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Demonstration of Remedial Techniques Against Radon in Houses on Florida Phosphate Lands

DEMONSTRATION OF
REMEDIAL TECHNIQUES AGAINST RADON
IN HOUSES ON FLORIDA PHOSPHATE LANDS

Final Report

EPA Contract 68-02-3559

AMERICAN ATCON INC.

DEMONSTRATION OF
REMEDIAL TECHNIQUES AGAINST RADON
IN HOUSES ON FLORIDA PHOSPHATE LANDS

Final Report

Report No. 1168/1199

by

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Appendix 1 House Summary Reports

This project has been funded with Federal funds from the U.S. Environmental Protection Agency under Contract Number 68-02-3559. The content of this publication does not necessarily reflect the views or policies of the U.S. Environmental Protection Agency, nor does mention of trade names, commercial products, or organizations imply endorsement by the U.S. Government, or by the authors of this report.

PROGRAM SUMMARY

This is the final report on a program carried out for the Environmental Protection Agency by AMERICAN ATCON INC. with the support of Acres American Incorporated to investigate and demonstrate means of controlling indoor radon levels in structures built on Florida phosphate lands.

The activities of the program were:

1. A review of current building practices in Central Florida to identify the openings in the building foundation that would allow the entry of radon in soil gas.

2. Development of foundation designs to avoid or eliminate these openings to produce radon-resistant foundations for new housing.

3. Identification of problems caused by the use of standard construction materials and methods in radon-resistant foundations, and possible solutions.

4. Demonstration of the effectiveness of radon resistant foundations by including them in the construction of houses.

5. An investigation of soil parameters that might influence the movement of radon from soil to house.

6. An experimental remedial action program to reduce the radon concentration in existing houses by closing the major foundation openings associated with the plumbing.

7. An experimental remedial action program to reduce the radon daughter concentration in existing houses by the use of electronic air cleaners.

8. Provision of guidance to Federal, State and local regulatory agencies in the framing of regulations concerning building in radon problem areas.

Over 100 houses in Central Florida were examined at all stages of construction, and foundation construction was followed in detail at selected sites. Common foundation openings were identified and photographed. Installation of the plumbing produced large openings in floor slabs, and concrete block foundations were also found to have many openings connecting the house interior to the soil.

An illustrated report "Common Building Practices and Soil Gas Entry Routes in Central Florida" was issued on completion of this phase of the work. For convenience, a copy is included in this report as Section I.

Radon-resistant foundations require either that the building be out of contact with the soil, or else that the foundation has no openings to the soil. The monolithic slab foundation, when a single concrete slab acts as both the floor slab and the wall footings, has very few openings to the soil compared with the common concrete block foundation, and all of the openings can be closed with a sealant without major changes in building techniques. The monolithic slab was therefore identified as the preferred form of radon-resistant foundation.

A local developer was planning a housing development on an area of reclaimed land with elevated soil radium concentrations, and intended to use monolithic slab foundations. He was approached, and agreed to participate in a program to test the feasibility of modifying and sealing these foundations to exclude radon from the houses. The average WL in these houses was lower than expected for conventional housing on soil of high radium activity, and was near background level in the one house where sealing had been performed under our direction. This work is described in "Modification of New Construction for Radon Resistance", which is included in this report as Section II.

The experience gained in this and the other programs was used to produce a report "Radon Resistant Housing for Florida Phosphate Lands", which summarised the technical and organisational problems involved in the routine production of radon resistant foundations, and suggested solutions. For convenience a copy is included in this report as Section III.

For a monolithic slab to be effective as a radon-resistant foundation, it must be free of major cracks. Concrete is unstable during its setting phase, and so a report was prepared to summarise the properties of concrete and identify what measures should and could be employed to make production of crack-free monolithic slabs a routine matter. This report was issued as "Concrete and Production of Radon Resistant Foundations", and for convenience, a copy is included in this report as Section IV.

Radon levels in houses are only poorly correlated with soil radium measurements. This lack of correlation may be due to difficulties in properly estimating average radium concentration from a few measurements, variation in the ease with which soil gas containing radon can enter a house, and variation in the ease with which soil gas can move through the soil to a house. A brief study was made of both the radon production rate and the grain size distribution of near surface soils in the Central Florida area. All soils, regardless of radium content, were found to have very similar size distributions, which suggested that the ease of soil gas movement through the soil was fairly uniform over the area, and that the potential of land to produce elevated radon concentrations in buildings depended mainly on the soil radium content. A report on this work was issued as "A Soil Structure Survey in Polk County, Florida", and for convenience, a copy is included in this report as Section V.

An experimental investigation and remedial action program was carried out at 10 houses and a mobile home. Each structure was located on land that had phosphate mineralisation or had been affected by phosphate mining activities, and the annual average WL was believed to be in excess of 0.03 WL.

Closing the major openings associated with the plumbing had mixed success, with significant reductions in radon concentration occurring in 6 of the 10 houses. This showed that other routes of entry through concrete block foundations, sub-floor services, and floor cracks could be equally important. Closure of these other routes of entry in concrete block foundations was evaluated, but not attempted, on account of the extensive work required and the high costs. Increased ventilation of the mobile home crawl-space significantly decreased the radon concentration.

Electrostatic air cleaners (EAC) have been suggested as a site-independent means of reducing radon daughter concentrations for many years, but field experience is lacking. As part of this program, EAC's were installed in the central air-conditioning system of those houses where the radon concentration remained high. If the air was circulated continually, EAC's reduced the concentration of radon daughters to less than 20% of the previous value, and their efficiency was constant over many months. All of this work is described in "Experimental Investigation and Remedial Action Program", a copy of which is included in this report as Section VI.

Active remedial measures to reduce radon concentration, such as ventilation or pressurization, were not investigated as they would involve major work plus a long-term commitment regarding increased energy costs. In view of the difficulties associated with extensive sealing as a remedial measure, further study of these measures is suggested.

Assistance was given to State and Local agencies in framing regulations concerning building in radon problem areas. In particular, input regarding house construction techniques and problems was provided to the State of Florida's Phosphate Related Radiation Task Force regarding the development of a Model Building Ordinance for use in areas of elevated soil radium.

SECTION I

COMMON BUILDING PRACTICES

AND

SOIL GAS ENTRY ROUTES

IN CENTRAL FLORIDA

Report No. 1168/1171

1.0 INTRODUCTION

This report is to document the results of an activity which forms part of a program intended to demonstrate means of controlling indoor radon levels in structures built on Florida phosphate lands. The work is being carried out by AMERICAN ATCON INC. with the support of Acres American Incorporated.

The natural radon content of the soil is elevated in some parts of the Florida phosphate lands, resulting in elevated radon concentrations in the soil gas. If building construction is such as to provide pathways, or routes of entry, between the interior of the building and the soil below, then this radon-bearing soil gas may enter the building and result in elevated indoor levels. This report therefore documents a review of current building practices, with the intention of identifying routes of entry. Based upon this knowledge, certain modifications to building practices may be seen as a means of reducing indoor radon levels.

2.0 DISCUSSION

Soil consists of finely divided rock particles enriched near the surface with organic materials. In most soils a significant fraction of the soil volume is taken up by the space between the individual grains. When the radium present in the soil decays, a fraction of the radon produced escapes from the soil grain and its surface layer of water into the intergranular space, and becomes a component of the soil gas. At depth, the radon concentration in soil gas is 1000 pCi/L or more, depending on the soil radium content, but near the surface, atmospheric convective and diffusive forces cause atmospheric air to mix with soil gas, and the radon concentration is much lower.

The sandy soils of central Florida have porosities of 30% and soil gas can move readily through the soil voids under the influence of pressure gradients. The pressure inside a building is usually lower than outside, as a result of suction forces developed by the wind blowing over the roof, operation of ventilation systems, or temperature differences between the interior and the soil. If there are direct open connections from the building to the soil, the lower pressure in the building will draw in soil gas, thus increasing the radon concentration in the building.

It is also possible for soil gas to be forced into buildings as a result of the soil gas pressure rising above atmospheric. This has been observed following heavy rainfalls which saturate the upper layer of porous soil, and this layer of water is then drawn down into the soil by capillary action, compressing the soil gas beneath it. If there are areas shielded from the rain, such as beneath houses, the compressed soil gas will tend to be forced out of the soil there.

The rate at which soil gas enters a building depends on the pressure differential, the resistance of the soil to gas movement, the number of connections to the soil, and their resistance to gas flow. The soil resistance is a complex and variable function of at least the size distribution of intergranular spaces, and the amount of soil water, which fills the smaller spaces. As the resistance of most connections is less than the overall flow resistance of the soil, the flow is not very dependent on the connection size. Large soil gas inflows often result from a number of soil connections, rather than a single large connection. The final radon concentration in a building depends not only on the soil gas inflow rate, but also on the radon concentration in the soil gas and the building ventilation rate.

The openings that connect a building interior to the soil are produced in three fashions. The first is that the opening is built-in to assist installation of sub-grade services, usually plumbing. The second is that the opening is the inevitable result of the materials or practices used in construction of the building, for example concrete blocks. The third is that the opening is the result of failures in the building materials, such as cracking in concrete.*

If a building has elevated radon concentrations, and the building materials do not have a high radium content, then the cause is usually soil gas entry. If the routes of entry can be found and closed, the radon concentration will be reduced. Some soil gas entry routes can be easily identified by visual inspection of those parts of the structure in contact with the soil, but this is not possible in existing buildings where finish has been applied over the walls and floors to conceal the basic structure. It is only when a building is under construction that the opportunity arises to view the naked structure, before the cosmetic finish is applied.

Although houses are constructed individually by individual workmen, there is a measure of standardization as a result of the constraints on the building trade. In the first place, there are legislated standards enforced by inspection. Although the codes themselves are not very specific, in a given area the inspectors enforce standardization by requiring certain things to be done in a certain way. In the second place there are economic pressures which make it more profitable for a builder to repeat a set of standard house designs with essentially the same work force, than to start from scratch with each house. In the third place, a combination of personal preferences, availability of materials, and fashion all combine to produce a form of standardization in a given area. As a result, examination of a number of houses under construction can be expected to show the methods and techniques generally in use in the area. As details of construction usually change only with the introduction of new

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* If none of these routes of entry exist, then the radon concentration in the building is set by the rate at which radon can diffuse from or through the building materials. Under normal circumstances, this is so slow that concentrations from this source in excess of 2 pCi/L are rare.

codes or new materials, the techniques observed today can be related to those used in the past. The potential for significant changes in construction details can be identified by establishing a historical sequence of changes in codes, inspection requirements, materials and building styles.

The criteria for foundation and slab construction to date have been the contractors' cost and the constructors' convenience, not exclusion of soil gas. As a result most forms of construction contain direct connections to the soil. These are not construction faults, but rather are the inevitable consequences of the materials or practices involved. As a result of the de facto standardization discussed above, we can expect that the connections to the soil produced in houses under construction today are similar to those produced in the past.

Therefore, the reasons for conducting a review of current building practices are that it provides an opportunity to 'see' what soil gas entry routes are being built into houses today, and to deduce what routes were built into houses in the past. This information is needed to plan the remedial actions to close existing routes and design those modifications to present techniques needed to prevent routes in future construction.

This report records current building methodology in central Florida, and ilustrates and discusses the techniques that produce soil gas routes of entry.

3.0 HOUSE CONSTRUCTION STYLES

There are five styles of foundation construction that have been used in the Lakeland area. These are described and discussed below.

3.1 Pier Foundation (Figure 1)

This was the most common form of southern house construction until the forties. Because of the threat of termite attacks on wood in contact with the ground, wood frame houses were raised on concrete or masonry piers so that the lowest part of the wood structure was more than a foot from the ground. The perimeter of the space beneath the house was left open, or closed with a metal or masonry screen. This form of construction is illustrated in Appendix A.

3.2 Ventilated Crawl Space (Figure 2)

In the early forties, masonry (concrete block) construction displaced wood frame, but suspended wood floors were retained. Masonry walls were constructed on a footing, and a wood floor was suspended from the walls about 18 inches (45 cm) from the ground. The space beneath the floor was ventilated by a variety of perforated concrete blocks, set into the wall at or below the joist level. This form of construction is illustrated in Appendix A.

3.3 Concrete Floors

In the early 50's, concrete floors supported by sand fill replaced suspended wood floors. The construction method was to clear the site of all organic material, and then dig footing trenches into undisturbed ground. Reinforcing bar was laid in the trench, and then concrete was poured in to make a level and solid footing on which to erect a concrete block foundation wall three blocks high. The space inside the walls was filled with compacted sand, and the floor poured on top. There are two different details where the floor meets the wall. The most common form met with today uses a specially formed notched block as the top course of the foundation wall, which allows the floor slab to enter the wall. This is identified as 'Fixed Floor'. The earlier form of construction just ran the floor up to the foundation wall, and is identified as 'Free Floor'.

3.3.1 'Fixed Floor' (Figure 3)

The top block of the foundation wall is specially formed with a recess 4 inches by 4 inches (10 x 10 cm) along the inside face to accept the floor slab. The sand is filled to level with the inside face of the recess, and may, or may not, fill the interior cavities of the wall. A layer of plastic is spread over the sand, and then wire mesh reinforcing and a concrete floor poured extending into the recess cut in the top block. Usually the plastic spread over the sand laps over the walls, and so prevents the concrete from filling the upper block cavities completely. The upper portion of the house walls are constructed with the interior face of the block wall resting on the concrete floor. This form of foundation construction is illustrated in Appendix B.

3.3.2 'Free Floor' (Figure 4)

A standard 3 block foundation enclosure is filled with sand to within 4 inches (10 cm) of the top of the wall. The interior face of the wall is usually lined with an "expansion joint" of fibre board of styrofoam to prevent the concrete floor from adhering to the walls. The sand is covered with plastic sheeting and reinforcing mesh and a concrete floor poured in the usual way. This form of foundation construction is illustrated in Appendix A.

3.4 Monolithic Slab (Figure 5)

This form of construction was introduced in the last few years, and is becoming more popular, but still represents only a small fraction of the houses constructed. The site is prepared and leveled. Wooden forms about 15 inches (38 cm) high are placed at the perimeter of the slab, and the space inside is filled with compacted sand to about 4 inches (10 cm) from the top of the forms. The slab is thickened to form perimeter and wall support beams by digging trenches in the sand. Plastic sheet and reinforcing mesh is spread over the sand and reinforcing bar laid in the trenches. A continuous concrete slab is poured over the area in the usual way. Frame or concrete block walls are erected on the slab. This form of construction is illustrated in Appendix C.

4.0 RESISTANCE OF CONSTRUCTION STYLES TO SOIL GAS ENTRY

4.1 Older Forms of Construction

Houses constructed on piers are designed to avoid contact with the soil, so it is not likely that there are any direct connections which would allow soil gas to enter the house. From the point of view of preventing radon entry, this is the most satisfactory form of construction.

Houses constructed with concrete block walls and ventilated crawl spaces have minimal connections to the soil. If there are cracks or openings in the walls below grade, the concrete block cavities can allow soil gas to move up inside the wall and subsequently enter the house through service openings in the wall. However, the shallow depth of the footings ensures that the radon concentration in the gas will be low, so this may not produce significant radon concentrations in the house. The ventilation in the crawl space may not always be sufficient to maintain low soil gas concentrations in the crawl space air, so it is possible that radon levels in the house may rise occasionally, as is known to happen in house trailers with skirted crawl spaces. On average, though, low radon concentrations can be expected in houses with properly ventilated crawlspaces, and this is a reasonably satisfactory form of construction to minimize soil gas entry.

4.2 Modern Construction

The 'free floor' and 'fixed floor' constructions not only have hollow concrete block walls in contact with the soil, but the floor itself rests directly on the ground. Any opening in the entire foundation structure has the potential to be a conduit for soil gas entry. Openings in the foundation walls contacting the soil can allow soil gas to enter the wall cavity and subsequently move into the house via service cavities in the walls. In addition to these indirect routes, soil gas may directly enter the house through openings in the floor created by the installation of services, and construction practices. Passage of soil gas through the concrete slab itself is very slow, for it is at least 4 inches (10 cm) thick and underlain by plastic sheeting.

With this in mind, the 'free floor' construction is the least satisfactory. When the concrete floor slab sets, it shrinks slightly, and the presence of the "jointing material" between the wall and floor ensures that there is small gap between the edge of the floor and the wall. This provides a direct connection between the house interior and the soil all around the floor perimeter. The area of this gap can equal the total area of all the service penetrations through the slab.

The 'fixed floor' construction is an improvement for it avoids the interior wall-floor joint by extending the floor into the top half of the foundation wall. As the house wall is constructed on top of the foundation wall, the routes of entry into the house are via the block wall cavities, and through openings in the floor slab. If the floor slab fills the top course of blocks completely, then the major routes will be those through the floor slab.

The most satisfactory form of modern construction is monolithic slab. The slab provides both the floor and the foundation for the walls, and is the only part of the structure to touch the soil. The only connections to the soil are therefore those through the slab itself created by service entries and building practices.

Openings in a floor slab enable soil gas to enter the building directly whenever the pressure differential is favourable. Soil gas may enter block walls through below-grade openings, but its path into the house will be less direct. For this reason, openings in the floor slab will be discussed first.

5.0 ROUTES OF ENTRY THROUGH FLOORS

Major routes of soil gas entry common to all houses are produced during the installation of plumbing services through the concrete floor slab. The types of services are water supply pipes, drain pipes, and vents; and connections to floor based fixtures such as toilets, showers, and baths.

5.1 Piping

The Standard Plumbing Code requires that metal pipes passing through concrete shall be protected against external corosion by a protective coating, wrapping, or other means. In modern construction the sanitary drain system is made of PVC plastic, so the only metal pipes now used are those for the water supply. These pipes are protected from contact with the concrete in a variety of ways, the most common being painting the pipe with asphalt. Other methods include placing the pipe through a short polyethylene plastic sleeve, or wrapping the pipe with foam rubber or fibreglass pipe insulation. Neither wrapping nor sleeving methods produce a gas tight seal between the concrete and the pipe, so whenever they are used, they produce routes of soil gas entry through the slab.

Under normal circumstances concrete adheres well to slightly roughened plastic pipe, and pipes coated with asphalt, so the joints with individual pipes are virtually airtight. As it is the practice for plumbers to run water pipes in groups, there is always the possibility that the concrete will not flow properly around the pipes and leave a small opening through the slab adjacent to the pipe. This is not common, for usually the concrete is sufficiently fluid when poured. These details are illustrated in Appendix D.

5.2 Sanitary Connections

The pipes that drain sanitary fixtures such as toilets and showers terminate in a flange at or just above floor level to which the fixture is sealed. This flange has to be attached to the pipe after the concrete floor is poured, and so to facilitate its installation, the concrete is held away from the pipe by a collar of styrofoam or cardboard, or by a half concrete block used as a form. When this temporary filling is removed a hole is left clear through the slab into the fill.

The hole is subsequently concealed by the installation of the fixture directly over the hole. As the joint between the fixture and the floor is not airtight, this provides a large route for soil gas entry.

Modern baths have the bottom of the bath just above the floor, and so the bath drain must be below floor level. The drain connection is generally 1-2 inches (2-5 cm) below the lower surface of the concrete slab,. so to provide access to this connection and space for the bath drain, it is practice to form an opening through the slab about 8 x 16 inches (30 x 60 cm) in size. An opening of about this size is needed to allow the plumber room to get his hands into the area to install and connect the bath drain plumbing. The usual form is a concrete block, which is pulled out by the concrete finishers when the concrete stiffens. A wooden form is occasionally used, and is often left in place.

After the bath drain plumbing is connected, a layer of liquid asphalt is often poured into the hole to close it. The original intent of this was to exclude insects, but the use of permanent insecticides on the site now makes this precaution redundant, and it is no longer required in the City of Lakeland.

If asphalt is used, it is usual to partially fill the hole with sand. Unfortunately, the surface of the sand is rarely level, and is often highest at the most remote end of the hole. The asphalt poured in is rarely deep enough to cover the high point, and so the covering is not continuous. At times the hole is filled right to the top with sand, and the asphalt merely forms a cap on the sand and does not touch the concrete at all. In each case, the asphalt covering is not able to exclude soil gas.

These details are illustrated in Appendix E.

5.3 Unintentional Routes of Entry

The modification of the building fabric to assist the installation of plumbing services produces intentional and identifiable openings which can, in principle, be closed by the plumbers after they have finished their work. There is however, a second group of openings that are produced more or less unintentionally as a side effect of some other goal. These are much more difficult to identify and prevent, for many of them are the result of individual enterprise seeking to ease a task, or to give concrete form to an architect's drawing.

Examples of the first kind are temporary plumbing supports made of pipe and left in the concrete; also temporary grade stakes and screeding bar supports which are withdrawn after the concrete is partially set, leaving holes through the slab. Occasionally holes are produced by modifications of standard plumbing techniques required to overcome the small errors inevitable in any human activity.

Architectural features that create openings through the floor slab include changes in floor level, sunken fixtures, and unusual perimeter treatments. Changes in floor level require either that the floor be poured in two separate slabs, which may produce a route of entry where the edges touch, or else the use of hold-back forms around the edge of the sunken portion. These forms are located by wooden stakes driven into the sand fill. When the concrete is almost set, the forms and the stakes are removed, and the holes in the concrete left by the stakes are concealed, but not sealed, with a layer of cement.

