fuel oil fired furnace and electric air conditioning system comprised the HVAC system for this house. For those spaces located above the wood floor system the return-air ducting was routed through the crawlspace, a typical condition for crawlspace houses (Figure 21-B). The return-air ducts for the master bedroom and study which were on the concrete slab were located under the slab. These sub-slab ducts entered the sub-slab area from the crawlspace. The former garage utilized an air return located in the wall of the HVAC closet which connected directly into the air handler. During the diagnostic testing program it was found that this return had been sealed off behind the grill. All supply ducting was routed through the attic cavities. All ducting, both return and supply, was constructed of sheet metal and covered with batt insulation.

PLUMBING SYSTEM

The most unusual condition found with the plumbing system was the amount of ridged copper waste piping installed. The sub-slab piping was not accessible for inspection except for a small area behind the washing machine. At this point a frame wall connected to the masonry foundation. A small hole existed in the wall board and the supply piping was visible. The block cell, that the piping was extending up through was not very well sealed with concrete. This was expected to be a significant entry point.

OTHER PERTINENT CHARACTERISTICS

Several years prior to this study, the homeowner had installed a piping system in the crawlspace to wet the soil along the foundation wall and at the piers. This system was an attempt to control the settling being caused by the shrinking of shrink/swell clay over which the house was constructed. Cracking in the concrete block exterior wall was observed but was very minor at that time. The homeowner subsequently removed the piping system to allow the installation of part of the final mitigation system. Structures constructed over shrink/swell clay usually experience movement related damage over time. This condition is a soil moisture related phenomenon and can manifest itself as either a settling type movement or a heave type movement.

IDENTIFICATION OF POTENTIAL ENTRY ROUTES

Potential entry conditions associated with this house included all slab penetrations, masonry wall conduction conditions, crawlspace return-air duct ingestion and wood floor system penetrations.

Several cracks were noted during the construction evaluation process and considered to be likely entry routes. As with most structures, the plumbing penetrations are inaccessible and can only be assumed to contribute to the overall radon accumulation. It was not conclusively determined if the slab was a "floating" slab or cast into the stemwall. If the slab was cast against the stemwall using an expansion joint at the point of contact, a major entry condition would exist around the perimeter of the floor slab. This would also result in the masonry wall cavity being continuous from the below grade zone to the superstructure.

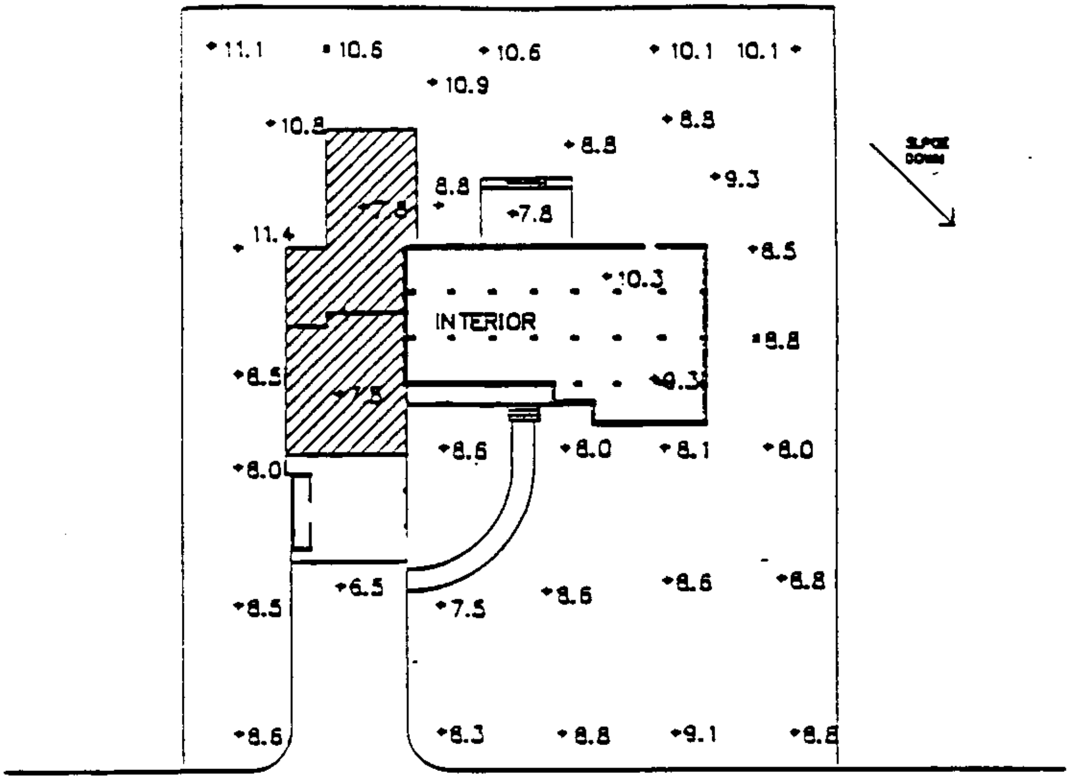
Crawlspaces, even though "ventilated," tend to trap radon laden soil gas and allow for elevated radon levels to develop. Traditional crawlspace ventilation is normally not effective in providing the amount of air circulation necessary to significantly dilute or purge the crawlspace cavity of accumulated radon. This house had numerous vents in the stemwall. However, the northern end (closest to the slab area) which had the least amount of clearance did not have any functioning vents on either side. The front porch was constructed in such a way that it did not provide any ventilation into the crawlspace for its entire length, and the rear stemwall had a wood deck constructed in front of those vents. Only the southern end of the crawlspace had operating vents which might have provided some dilution and ventilation of accumulated radon. This lack of ventilation adequate for radon removal allows a radon enriched atmosphere to accumulate where it can migrate into the house through openings in the floor system, or more importantly, into leaky return-air ducting. Infiltration of radon from the crawlspace into the return-air duct system was expected to be a significant contributor to the indoor levels. Migration of radon through the wood floor system was not considered to be a major entry route but certainly a contributing source.

DIAGNOSTIC TESTING

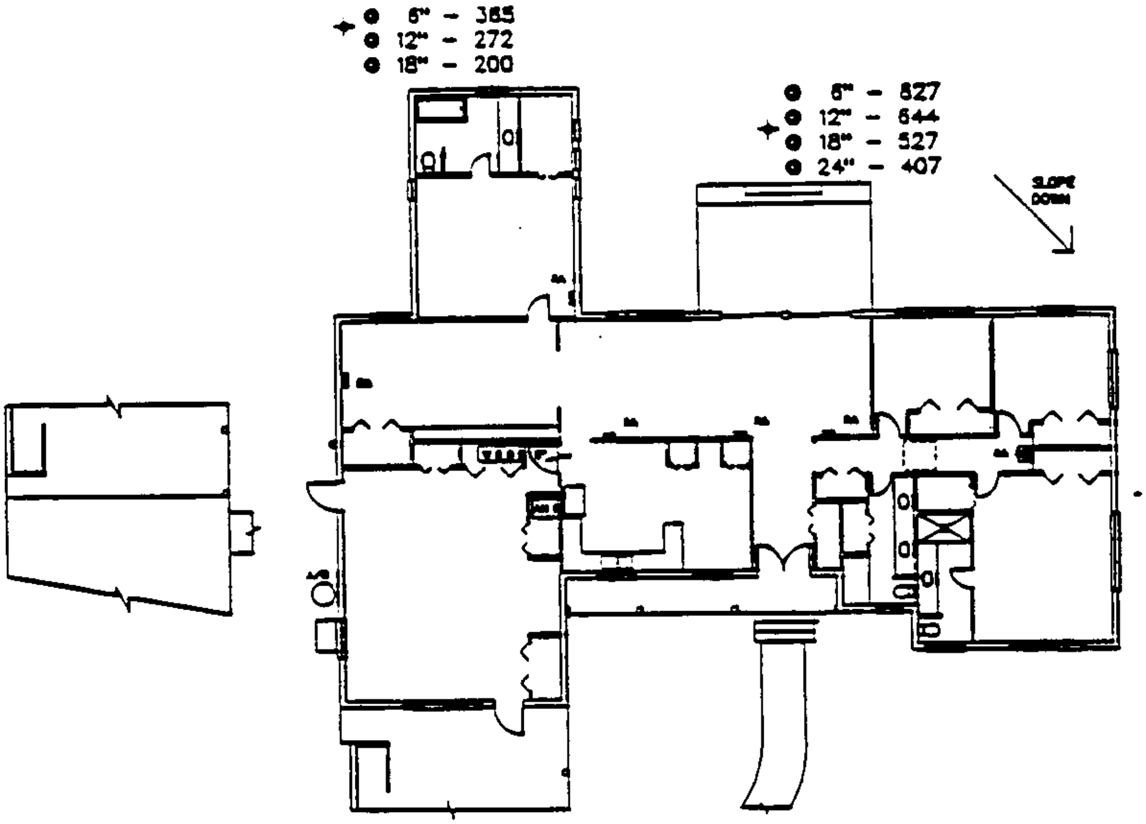
Diagnostic testing commenced with Gamma radiation measurements of the site and concluded with several measurements being taken inside the house (Figure 22-A). The levels recorded for Case Study #2 are approximately half of the magnitude of those radiation levels recorded for Case Study #1. These results, for Case Study #2, indicate a higher source potential in the northeast corner of the site than in the southwest corner which was approximately three feet lower in elevation.

A comparison of Figure 22-A with Figure 22-B does not show a direct correlation between the gamma radiation from the soil and the level of radon in the soil gas. One plausible explanation is that the soil gas is migrating through a more permeable, but less radium enriched, strata of soil.

Grab samples and sniffer measurements were taken inside the house and in the crawlspace; see Figures 23-A & 23-B and Table 2 for the results. These tests confirmed the presence of elevated levels of radon and indicated that the area of higher concentration was in the new master bedroom area. This information, coupled with the outdoor gamma readings, seemed to reinforce



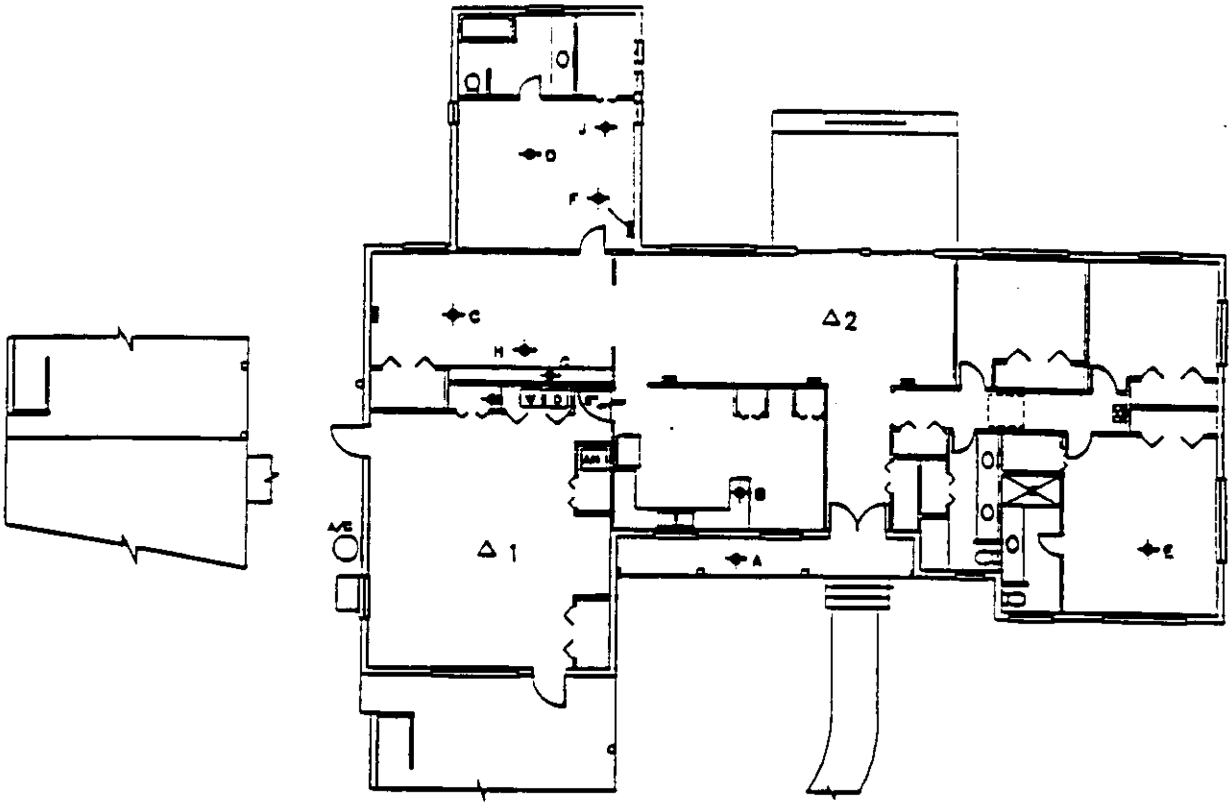
A - GAMMA RADIATION MEASUREMENTS (μR)



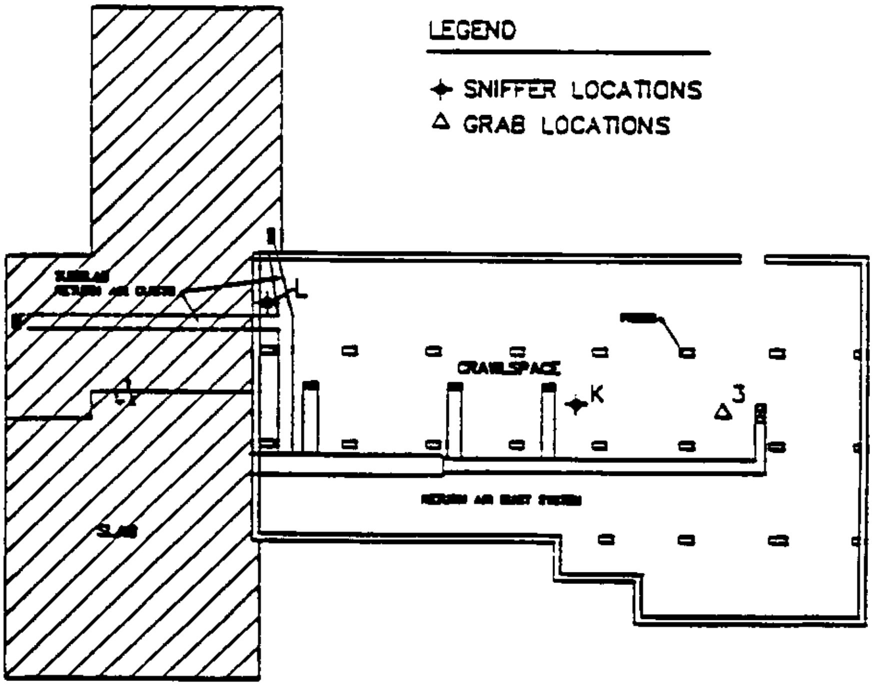
B - SOIL GAS RADON LEVELS (pCi/l)

GAMMA RADIATION AND SOIL GAS RADON MEASUREMENTS

FIGURE 22



A - INTERIOR MEASUREMENTS



B - CRAWLSPACE MEASUREMENTS

GRAB SAMPLE AND SNIFFER MEASUREMENT LOCATIONS

FIGURE 23

MARK	SAMPLE LOCATION	RADON LEVEL (pCi/l)
A	OUTDOOR BACKGROUND	0.9
B	KITCHEN - ON COUNTER	26.7
C	STUDY	32.2
D	MASTER BEDROOM	53.8
E	BEDROOM #2	34.8
F	MASTER BEDROOM - INSIDE RETURN-AIR DUCT	51.7
G	STUDY - INSIDE WALL RECEPTICLE	19.2
H	STUDY - ON FLOOR UNDER RECEPTICLE	12.7
I	FAMILY ROOM - SUB-SLAB	4914.5
J	MASTER BEDROOM - SUB-SLAB	3305.5
K	CRAWLSPACE - CENTER	23.3
L	CRAWLSPACE - NORTH END	32.4
GRAB 1	FAMILY ROOM	64.3
GRAB 2	LIVING ROOM	71.5
GRAB 3	CRAWLSPACE	62.7

TABLE 2

GRAB SAMPLE AND SNIFFER MEASUREMENTS

the concept that the major entry conditions were with the slab portion of the house. Sniffer measurements taken inside the wall cavities confirmed the presence of radon at elevated levels, confirming the thought that this slab was not cast fully into the stemwall. If this was the case, then there would not be a perimeter expansion joint.

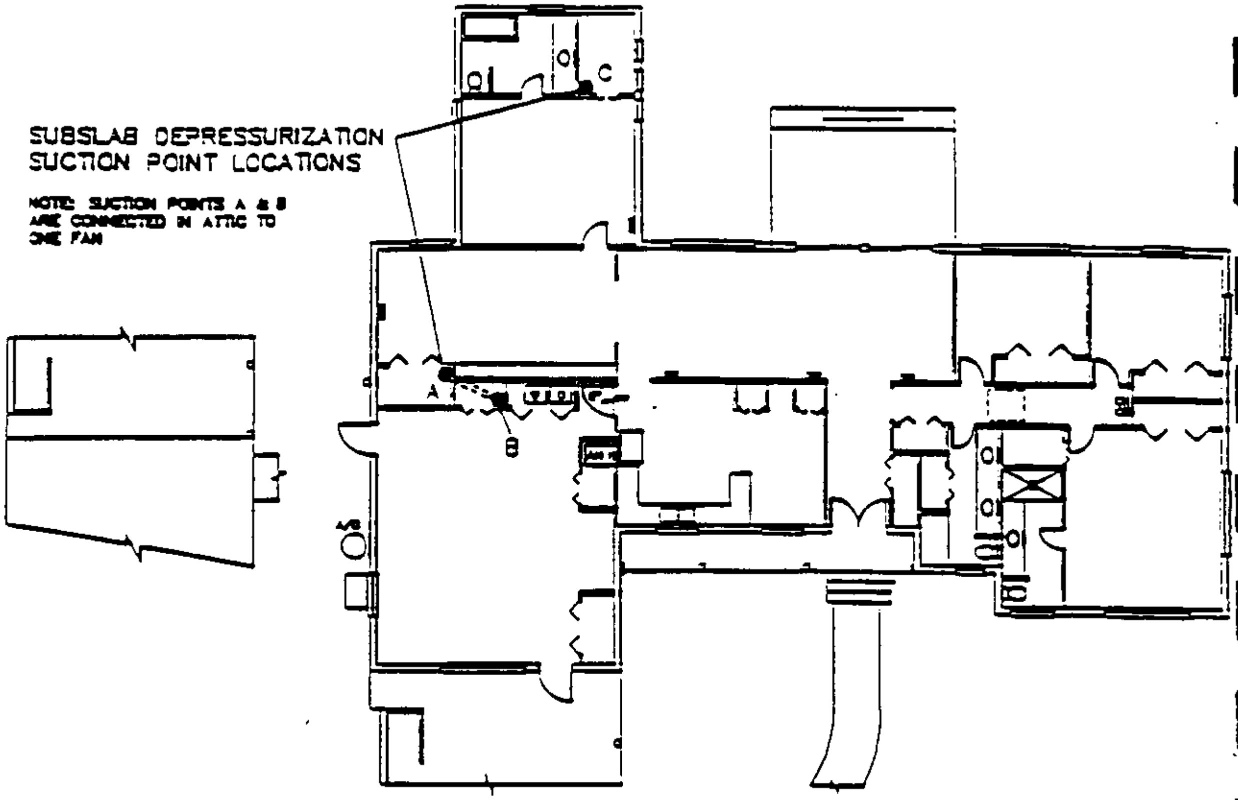
After all radon measurements were concluded two Minneapolis Blower Door units were set up in an attempt to estimate the approximate leakage area of the wood floor system. This testing procedure estimated that there were approximately 74 square inches of net open area through the wood floor system. By comparison with houses constructed on either a monolithic slab or a slab that is cast into the stemwall the magnitude of the net penetration of this wood floor system is enormous. However, after sub-slab radon measurements were taken and the radon levels just under the slab were measured at almost 5000 pCi/L it was decided that the most likely area of concern was the slab portion of the house.

MITIGATION STRATEGY

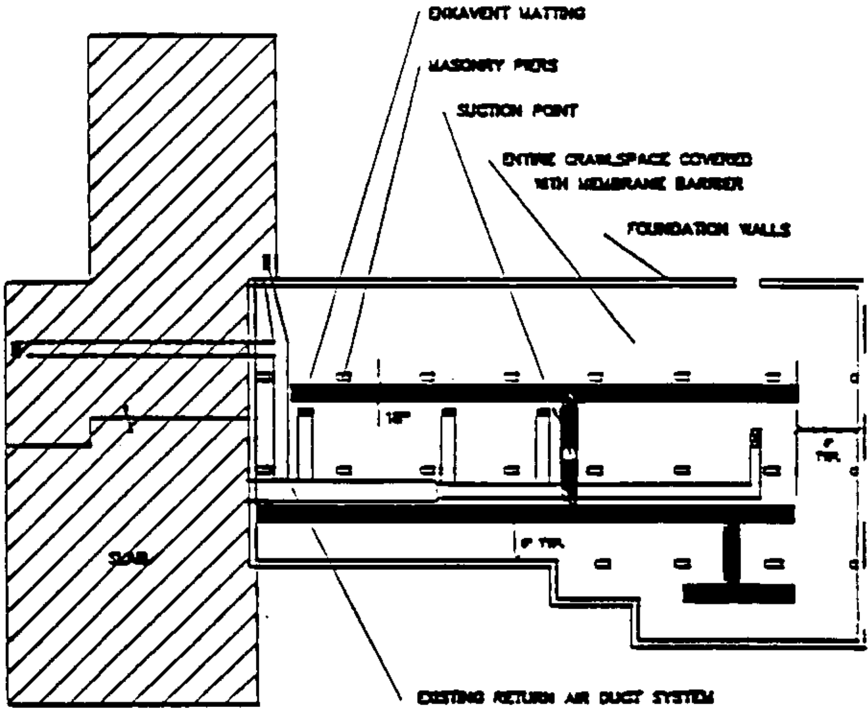
Case Study #2 provided the opportunity to mitigate a structure with a combination of foundation/floor systems. Since each of the floor systems used on this house were separate from one another, a phased mitigation plan was recommended. The high gamma radiation levels and the sub-slab radon levels suggested that the major entry conditions may be associated with the slab portion of the floor system. For these reasons the Phase 1 plan was to mitigate the concrete floor system prior to implementing the Phase 2 plan, which would mitigate the crawlspace area.

PHASE 1 MITIGATION ACTIVITIES

In recognizing the very limited opportunities to effectively seal all the contributing penetrations through the slab system, the sub-slab depressurization technique was selected. Because of the limited number of locations to install the suction systems, less than optimal effectiveness was expected. Figure 24-A illustrates the locations selected for installation of the suction points. Three suction points were required because the foundation walls were separating the sub-slab fill into three separate areas. Unfortunately, the opportunity to centrally locate the suction points in each of the three slab areas was not provided by the floor plan. Locations as close as possible to the center of each area were selected. Suction Points A & B were close enough that they could be easily joined together in the attic cavity to operate from the same suction fan. This was beneficial in that only one fan was required for two suction points and only one roof penetration was required. Suction Point C, however, was located at such a distance away from Points A & B that the opportunity to join all three points together was not available. Also, when more than one suction point is operating from one fan, then the fan should be located such that the distance from the fan to each suction point is equal. Due to the inaccessibility of the attic cavity over the master bedroom suite a 2" PVC pipe had to be fed through the attic cavity over this area from the main attic cavity. The length of suction pipe from the fan to the sub-slab pit was many times longer than the distance between Suction Points A & B. For this reason a separate suction fan was required for Suction Point C. The fan for this suction system was physically located in the same attic cavity as the fan for the other suction points. After all three suction points were installed, as shown in Figure 25, two roof penetrations were made and two fans were installed. Care was taken during the installation of the horizontal runs of piping in the attic to insure that any condensation that might result would drain either