Sunken baths and showers often have their bases below the level of the slab, and so are installed in openings that are formed through the slab. The openings around the edges are not airtight. Large openings can be produced in this way. If the change in level is large, an internal wall may be used instead of a temporary wooden form. If the foundation walls are of block, the internal wall will be of block also, the cavities of which will produce a set of openings through the floor. A similar situation can be produced when a room is extended out beyond the edge of the foundation. The resulting floor openings in all these cases will be concealed by decorative edging round the tub, frame walls, or by carpet. They still remain as routes of soil gas entry.

These details are illustrated in Appendix F.

5.4 Accidental Routes of Entry

The routes of entry discussed above have all been produced at the time of construction, and in principle could be avoided by changes in building methods or design. Accidental routes of entry are produced by failures of the building materials after their installation. The most common failure of interest is cracking of the concrete floor slab. This can occur as the result of differential site settlement, or of tensions in the concrete from the shrinkage forces developed while the concrete cures. A shrinkage of 7 mm on a 7 metre slab has been observed, and if the slab movement is restrained, the tension forces developed may be higher than the tensile strength of the concrete, and a crack will develop at the point of highest stress. As most of the shrinkage takes place within a few days of pouring the cement, these tension cracks can be observed in the floors of houses under construction.

In simple houses with a basically rectangular slab with no changes of section, the slabs were found to be free of cracks. More elaborately designed houses with 'L' or 'U' shaped slabs were often found to have one crack across the narrowest part of the slab, usually starting at an inside corner which acted as a stress-raiser.

Although cracks in the floor are potential routes of entry for soil gas, the actual amount that passes through any one crack depends very much on the state of the plastic sheeting immediately beneath the slab. If the plastic is intact, and lapped well at the joints, no soil gas may enter the crack at all, but if the plastic is missing from under the wider portion of the crack, the entry rate of soil gas can be quite considerable. If plumbing penetrations are located in the areas where tensile cracking takes place, the crack tends to pass through them as they are weak spots. In this case the crack may be a significant route of entry, for the plastic sheeting is never continuous around the pipes.

These details are illustrated in Appendix G.

6.0 ROUTES OF ENTRY VIA CONCRETE BLOCK WALLS

6.1 Soil Gas Entry Routes Into Block Walls

Concrete block walls are constructed by placing a layer of mortar approximately 1 inch (3 cm) wide on the inner and outer edges of a block wall, and placing a block on top. The mortar does not run across the wall, and so there are horizontal channels from block to block as well as the vertical connections provided by the aligned cavities. It is quite common for there to be small gaps in the mortar, particularly on the inner face of the wall, and so a concrete block wall is far from airtight as constructed. A stucco finish is often applied to the above grade exterior surface of the wall, and will fill most of the holes there, but the subgrade portion is left as built. There are numerous openings to the soil at the junctions of the block work.

Where sinks are placed on outside walls, it is usual to run the water, drain and vent pipes to the fixture through the wall cavity. As the plumbing runs below the slab, a portion of the inner face of the wall is usually broken away to bring the pipe into the wall cavity. Even in those buildings where the floor slab fills the upper block cavities, the concrete is excluded from those block cavities through which the pipes pass. In these areas there is a direct connection to the soil, and a vertical connection to the upper portion of the wall.

The pipes leave the wall cavity through holes opened in the inner face of the block wall, which are subsequently concealed by the wall board applied as finish. These are not the only holes in the blocks, for electrical outlets, switches, and telephone jacks are usually too thick to be placed in the space between the block wall and the wall board, and so holes are made for them in the blocks.

These details are illustrated in Appendix H.

The Building Code requires that concrete block houses be reinforced to resist the wind forces produced by hurricanes. This is done by placing horizontal reinforcing bar in the upper courses of the wall, and filling the blocks with concrete to form a reinforced tie bar around the top of the wall. This beam is tied to the footing by vertical reinforcing bars at each corner of the building.

The corner cavities are also filled with concrete. These reinforcing beams effectively close the top and ends of each concrete block wall, and prevent the direct movement of air within the cavities from one house wall to the other.

As a result of all these building practices, the pressure differentials between the inside and the outside of a house are developed mainly across the exterior face of the block walls and the ceiling. If the pressure inside the house is lower than in the soil, then it is likely that soil gas will move from the soil into a wall cavity, up inside the cavities, and then into the house through the openings in the interior face of the blocks.

The amount of soil gas that will enter the house will be greatly influenced by leakage of external air into the wall, through openings around windows, doors, water entries etc. As each wall is isolated from the others, high leakage into or out of one wall will reduce the gas transfer rate only from that wall.

7.0 BUILDING MATERIALS

The materials used in foundation construction have changed very little since the use of pier foundations was abandoned, but the quality of the materials used has improved. Some comments on the materials used are listed below.

7.1 Concrete

The quality of concrete has generally improved over the years as on-site mixing has been replaced by central batching and delivery to site in special trucks that provide controlled agitation of the mix. The Building Code requires a minimum concrete strength of 2500 psi, and specifies the ratios of cement and water required to achieve this. The mix as delivered to site generally lies within these limits. Unfortunately, this mix is usually too stiff for easy placement, and so common site practice is that the workmen add water to the mix while it is in the truck. The increase in water makes the mix more fluid, easier to pour and spread, but decreases the strength of the concrete and increases shrinkage while curing. Both these factors increase the probabililty of tension cracking of the slab.

7.2 Slab Reinforcing

A steel mesh is used in concrete floors to reinforce the floor against tension cracking. To be effective, the tension forces must be transferred from the concrete to the steel, and this requires that the mesh should be embeded in the concrete.

The steel mesh is usually laid over the prepared area, without any chairs to raise it above the ground. When the concrete is poured over, the mesh remains at the bottom of the slab. Tension forces cannot be fully transferred to the mesh in this area, so the reinforcement provided is not fully effective.

It is the combination of ineffective reinforcing and the high shrinkage of watered concrete that causes the observed cracking in some large floor slabs.

7.3 Vapour Barrier

The area over which the floor slab is to be poured is covered by a layer of heavy plastic. This material initially prevents loss of cement from between the aggregate (honey-combing) by capillary attraction into the ground. When the cement has set, it may prevent the soil moisture from wetting the lower surface of the slab and setting up stresses in the slab from differential expansion of the concrete. The material may also prevent the movement of soil gas through cracks that pass over intact areas of the plastic sheet, but is neither heavy enough nor applied in such a manner as to prevent the passage of soil gas generally.

For the material to be effective, it would have to be a reservoir grade plastic, to remain unpunctured while the concrete placers walk over it with their boots while pouring and leveling the concrete. In addition, special sealing would have to be performed at joints in the plastic sheet, and wherever there are openings for the plumbing services.

These details are illustrated in Appendix I.

7.4 Concrete Blocks

Blocks are made by casting concrete in a mold. Over the years the quality of the block has improved as filling and curing procedures have changed to give a stronger and lighter block with well defined dimensions. As part of this procedure, the blocks have been changed from 3 hole to 2 hole block.

7.5 Backfill

Sand is used in large amounts to level the site, to fill the foundation area to floor slab level, and to provide initial grading for the landscaping. One source of sand used in the past was the sand tailings from phosphate mining. As those sands can contain elevated concentrations of radium, elevated radon concentrations could be expected in these houses. Present day builders may still be using these tailing sands.

7.6 Plumbing Services

The materials used for the installation of plumbing services are commonly copper for water lines and PVC plastic for waste lines. A few years ago, the most common materials were galvanized iron for water lines and cast iron for waste lines. The change in materials has not changed the way the lines pass through the slabs nor the methods used by the trade in producing the recesses and openings needed for the connections.

7.7 Mechanical Services

Most houses are heated and cooled by a forced air system, mounted in the attic. The system typically recirculates 1200 cfm (34 m^3/min.) and fresh air is supplied by infiltration alone. Its infiltration rates tend to be lower in the summer, this may lead to lower summer ventilation rates, and correspondingly higher radon concentrations.

As the duct-work and fan are in the attic, any leaks from the pressurized supply ducts will withdraw air from the building, and the pressure then will fall slightly. This pressure decrease will increase infiltration, but will also induce soil gas into the building. The increase in radon supply rate may be much larger than the increase in ventilation rate, with the net result that the radon concentration in the house rises considerably during operation of the air circulation system.

7.8 Building Codes

Paths through which soil gas containing radon can enter a building are produced during construction of the foundations (including footing, foundation wall, slab and exterior walls) and during the installation of the plumbing up to the point where it enters the interior of the building.

The 'Standard Building Code' governs design and construction of the foundation and exterior walls, and the 'Standard Plumbing Code' governs design and construction of the plumbing. The actual construction is inspected at fixed stages by the Building Inspectors, who are representatives of the local authority (city, town or county). The Building Inspectors interpret the codes, and by requiring compliance with the codes, enforce a standarization of building designs and construction methods.

The Standard Building Code and the Standard Plumbing Code are publications of the Southern Building Code Congress International Incorporated.

This is a non profit organization based in Birmingham, Alabama, and its services are intended to be used by authorities regulating the construction industry. The codes have been adopted as a legal requirement for construction in many jurisdictions in the South Eastern United States, and were adopted in Lakeland and Polk County several years ago.

The purpose of the codes is to provide minimum requirements to safeguard life and health, and for protection of property. They are based on the experience of the building industry generally. A second purpose the codes have is to provide design guidance so that constructors can choose the building material best suited to their needs.

As the codes provide only minimum standards and guidnace, they are not a barrier in themselves to the introduction of new practices designed to prevent or close soil gas entry routes. However, as it is usual to design to the code requirements, a considerable effort would be required to ensure that details of the new practices reached all interested parties.

8.0 CONCLUSION

Houses presently constructed in central Florida have numerous soil gas entry routes built into them, either as a result of their design, construction, or plumbing installation. The major barriers to the entry of soil gas are probably the resistance of the soil to gas movement, and the generally small pressure differentials produced between the house and the ground.

Land that has been disturbed by phosphate mining operations not only has a higher radium content than normal, but may allow soil gas to move through it more easily than through undisturbed ground. Under these circumstances it is not surprising that there are many houses in those area where the leakage of soil gas is demonstrated by elevated levels of radon.

If it is desired to build houses with low level of radon, there are two possible courses of action. The first is to identify those areas where the soil radium is low, and the resistance to gas movement is high enough that conventional housing can be constructed, and limit all new building to these areas. The second is to modify house designs and construction so that new houses have no major soil gas entry routes built into them, and limit new building to these new 'radon-resistant' designs. These houses could then be built anywere, regardless of soil conditions.

The difficulties with the first approach are that although it is easy to estimate the radium content of soil by a radiation measurement, the techniques to determine the resistance of the soil to gas movement have not yet been developed. In addition, even if an area could be identified as acceptable, it might not be suitable for housing, or might not be where housing was wanted.

The difficulties with the second approach are not those of designing a suitable foundation structure, as the existing slab-on-grade foundation would be satisfactory with small modification, but those of quality control. It is very difficult to persuade the building trades to change their accustomed ways of doing things, but to close the entry routes successfully would depend on doing just that. In addition, some hardship might be caused to local builders and suppliers by excluding the use of certain designs and materials.

Despite these problems, 'radon-resistant' housing would seem to be a more generally applicable solution than land control. In the southern part of Polk County the areas disturbed by mining are so extensive that it may be difficult to find 'safe' housing areas close to many of the communities there. A land control policy might effectively stop further expansion in these communities. On the other hand, 'radon-resistant' housing would enable expansion to proceed in those areas with minimum hinderance.

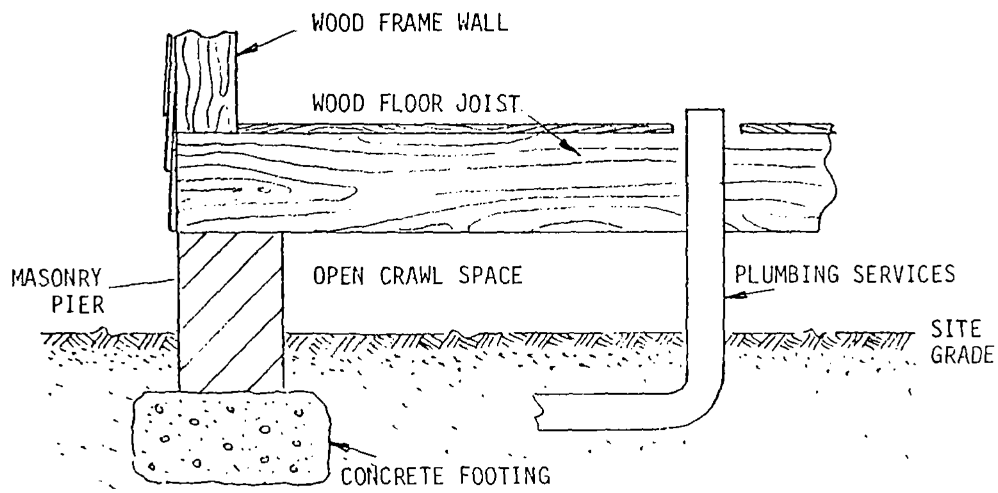


Fig. 1 PIER FOUNDATION

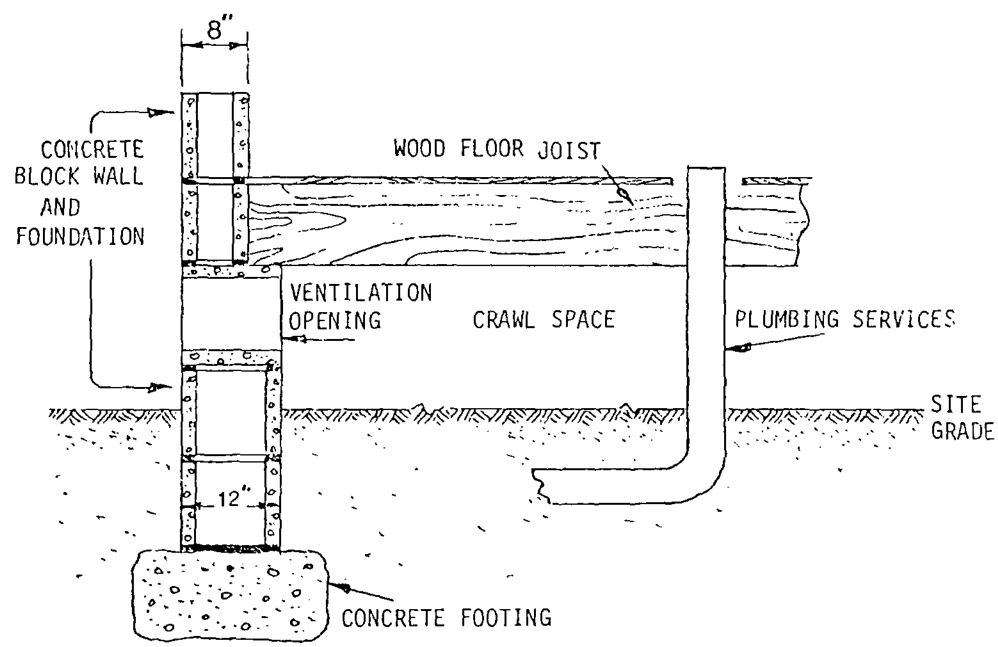


Fig. 2 VENTILATED CRAWL SPACE

FOUNDATION CONSTRUCTION STYLES

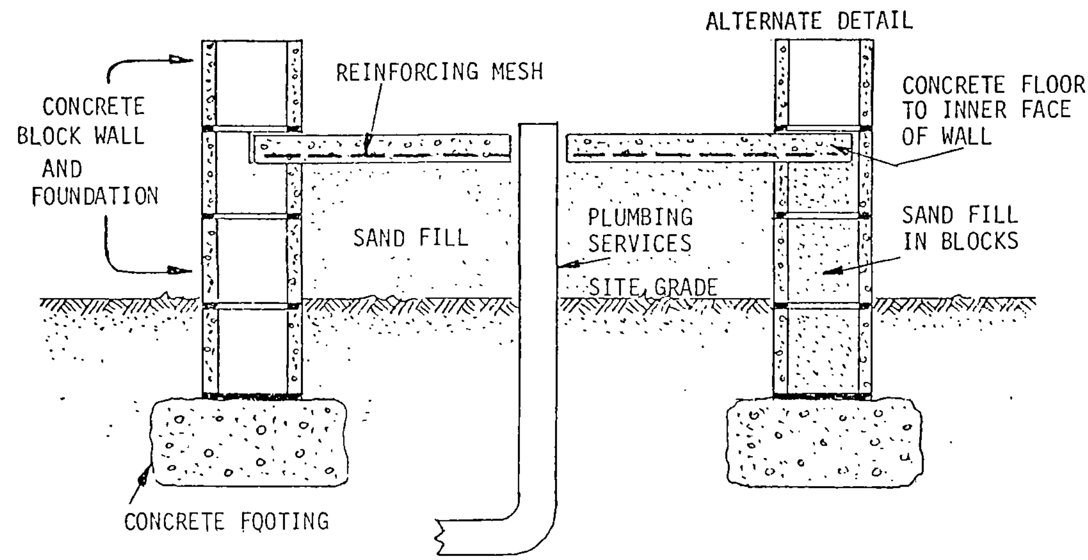


Fig. 3 FIXED FLOOR

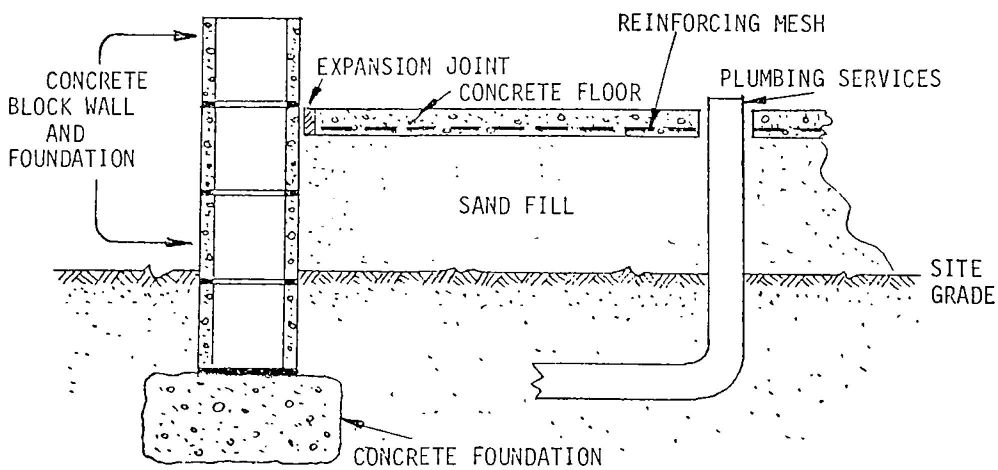


Fig. 4 FREE FLOOR

FOUNDATION CONSTRUCTION STYLES

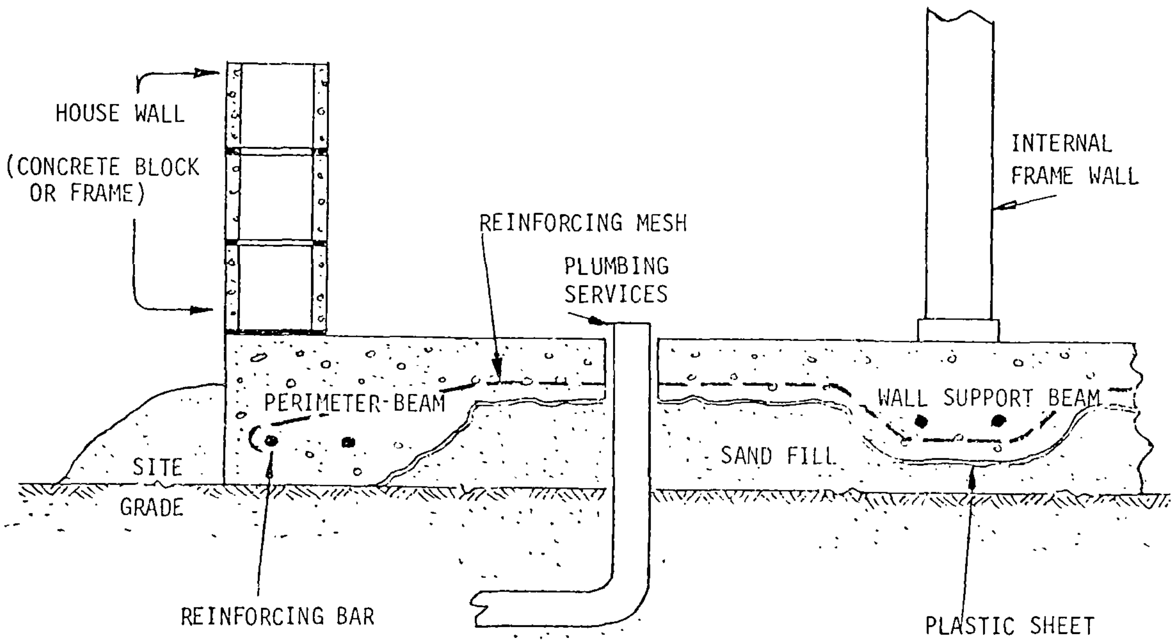


Fig. 5 MONOLITHIC SLAB

APPENDICES

Appendix A - Early Construction Types

Photo #	Description
	Pier Construction
A-15.17	Wood frame building on masonry piers with an open crawl space.
A-15.13	Wood frame building on brick piers with ornamental brick screening of the crawl space.
	Ventilated Crawl Space
A-15.16	Crawl space ventilation holes in block wall. Formed of 3 hole blocks laid on side.
	Free Floor
A-12.8a	Styrofoam "expansion joint" placed between the foundation wall and floor slab.
A-12.17a	Pen inserted into gap between the "expansion joint" (styrofoam still in place) and the foundation wall.

Appendix B - Fixed Floor

Photo #	Description
B-7.1	Footing excavation showing reinforcing bar and footing grade stakes.
B-8.16	Poured footing showing corner reinforcing bars. Note top of footing not far below grade level.
B-4.1a	Foundation wall under construction on footing.
B-1.31	Constructed foundation wall showing special notched block. Note interior block wall (unusual).
B-1.26	Foundation wall with floor support sand in place. Note (a) that the block cavities are open, and (b) the plastic does not reach the wall (unusual).
B-6.00	Foundation wall with floor support sand in place. Note that (a) sand fills the block cavities, (b) the styrofoam collar around a toilet connection, and (c) the excavated area for a sunken shower.
B-1.27	Typical site before pouring concrete floor. Note collars on the sanitary connections, asphalt on water pipes, and holes in plastic around pipes.
B-4.20	Plastic holding concrete out of block cavities.
B-4.21	Concrete filling block cavities on a hit or miss basis.

Appendix C - Monolithic Slab

Photo #	Description
C-8.30	Forms in place. Note extensive use of sand to build up site to above grade level. Strings in background are used by plumbers to give an approximate slab surface level.
C-3.11	Sub-slab plumbing complete and covered with sand. Interior of forms filled with sand to within 4 inches of top of forms. Trenches dug to thicken slab and take reinforcing bars.
C-7.10	Sand covered with plastic and reinforcing mesh. Reinforcing bars laid in trenches. Note projection on forms to produce peripheral ledge for brick facing.
C-11.13	Finished slab. Plates for frame walls being attached. Note ledge for brick veneer. Sand area in background is for a carport area which will be poured separately.

Appendix D - Piping

D-1.24	Pipes painted with asphalt.
D-6.0a	Pipes wrapped with plastic sheet.
D-14.8a	Pipes sleeved with orange plastic tubing.
D-9.00	Pipes wrapped with foam rubber insulation.
D-4.4a	Hole in concrete adjacent to asphalt painted pipe. Note pen inserted in hole.

Appendix E - Sanitary Piping

Photo #	Description
E-1.14	Shower drain fixture showing opening through slab.
E-8.24	Toilet flange - pencil in opening through slab.
E-7.10	Cardboard collar on shower drain pipe. Note opening in plastic at base of collar.
E-9.0a	Concrete block used as form for shower drain opening.
E-4.34a	Concrete block used as form for bath drain opening. Note opening in plastic.
E-7.4	Wooden form for bath drain opening. Note toilet pipe in background wrapped with styrofoam, and reinforcing bar supported on bricks.
E-1.1	Bath drain opening after concrete block broken out. Bath, at left hand edge of picture, to be moved into position.
E-1.13	Bath with drain connected.
E-9.2a	Asphalt poured into drain opening. Note asphalt does not reach corner at rear left (shown by pen) as sand filling slightly higher there.
E-4.9a	Asphalt poured on top of sand in drain opening. Note larger amounts of sand split around opening, preventing the asphalt from adhering. Asphalt about 1/8 inch thick, and peeled back at left front, shown by pen into sand.

Appendix F - Unintentional Routes of Entry

F-7.14	"Monolithic" slab during pouring. Note screeding bar and stakes in foreground, and hold back forms for change in floor level in background.
F-4.23a	Opening left in floor to produce a sunken floor section in a second pour. Note the narrow section in the slab (left rear). Tension cracking is likely in this area.
F-1.25	*Temporary support for horizontal plumbing run made from a section of pipe.*
F-15.5	Temporary support made permanent by concrete. Note the plastic sleeves on the water pipes.
F-1.17	Vent/drain pipe passing through floor at angle, and extending into room. An evident mistake. It appears that the concrete was kept away from the pipe to allow the plumber to make the angle connection after the slab was poured.
F-8.1	Sunken bath. The forms will be removed and the bath placed in the opening.
F-1.7	Sunken shower outside the foundation wall. Note the concrete slab is kept from filling the blocks by the plastic, leaving direct connections to the soil.
F-1.5	Kitchen extension outside the foundation wall. Note open block cavities. These will be concealed by the edge of the cabinets that will be installed.

Appendix G - Accidental Routes

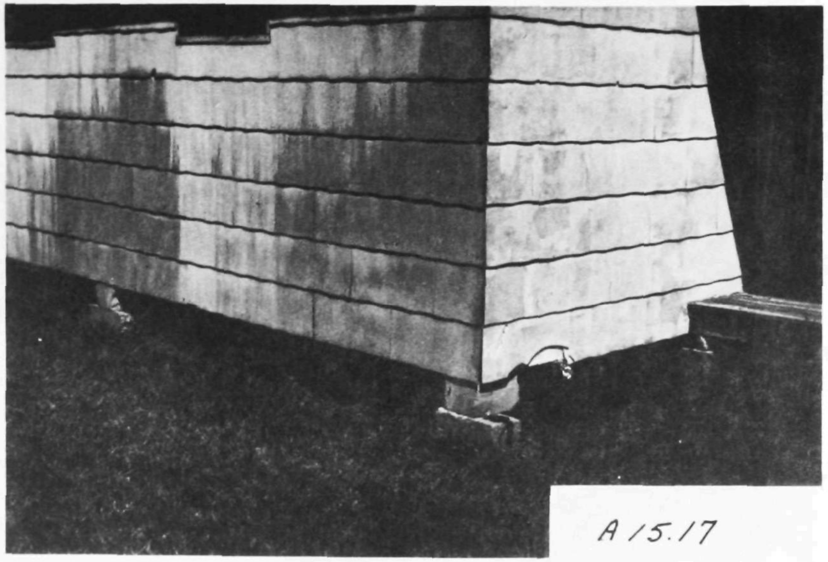
Photo #	Description
G-4.7a	Monolithic slab has shrunk about 3 mm in from the wood forms, but there was no cracking in the rectangular slab.
G-4.36a	Tension crack in corner of large L shaped floor slab on block foundation.
G-10.5	Tension crack at narrow part of L shaped slab passing through shower opening in that area.

Appendix H - Block Walls

H-1.29	Inside face of foundation wall. Note gaps in mortar at footing (shown by pen) and in vertical joint.
H-4.14a	Outside face of constructed foundation wall. Note gap in mortar (shown by pen), and hole made for water line which will be covered by soil after landscaping. Also note that though the concrete floor slab is run to the outer edge of the wall, the space between the blocks is still open.
H-1.34	Drain/vent pipe, and water pipes. Note broken blocks below slab level. Note also the piping laid in shallow excavation for piping, and cardboard collar round toilet connection.
H-5.19	In wall plumbing. Drain/vent pipe. Note the concrete floor slab has been kept away from pipe, providing an opening direct to the wall cavity.

Appendix I -Materials

I-7.16	Placing concrete. Extra water was added to this mix to make it flow more readily. Note that there is no significant pile of concrete where the discharge strikes the ground.
I-5.8	Workmen levelling concrete. Note that they are standing in the concrete, on the mesh and plastic.
I-5.7	Reinforcing mesh trapped beneath concrete. Note the opening in the plastic around the water pipes.



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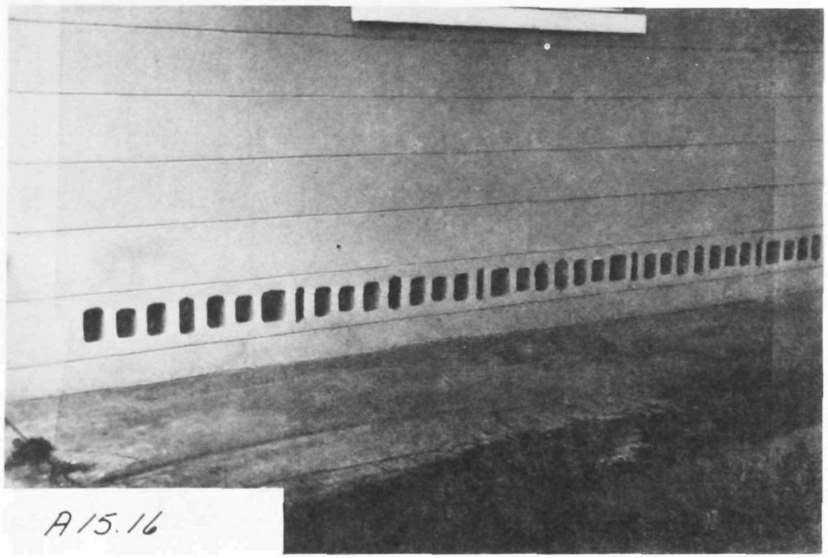

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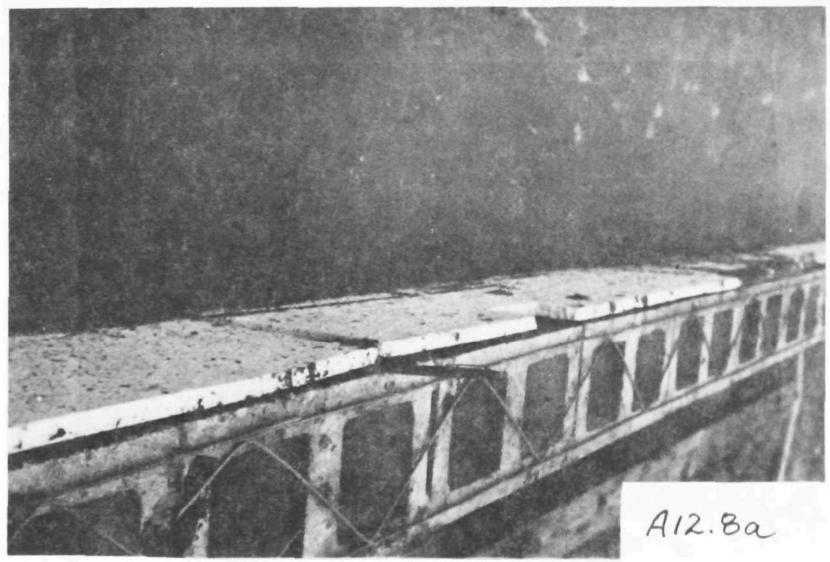

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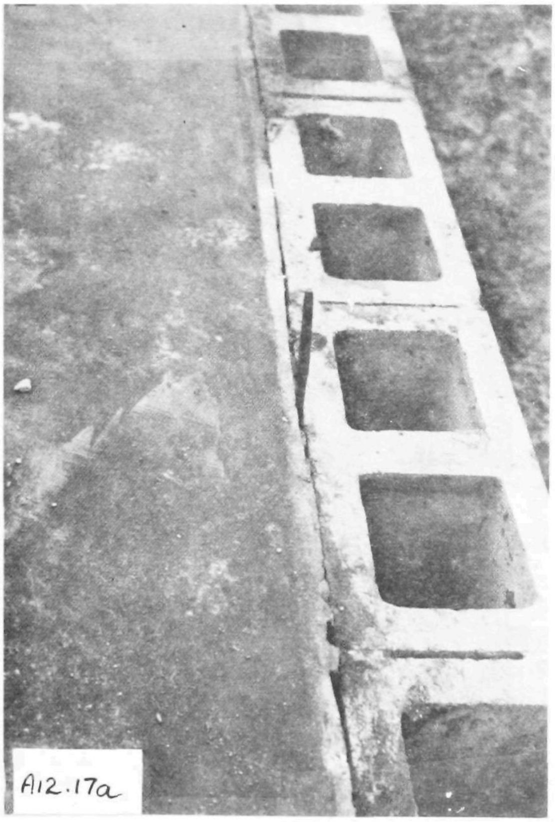
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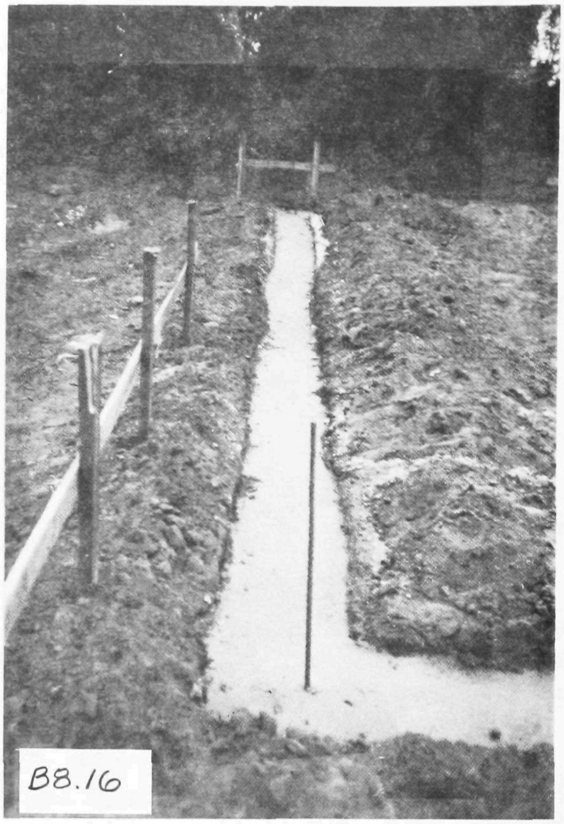
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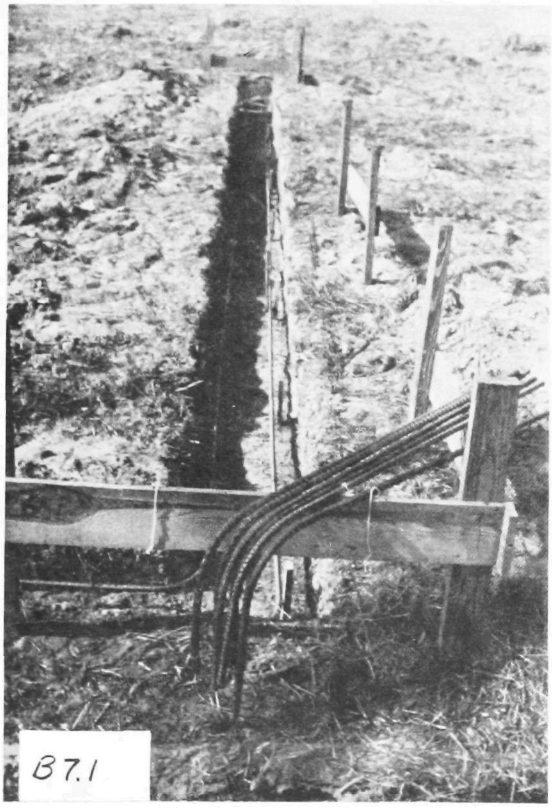
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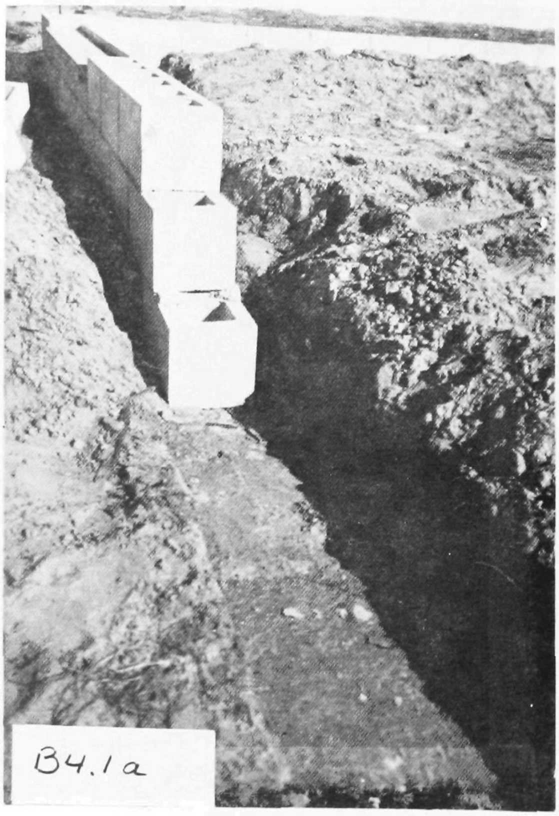
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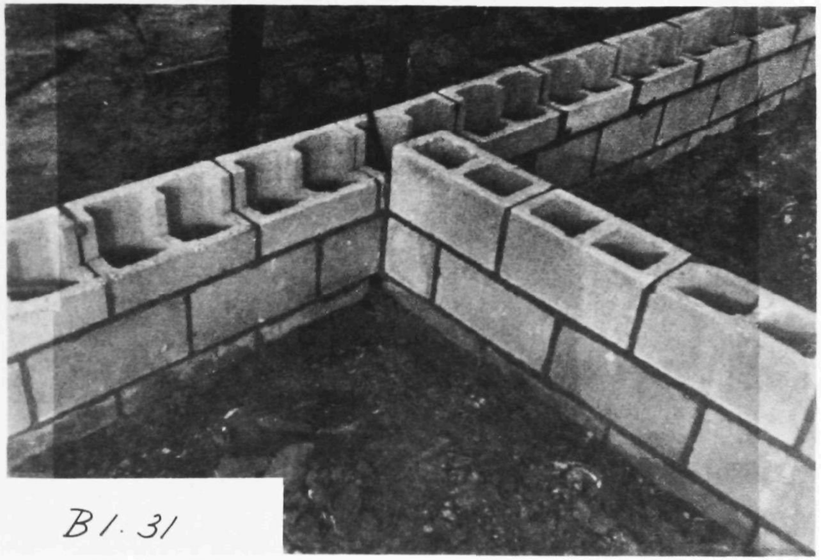

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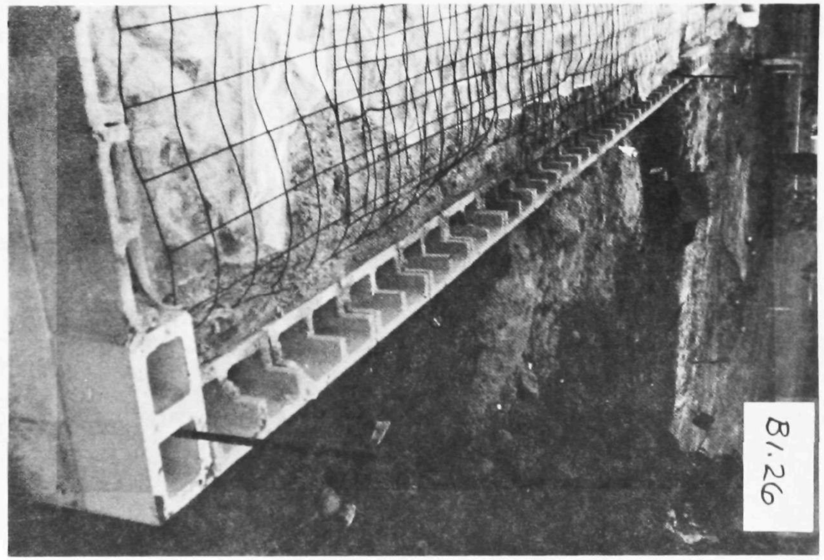

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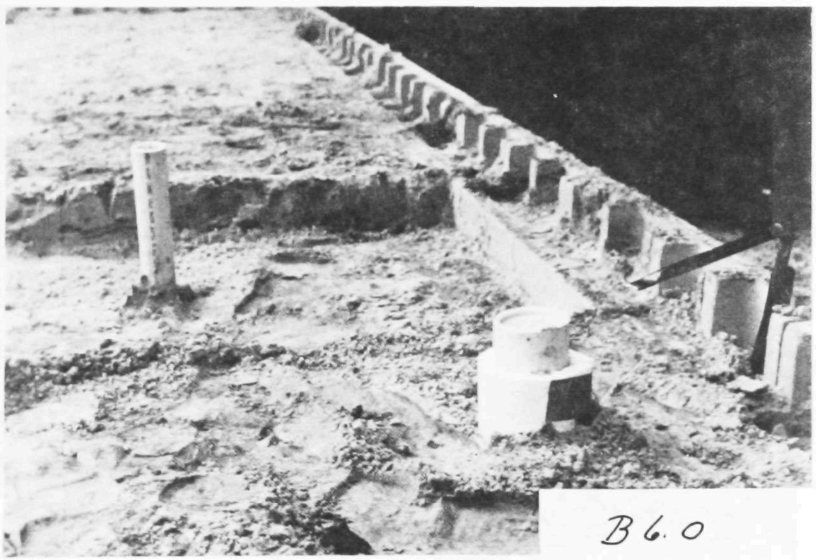

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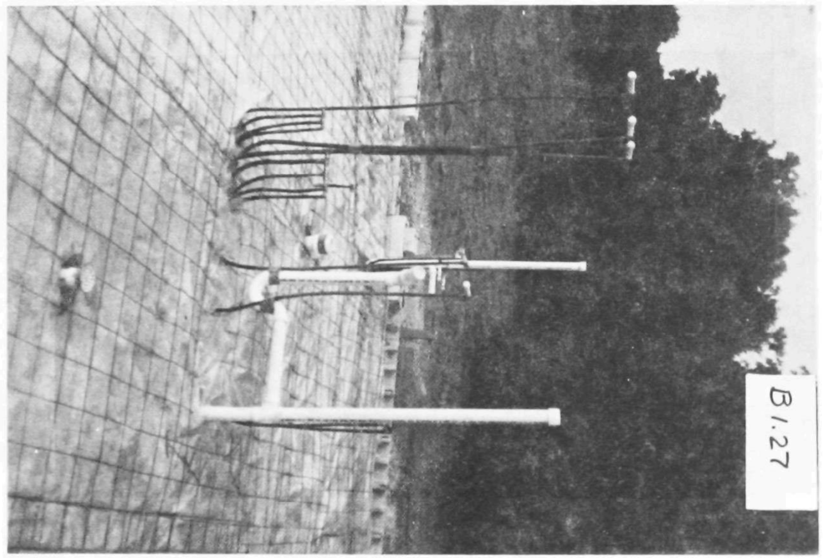