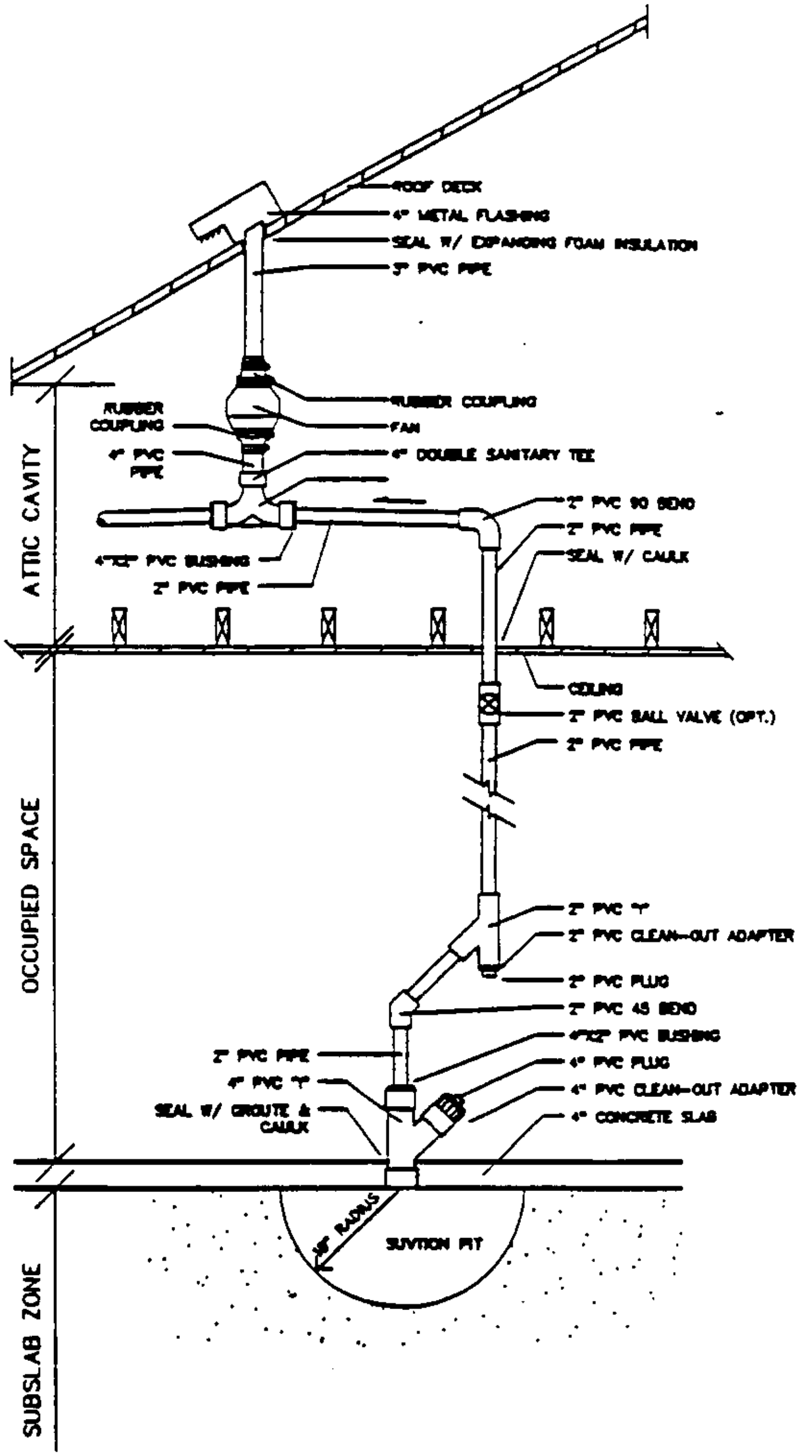
A - SUB-SLAB DEPRESSURIZATION SYSTEM SUCTION POINTS



B - SUB-BARRIER DEPRESSURIZATION SUCTION LAYOUT

SUB-SLAB & SUB-BARRIER DEPRESSURIZATION SYSTEM LAYOUTS

FIGURE 24



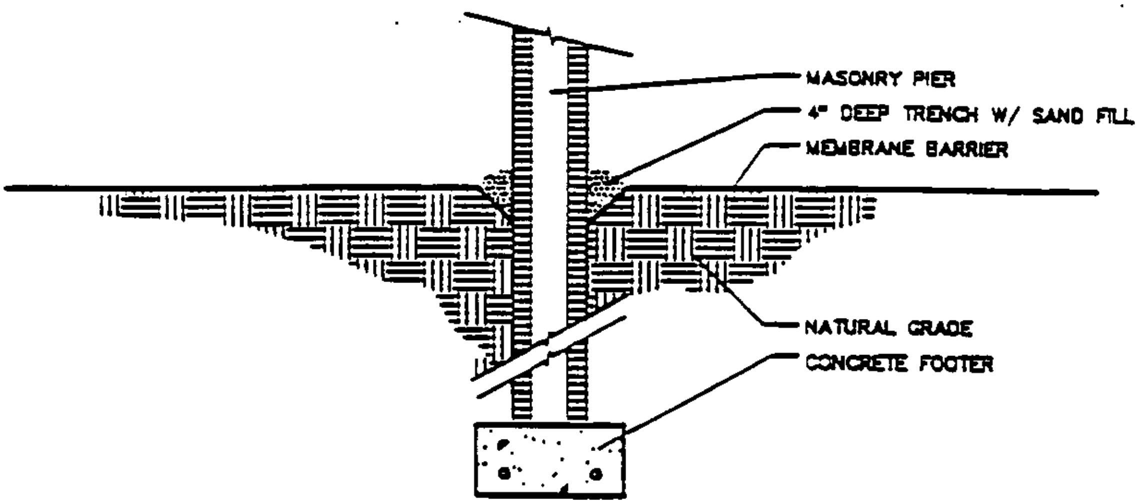
TYPICAL SUB-SLAB DEPRESSURIZATION SYSTEM

FIGURE 25

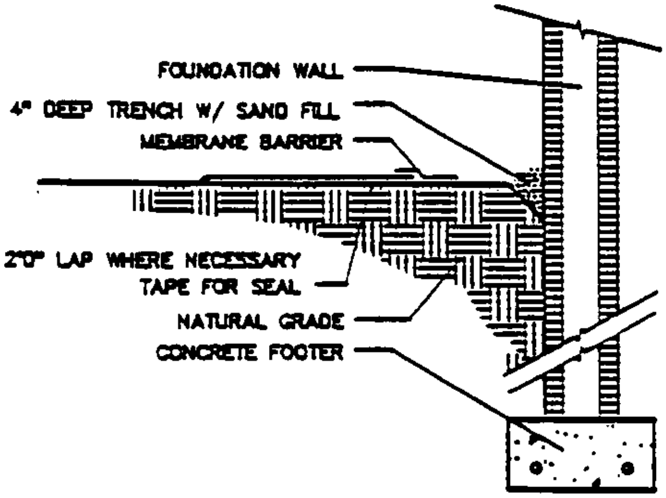
back into the suction pit or to the drain point furnished at the fan.

PHASE 2 MITIGATION ACTIVITIES

The Phase 2 mitigation plan was to provide a sub-barrier depressurization system in the crawlspace. Cleaning the crawlspace of any debris and objects that might puncture the membrane barrier material had to be completed first. Following the cleaning and grading of major ground irregularities the ground surface was roughened with a steel rake. A small pattern of grooves in the soil would aid in the pressure distribution under the membrane barrier material. Strips of 18" wide drainage type matting, such as EnkaVent, were placed in a configuration that would allow the suction pressure to be evenly distributed under the membrane (Figure 24-B). Following the installation of the drainage type matting, the entire crawlspace was covered with cross laminated polyethylene sheeting. This particular type of sheeting is highly puncture resistant and considered to be more durable than standard polyethylene materials. Three strips of sheeting were installed parallel to the long axis of the crawlspace and the lapped joints were taped with a mylar tape. The edge of the membrane along the perimeter foundation wall was turned down into a four to six inch deep excavation immediately adjacent to the foundation wall. Standard construction grade fill dirt was then used to cover the membrane along the entire length of the excavation (Figure 26-A). The burying of the edge of the sheeting under four to six inches of sand effectively eliminated any major air entry conditions under the edge of the membrane and also served to hold the membrane in place. Where the piers penetrated the membrane, care was taken to seal all cuts made to fit the membrane around the piers. The homeowner elected to install this system himself, with assistance, and terminated the edge of the membrane around the piers by turning the edges up the sides of each pier and wrapping them with mylar tape to



A - TERMINATION AT PIER



B - TERMINATION AT PERIMETER FOUNDATION WALL

MEMBRANE BARRIER TERMINATION DETAILS

FIGURE 26

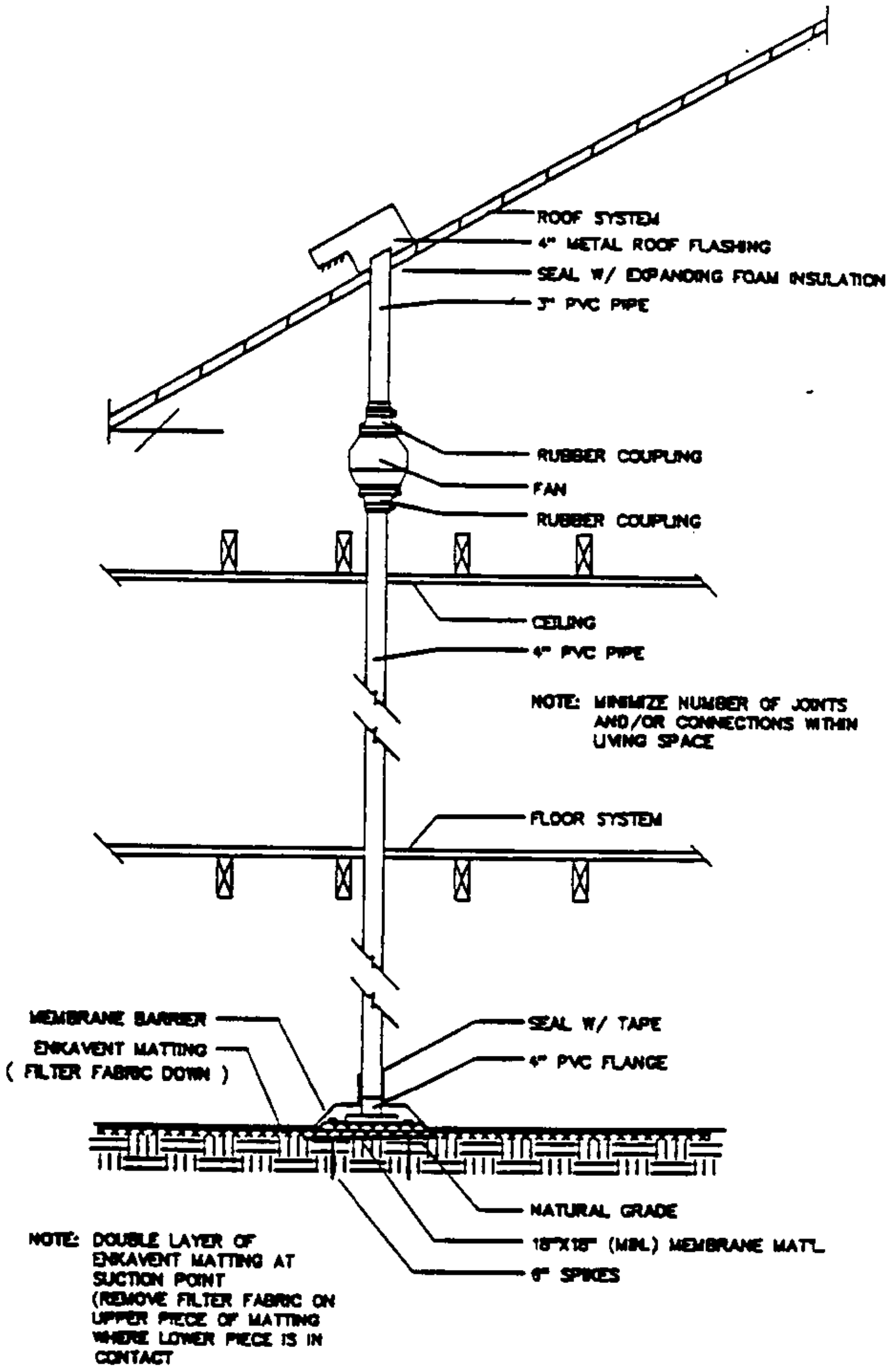
produce an adequate seal. Future installations will be installed in the same manner as the perimeter of the membrane. Figure 26-B illustrates how these terminations should be made.

Installation of the suction fan and piping system involved routing a four inch PVC pipe from the attic, through the interior space and into the crawlspace (Figure 27). The fan was installed in the attic cavity and the pipe was then extended through the roof decking and finished with a weather proof termination flashing.

In the crawlspace, the piping was routed horizontally to the suction point location which was established at a position approximately at the center of the drainage matting network. A four inch PVC pipe flange was used to terminate the suction piping to the drainage matting. Long spikes were used to secure the pipe flange to the drainage matting. A double layer of drainage matting was constructed at the suction point by placing an 18" square piece of matting, with filter fabric removed, on top of the network matting. This double layer of matting at the suction point enhanced the pressure distribution at this point. To prevent high suction pressures from pulling fine grain sands through the filter fabric on the bottom of the drainage matt, an 18" square piece of polyethylene sheeting was placed between the filter fabric and the soil and centered on the suction pipe.

ALTERNATIVE MITIGATION STRATEGIES

If after implementation of the Phase 1 and Phase 2 mitigation plans, indoor radon levels had not been reduced to acceptable levels, other strategies would have had to be employed. The two mitigation techniques which would have been considered are the masonry wall cavity



NOTE: MINIMIZE NUMBER OF JOINTS AND/OR CONNECTIONS WITHIN LIVING SPACE

NOTE: DOUBLE LAYER OF ENKAVENT MATTING AT SUCTION POINT (REMOVE FILTER FABRIC ON UPPER PIECE OF MATTING WHERE LOWER PIECE IS IN CONTACT

TYPICAL SUB-BARRIER DEPRESSURIZATION SYSTEM

FIGURE 27

depressurization system and, if necessary, a whole house pressurization and ventilation system.

The masonry wall cavity depressurization system would have required the installation of a four inch diameter PVC pipe around the exterior side of the slab foundation wall. Smaller suction pipes would connect the four inch manifold pipe to the wall cavity at however many points would be necessary in order to achieve total wall depressurization (Figure 20). Since the exterior of this house was painted, the installation related impacts of this system could have been cosmetically disguised. On Case Study #1, this was not the case because the house was built with a natural finish block. A vertical four inch PVC pipe with a suction fan would have been installed in the most inconspicuous location possible. This pipe would provide for the depressurization of the wall and also exhaust the radon laden air above the roof line.

If this system, in conjunction with Phase 1 & 2 mitigation systems, did not adequately lower the indoor radon levels, the HVAC system would have been modified to increase the air exchange rate. This would be accomplished by inducting outside air into the return-air ducting. Increased ventilation would decrease indoor radon levels by dilution and, at the same time, cause a high pressure zone inside the house. If this procedure had been required, consideration of a heat pipe heat exchange system would have been prudent. However, with the total leakage area of the house at approximately 192 square inches in size, including the 74 square inch leakage of the wood floor system, over pressurization of the house may not have been achievable.

Other alternative mitigation strategies were not considered.

POST-MITIGATION EVALUATION

After completion of the Phase 1 mitigation system post-mitigation testing commenced. The extended monitoring program found that average indoor radon levels had dropped from a pre-mitigation indoor average of 26 pCi/L to only 18 pCi/L. This level of reduction was not as good as had been expected and conclusions were that the crawlspace was a larger contributor to the overall problem than had originally been thought. Also, since the suction pit locations were not close to the center of the various slab areas, optimum performance of the suction systems was not expected. During the installation of Suction Pit B, a 1/2 to 3/8 inch gap was observed between the top of the sub-slab fill and the bottom of the concrete. This type of settlement can result in an increase in the size of the sub-slab pressure field, but it can also allow for high volumes of air to flow through the system thereby effectively short-circuiting the pressure field.

The Phase 2 system was installed and indoor radon levels dropped drastically. Pre-mitigation radon levels were in the 26 pCi/L range and after the installation of Phase 1 and Phase 2 mitigation systems dropped to an average of 1.8 pCi/L. This level of reduction was with both systems operating. Table 3 records the various radon levels taken during the study.