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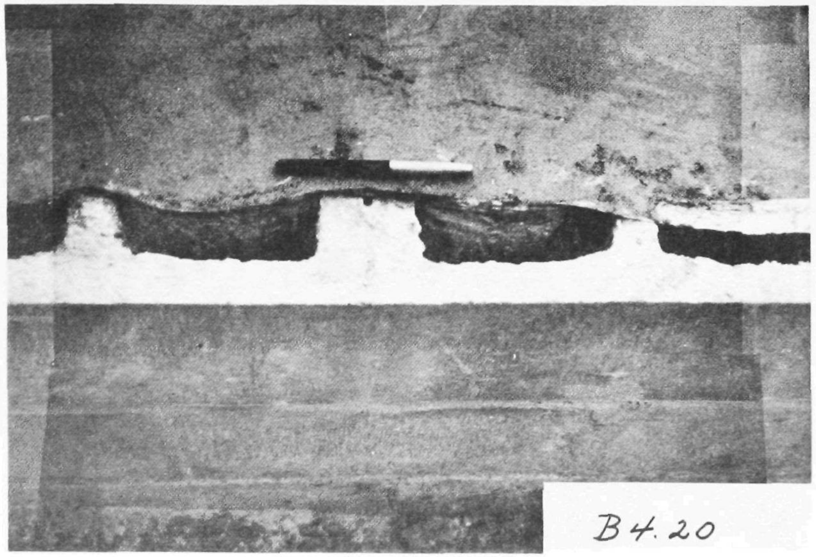

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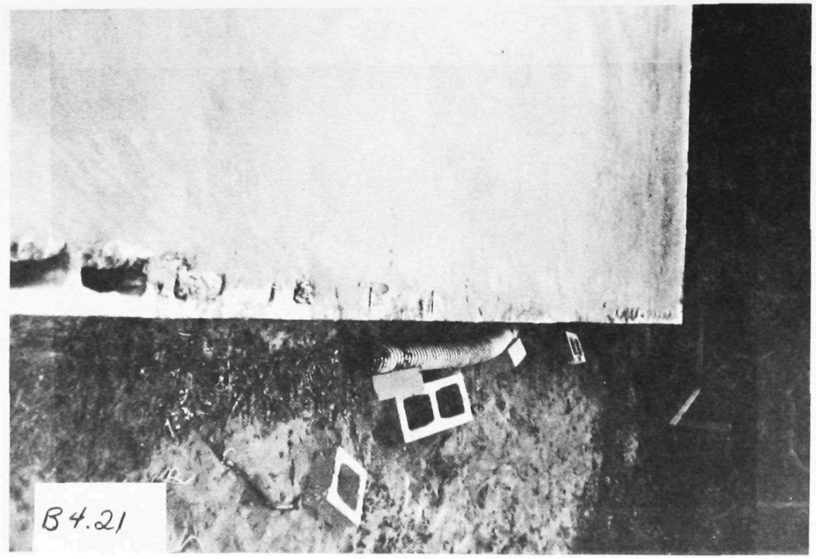

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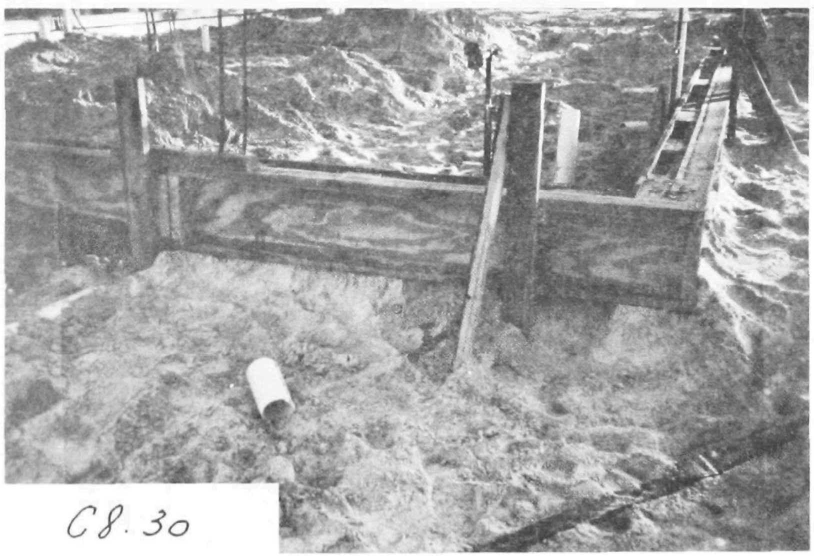

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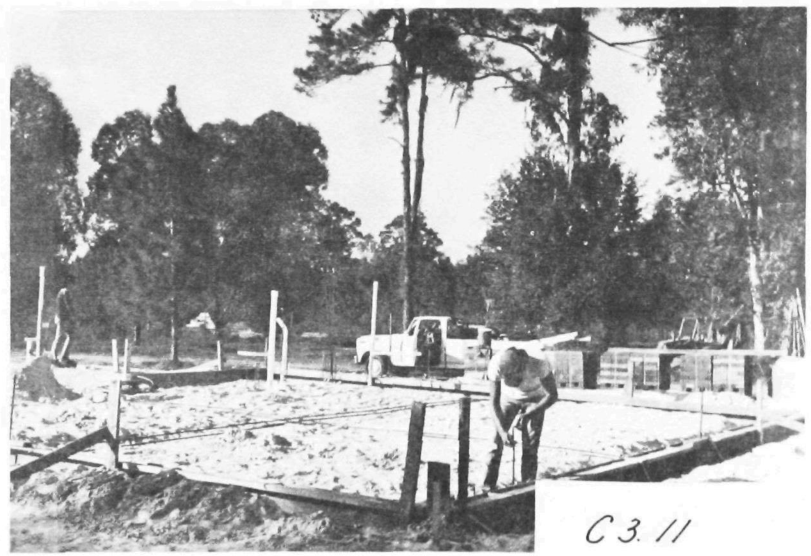

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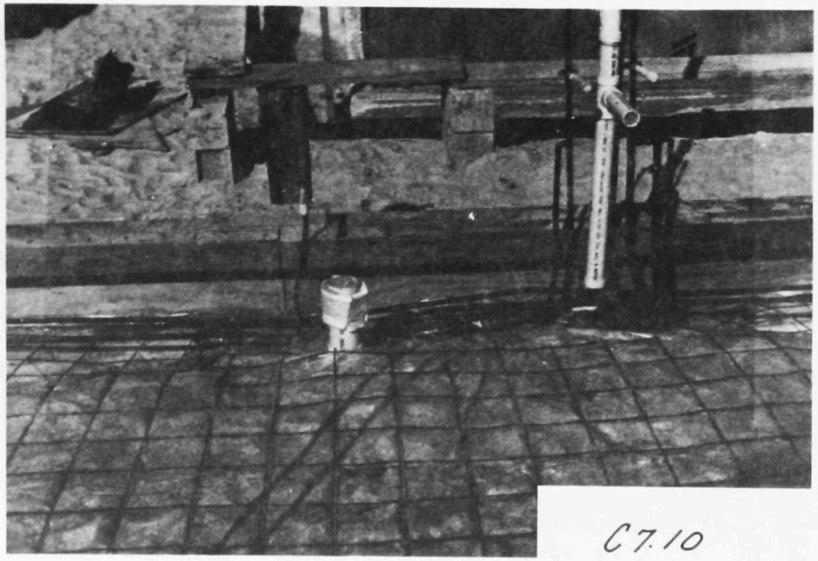

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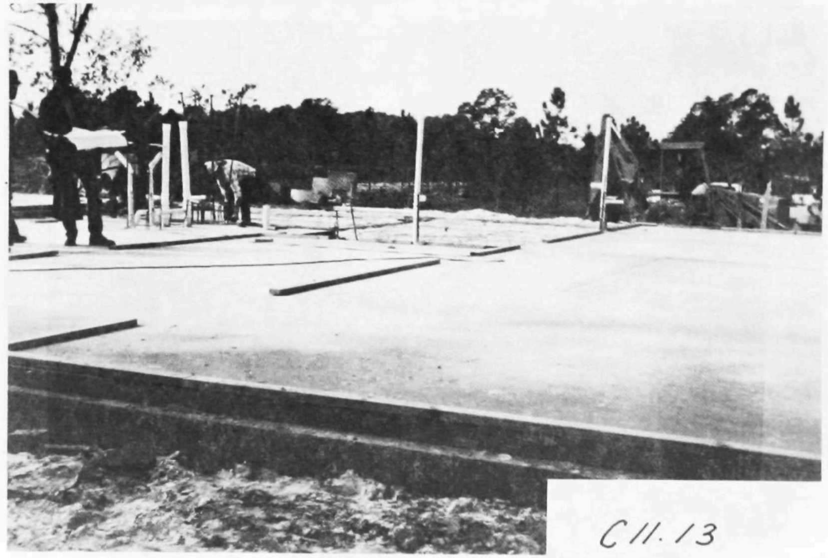

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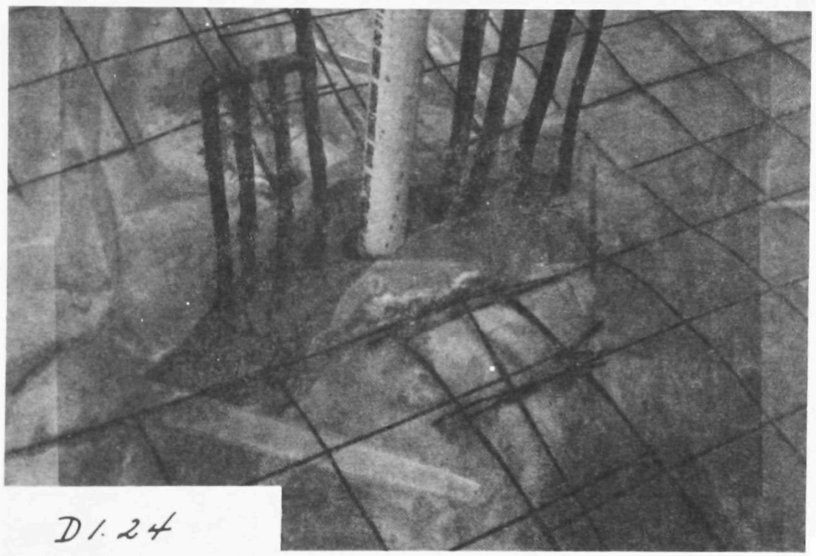

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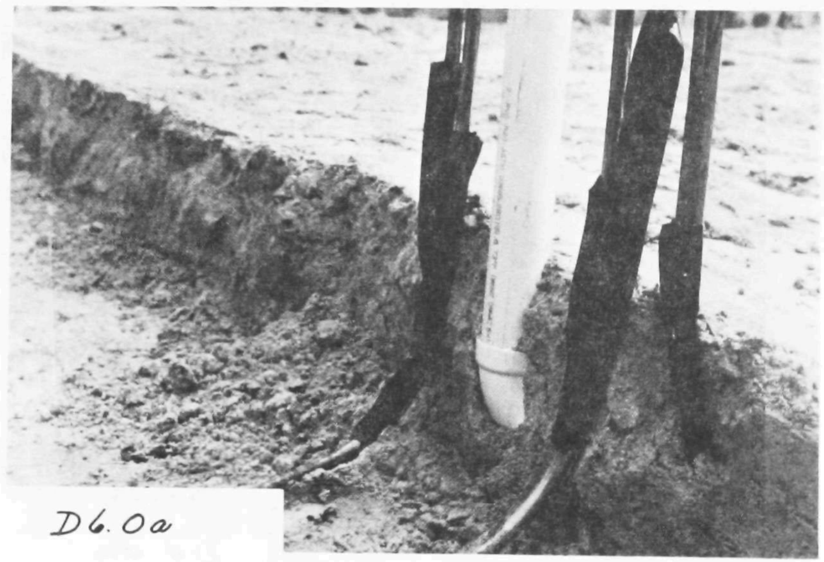

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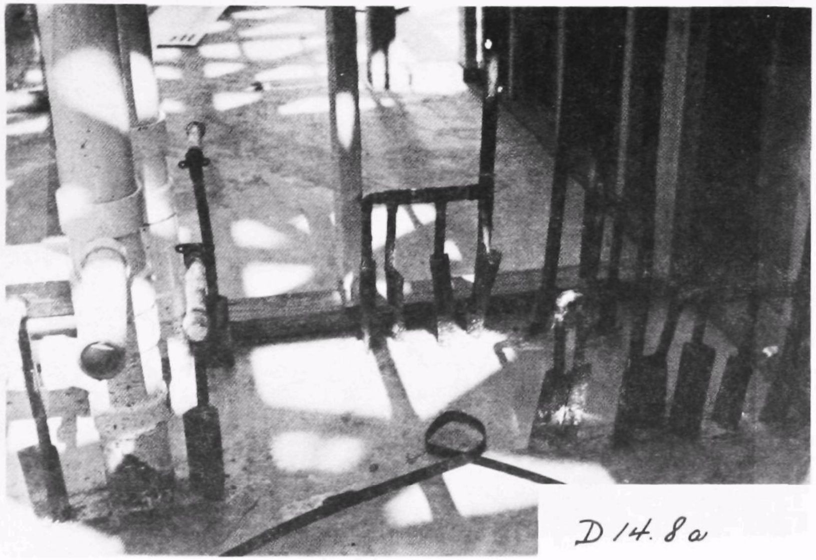

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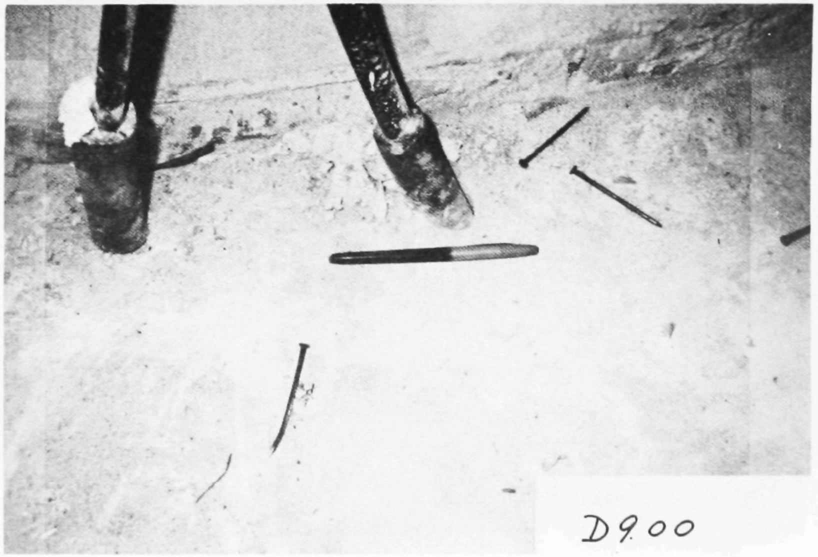

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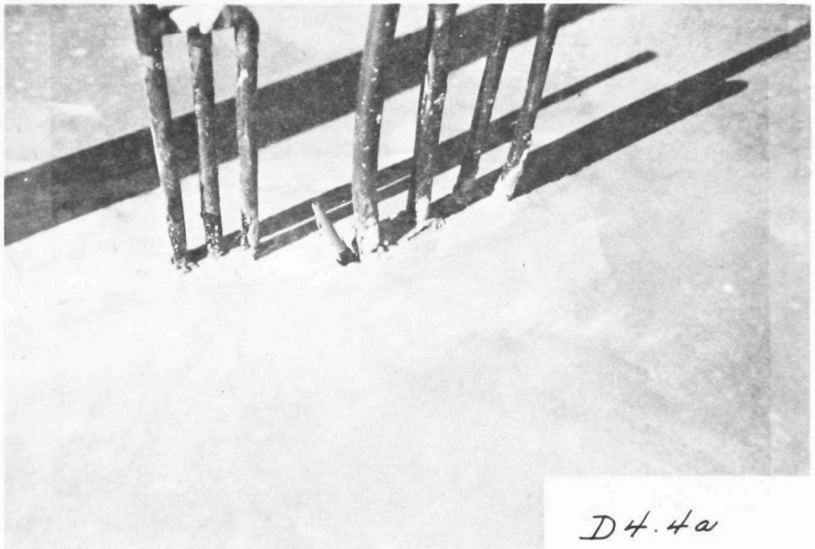

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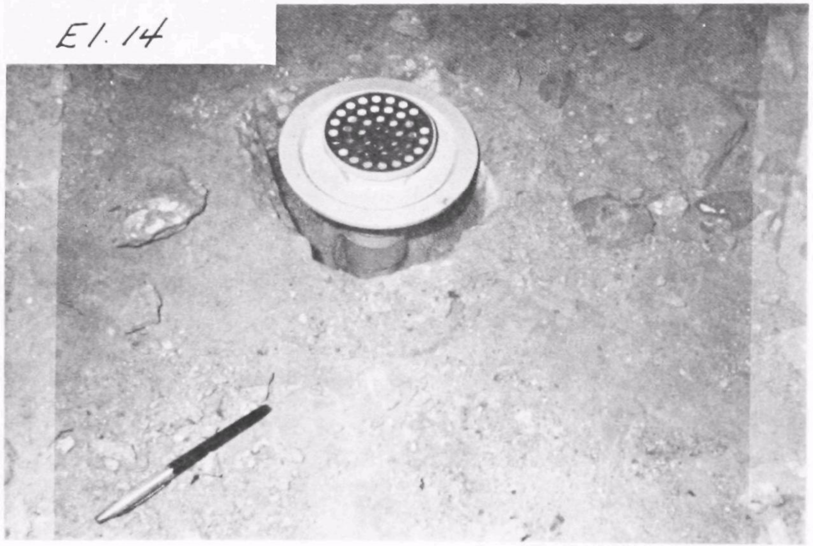

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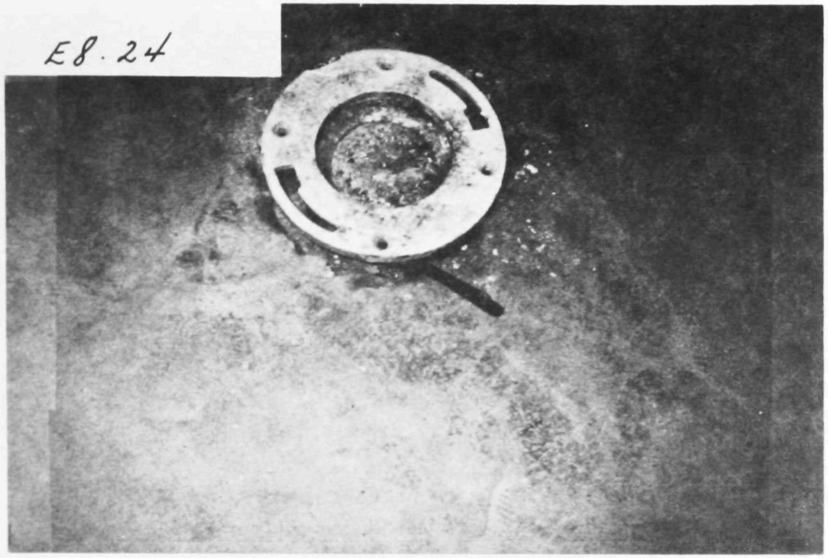

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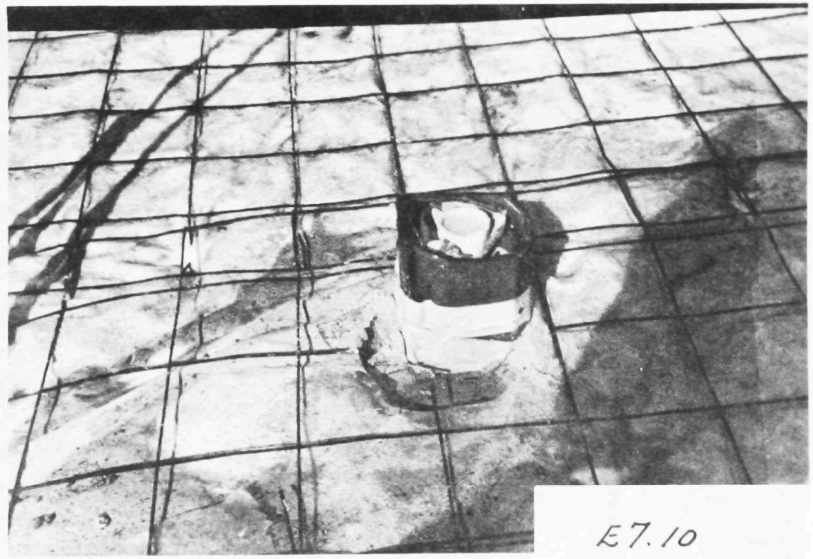

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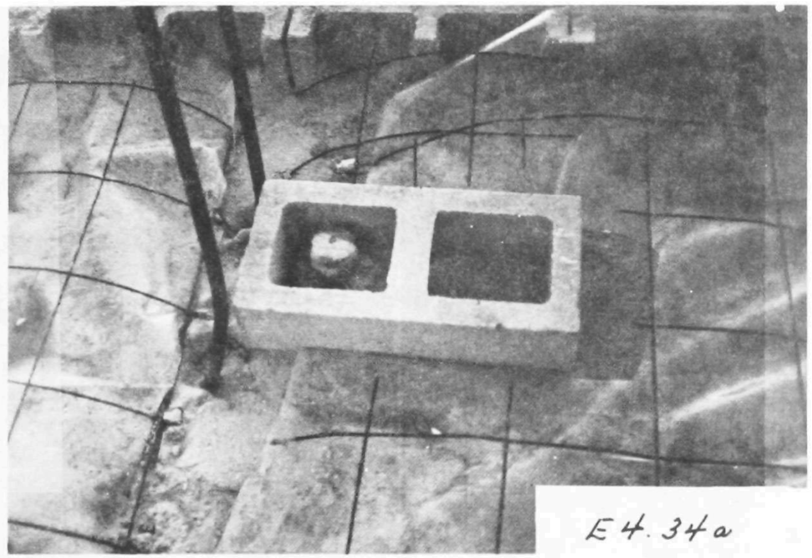

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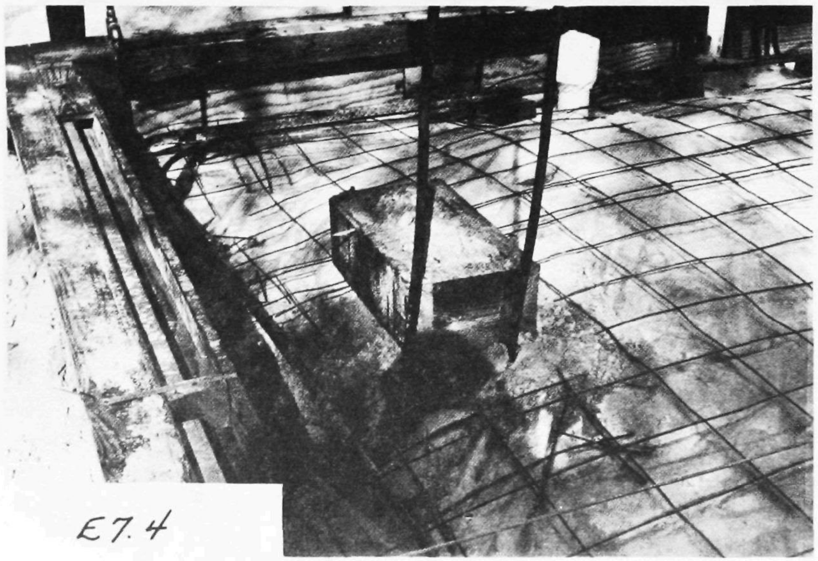

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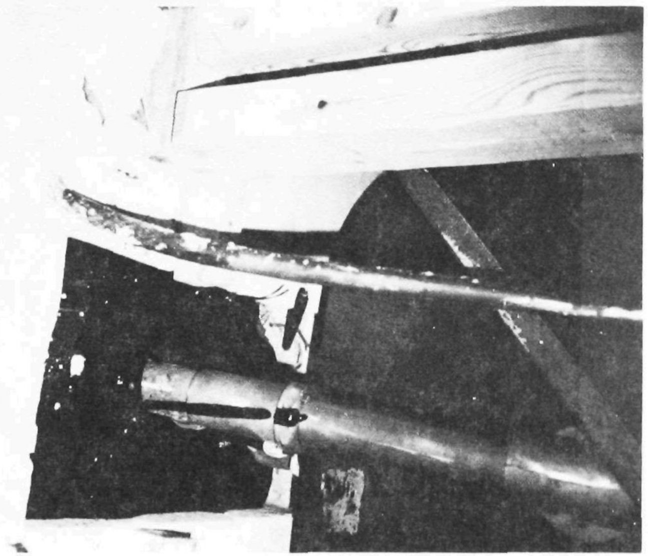

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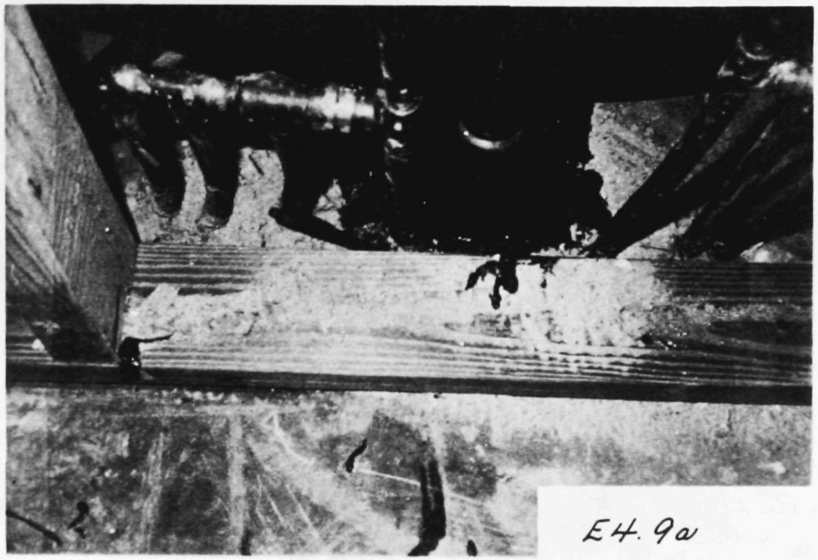

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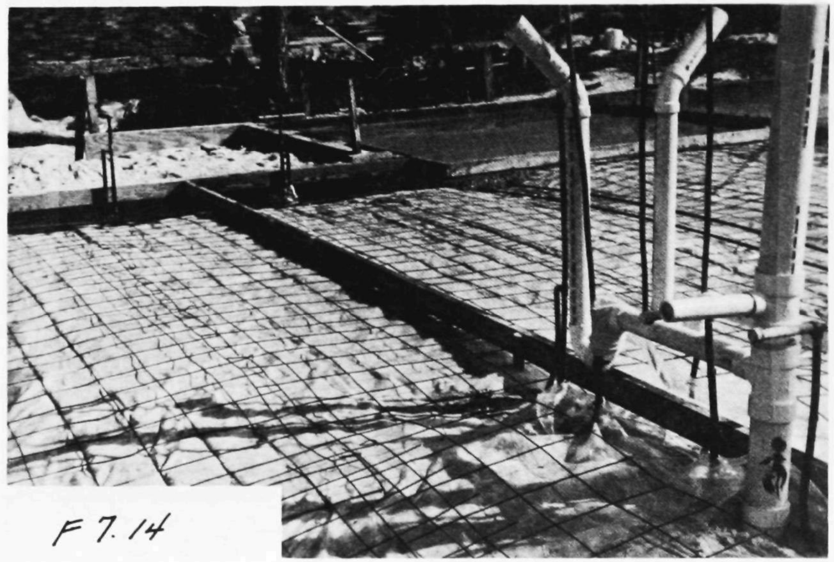

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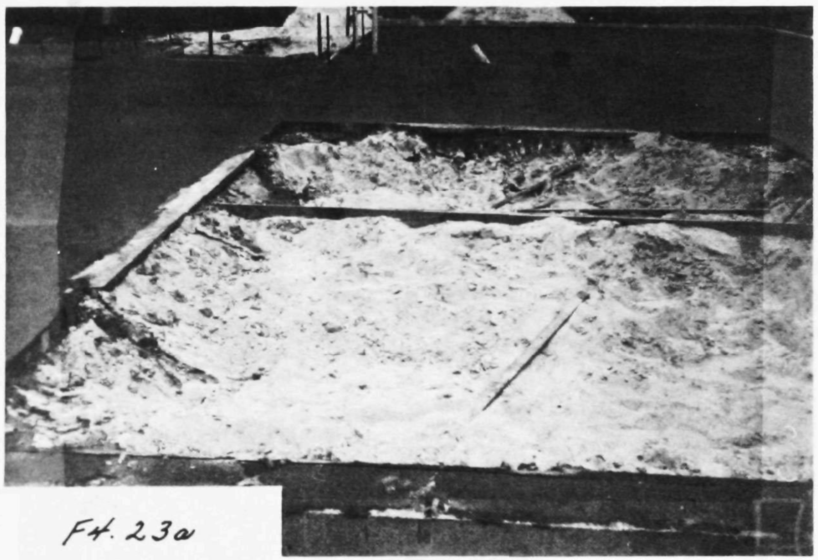

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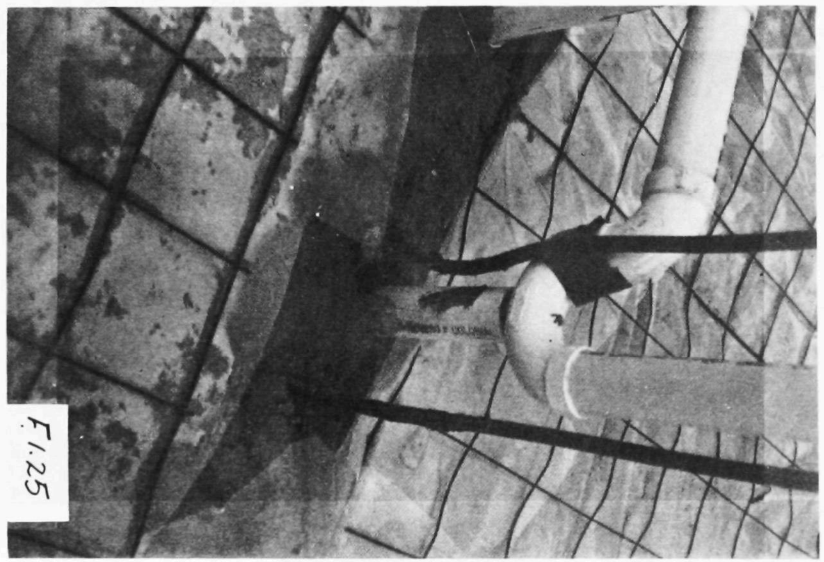

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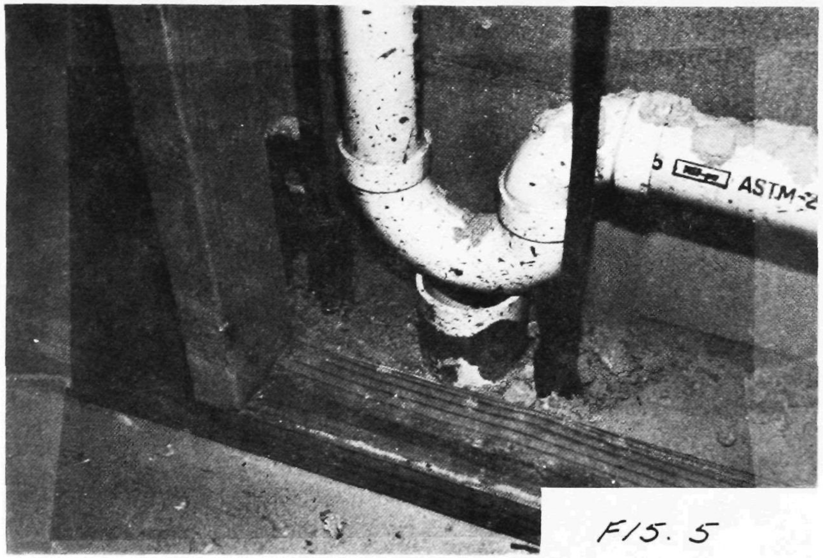

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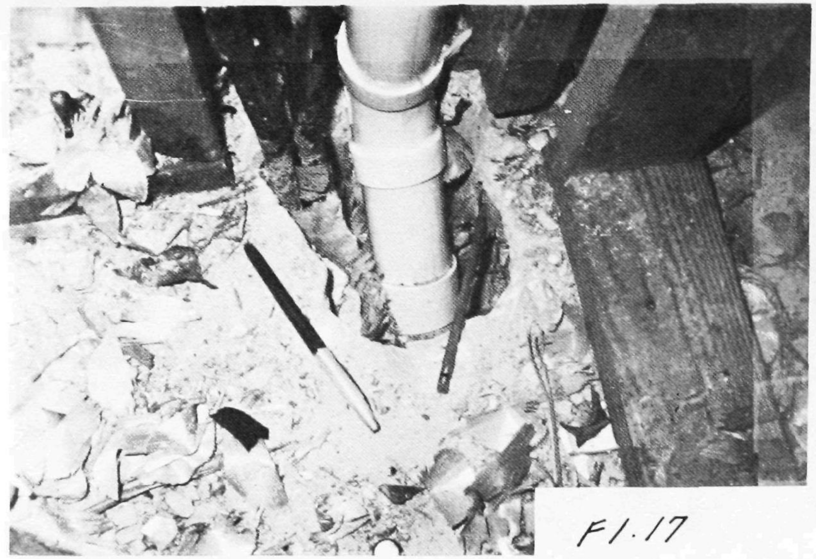

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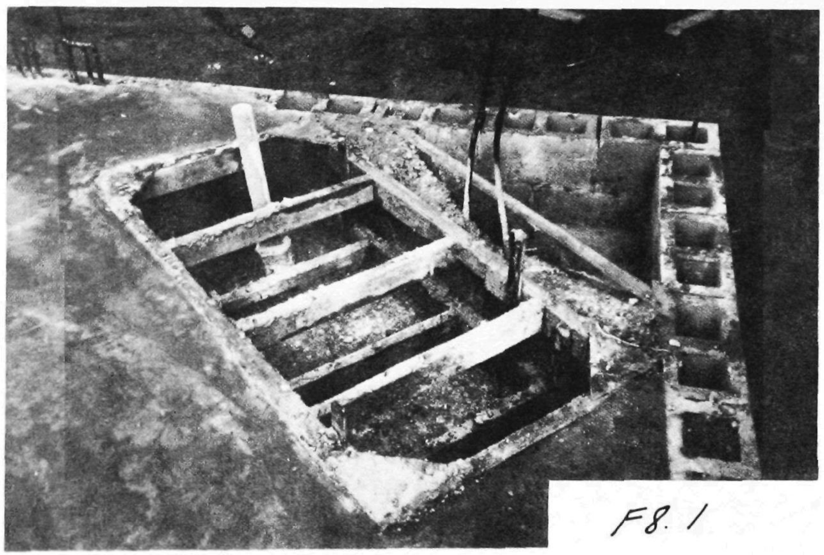

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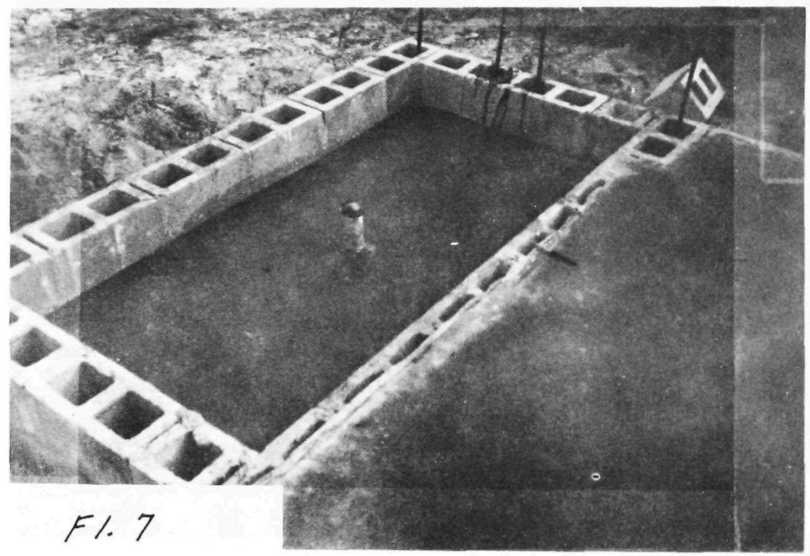

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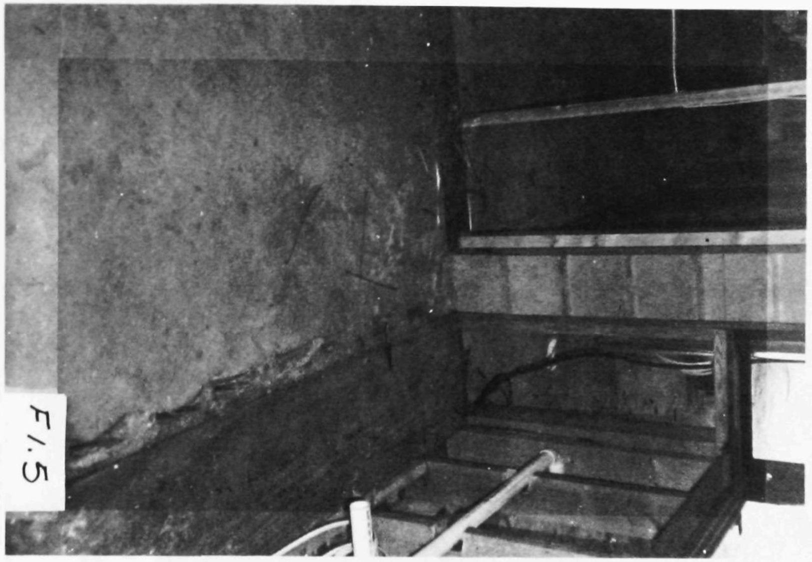

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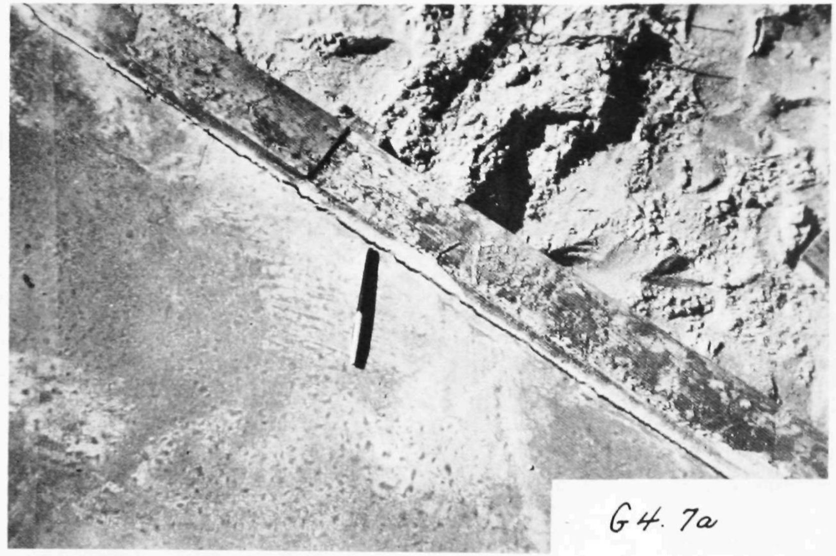

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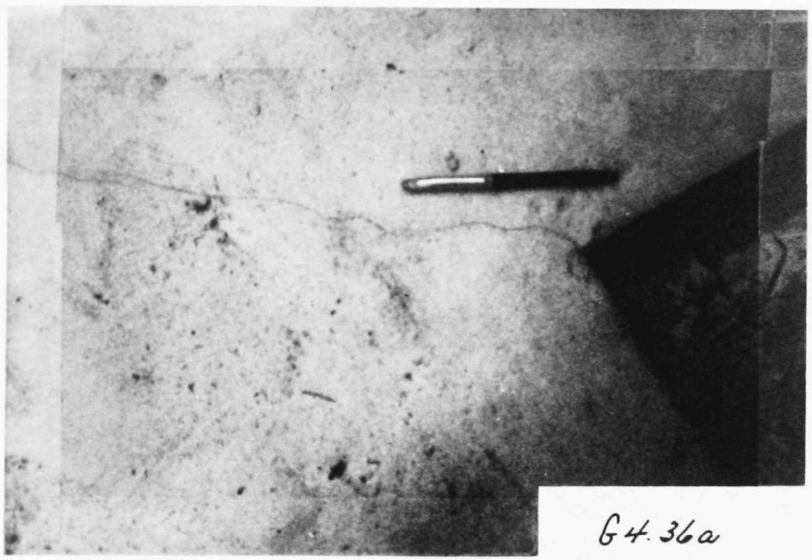

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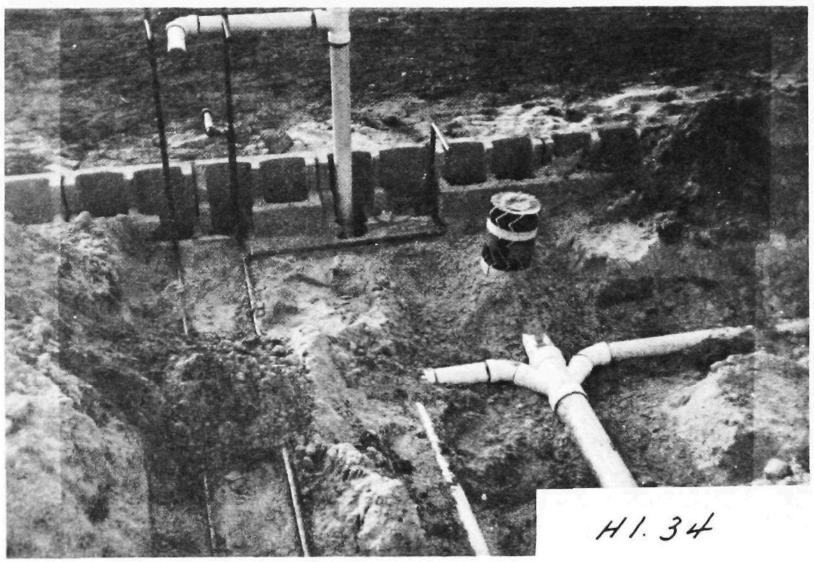

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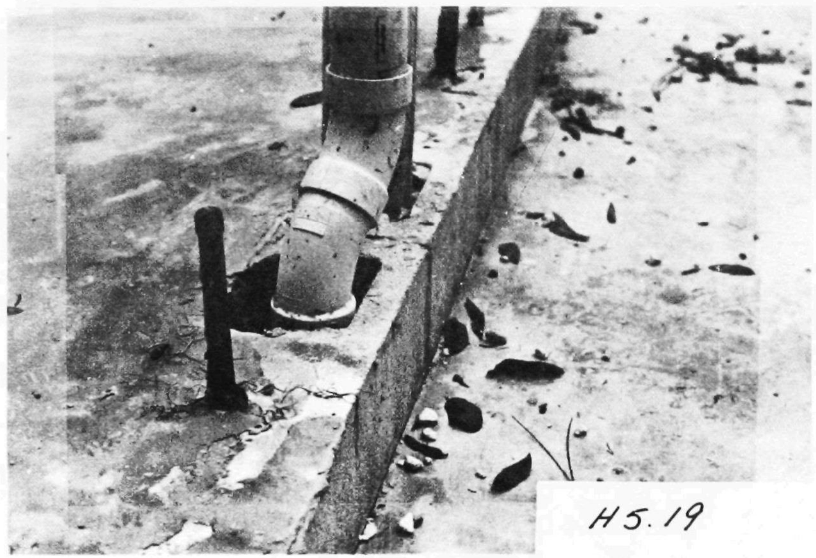

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SECTION II

MODIFICATION OF NEW CONSTRUCTION

FOR

RADON RESISTANCE

1.0 Introduction

This report is to document the results of part of a program to demonstrate means of controling indoor radon levels in structures built on Florida phosphate lands. The work was carried out by AMERICAN ATCON INC. with the support of Acres American Incorporated.