CASE STUDY #2		RADON MEASUREMENTS
PREMITIGATION RADON LEVELS	LIVING SPACE (Ave.)	26.0 pCi/L
POST-MITIGATION RADON LEVELS		
PHASE 1	LIVING SPACE (Ave.)	18.0 pCi/L
PHASE 1 & 2	LIVING SPACE (Ave.)	1.8 pCi/L
Details:	Master Bedroom	1.8 pCi/L 1.6 pCi/L
	Recreation Room	2.6 pCi/L
	Bedroom #2	1.9 pCi/L
	Bedroom #3	1.8 pCi/L
	Crawlspace	
	Above Barrier	2.7 pCi/L
	Under Barrier	118.0 pCi/L

TABLE 3
RADON MEASUREMENTS - CASE STUDY #2

CHAPTER 8

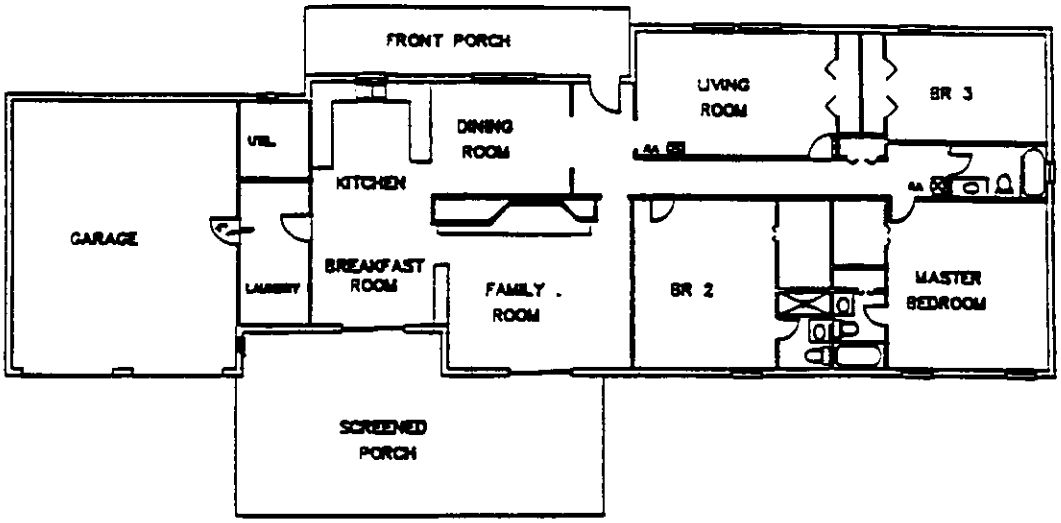
CASE STUDY #3

Case Study #3 offered a unique opportunity to study the mitigation aspects of a traditional crawlspace constructed house. Unfortunately, the homeowner sold the house and moved back to New Jersey before the mitigation system could be installed. The new homeowners were offered the opportunity to continue the study, but did not feel it was an issue worth being concerned about. The basis of their decision was that they spend much of their time traveling and did not feel that the amount of time they would be spending in the house would pose a significant health threat to themselves. Even though the opportunity was lost to mitigate this house, the amount of data and analysis that was collected and the experience gained on other houses gave the researchers a high level of confidence in the mitigation plan that was developed. Therefore the mitigation strategy will be presented even though post-mitigation testing could not verify the effectiveness.

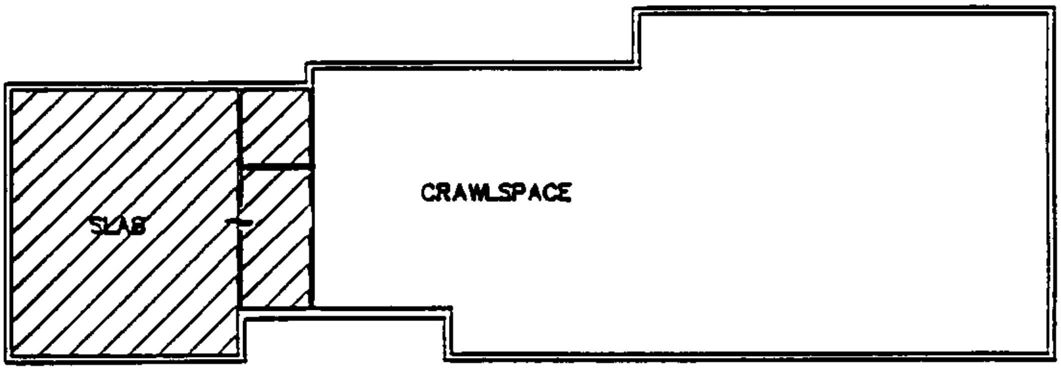
CONSTRUCTION CHARACTERIZATION

GENERAL

Case Study #3 is a 2256 square foot single-family detached residence located in Ocala, Florida. The living area of this three bedroom, two bath house was constructed entirely over a crawlspace (Figure 28-A). The garage, utility room and combination pantry/laundry room were, however, located over a concrete floor slab (Figure 28-B). A small patio at the rear of the



A - FLOOR PLAN



B - FOUNDATION/FLOOR CONFIGURATION

FLOOR PLAN & FOUNDATION/FLOOR CONFIGURATION

FIGURE 28

house had been converted into a covered screened porch before the current homeowner purchased the house. The site was moderately covered with mature pine and oak trees and had a very slight slope increasing from the front of the lot to the rear.

STRUCTURAL SYSTEM

The exterior load bearing walls were constructed of a 2 x 4 inch frame wall with a brick veneer of standard face brick. The frame wall was supported by a single course of 8 inch high masonry block laid directly on top of a continuous reinforced concrete strip footing. The brick veneer extended from the top of the footing to above the soffit. Two rows of piers provided support to quadruple 2 x 8 inch floor beams which ran parallel to the long axis of the crawlspace. The edge of the concrete footing was exposed for approximately six to eight inches. This was also the case for those pier footings that could be seen. It appeared, from inside the crawlspace, that the concrete footings were constructed on top of the ground with little or no excavation. From outside the crawlspace, the footings were covered by a minimum of 2 to 3 inches of soil.

FLOOR SYSTEM

A traditional oak hardwood flooring system was utilized for the inhabited areas of the house. A concrete slab comprised the flooring system for the garage, utility room and the combination pantry/laundry room.

The wood floor system was constructed of 2 x 8 inch wood joists placed 16 inches on center and supported by the perimeter foundation wall and interior wood beams on piers. The joists were covered with 1 x 8 inch diagonal sub-flooring and finished with a traditional oak hardwood finish floor. The crawlspace height was very limited, with the maximum clearance from the ground to the bottom of the floor joists ranging from 16 to 20 inches. Access to all areas of the crawlspace was extremely restricted because of the interference of the supply and return-air ducts.

Penetrations through the wood flooring system were numerous and large holes through the sub-flooring existed where plumbing lines passed through. Older wood flooring systems, especially those that do not use plywood sheeting for the subfloor material, are expected to be exceptionally porous or leaky.

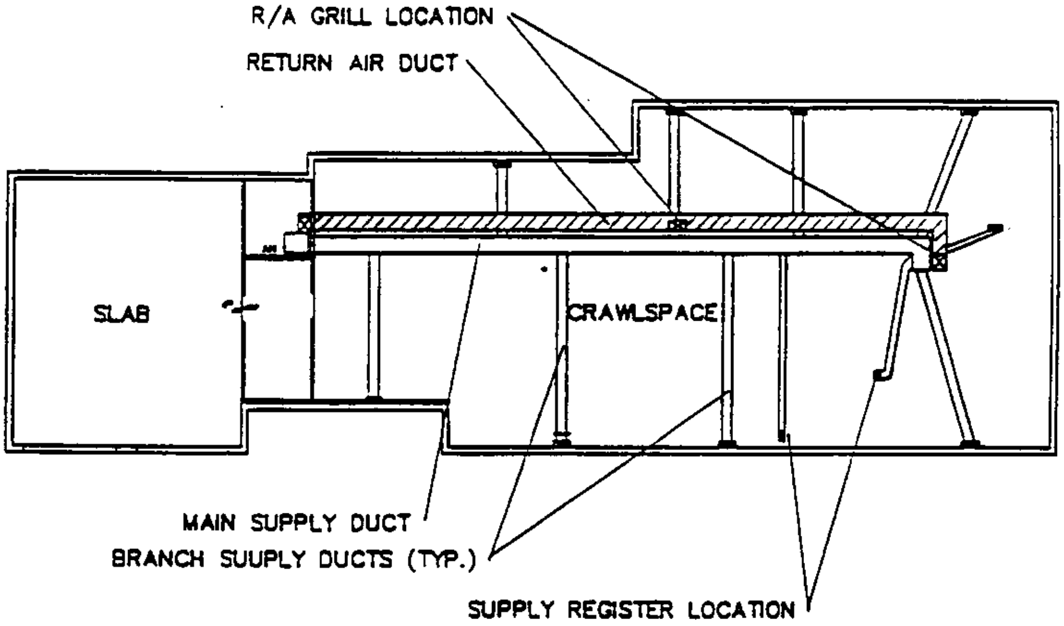
Those spaces constructed over the concrete slab were not part of the conditioned area. The garage door was typically left open because it was located at the rear of the house and could not be seen from the street. The combination pantry/laundry room was adjacent to the kitchen but kept closed off since it was not a conditioned space. Limited activity occurred in this space and was not considered to be a significant contributor to the radon problem. The utility room contained the HVAC equipment and the hot water heater. A large recess was formed in the floor of the utility room under the airhandler to allow the supply and return air ducts to access the crawlspace. The floor of this recess was natural soil and no attempts to isolate this area from the crawlspace had been made.

ROOF SYSTEM

A traditional gable roof with fiberglass shingles covered all parts of the structure. The roof framing was conventionally constructed without the use of pre-fabricated trusses. Plywood was used as the roof sheathing material. Easy access was provided to the attic cavity where ample room was found for any mitigative system.

HVAC SYSTEM

Case Study #3 was equipped with a natural gas fired furnace and an electric central air conditioning system. The air handler is located in the utility room which opens into the garage. The door to the utility room is a full louver design allowing for adequate ventilation and combustion air for the furnace and gas water heater. Both the return-air and supply ducts are located in the crawlspace and enter the utility room through a recess formed in the floor (Figure 29). This recess was approximately 20" wide by 40" long by 12" deep. The bottom of the recess had been excavated into the natural earth and was not finished with any material. This recess opened on the back side into the crawlspace, also with an earthen floor. The ducting was fabricated from galvanized sheet metal and suspended from the floor joists. The entire supply duct system was insulated from the airhandler to the furthest discharge point. The main duct trunk lines barely cleared the natural earth floor by one to two inches. When the supply branch lines crossed under the return-air trunk line, insufficient clearance was provided for a person to crawl under them. Large openings were found during the diagnostic testing program around the return-air intake points. The sheet metal ducting extended through the floor into the wall cavity which was lined with sheet metal. The ducting had partially collapsed along the long sides, which resulted in very large openings directly into the crawlspace. Inspection of the supply registers did not disclose similar problems. All of the supply discharge points terminated with a sheet metal enclosure on which the louvered grill was attached.



EXISTING HVAC DUCT CONFIGURATION

FIGURE 29

PLUMBING SYSTEM

All of the water supply piping was installed with rigid copper piping. The waste lines were fabricated with cast iron pipe. Nothing unusual was noted with the plumbing system. However, the penetrations through the floor were not made with any attempt to minimize the size of the opening. Most of the openings appeared to have been cut with a saw rather than drilled. This resulted in large rectangular holes being produced.

OTHER PERTINENT CHARACTERISTICS

Other than the fireplace, there were no other combustion appliances located inside the occupied space. The interior wall framing did result in a thermal bypass being produced connecting the crawlspace with the attic. A thermal bypass can produce convective air flow currents moving radon laden air from the crawlspace into the attic. This process can result in radon accessing many additional pathways to enter the occupied space.

A large whole house attic fan was installed in the ceiling of the hallway. No other depressurization type equipment was observed.

IDENTIFICATION OF POTENTIAL ENTRY ROUTES

Radon entry into this structure was predicted to be associated primarily with the crawlspace duct systems. The second source of entry was deemed to be the highly porous wood floor system.

Leaky joints in the metal return-air ducting and the large openings into the return-air registers from the crawlspace caused vast amounts of radon laden air from the crawlspace to be ingested into the duct system. The dirt floored opening between the crawlspace and the utility room also provided ample opportunity for radon laden crawlspace air to be drawn into the airhandler and redistributed throughout the house.

The raised wood floor system with its many penetrations from plumbing lines and ductwork was also considered a major entry condition. The use of 1"x 8" diagonal sub-flooring instead of plywood sheeting resulted in a significantly greater number of entry routes than would be found in more recent wood floor construction using plywood sheeting.

The contribution of these two entry conditions to the indoor radon levels was predicted to be of such magnitude that the entry conditions in the slab area were discounted as being of any real significance.

DIAGNOSTIC TESTING

Outdoor gamma radiation levels were measured, and it was found that a fairly uniform condition existed. No "hot spots" were found and the levels measured were not exceptionally high (Figure 30).