A cooperative project was carried out to determine if it was feasible for a local developer/builder to construct radon resistant foundations if advice and assistance were provided. Experience gained in this project showed that production of radon resistant foundations was not beyond the skill of the building industry, but that there were considerable practical difficulties in achieving this. Advice and assistance alone was insufficient, and specific training for the tradesmen involved in foundation construction would be required to make production of radon resistant foundations a routine matter.

2.0 Background

Although the identification of high radon levels in housing in central Florida led to a withdrawal of HUD mortgage approvals in the area, development did not stop. Those developers who where able to raise mortgage money without HUD involvement continued to build. One such developer had a housing project planned to start in early 1981 on land which had been mined for phosphate and reclaimed in the 1930's, resulting in elevated soil radium concentrations. He was contacted, and offered advice and assistance in excluding radon from his houses at no cost to him, in return for his cooperation. The Florida Department of Health and Rehabilitative Services assisted in this program by making the radiation measurements needed. The work was carried out by the staff of District 8, the Polk Country Health Department (PCHD).

3.0 Site Measurements

Detailed measurements of soil radioactivty were made at 7 house lots, in 2 well separated areas of the development. In November 1980, 4 surface soil samples were taken at each lot, and a 6 foot (1.8m) soil core was drilled at the centre of the actual house site. The random mixing of phosphatic material with overburden during the mining and reclamation process was evident from the wide variations in soil radium concentrations both at the surface and with depth, but the average surface concentration lay in the range 5 - 12 pCi Ra/g, typical of mining debris land.

The surface exposure rate over the complete development varied from 6 uR/h (background) to a high of about 30 uR/h, with an average in the range of 14-22 uR/h. These values are compatible with the estimated surface radium concentration.

The radon flux from the soil on these 7 sites was measured at least once using the charcoal cannister accumulator method.[1] The procedure was to place 10 to 16 MII cannisters on the site of the house or around the edge of the floor slab for 3 days. The cannisters were then removed, sealed, and taken to the PCHD laboratory where the radon content was estimated by a calibrated gamma counter. Flux measurements were made at intervals from November 1980 to March 1981, by which time the houses on these lots had been completed.

The radon flux measurements were very variable, due in part to the high variability of radium concentration in the soil on which the accumulators were placed, and also due to seasonal effects. Sites were not measured simultaneously, and measurements made in November gave lower average values than those in later months.

Table I summarises the results of surface measurements, and Table 2 shows the results of the soil core measurements. Comparisons with other sites in the area where the houses were known to have elevated radon levels, confirmed that these soil radium concentrations were as high or higher. It was therefore anticipated that this site would be a fair test of the ability to produce radon resistant foundations.

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1. Countess R.J., 1976, "222 Rn flux measurement with a charcoal cannister" Health Phys. 31, 456.

4.0 Foundation Design

The land on which these houses were to be constructed had been disturbed by phosphate mining, and the degree of consolidation varied from place to place over the site. If conventional strip footings are used on ground like this, the concentrated weight of the house walls and roof may cause settlement at the less consolidated areas, leading to damaging cracks in the walls. To prevent this, a raft or monolithic slab foundation is used. A single slab of concrete acts as both the house floor and as the foundation for the walls, and so the weight of the house is spread over the house floor area, instead of being concentrated on a footing at the house perimeter. Both these forms of construction are described in Section I.

Although many houses in the area had been constructed with concrete block walls on strip footings, even where the ground was known to be disturbed, this developer intended to use monolithic slab foundations for his houses. He had experience with this type of construction on unstable ground in other areas of the South, and as a result believed it to be a more economical method of producing a foundation and floor than the conventional strip foundation and separate floor. A number of other builders in the area are also using monolithic slabs in preference to strip foundations, even in areas of solid ground, so the economics must be relatively favourable.

As the monolithic slab comprises both floor and foundation, and is poured in one single piece, the number of connections from the house to the soil is limited to those that are deliberately introduced at the time of construction. This favourable circumstance suggested that it might be possible to produce airtight and therefore "radon resistant" foundations for these houses with minimal effort.

5.0 Construction Phase

5.1 Project Organization

Prior to the start of construction, meetings were held with the developer and his building contractor where the intent of the program was described, and methods of achieving an airtight foundation discussed. Full cooperation was offered by both the developer and the builder. It was not possible to speak to the tradesmen who would actually carry out the work, for they appear on the site only as and when their skills are needed to perform a task. It was hoped that by demonstrating the techniques involved to the builder's site representative (foreman) on the first three houses constructed, he would be able to provide the necessary direction to the tradesmen on the subsequent houses.

5.2 House Designs

The first house to be constructed was a single story detached dwelling on rectangular floor plan, about 1200 ft^2 in floor area, located on lot #1. The second and third houses were combined in a "U" shaped semi-detached dwelling, located on both lots #2, #3. Each half of the dwelling had an L-shaped floor plan of about 1100 ft^2, and the halves were joined at the short arm of the "L". For noise reduction, the kitchen, laundry room and bathroom were located at the junction. A similar design of semi-detached dwelling but with a slightly smaller floor area was built on lots #4, #5. The semi-detached dwelling built on lots #88, #89 consisted of two units of 950 ft^2 floor area, and approximately rectangular floor plan, joined along the long side of the rectangle.

5.3 Foundation Construction

The foundation construction was observed for houses on lots #1, #2, #3. The house site was first stripped of vegetation, and several truck loads of sand were dumped over the site. This was spread round to give a level pad of sand, and the slab forms were erected on the sand base. The upper surface of the concrete slab was then defined by stretching strings across the forms, and the sand within the forms was spread around so as to provide at least 4 inches (10cm) of concrete over the central portion of the slab, and at least 12 inches (30cm) at the perimeter. The sand was then levelled and compacted with a portable vibrator. The sub slab piping was laid in shallow trenches dug into the sand. Wherever there were sewer drain connections to toilets or showers, a collar of beadboard or paper was placed around the pipe to provide a space in the concrete so that the sealing flange could be attached without difficulty later. The bath drain connection was surrounded by a small wooden form to provide space for the installation of the bath drain trap and overflow pipe.

After the plumbing installation had been inspected, the sand inside the forms was covered with plastic sheet (the vapour barrier). Holes had to be cut in the sheet to allow the plumbing pipes to fit through, so the plastic sheet provided no barrier to the movement of soil gas and radon into the house at the plumbing connections. Reinforcing mesh was then laid over the plastic sheeting, and tied to reinforcing bars laid round the slab perimeter.

5.4 Modifications to Exclude Radon

It was known from laboratory and field work that joints between pipes and concrete, and even large openings in the concrete, could be sealed by use of a rubberised asphalt sealant. Accordingly, the only modification made to the foundations on lots #1, #2, #3, was to reduce the height of the collars that were attached to the sewer drain connections to 4 inches (10cm), tape them to the top of the pipe, and remove sand from the area so that at least 2 inches (5cm) of pipe below the collar would be in contact with concrete. This ensured that the leakage area associated with the fixture would be very small, even if the opening was not sealed. As the toilets are installed late in the house finishing procedure, it was anticipated that it might be difficult to schedule sealing these openings.

5.5 Construction Problems

The slab for the house on lot #1 was poured in one continous pour. To avoid penetrations of the slab, grade-stakes were not used. A 4-inch diameter PVC pipe was used as a removable screeding bar. Additional water was added to the concrete to make it easier to place, and as a result the initial set was delayed. Final finishing of the slab was completed in the light of truck headlamps. Despite the watered concrete, no shrinkage cracks occured in the floor slab.

The slabs for the houses on lots #2, #3 were poured on two consecutive days, with the junction running along the dividing line between the houses, so although the slab for each house was monolithic, the slab for the building as a whole was in two separate parts. In addition, the sunken portions of the slab required the use of hold-back forms, with their support stakes leaving holes in the sunken slab. The concrete finisher filled the holes with partially set concrete from his trowel. No grade stakes were used, the 4-inch PVC pipe was again used as a screeding bar. No shrinkage cracks occured in the separate slabs.

As a result of the experience gained at these houses, subsequent semi-detached house slabs were always poured in one pour, interior sunken slab sections eliminated, and the slab grade was maintained by means of tensioned steel cables that were stretched across the forms, rather than the 4-inch PVC pipe. These changes were for the convenience of the workmen, but fortunately they did increase the general radon resistance of the foundation.

5.6 Sealing

At the house on lot #1, the joint between the concrete and every water or drain pipe was sealed with a rubberised asphalt sealant. About 2 weeks later the plumber connected the bath to the bath drain, and the pit was sealed by him. Sand was added to the pit to fill it near to the top, and asphalt roofing cement (a 50/50 mixture of asphalt and solvent) poured into the pit produce a continous layer of asphalt over the sand. The asphalt appeared to touch the concrete on all sides of the pit. The shower and toilets were installed before the openings were sealed. As a result this structure did not have a fully sealed slab, but certainly had one with minimal openings.

At the houses on lots #2, #3, it was not possible to seal the joint between the two slabs before the party wall was built, enclosing the joint and most of the water and drain pipe penetrations which were not sealed either. The bath pit opening was sealed in each house by the plumber, in the same manner as at lot #1, and the showers and toilets were installed before their openings could be sealed. As a result, these structures were on only partially sealed slabs.

6.0 Subsequent Work

Our input to subsequent houses was deliberately limited to inspection of the work performed by the tradesmen and comments to the builder. The tradesmen rapidly reverted to their usual practices. Full depth collars were used on sewer drain connections, short pieces of pipe were used as temporary supports for plumbing causing holes through the slab, and the bath pits were incompletely sealed. The most common fault was to fill the pit to the top or higher with sand so that when the asphalt was poured in it could not form a bond with the concrete walls. At other places, the sand in the pit was uneven, and the asphalt poured in was insufficient to cover the sand completely.

7.0 Average WL

The average WL in each house was measured over the period of January to May 1981 by the PCHD with Integrating Radon Daughter Samplers. Measurements were made over at least two 3-day periods between completion of the house and either its occupation or termination of site electrical construction power. As doors and windows were closed throughout each measurement period, the values obtained can be regarded as near maximum. The results are shown in table 3. Only the house on lot #1 had an average WL near background. The averages in the other houses, although higher, were still much lower than would be expected for conventional housing on soil of such high activity. Monolithic slabs alone have some merit in reducing the entry rate of soil gas and radon.

8.0 Conclusions

Although the results of this program were disappointing in that only one house demonstrated that sealed monolithic slab construction could produce average WL's approaching background, the program as a whole was far from a failure. First, it showed that limiting the number of soil connections by use of a monolithic slab was a valid approach to reducing the average WL in a house. The highest average WL found in these houses was 22 mWL, whereas concrete block foundation houses on soils of similar activity generally have annual averages of 40 mWL or more.

Second, examination of the reasons why most of the foundations were not fully radon resistant identified the obstacles that would have to be overcome to make the construction of radon resistant foundations routine. The primary cause of failure was clearly that the tradesmen had not received specific instruction in the goals of the program, and that it was not feasible to expect the site foreman, who has many problems to occupy his mind and time, to carry out that instruction. A much larger input of time in tradesmen and inspector training was clearly required.

The experience gained in this program was used to define the basic requirements for a successful program. A report "Radon Resistant Housing for Florida Phosphate Lands" (Section III) was produced summarising the problems, and suggesting how they might be overcome.

TABLE I

SURFACE SOIL MEASUREMENTS

Lot #	Surface Radium Concentration (pCi/g)		Radon Flux (pCi/m^2s)		
	Average	Range	Average	Range	# of Tests
1	8.9	5.2 - 12.0	1.7	0.1 - 8.0	4
2	10.0	5.5 - 19.1	3.4	0.3 - 29.4	3
3	5.2	4.4 - 6.4	2.5	0.2 - 8.3	3
4	6.5	3.2 - 8.5	0.6	0.2 - 2.7	1
5	5.0	1.5 - 8.3	0.4	0.1 - 1.1	1
88	12.2	9.7 - 17.1	3.5	0.4 - 13.8	6
89	8.9	5.3 - 15.3	3.4	0.4 - 11.0	6

OTHER MEASUREMENTS

Emanating radium content (average)	1.2 pCi/g
Surface exposure rate (average)	20 uR/h
Sand used to level lots #1-5	7.6 pCi/g Ra

TABLE 2

SOIL CORE MEASUREMENTS

Lot #	Interval Radium Concentration (pCi/g) 0 - 1 (ft)	1 - 2 (ft)	2 - 3 (ft)	3 - 4 (ft)	4 - 5 (ft)	5 - 6 (ft)
1	9.2	8.1	8.4	6.7	10.7	7.9
2	10.4	6.1	7.9	9.9	24.7	15.6
3	7.1	5.0	4.5	4.9	6.7	5.6
4	7.9	20.4	13.4	14.6	11.7	7.8
5	6.2	5.5	0.9	1.3	0.7	0.5
88	17.6	12.7	16.0	16.1	17.1	16.3
89	8.3	1.0	7.4	13.2	8.7	19.3

TABLE 3

AVERAGE WL

Lot #	Measurements Period	#	Average WL (mWL)	Comment
1	Jan - Mar	2	7	Single dwelling - good sealing
2	Feb - Mar	2	20	Semi-detached pair - joint in
3	Feb - April	3	11	slab
4	Mar - April	2	17	Semi-detached pair - incomplete
5	Mar - April	3	15	sealing
88	Mar - May	7	22	Semi-detached pair - incomplete
89	Mar - May	5	17	sealing

SECTION III

RADON RESISTANT HOUSING
FOR
FLORIDA PHOSPHATE LANDS

Report No. 1168/1197

1.0 INTRODUCTION

This report is to document the results of part of a program to demonstrate means of controlling indoor radon levels in structures built on Florida phosphate lands. The work is being carried out by AMERICAN ATCON INC. with the support of Acres American Incorporated.

The radon arises from the presence of naturally occurring radium in the soil of the area, which results in significant radon concentrations in the soil gas. When the building construction provides pathways between the interior of the building and the soil, this radon-bearing soil gas enters the building and results in elevated indoor radon levels.

This report describes how current building practices and design may be changed to eliminate these pathways, and identifies the obstacles to implementation of these changes. Suggestions are given as to how the obstacles may be overcome.

2.0 RADON PRONE AREAS

2.1 Causes

Uranium is naturally present in trace amounts in most rocks and soils, and so its radioactive decay product, radium, is also present in trace amounts. The radioactive decay of radium produces the radioactive gas, radon, whose decay products are known to increase the incidence of lung cancer in miners who breath high concentrations for several years. Radon is always present in buildings for two reasons. First, the mineral building materials (concrete, brick, stone) contain radium, and the radon produced by its decay can diffuse from the materials and enter the building air. The radon concentration from this cause is set by the radium concentration, the release rate from the building materials, and the building ventilation rate.

Second, the individual rock fragments which make up the ground contain radium, and the radon produced by its decay diffuses into the soil gas that fills the spaces between the fragments. When the air pressure in a building is lower than the air pressure in the soil, the radon charged soil gas is drawn into the building through any opening to the soil. The radon concentration from this cause is set by the ease of soil gas entry into a building, the radon concentration in the soil gas, the pressure differential between building and soil, and the building ventilation rate. If conditions are favourable, building radon concentrations as high as the occupational standard for uranium miners are possible.

There are several areas of the United States, Canada and Sweden where entry of radon with soil gas produces concentrations in buildings that are much higher than those expected from the radium content of their building materials. In some of these areas the soil radium content is elevated either by admixture of fragments from nearby rocks that are enriched in uranium, or by precipitation of dissolved uranium in the geological past. As the soil radium content is high, the radon concentration in soil gas is also high, and high radon levels can be produced in houses by the entry of relatively small amounts of soil gas. These areas can be detected by their higher gamma activity, and if they are small and well localised, low radon housing could be constructed by simply not building on these areas.

In other areas, the soil radium content and the radon concentration in soil gas is 'normal', but the gas can move very readily through the soil. These areas often have well drained gravel soils containing little clay, so the passages between the soil grains are relatively large and unobstructed. In these areas small pressure differences between the house and soil can draw in large volumes of soil gas because of the low resistance to gas movement. As the radium content of these areas is normal, a soil structure survey would be required to determine their extent.

2.2 Housing

Declaring areas unsuitable for building is not a generally acceptable method to produce low radon housing. Existing communities were located in the past without concern for radon, and in most regions orderly development will require new construction to take place on soils and in areas similar to those known to produce elevated radon levels in existing buildings. In these regions the only possibility of achieving low radon levels in new construction is to reduce the ease with which soil gas can enter the structures.

Conventional building styles and the actions of the building trades produce many connections from the soil to the house interior, through which soil gas containing radon can flow. 'Radon resistant' housing requires that these connections be eliminated or closed. Home building practices, and the resulting soil connections, have been studied in Central Florida (ATCON Report 1168/1171). In that area, the predominant housing type is a single storey house built with a poured concrete floor and hollow concrete block foundations and walls. The floor slab is essentially impermeable to the passage of soil gas, and so the soil connections are those openings in the foundations and slab created by the builders. Predictable connections are openings left in the floor slab to assist in the installation of plumbing fixtures, junctions between walls and floors, and the voids in hollow concrete block walls. Upredictable connections are produced as a side effect of architectural features such as sunken living rooms and sunken baths, openings made to correct errors in plumbing instalations, and cracks through the building materials themselves.

If 'radon resistant' housing is to be produced without a significant economic penalty, soil gas exclusion techniques must be compatible with current building styles and existing skills in the house building trades. To be successful, the techniques must not require unusual skills to apply, nor can they change the design and appearance of the house significantly from those the public is accustomed to purchase. These objectives are readily achievable in those areas where single storey construction is the norm. In areas where houses are constructed with basements, the task is more difficult, but still achievable.

3.0 DESIGN OF RADON RESISTANT HOUSING

3.1 Ventilated Crawl Space

The most obvious and simple method of preventing the entry of soil gas is to elevate the building, so that the space between building and ground is constantly ventilated. This is presently done with mobile homes, and some prefabricated housing in the southern States, but these are not generally acceptable housing types. Masonry houses were built for many years in the southern States with suspended wood floors and ventilation in the sub-floor space, but this style of construction is now obsolete. Modern houses are built with concrete slab floors, because suspended wood floors are more expensive to construct, noisier, may be attacked by termites despite ventilation, and unless well insulated, are cold during the heating season. Most of these disadvantages could be overcome by the use of precast hollow slab floors, similar to those used in apartment buildings, but the equipment and skills involved are outside the range of those normally used by small builders.

The major disadvantages to crawl space construction are that as the design is no longer common, it would be obviously an 'anti-radon' house, and also have an 'old fashioned' appearance. This would probably reduce its attractiveness to potential purchasers. For these reasons, although houses with well ventilated crawl spaces are effective in excluding radon, they are not likely to be widely acceptable. Purchasers and builders will prefer radon resistant housing to appear similar to other housing in the area.

Radon resistant housing can retain current housing styles and appearance if the soil connections produced by existing practices and designs can be closed or eliminated. In the southern United States where the predominant housing style is slab-on-grade housing, the problem reduces to constructing a floor slab and foundation so that there are no openings or cracks through which soil gas can enter the building.

3.2 Monolithic Floor Slab

The requirement of minimum special skills rules out effective but unusual techniques such as covering the site with a reservoir grade plastic membrane or with an impermeable clay layer. The only practicable solution is to construct a simple floor slab and foundation with the minimum of openings, and to close those remaining openings at an early stage in construction. Such a foundation style already exists, and is called a monolithic slab.

The monolithic slab foundation consists of a reinforced concrete floor slab which is thickened at the perimeter to form the foundations (Fig.1). The complete slab is poured at one time, and so the floor and foundations are integral. The walls are erected on top of the slab, and are not in contact with the soil. As a result, the only openings in the slab and foundation are those made deliberately to assist in the installation of services and they can be sealed.