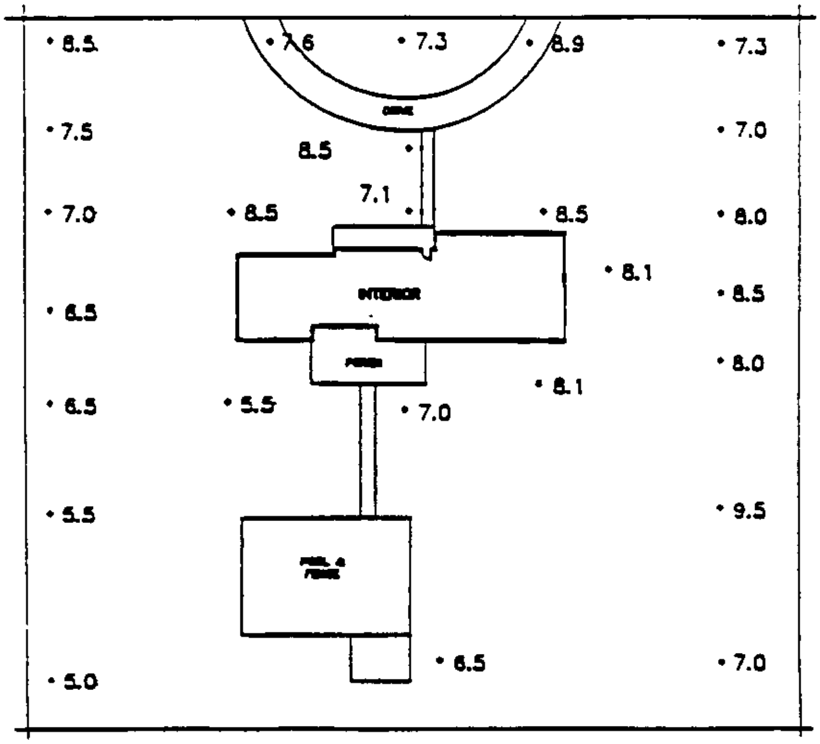
Grab samples were taken upon arrival, and indoor levels were found to range from 7.5 pCi/L to 8.8 pCi/L (see Table 4 and Figures 31-A & 31-B). One grab sample was taken in the crawlspace and a level of 59 pCi/L was measured.

MARK	SAMPLE LOCATION	RADON LEVEL (pCi/l)
A	KITCHEN - WALL RECEPTICLE	3.4
B	KITCHEN - WALL SWITCH	1.5
C	LIVING ROOM - WALL RECPTICLE	4.0
D	HALL - RETURN-AIR DUCT	39.0
E	CRAWLSPACE - HOLE IN HALL RETURN-AIR DUCT	26.3
F	BEDROOM #3 - WALL RECEPTICLE	6.9
G	MASTER BEDROOM - INSIDE WALL RECEPTICLE	5.6
H	MASTER BATH - BASE OF TOILET	7.3
I	BEDROOM #2 - LIGHT SWITCH	6.8
J	KITCHEN - ON COUNTER	5.4
K	GARAGE - SUB-SLAB	475.8
GRAB 1	MASTER BEDROOM	8.8
GRAB 2	DINING ROOM	7.5
GRAB 3	CRAWLSPACE	59.0

TABLE 4

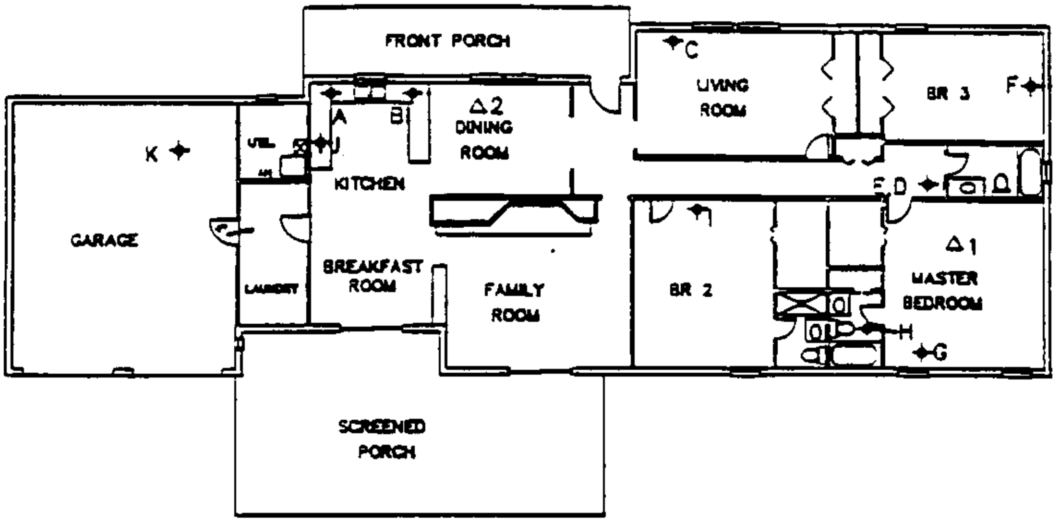
GRAB SAMPLE AND SNIFFER MEASUREMENTS

(See Figures 31-A & 31-B)



GAMMA RADIATION MEASUREMENTS (μR)

FIGURE 30

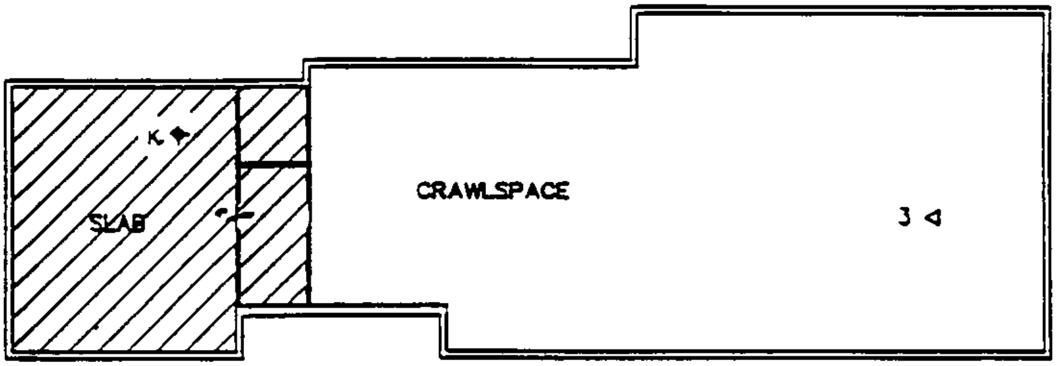


LEGEND

✦ SNIFFER LOCATION

△ GRAB LOCATION

A - INTERIOR MEASUREMENTS



B - CRAWLSPACE & SUB-SLAB MEASUREMENTS

GRAB SAMPLE AND SNIFFER MEASUREMENT LOCATIONS

FIGURE 31

Sniffer testing was conducted and found that the only levels of significance were in the return-air ducting and under the slab (see Table 4 and Figures 31-A & 31-B). Levels measured inside the exterior walls were not high enough to imply that conduction through the wall system was anything to be concerned about.

The results of the diagnostic testing conducted on Case Study #3 confirmed the predictions of the major entry conditions.

MITIGATION STRATEGY

The mitigation strategy for Case Study #3 is a fairly straight forward plan. The approach is two-fold:

1. Remove the supply and return-air ducting from the crawlspace and reinstall in the attic cavity,

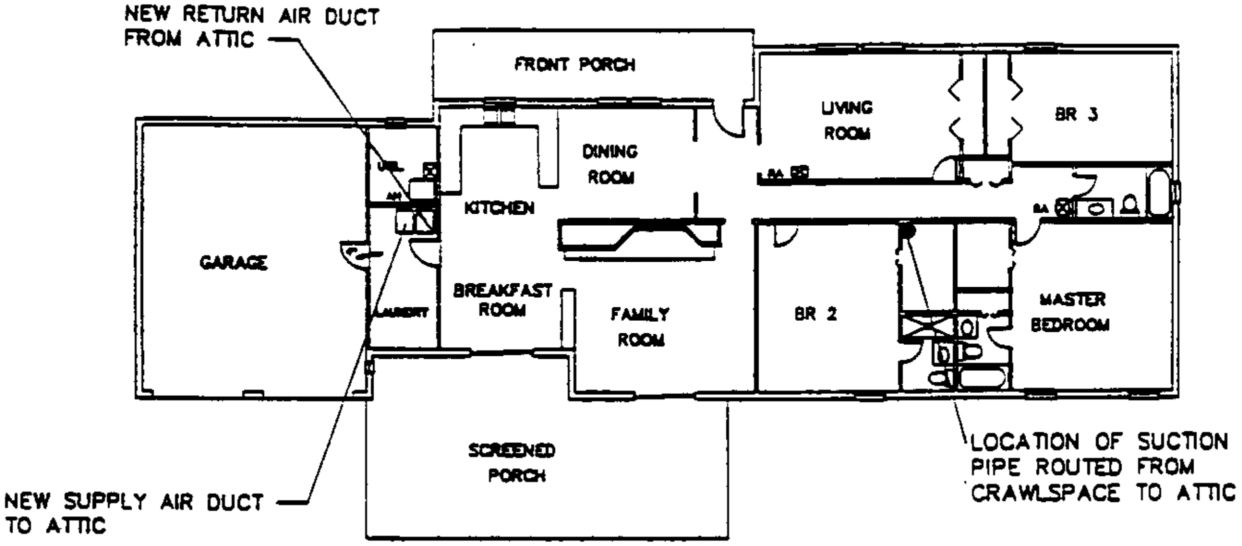
2. Install a sub-barrier depressurization system in the crawlspace.

Removal of the ducting is recommended for several reasons. First, the ingestion of radon laden crawlspace air into the duct system was confirmed in the diagnostic testing program. In order to eliminate this from happening in the future it is necessary to relocate the ducting to the attic. Second, the crawlspace is functionally impassable with the existing ducting in place. Because of the inability to access all parts of the crawlspace it would be impossible to install the sub-barrier depressurization system.

Reconfiguration of the HVAC unit in the utility room to accommodate the new duct system would be required. The best route for the new attic ducting to take, in order to connect with the air handler is shown on Figure 32. This location, unfortunately, utilizes part of the existing pantry space but is necessary to access sufficient room in the attic cavity for the new duct lines. Figure 32 also shows the location of the sub-barrier depressurization systems suction pipe as it passes through the occupied space.

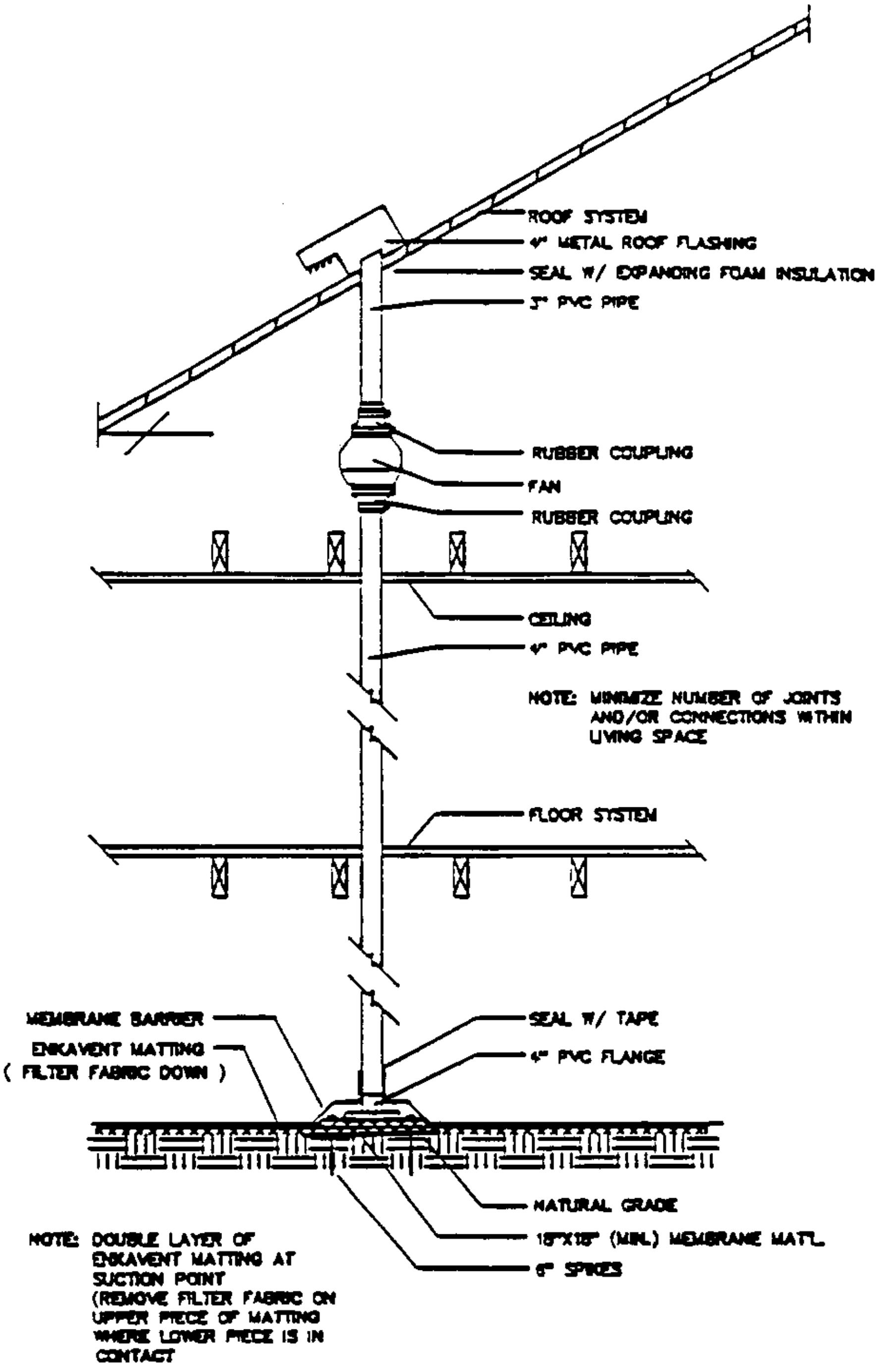
The sub-barrier depressurization system is recommended to be installed as illustrated in Figure 33. The drainage matting would be installed in the pattern shown after the ground surface had been prepared (Figure 34). This preparation would include the removal of all debris and large rock. All holes and depressions would be filled and the entire crawlspace raked smooth with a steel rake. Location of the suction point would be as shown on Figure 34. Following the installation of the drainage matting the cross-laminated polyethylene sheeting would be installed. Care would be taken to ensure that all seams and punctures would be taped closed with an acrylic tape. Edge terminations at the foundation walls and piers would be as shown in Figures 35-A and 35-B. The vertical PVC piping from the crawlspace to the attic would be routed through the closet in Bedroom #2 as shown in Figure 32. A fan would be installed on the piping in the attic cavity and terminated through the roof deck with a weather-proof flashing.

Consideration was given to recommending only the sub-barrier depressurization system be installed and to leaving the ducting in the crawlspace. But, in consideration of the accessibility problems within the crawlspace caused by the extremely low crawlspace clearances and the interference of the ducting it was agreed that the ducting would have to be removed.



RECOMMENDED DUCT AND SUCTION PIPE LOCATION

FIGURE 32

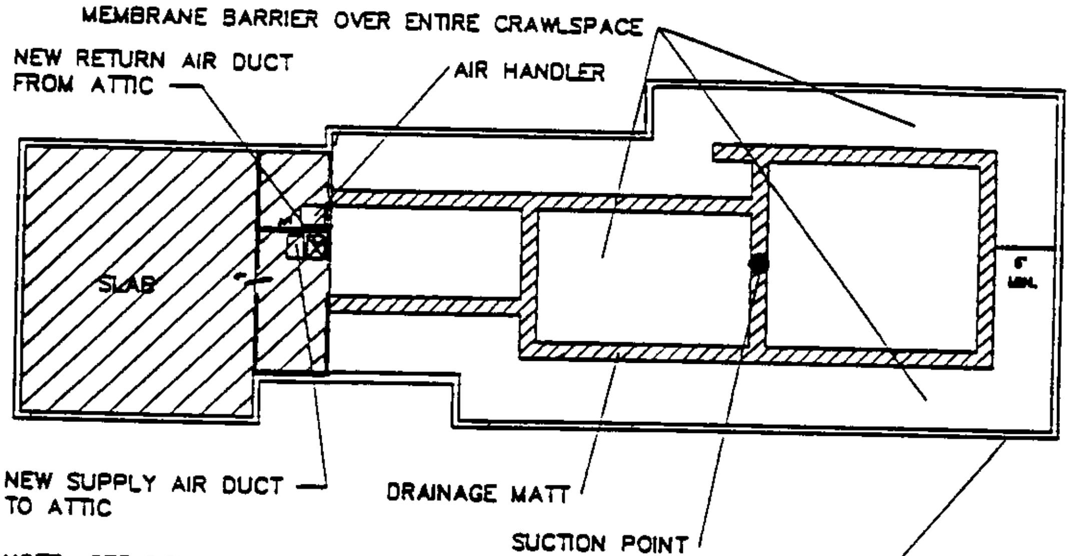


NOTE: MINIMIZE NUMBER OF JOINTS AND/OR CONNECTIONS WITHIN LIVING SPACE

NOTE: DOUBLE LAYER OF ENKAVENT MATTING AT SUCTION POINT (REMOVE FILTER FABRIC ON UPPER PIECE OF MATTING WHERE LOWER PIECE IS IN CONTACT

TYPICAL SUB-BARRIER DEPRESSURIZATION SYSTEM

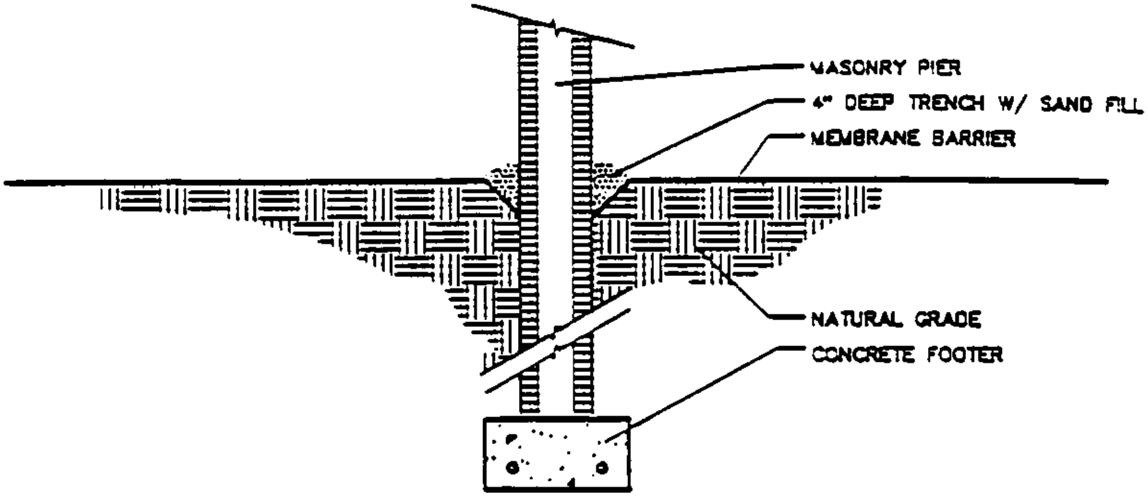
FIGURE 33



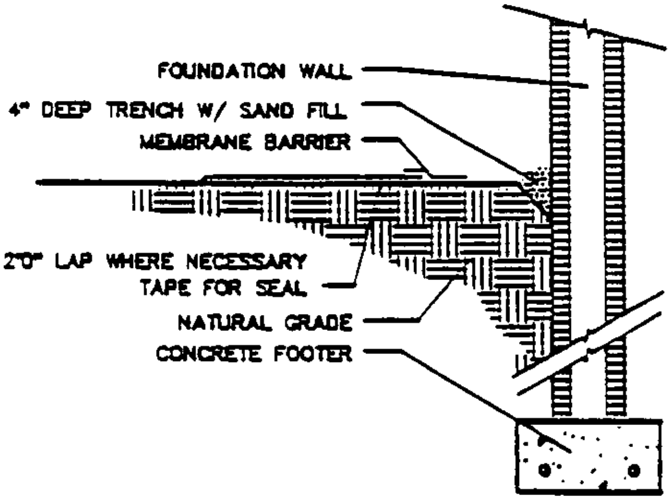
NOTE: SEE DETAIL FOR BARRIER INSTALLATION

SUB-BARRIER SUCTION SYSTEM LAYOUT

FIGURE 34



A - TERMINATION AT PIER



B - TERMINATION AT PERIMETER FOUNDATION WALL

MEMBRANE BARRIER TERMINATION DETAILS

FIGURE 35

Reinstallation of new ducting in the crawlspace after the barrier system was complete was determined not to be cost effective since there was much more space provided in the attic cavity. Also, damage to the barrier system could occur and not be repairable due to new access problems. From a construction and cost perspective it was decided that the best approach would be those actions recommended above.

POST-MITIGATION EVALUATION

No post-mitigation evaluation of this plan was made because, as stated earlier, the homeowner sold this house during the course of the study and the new owners did not wish to continue the project. The recommended mitigation plan was not installed, and therefore was not tested for effectiveness. However, other installations of this mitigation strategy have proven to be highly effective. The confidence of this mitigation plan being effective over time is very high.

CHAPTER 9

CASE STUDY #4

Case Study #4 is a typical concrete masonry house constructed in 1968 in Ocala, Florida. The house is a simple rectangular structure having four bedrooms and two baths (Figure 36). This house is constructed with a concrete slab and has no sub-slab HVAC ducting.

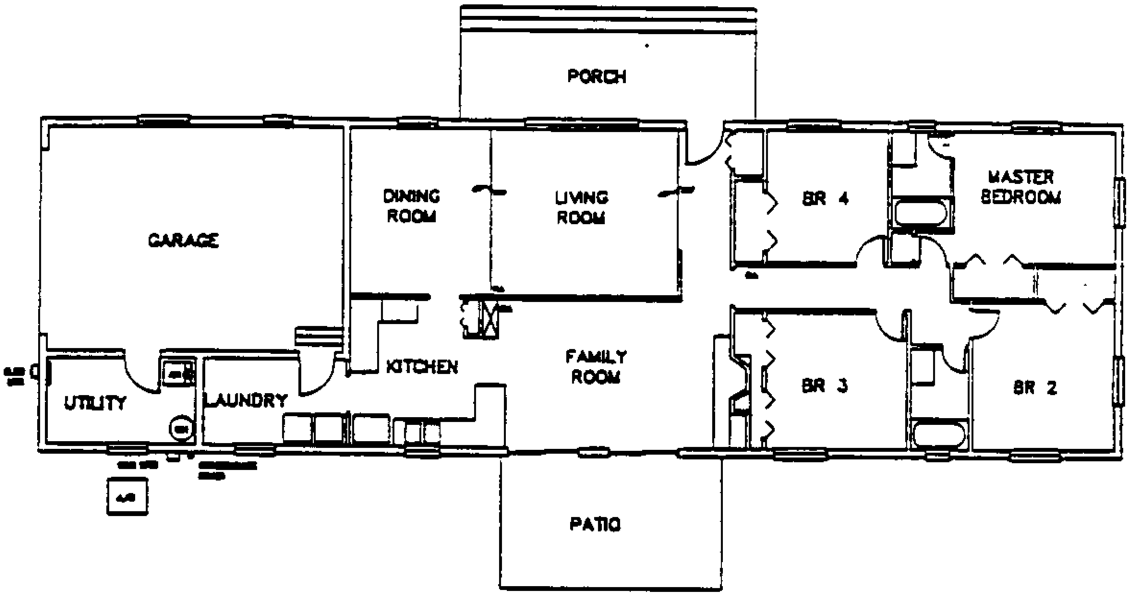
This case study house did not progress to the implementation stage. However, a recommended mitigation plan was developed and will be presented and discussed.

CONSTRUCTION CHARACTERIZATION

GENERAL

Case Study #4 is a masonry house typical of those constructed in the 1970's and 1980's. Prior to this time, as shown in Case Studies 1 and 2, contractors were still using some construction techniques common to wood floor systems with a new and emerging concrete floor slab system. Specifically, HVAC ducting after the early 1960's has normally been placed in the attic cavity instead of under the floor system. The masonry units used in the exterior walls are 8" in height rather than the 4" high units more common to the earlier period.

During the preliminary construction investigation the homeowner disclosed that some settlement had occurred along the rear of the house during the early 1980's. At this time, the



FLOOR PLAN

FIGURE 36

homeowner hired a geotechnical engineering firm to perform a sub-soil investigation program in order to determine the cause of the settlement. A sinkhole was suspected by the homeowner to be the cause of the problem, but following the sub-surface testing it was revealed that the house had been constructed over a depression that had been filled with debris and rubble. Much of this material was compressible in nature and over time had decayed and resulted in the settling of overlying soils to settle. This subsidence caused observable external cracking of the exterior masonry wall and the interior slab, and major cracking to the exterior patio slab. The patio slab was removed and replaced some time later.

STRUCTURAL SYSTEM

The only structural walls associated with this house were the exterior masonry walls. Eight inch high concrete block was used to construct the walls from the reinforced concrete strip footing to the bond beam.

FLOOR SYSTEM

The entire floor area of Case Study #4 was constructed over a concrete slab. A 4" recess was created in the living room area. The main floor slab was approximately 24" above natural grade. The fill material used under the main floor slab was a standard medium to fine grained sand. Two concrete blocks, one on the front and one on the rear, had been removed from the foundation wall, exposing the fill material. Through these points, some of the fill was removed to the underside of the concrete slab. It was determined through this excavation that plastic sheeting had been used as the vapor barrier material.

Cracks in the slab were observed around the recessed floor area in the living room. The homeowner described several significant cracks that were not able to be uncovered that had resulted from the settlement caused by the compressible debris. A construction joint under the kitchen/laundry room door was found.

It was not determined during the investigation program if the slab had been cast into the foundation wall.

ROOF SYSTEM

The roof was constructed with prefabricated wood trusses placed 24" on center. The roof decking was plywood covered with fiberglass shingles. Extending from the main gable roof was a short gable roof covering the front porch.

The attic cavity was accessible and sufficient space was available for the installation of any attic mitigation system component.

HVAC SYSTEM

A utility room accessible from the garage housed both the furnace/air handler and the hot water heater. Both the furnace and hot water heater are fueled by natural gas. The ducting, both return and supply are routed into and through the attic. The supply registers are ceiling mounted units while the return-air grills were located in the wall, close to the floor. A large return-air chase was constructed at the back of the kitchen pantry and served the family room area and living room area from that location. Another return-air grill was located low on the wall in the hallway (see Figure 36).

PLUMBING SYSTEM

No unusual plumbing conditions were found in this house. Typical slab penetrations were expected in the kitchen, laundry and bathrooms. However, these points were not accessible for inspection.

OTHER PERTINENT CHARACTERISTICS

A fireplace, located in the family room, was not constructed with an outside combustion air intake. This would result in a depressurization condition occurring when the fireplace is used. The fireplace foundation system was not able to be determined.

The laundry room was constructed as part of the conditioned space. By having the clothes dryer inside the conditioned space, a depressurization condition can occur when it is operating. With the control joint between the laundry room and the kitchen providing a easy pathway for radon to enter the house, any localized depressurization conditions should be avoided.

No other significant conditions were noted.