Use of a monolithic slab foundation eliminates concrete blocks from the foundation structure. The soil connections provided by the voids in the blocks, and the necessary joints between the block foundation walls and the floor slab are therefore eliminated. Although concrete blocks cannot be used in the foundations of radon resistant housing, they can still be used to construct exterior and interior walls provided they are placed on the monolithic slab, out of contact with the ground. Therefore specification of a monolithic slab foundation for radon resistant construction would be at most a slight inconvenience to those builders who presently use concrete blocks exclusively, for they could continue to construct block walls above grade.

Building sites in central Florida are sprayed with long-lasting insecticides prior to pouring the concrete floors to prevent termites and other burrowing insects from entering the building. Additional treatments are often carried out inside concrete block walls after a house has been occupied for a few years. A sealed monolithic slab house would not require site insecticide treatment, for it would exclude termites as effectively as it excludes soil gas. There would be no openings from the soil into the building through which termites could enter. Elimination of site insecticide treatment would reduce builders' costs, and a long term 'insect proof' foundation might have an additional perceived value by the construction industry and its customers.

3.3 Slab Construction

If the slab is to prevent the entry of soil gas, it must remain intact. The causes of cracking in concrete slabs are tension forces due to restrained shrinkage while the concrete is curing, and torsion forces due to differential settlement of the ground under the weight of the building. When the tension force is greater than the tensile strength, the concrete is pulled apart, producing a crack.

As monolithic slabs rest on the ground, the edges are only lightly restrained from moving as the concrete shrinks, and so rectangular house slabs do not generally develop tension stresses high enough to cause cracks. However, if the slab has a narrow section between two large areas, or is 'L' shaped, even these small restraining forces can cause stress concentrations at internal corners high enough to cause cracking.

Differential settlement usually takes place in areas where ground has been reclaimed and the fill not evenly consolidated. As it leads to such obvious defects as cracked walls and ceilings, these areas are usually avoided by builders. If development must take place on unstable ground, the monolithic slab (or raft foundation as it sometimes is called) is preferred. As the building weight is distributed over the floor area, rather than concentrated on the wall footings, settlement is minimized. If settlement does take place, a properly reinforced slab will withstand the forces generated, and allow the house to settle as a whole without cracking in the structure.

Slab reinforcement usually consists of reinforcing bars in the foundation beams, and wire mesh in the rest of the slab. As the wire mesh is placed in position before the slab is poured, and is continually walked over by the tradesmen during the concrete placement, it ends up near the bottom of the concrete slab, not in the centre. As it is difficult to transfer forces to the mesh in that position, it is not very effective reinforcing. Despite this, if the ground is reasonably stable this reinforcing is adequate.

Where the ground conditions are known to be unstable, slabs with post-tensioned reinforcing have been used for housing, and this is presently being tried on an experimental basis in Florida. Instead of reinforcing bars and wire mesh, a network of steel cables is laid in the slab at 2.0 m intervals. After the concrete has cured for some days, and developed much of its final strength, the cables are stretched and clamped in their extended position by anchors set into the edge of the slab (Fig. 2). The cable tension compresses the slab thus reducing internal tension forces, and supports the slab against external forces. The equipment is available in a form suitable for small builders, and so the long term integrity of a monolithic slab can be assured in all ground conditions.

A reinforced monolithic slab is therefore recommended as the most practicable form of 'radon resistant' foundation, given the constraints of minimum change in appearance, and construction techniques suitable for small builders. To prevent shrinkage cracking in the slab, the basic plan should be rectangular with no large changes in section, and no changes in level. More complex house plans are possible, but would require individual engineering review.

4.0 SERVICE OPENINGS

If a monolithic slab is adopted as the standard foundation, then the soil gas entry routes through junctions between the floor and the foundation walls are eliminated. Although this is a major step, a monolithic foundation alone will not produce a gas tight foundation, as openings are still required in the slab to install plumbing services. Unless these openings are also closed, the goal of radon resistant foundations cannot be achieved.

4.1 Pipe Entries

Water supply lines, and drain and vent lines are usually run beneath the floor slab, and brought up through the floor at the place they are required. A requirement of the Southern Standard Plumbing Code is that metal pipes passing through concrete must be protected against corrosion, and this is usually complied with by painting that portion of the pipe with asphalt, which gives an essentially airtight joint between the pipe and concrete. However, sometimes the protection is supplied by wrapping or sleeving the pipe with plastic or foam rubber sheeting, which is not airtight (Fig. 3). This practice would have to be specifically forbidden for radon resistant housing.

Drain and vent piping in modern housing is of rigid plastic, and so requires no protection when passing through concrete. The joint between the pipe and concrete is virtually airtight, and can be improved by slightly roughening the very smooth pipe surface so as to increase the bond between concrete and pipe.

4.2 Sanitary Services

Floor mounted sanitary fixtures such as toilets and showers are drained by a pipe that terminates in a floor level flange to which the fixture is sealed. This flange has to be attached to the pipe after the concrete floor is poured, so the concrete is held away from the pipe by a collar of styrofoam or cardboard (Fig. 4A). When this temporary collar is removed, a hole is left clear through the slab into the fill. The hole is subsequently concealed by installation of the fixture. As the joint between the fixture and the floor is not airtight, this provides a major route for soil entry at every toilet and shower. This opening can be made airtight by filling the space between concrete and pipe with a sealant after the flange is attached (Fig. 4B).

Modern baths have the bottom of the bath just above the floor, and so the bath drain must be below floor level. The drain connection is generally 1 to 2 inches (2 to 5 cm) below the lower surface of the concrete slab. To provide access to this connection and space for the bath drain, it is usual to form an opening through the slab about 8 x 16 inches (20 x 40 cm) in size (Fig. 5). An opening of about this size is needed to provide access to the drain connection and give a little flexibility so that the bath can be positioned against the bathroom walls. The usual "form" is a concrete block, which is pulled out by the concrete finishers when the concrete sets. A wooden frame is occasionally used, and is often left in place.

This large opening through the slab could be eliminated entirely if the bath had sufficient clearance from the floor to allow the drain to be installed above the floor slab. This type of bath is used for renovation work, but the accuracy required in positioning may make it unacceptable in new construction. Provided that formwork is removed from the opening, and the concrete edges are cleared and prepared, any one of a number of sealants can be used to provide an airtight membrane layer across the opening.

In principle, an airtight foundation which will exclude soil gas and its associated radon can be produced by the use of a monolithic slab and sealing the penetrations associated with the plumbing. There are therefore no theoretical obstacles to production of radon resistant housing. However, experience in similar building projects shows that there are considerable practical difficulties in applying theoretical solutions in the field.

5.0 UNCONTROLLED OPENINGS

The openings made in the slab to assist the plumbers are predictable, but there are another group of openings that are produced more or less unintentionally as a side effect of some other goal. These are much more difficult to identify and prevent, for many of them are the result of individual enterprise seeking to ease a task, or to give concrete form to an architect's drawing. As an example, changes in floor level require either that the floor be poured in two separate slabs, which may produce a route of entry where the edges touch, or else the use of hold-back forms around the edge of the sunken portion (Fig. 6). These forms are located by wooden stakes driven into the sand fill. When the concrete is set, the forms and the stakes are removed, and the holes in the concrete left by the stakes are concealed, but not sealed, with a layer of cement.

Openings can be produced by temporary plumbing supports made of pipe being left in place, and by grade stakes which are withdrawn after the concrete is partially set. Sunken baths and sunken showers have their bases below the level of the slab, and so are installed in openings that are formed through the slab. Large openings can be produced in this way.

Complex floor slabs, including changes in level or sunken areas, can be constructed to exclude soil gas if adequate precautions are taken in both design and construction. However this will lead to greater cost and may require the use of skills beyond the usual range available to the small builder. For example, if floors must be poured in sections, the junctions can be sealed by the use of specially designed plastic strips (waterstops) placed in the concrete at each junction. This is a standard technique in industrial construction, but quite unknown to most small builders. Experience in similar projects is that construction methods that are novel to the workmen are characterised by a high percentage of failures. As simple and as standard an approach as possible is therefore recommended as having the highest probability of success.

Most problems can be prevented by both architect and builder working within well defined limits on design and construction techniques. For instance, if routine production of radon resistant housing requires monolithic slabs without changes in level or sunken baths, then the architects designing houses to be built in the area must be informed of these requirements. Likewise, if monolithic slabs are to be produced without grade-stake holes, the concrete tradesmen and the builders must be informed of the requirement, and there must be practical techniques available to pour and finish slabs without using grade stakes.

6.0 REQUIREMENTS FOR RADON RESISTANT HOUSES

Before a general program of radon resistant housing can be successfully implemented, a number of preconditions must be met.

These are:

1. the area over which buildings are required to have radon resistant foundations is defined,
2. a mechanism is in place to inform architects and builders of the requirement to use radon-resistant foundations,
3. standard foundation designs and details are available,
4. where changes in current practices or techniques are required alternate field tested methods are available to the tradesmen.
5. a mechanism is in place to inform and train builders and tradesmen in use of those alternate methods and materials, and
6. there is an inspection mechanism to verify that the foundation and the sealing has been completed properly.

6.1 Definition of Area

In those areas where problem lands can be identified by a gamma survey it will be a technically simple task to determine the extent and limits of the area where radon resistant foundations are required. In other areas the problem will be more complex, and the area may have to be defined by extensive soil tests, or even by radon levels in existing housing. However, after a technical determination of the area has been made, legislation will be required to define the area legally.

6.2 Information Mechanisms

Once areas requiring radon resistant foundations are legally defined, the designers and builders of structures within these areas must be informed of this. Most areas have a system that requires a building permit before construction can start, and this system could be modified to include this information if the site is inside the defined area.

6.3 Design Assistance

There is no point in informing designers and builders that radon resistant foundations are required without also providing guidance as to how this can be achieved. Any other course leads only to ineffective design and construction. It is therefore vitally important that a design guide containing standard foundation designs and details be available to the building designers. The guide should also include examples of design items that should not be used, so that the constraints under which architect and builder must operate will be quite clear.

6.4 Additional Trades Training

Although it is quite feasible to pour a monolithic concrete slab with limited penetrations, it is not usual to attempt to do so. Construction methods have been refined over the years to produce an acceptable structure at minimum cost to the builder given the skills of the available labour force. Production of an airtight foundation has not previously been a matter of concern.

It is not beyond the skill of the building industry to meet this new requirement, but new techniques will be needed. The building trade is noted for its conservatism, and so it is certain that any suggested deviation from established practice will be initially greeted with resistance. As the main responsibility for providing an airtight foundation rests firmly on the shoulders of those tradesmen actually performing the work, it is imperative that any changes suggested should be as acceptable to those persons as possible. Systems can be satisfactory in the laboratory, but if they are not convenient in the field they will be ignored and the workmen will revert to old and familiar methods that may well compromise the airtightness of the foundation.

As an example of the problems that may be encountered, consider that the level surface on a concrete slab is usually produced with the aid of horizontal wooden bars nailed to stakes driven into the subgrade material. Concrete is poured on the top of the wooden bars, which are often left until the concrete has taken its initial set. When the bar is removed, the stakes leave holes through the concrete slab and the underlying plastic sheet. Occasionally only the bar is removed and the stakes are left in the concrete, where they rot away in time. Clearly the use of grade stakes is undesirable, but if they are banned, how is the surface of the concrete to be kept level? Unless the teams of concrete workers are shown simple alternative techniques, and provided with the necessary tools, they will simply proceed in the usual fashion and devote their ingenuity to concealing this fact from the inspector, rather than to ensuring the integrity of the floor slab.

Implementation of radon resistant foundations therefore requires that those tradesmen most intimately connected with construction of the floor slab, and sealing its penetrations, should receive some training in which new techniques are demonstrated and the reasons behind them explained The tradesmen involved are the concrete trades, who will have to produce slabs with limited penetrations, and the plumbers, who will have to seal those openings left for them to complete their tasks. Of the two, the plumbers pose the greater problem. Although they are the logical persons to seal the openings, this will be a completely new skill for them to acquire. In most cases the openings are concealed when they have finished their work, rendering inspection very difficult. It is possible that the traditional timing of inspections will have to be modified so that the presence and quality of the seal can be verified before the area is covered over or built in.

6.5 Inspection

As a final point, if there are to be inspectors, the inspectors must know what faults they are looking for, and what a good job looks like. Inspectors must be trained before the tradesmen are turned loose.

7.0 A PROGRAM TO PRODUCE RADON RESISTANT HOUSING

The major obstacle to development in radon prone areas is uncertainty. The public is uncertain of the risks they would be exposed to if they lived in a house in the area; the builders are uncertain of what they can do to minimize the risks; the regulatory agencies are uncertain of the extent of the areas, and the financial institutions are uncertain if housing in these areas would be a good investment, given the level of public concern. Of these obstacles, the most significant is the uncertainty of financial insitutions, for, as long as they are uncertain, they may prefer to make or guarantee loans in other areas. This policy will inevitably turn radon prone areas into 'no construction' areas, to the great disadvantage of those communities with large radon prone areas within their borders. If the institutions can be convinced that an acceptable solution exists, there is every prospect that they will then treat these areas on an equal footing with other parts of the country. Of course, the financial institutions are not likely to be convinced that a solution exists until this has been demonstrated in some buildings. This circle must be broken before development can proceed.

Although technical solutions exist, a program that merely changes regulations and gives the builders a guide book is not likely to produce the kind of results that will convince the financial institutions that effective control is possible. A number of early failures might well cause a permanent withdrawal of financing assistance from the area. It is therefore imperative that any program demonstrate early success. It may be feasible to persuade a financial institution to assist with the financing of a small housing project in a radon prone area if they were assured that the best available radon control technology was to be used together with intensive and experienced direction and inspection. In which case the risk to their investment would be slight and would be further limited by the small size of the project. If the project were also organized to provide on-the-job training to the foundation tradesmen and inspectors, it would produce a nucleus of experienced workers.

Satisfactory results from this demonstration/training project would give the institutions confidence that suitable construction methods exist and hopefully would encourage them to finance more houses. The experience gained by the building trades and local inspectors in this initial program would greatly reduce the additional inspection and direction needed for subsequent houses. Finally, when the techniques and methods are well understood, the local building industry and the local inspectors will be able to produce radon-resistant foundations as a matter of routine.

It may well be that a project of this kind can be organized before a definitive decision has been made on the official definition of the limits of radon-prone areas. The small size of the proposed project would enable it to be located on lands that would be a "problem area" by any definition, and so demonstration of a solution would not have to wait for full definition of the problem areas.

It is therefore suggested that a small demonstration project be carried out, with the aims of

(a) demonstrating that radon resistant foundations can be construced economically,

(b) developing data on the methods required to produce such foundations on a routine basis,

(c) developing the training methods to be used with local tradesmen and inspectors, and

(d) determining the information, training and inspection required to make production of such foundations an everyday practice.

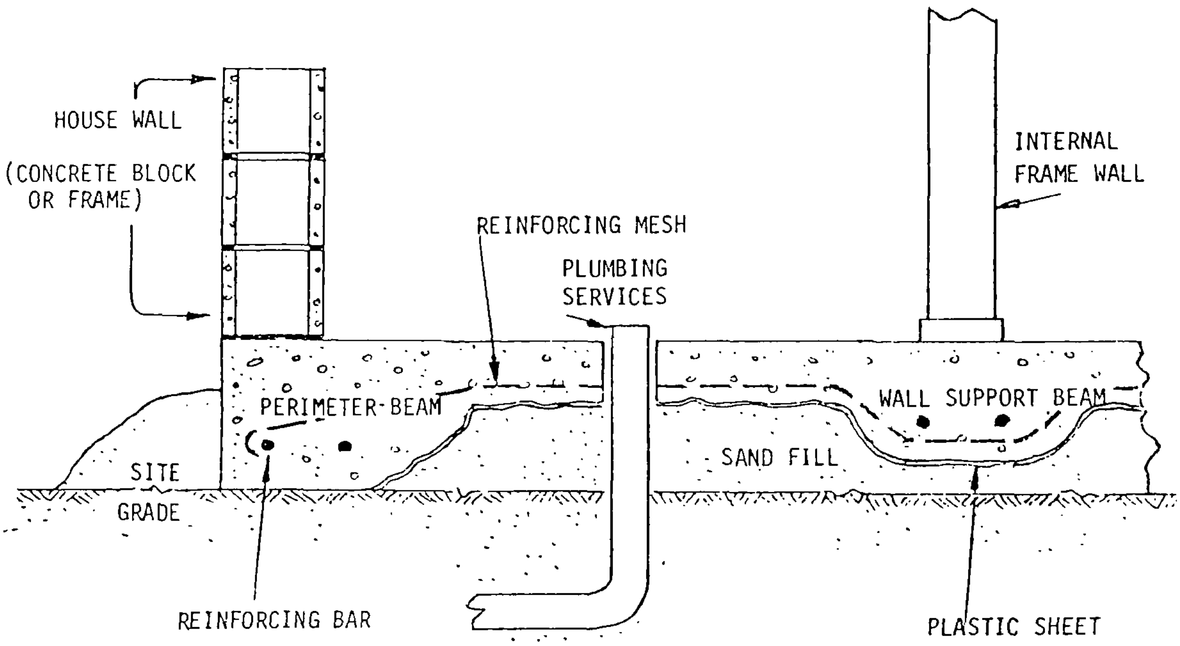


FIG. 1 MONOLITHIC SLAB
STANDARD REINFORCING.