IDENTIFICATION OF POTENTIAL ENTRY ROUTES

The primary entry conditions associated with Case Study #4 are associated with slab cracks and a possible block wall conduction problem. No duct related entry conditions exist on this house.

Slab cracks caused by settlement in the family room/kitchen/bedroom #3 area are expected to be significant contributors to the indoor radon levels. Cracks around the recessed floor in the living room are also entry routes of concern. The control joint between the kitchen and the laundry room was expected to provide for easy radon transport.

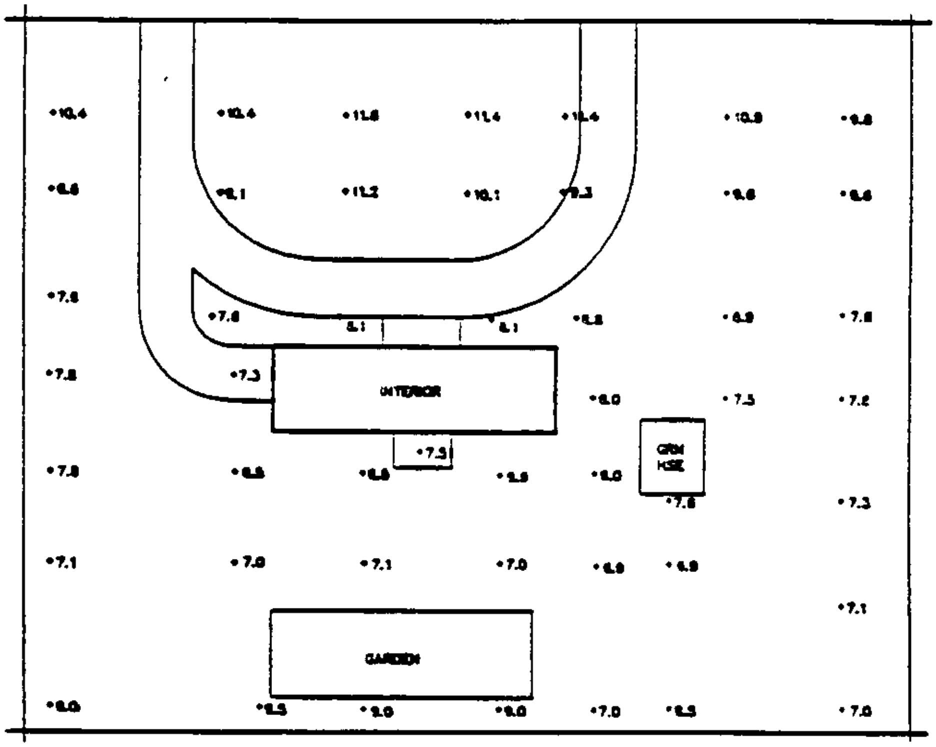
Since it was not determined if the slab was cast fully into the foundation wall, the block wall cavity was under suspicion. With over 20" of stemwall in contact with the sub-slab fill dirt, ample opportunity was present for the radon to enter the wall cavity. Negative pressure conditions, either naturally or mechanically induced, would result in the radon migrating from the wall cavity into the occupied space. The fireplace, clothes dryer and HVAC system were the mechanical systems capable of causing these negative pressure conditions.

DIAGNOSTIC TESTING

Outdoor gamma radiation testing was conducted on the property and produced results in the 7.0 to 11.6 uR/hr range (Figure 37). This range is not representative of a high source potential but may be associated with significant quantities of radon.

Grab samples were taken in the living room and the master bedroom and produced radon concentrations of 8.6 pCi/L and 10.2 pCi/L respectfully. Although these levels are not especially high they do confirm the presence of elevated levels of radon (Figure 38).

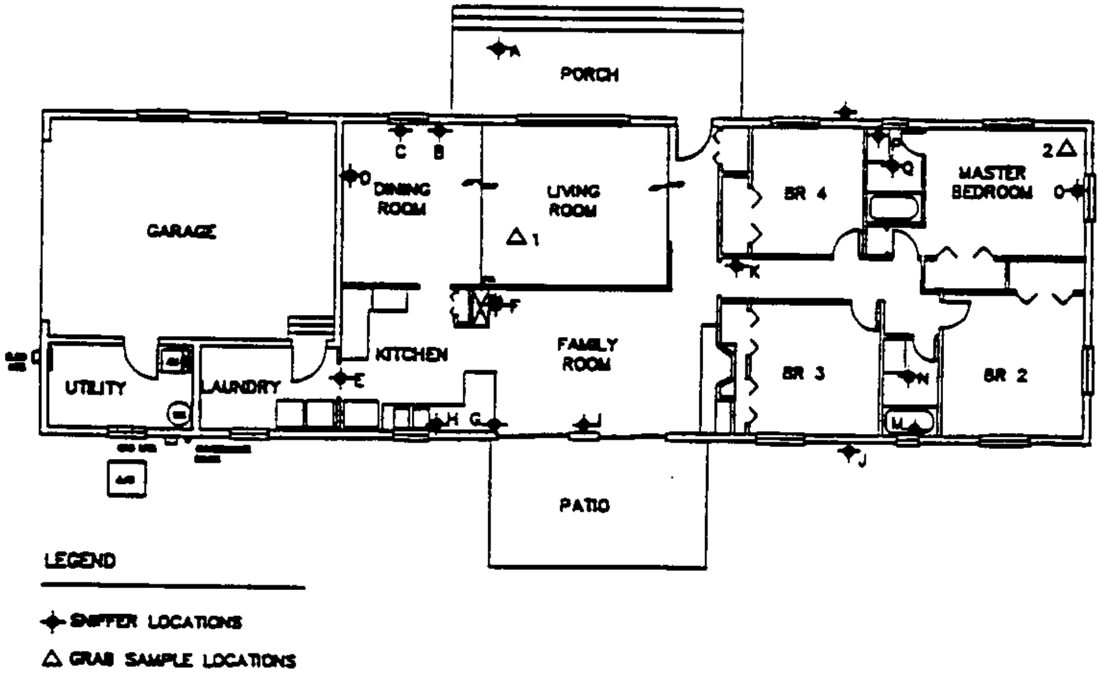
Sniffer measurements were made in various locations in an attempt to locate any "hot spots." Figure 38 shows the locations of the tests and the resulting radon levels. Test point "S"



GAMMA RADIATION MEASUREMENTS (μR/hr)

FIGURE 37

MARK	SAMPLE LOCATION	RADON LEVEL (pCi/l)
A	BACKGROUND - OUTSIDE	1.9
B	DINING ROOM - INSIDE WALL RECEPTICLE	22.8
C	DINING ROOM - JUNCTION BOX - DEEP	53.5
D	DINING ROOM - RECEPTICLE	30.9
E	KITCHEN - FLOOR EXPANSION JOINT	301.8
F	FAMILY ROOM - RETURN-AIR PLENUM	7.5
G	FAMILY ROOM - INSIDE WALL RECEPTICLE	17.4
H	KITCHEN - INSIDE WALL RECEPTICLE	31.9
I	FAMILY ROOM - INSIDE WALL SWITCH	13.6
J	SUB-SLAB - THROUGH FOUNDATION WALL OPENING	156.6
K	HALL - RETURN-AIR DUCT	44.0
L	SUB-SLAB - THROUGH FOUNDATION WALL OPENING	42.5
M	HALL BATH - TUB GROUT JOINT	17.3
N	HALL BATH - TOILET BASE	28.0
O	MASTER BEDROOM - INSIDE WALL RECEPTICLE	13.3
P	MASTER BATH - INSIDE WALL RECEPTICLE	12.7
Q	MASTER BATH - TOILET BASE	15.4
R	SUB-SLAB - BEDROOM #2 CLOSET - NEAR EXTERIOR WALL	352.0
S	SUB-SLAB - BEDROOM #2 CLOSET - AWAY FROM EXTERIOR WA	6861.0
GRAB 1	LIVING ROOM	8.6
GRAB 2	MASTER BEDROOM	10.2



GRAB SAMPLE AND SNIFFER MEASUREMENTS

FIGURE 38

indicates that there is a source strength under the slab close to 7000 pCi/L. Other sniffer measurements taken of sub-slab air at points 'E', 'J', and 'L' confirm the presence of much higher levels of radon under the slab. Points 'J' and 'L' were taken outside of the house at the points in the foundation wall where the masonry blocks had been removed. The substantially lower levels measured at these two points are reflective of the amount of dilution that occurs when soils are exposed to the atmosphere. The same condition exists at sample point 'E' where the radon is escaping into the atmosphere.

Tests taken in the wall cavities at switch and receptacle locations indicate the presence of significantly elevated levels of radon. These levels can be interpreted to conclude that the slab was not cast fully into the stemwall, if at all. Block wall conduction could certainly be a significant contributor to the overall indoor radon problem.

Test point 'K' was inside the return air grill in the hallway. Since the ducting did not penetrate the slab, it was presumed that this elevated level was the result of radon migrating through cracks in the slab and being drawn into the duct. The return-air grill was located in the wall cavity and close to the floor. The sub-slab radon level measured close to this point was almost 7000 pCi/L. Therefore, major radon entry could result from the localized depressurization caused by this return-air point.

A small tent was constructed over the control joint between the kitchen and the laundry room (Point 'E') and the radon levels were measured. The resulting measurement confirmed that this crack was definitely a contributor to the radon problem. Considering the localized depressurization condition that is created when the clothes dryer is operating, radon transport through this crack could be significant.

MITIGATION STRATEGY

The mitigation approach selected for Case Study #4 was two phased. Phase 1 would be to install a sub-slab depressurization system, and if after evaluation additional radon reduction was necessary, Phase 2 would be installed. Phase 2 was to employ a block wall depressurization system. In addition to Phase 1 were two recommendations for controlling the indoor depressurization effects of the fireplace and clothes dryer.

PHASE 1 MITIGATION PLAN

Even though numerous slab cracks were observed, and even more were suspected, none were totally accessible for sealing. Sealing cracks in concrete floor slabs is very costly and highly disruptive to most homeowners' daily routines. Considering that possibly all flooring materials would have to be removed in order to ensure that the full length of all cracks could be accessed for sealing, this was not considered to be a reasonable or cost effective approach.

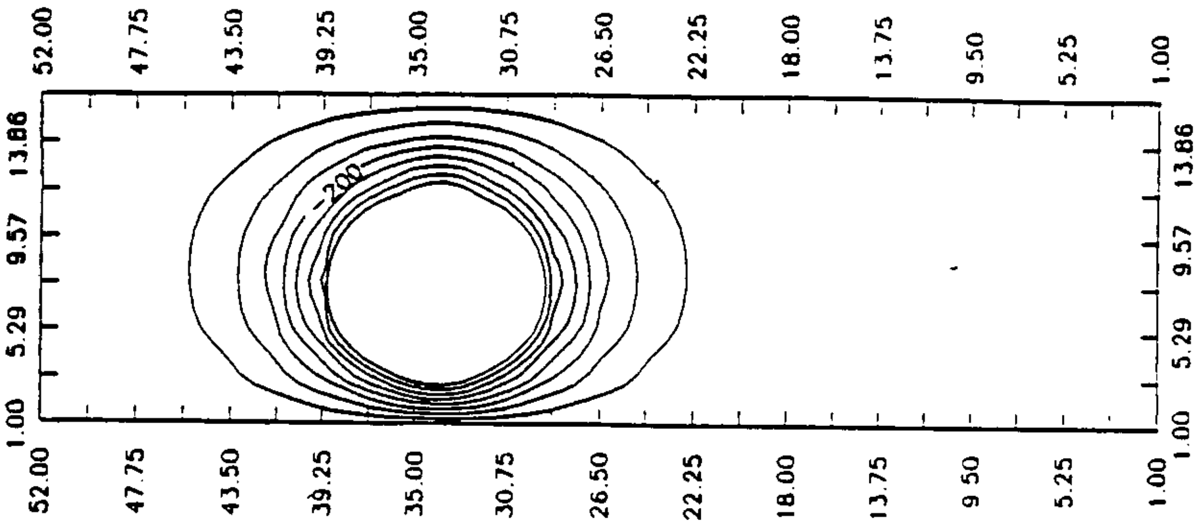
Previous installations of sub-slab depressurization systems had, however, proven highly effective at reducing indoor radon levels. The simple slab geometry and the uniform depth, approximately 20", of fill material of this house provided almost ideal conditions for the employment of this technique. By the time this plan was developed, another research project being conducted by the UF Indoor Radon Task Force had produced a computer model that could predict the sub-slab pressure field extensions associated with various suction point locations. The model also provided the ability to consider different slab sizes, geometries and fill characteristics. Using Case Study #4 criteria, the model was run and used to illustrate the sub-slab pressure field extensions associated with one and two suction points (Figures 39-A & 39-B). It was clear from this model that two suction points would be significantly more effective than one point in providing total coverage of the sub-slab area. From this additional analysis a two suction point sub-slab depressurization system was recommended for installation at the locations shown in Figure 40. The system would be installed as illustrated in Figure 41.

In conjunction with the installation of the sub-slab depressurization system it is recommended that an outside air intake be installed behind the clothes dryer. This would allow the dryer to operate without depressurizing the room. By minimizing the negative pressure conditions created by the clothes dryer, radon entering the house through penetrations in the slab, especially the control joint between the kitchen and laundry room, could be minimized. In order to minimize any negative pressure conditions associated with the operation of the fireplace it is recommended that the homeowner partially open a window in the vicinity of the fireplace.

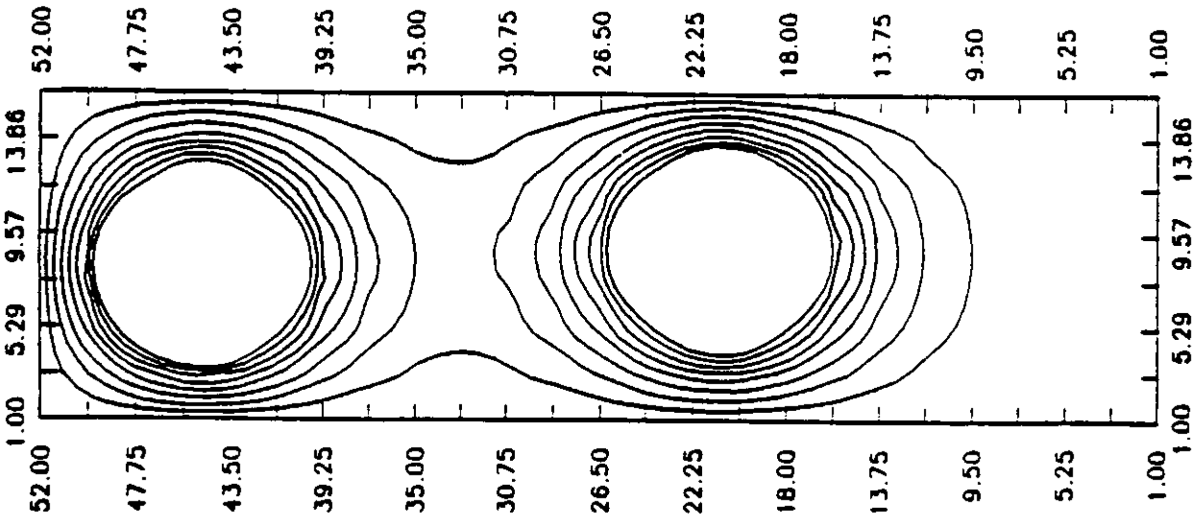
PHASE 2 MITIGATION PLAN

If the Phase 1 activities did not adequately reduce the indoor radon levels, installation of the block wall depressurization system is recommended.

The installation of the block wall depressurization system would involve first conducting pressure tests to determine where vertical cells in the block had been poured with concrete thereby creating several isolated wall cavities. Once these separate wall cavities had been



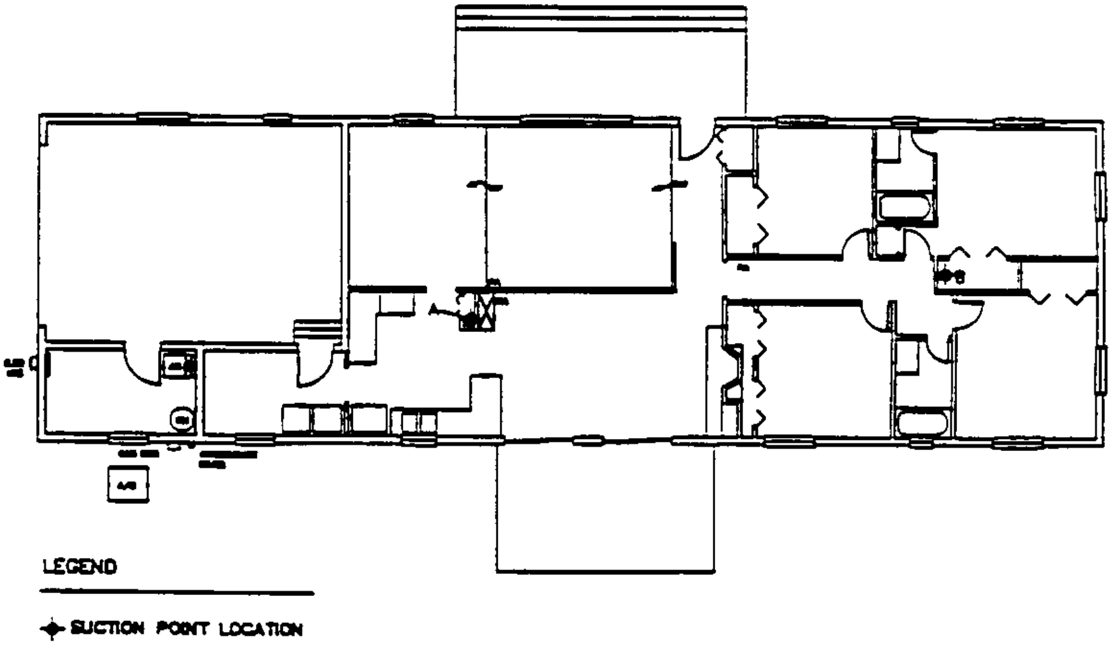
A - ONE SUCTION POINT @ -400 Pa SUCTION PRESSURE



B - TWO SUCTION POINTS @ -400 Pa SUCTION PRESSURE

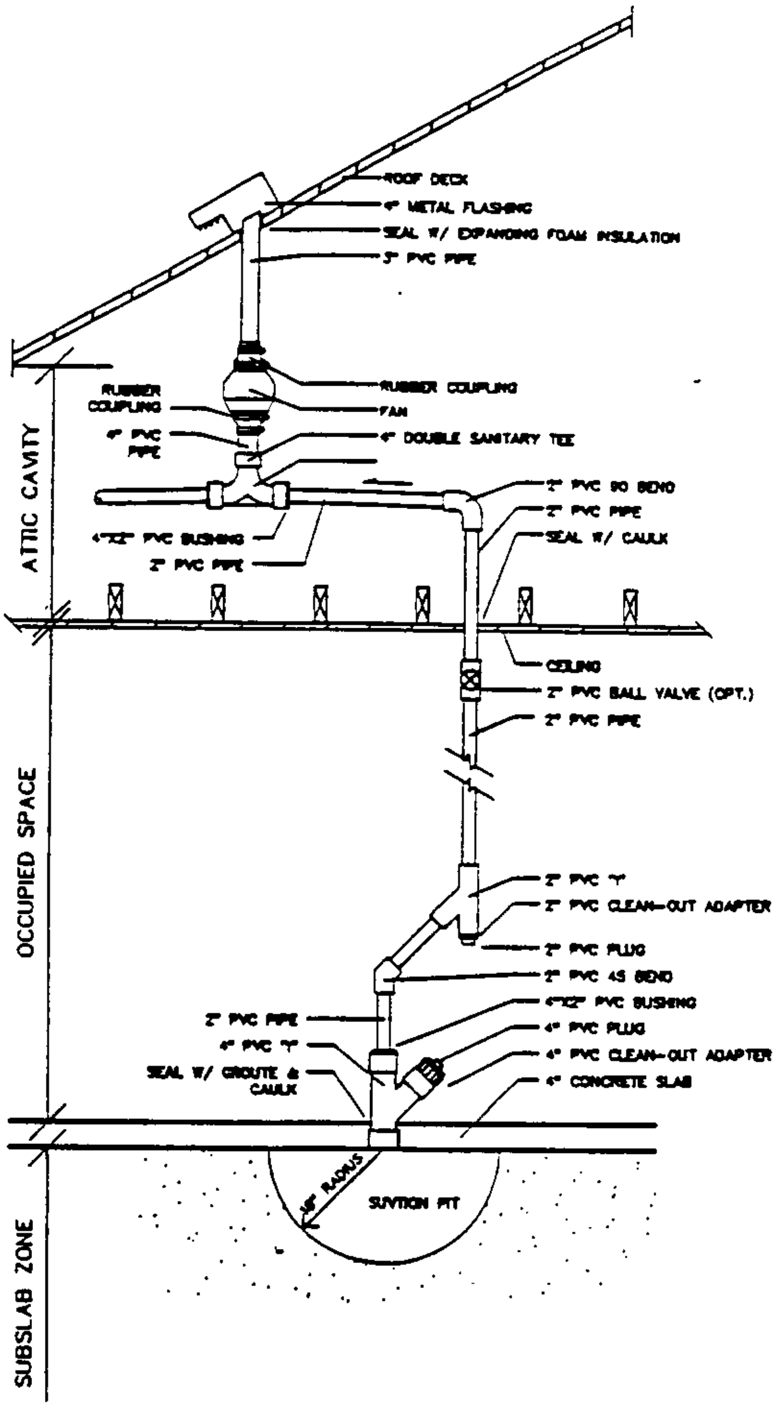
SUB-SLAB PRESSURE FIELD EXTENSIONS
PREDICTED WITH COMPUTER MODEL

FIGURE 39



SUB-SLAB DEPRESSURIZATION SYSTEM
SUCTION POINT LOCATIONS

FIGURE 40



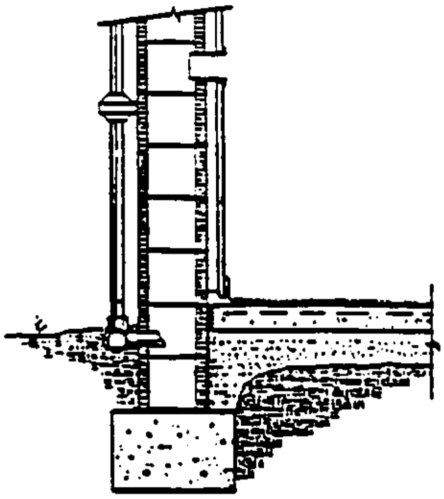
TYPICAL SUB-SLAB DEPRESSURIZATION SYSTEM

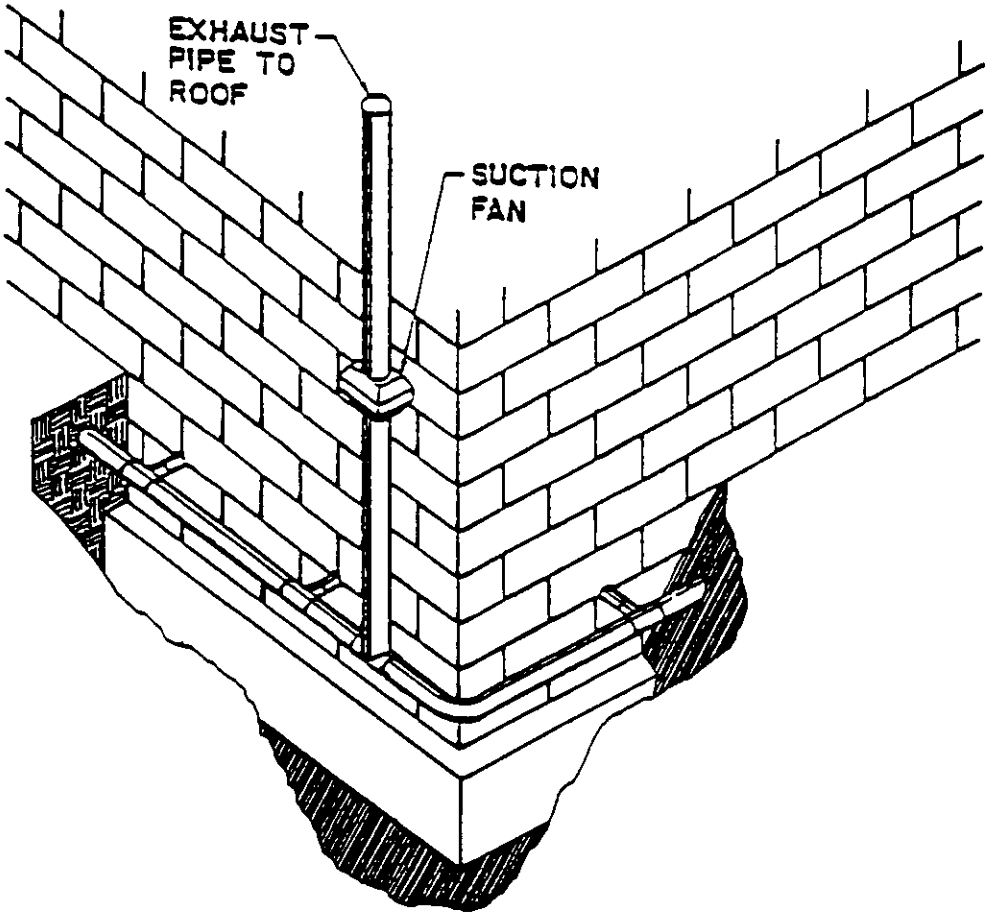
FIGURE 41

identified a 4" diameter PVC pipe would be placed just below grade around the outside of the exterior wall. Following the installation of the 4" manifold, 2" PVC pipes would be tapped into the block wall cavity, below grade if possible, and connected to the manifold (Figure 42). After all wall cavities had been connected to the manifold, a 4" diameter PVC pipe would be run vertically to the underside of the soffit where a fan would be installed. The discharge from the fan could either be routed through the roof and terminated with a weather-proof flashing or turned horizontal just under the soffit and terminated at the edge of the fascia. A screen would be necessary at the end of the pipe to keep birds and other animals from nesting in this pipe. One concern about discharging active radon mitigation systems is that the closer the termination point is to the ground the greater the opportunity there is for re-entrainment. This condition occurs when the highly radon enriched discharge is drawn back into the house through windows, doors or other openings. If this discharge is in close proximity to outdoor areas that are frequently used, such as a patio or deck, elevated health risks can result.

POST-MITIGATION EVALUATION

Installation of the mitigation plan was not made during the project period and therefore no post-mitigation evaluation of Case Study #4 was performed. However, several existing slab-on-grade residential structures have been successfully mitigated in Alachua and Marion Counties with the sub-slab depressurization technique being the only mitigation strategy employed. This technique has the ability to overcome many difficult conditions, such as inaccessible cracks, without a significant reduction in effectiveness.





WALL CAVITY DEPRESSURIZATION SYSTEM

FIGURE 42

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