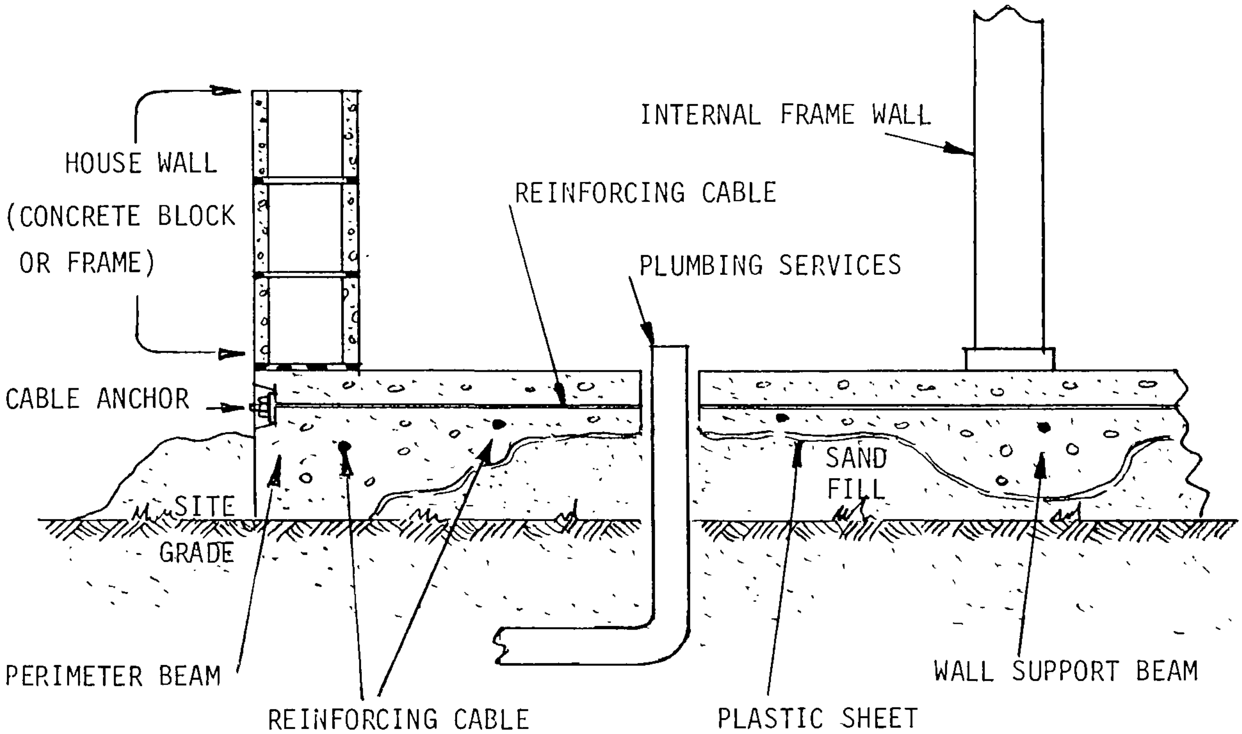


FIG.2 MONOLITHIC SLAB
POST - TENSIONED REINFORCING

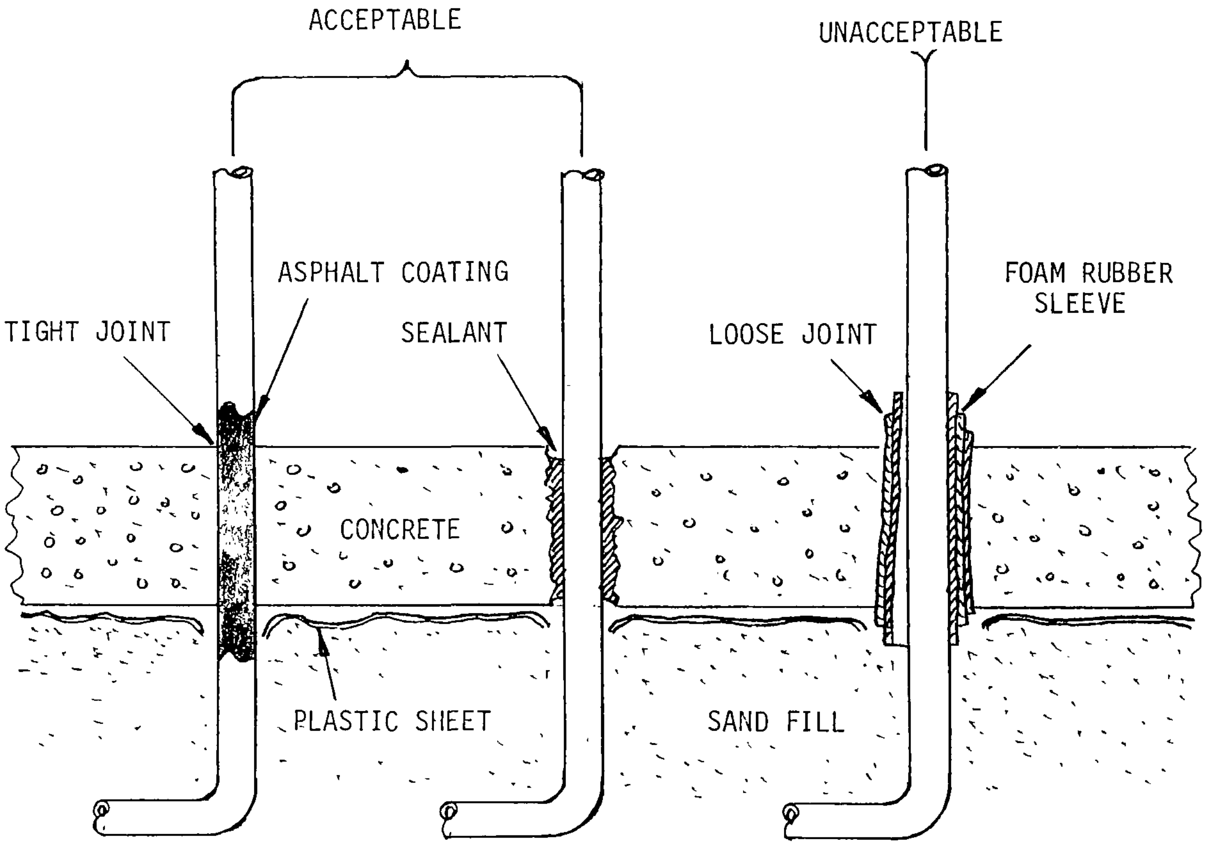
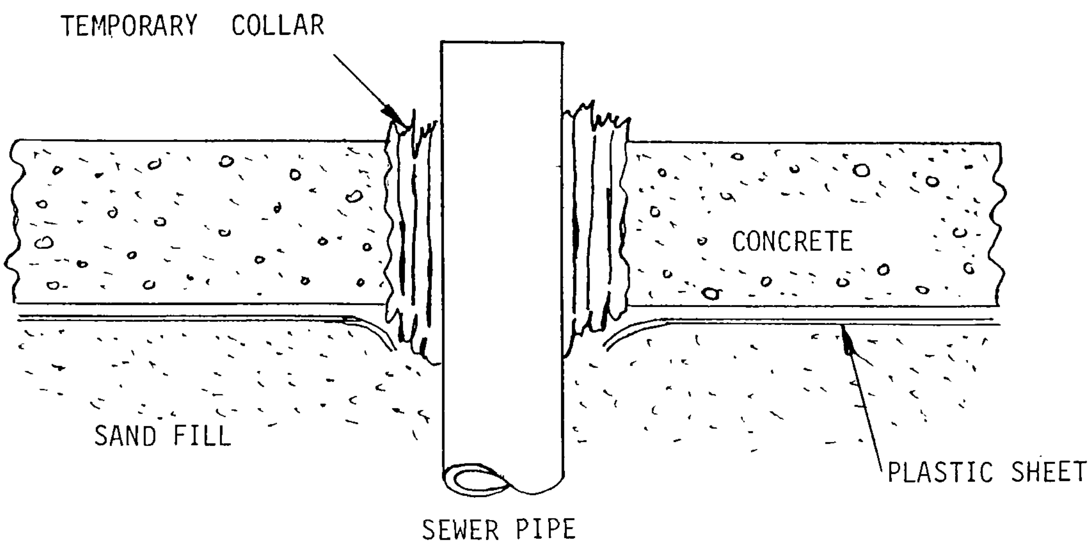
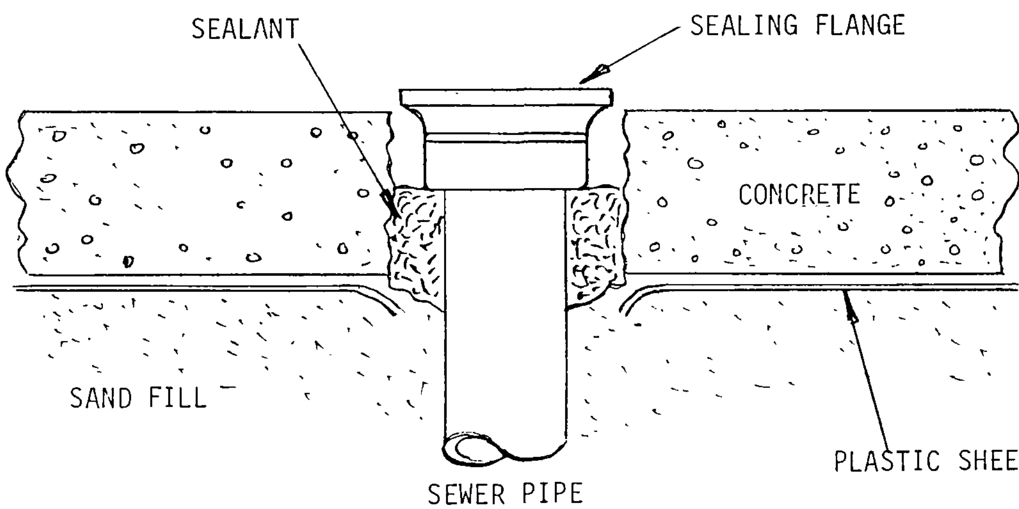


FIG. 3 PIPE ENTRIES



4A SANITARY SERVICE ENTRY - CONSTRUCTION PHASE



4B SANITARY SERVICE ENTRY SEALED

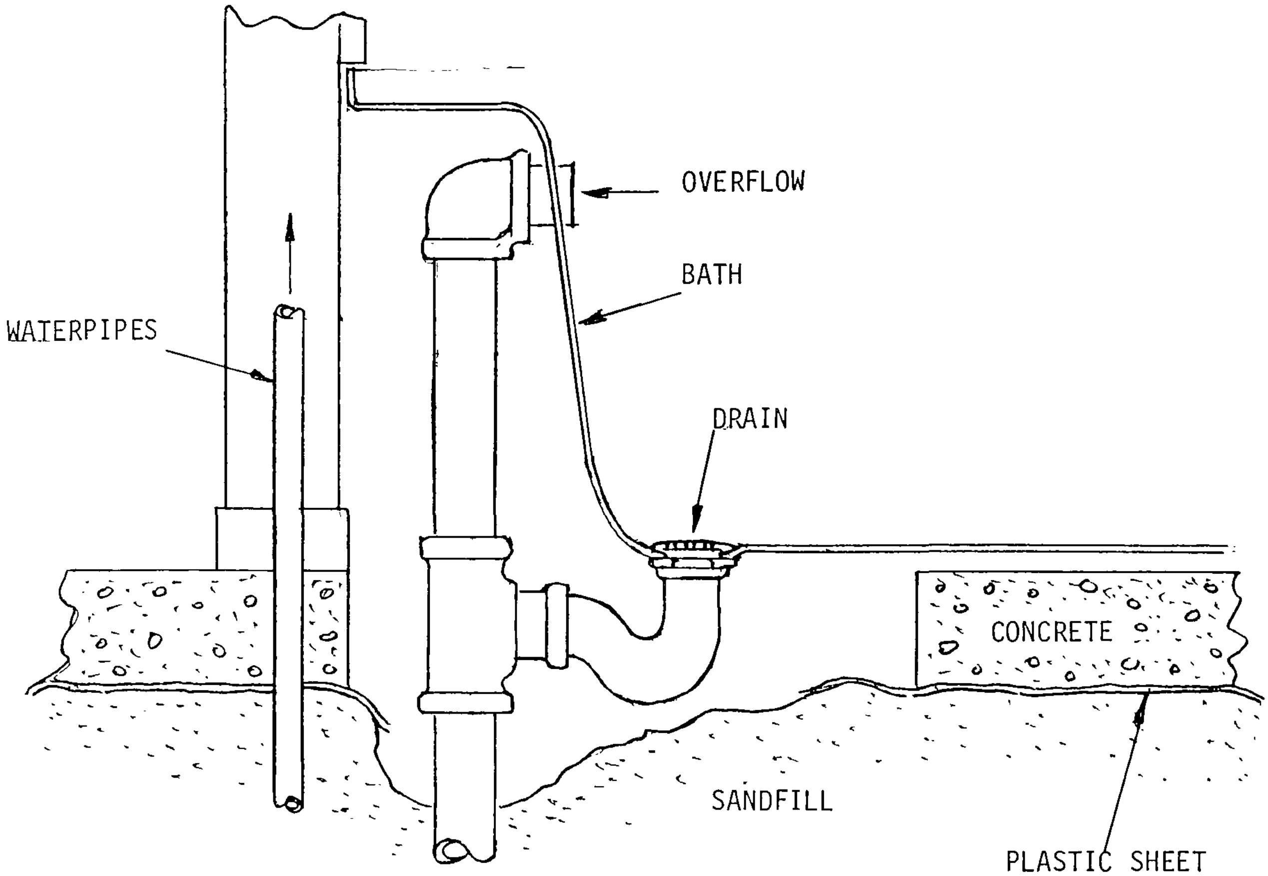


FIG. 5 BATH DRAIN INSTALLATION

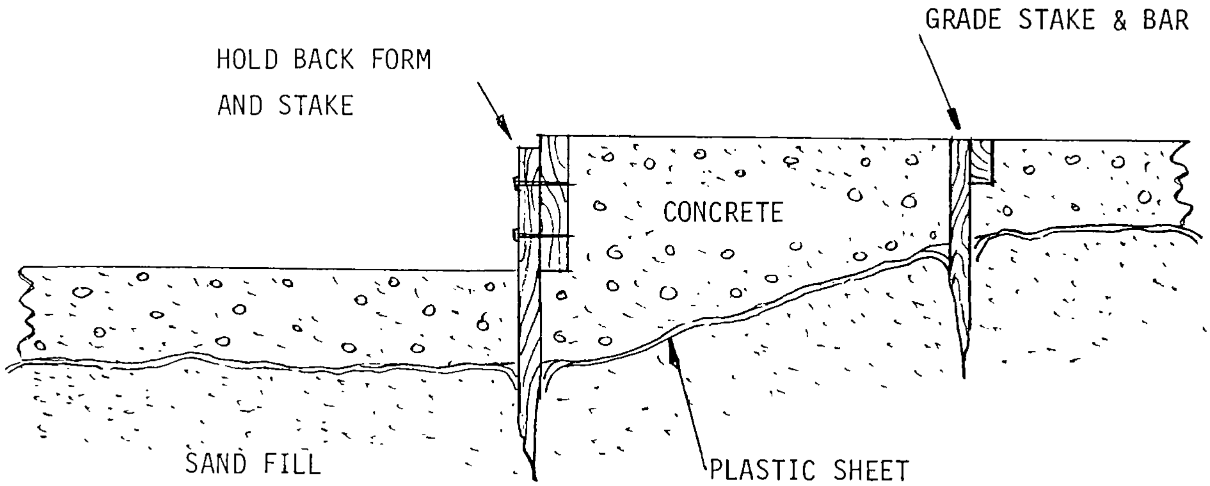


FIG. 6 UNCONTROLLED OPENINGS

SECTION IV

CONCRETE AND PRODUCTION
OF
RADON RESISTANT FOUNDATIONS

Report No. 1168/1209

1.0 INTRODUCTION

This report is to summarize the properties of concrete, and how they affect the production of radon resistant foundations. This report is part of a program to demonstrate means of controlling indoor radon levels in structures built on Florida phosphate lands. The work is being carried out by AMERICAN ATCON INC. with the support of Acres American Incorporated.

Concrete is a composite material consisting of a cement-water paste in which are embedded fragments of rock, called aggregate, as a filler. The fragments are graded in size from fine sand to pebbles or crushed stone particles up to several centimetres in diameter, so that about 75% of the volume of concrete is aggregate. The cement-water paste fills the voids between the aggregate particles and provides lubrication to the whole mass while it is plastic, and holds the particles together when it has hardened. As the aggregate is essentially an inert filler the properties of concrete are largely those of the paste, and depend on: the characteristics of the cement, the relative proportions of cement and water, and the completeness of the chemical reaction between cement and water. An understanding of the behaviour of cement is therefore necessary to an understanding of concrete behaviour.

2.0 THE CEMENT-WATER REACTION

Portland cement is mainly a mixture of anhydrous calcium silicates and aluminates, so finely ground that many of the particles are only 10 to 15 microns in diameter. When the powder is mixed with water, a continuous coat of aluminium and silicate gel is rapidly formed at the surface of each particle. As water can now only reach the interior of the particle by the slow process of diffusion through the gel coat, these particles are stable for some time. The surface electrical charges associated with the gel gives the suspension of cement particles in water lubricating properties, and renders the mixture initially semi-fluid by enabling the aggregate particles to slide easily over each other. About twice as much water as is necessary to completely hydrate the cement is added to the mix in order to produce workable concrete.

Water diffusing through the gel coat on each particle reacts with the cement, producing a larger volume of gel, which strains the gel coat. Finally it ruptures, and liquid water then enters the particle to react directly with the cement. As each particle is converted to gel, the gel joins with that from other particles to form a connected skeletal structure filling the spaces between the aggregate. This gel structure has mechanical strength, and binds the aggregate together, producing the initial set of the concrete. This normally occurs about 2 hours after mixing. The initial set can be delayed by mechanical agitation which ruptures the connected gel structure, adding water to the mix which dilutes and weakens the gel, or lowering the temperature, which reduces the chemical reaction rate.

When the initial set develops, only the smallest cement particles in the mix have been converted to gel. Most of the water in the mix is trapped in the gel by capillary forces; the remainder is bound to silica and alumina molecules in the gel. As time goes by, the trapped water hydrates the larger cement particles producing more gel to strengthen the bond between the aggregate particles. As long as the trapped water is present, the concrete will increase in strength with time. Most of the increase in strength takes place within a month, but it takes many years before all the cement is hydrated. There is a further increase in strength as the concrete dries, since dry gel is stronger than moist gel. When the trapped water evaporates, it leaves behind a network of capillary channels through the gel. This results in a sponge-like structure of silica and alumina gels and crystalline material. The higher the water/cement ratio, the more extensive the capillary network, and the weaker the gel structure. This reduces the strength of the concrete.

Many concretes have 10 to 30% of the cement replaced with finely ground pozzolanic materials. These are natural siliceous materials, such as fly ash, which will react with the lime liberated by the cement/water reaction to produce a silicate gel. The final strength of fully hydrated concrete is not greatly affected by the substitution. Pozzolans are used to reduce cost, as fly ash is cheaper than cement, and to improve the workability of the mix. The pozzolan reaction does not take place until the concrete has set, and so it acts as additional fine aggregate (a lubricant) while the paste is fluid.

3.0 STRENGTH OF CONCRETE

As the cement paste develops most of its strength in the first month, it is usual to measure concrete strength at 28 days after mixing. The quoted strength is actually the compressive stress at failure of a cylinder 30cm high and 15cm diameter, which has been kept moist to prevent evaporation of the trapped water and is tested moist. The drying history of the concrete poured at the site is usually quite different from that of the cylinder, and so its strength is only an estimate of the potential strength of the concrete.

For a given aggregate mix, the 28 day strength of concrete varies in a predictable fashion with the water/cement ratio, as shown in Figure 1. Typical concrete strengths used in building are 21 MPa (3000 psi). The effect of moisture loss on concrete strength is shown in Figure 2. Early drying leads to weak concrete as only a fraction of the cement is converted to gel, but if hydration is almost complete, drying increases the strength.

It is usual to retard the evaporation of trapped water from the concrete for several days after it has been poured. This is called curing the concrete. The common method is to keep the surface continually damp with sprinklers, or wetted fabric covers. Other methods rely on preventing evaporation by the use of plastic sheets, or liquid sealers that are brushed onto the surface and form a layer impervious to moisture. In practice it is often impracticable to carry out curing for more than 4 to 7 days, by which time the concrete has developed about 50% of its ultimate strength. As it takes some days for the water to evaporate, the final strength of the air-dry concrete (often referred to as fully cured concrete) is about 80% of the ultimate strength.

Concrete is much weaker in tension than in compression, and the tensile strength depends to some extent on the surface texture of the aggregate, for failure often occurs at the bond between the paste and the aggregate. In general, the tensile stress at failure is only about 7 to 10% of the compressive stress. If a concrete structure is exprected to stand tensile stress, steel reinforcement is placed in the concrete to carry these stresses.

4.0 CONCRETE SHRINKAGE

The hardened cement paste is not dimensionally stable. The volume of the gel component initially increases as long as the concrete is kept moist and hydration of unreacted cement can proceed. When curing is over, and the trapped water evaporates, the gel shrinks in response to the fall in the humidity of the concrete. This shrinkage is inevitable for any structure in contact with the air.

Total concrete shrinkage depends on shrinkage of the aggregate, shrinkage of the cement paste itself, and the average thickness of the paste between the aggregate particles. Hardened cement paste shrinks much more than aggregate in response to humidity changes, but most of the concrete volume is aggregate. As a result aggregate shrinkage is nearly as important as cement shrinkage in determining total concrete shrinkage.

If a mix is made more fluid by adding more cement paste, the shrinkage will be increased, for the paste volume, and hence average thickness between aggregate particles will be increased. If a mix is made more fluid by adding water, the shrinkage will be higher because the additional water not only increases the paste volume, but the diluted paste also has higher shrinkage.

Experiments show that for a given aggregate, shrinkage is related to the total amount of water in the mix, as shown in Figure 3. At a fixed water content, variation in the water/cement ratio hardly affects the shrinkage. The slight increase in gel volume produced by additional cement is counteracted by the lower shrinkage of the more concentrated paste. There is therefore no relationship between shrinkage and strength.

To maintain workable fluidity in the concrete, about 25% of the volume must be paste. Most of the paste volume is water, so changes in the water/cement ratio hardly change the paste volume. As a result, concrete of similar fluidity contains about the same amount of water, regardless of strength. As shrinkage is related to water content, there is a direct relationship between fluidity and shrinkage. Typical mixes contain about 150 to 190 kg water/m^3, so typical shrinkage strains from end of curing to air-dry are 3 to 6 x 10^{-4}.

5.0 SHRINKAGE STRESSES

If a concrete slab is restrained from shrinking, the resultant tensile stress in the concrete is E.s, where E is Young's Modulus and s is the effective strain. For typical concrete, Young's Modlus is approximately 1000 times the compressive strength, or 21 GPa (3 x 10^6 psi), and s is 4 x 10^{-4}, therefore the tension stress produced by restrained shrinkage would be about 8.4 MPa (1200 psi). The maximum tensile stress that concrete can withstand is about 10% of the compressive strength, or about 2 MPa (300 psi), consequently fully restrained concrete is not strong enough to withstand the tension generated by its own shrinkage, and will crack.

In practice, concrete is rarely fully restrained, and the slow development of the shrinkage forces allows some strain relief by creep. Stresses applied to the gel can cause permanent distortion of the gel structure. This takes place most readily in the first month or so after pouring, before the gel has acheived its maximum development, but can continue for years. The ultimate deformation due to creep is typically 2 to 3 times the elastic deformation of the concrete under the same stress. Even taking into account the stress reduction due to creep, the maximum stress in fully restrained concrete is still greater than the tensile strength. Therefore only lightly restrained concrete can be produced crack-free.

Shrinkage is caused by the evaporation of the trapped water from the gel, which is delayed by curing. If the curing period is only a few days, shrinkage takes place long before the concrete has developed its full strength, and even slight restraint may produce tensions greater than the concrete can bear.

The coefficient of thermal expansion for concrete is about 1.2 x 10^{-5o}C, and so the contraction due to shrinkage is equivalent to that produced by a temperature change of 20 to 40°C. However, shrinkage takes place over many days, and creep can relieve the stresses to some extent. Surface temperature changes from day to night are often 20°C, and so thin concrete sections can undergo comparable contractions in a matter of hours. Concrete that is set by noon of a sunny day can crack as a result of the thermal contraction forces developed by a cool night.

6.0 REINFORCED CONCRETE

Concrete is reinforced with steel bars or mesh against external tensile forces, but they are not effective against the internal tensile forces produced by shrinkage. If the concrete is restrained, there is no relative movement between the reinforcing and the concrete until it cracks under tension. Local movement will then stress the reinforcing steel, which will try to hold the edges of the crack together. In many cases shrinkage takes place before the concrete has developed enough strength to transfer forces effectively to the reinforcing, and early cracks can grow to a significant width without greatly stressing the reinforcement.

The light reinforcement often used in floor slabs does not prevent development of stresses large enough to crack the concrete, but merely prevents the resulting cracks from exceeding a certain size. For example, typical wire mesh reinforcing a 9 cm thick floor slab consists of 6 mm diameter wires on 10 cm centres. Young's modulus for steel is about 10 times that of concrete, and so the effective increase in slab modulus is only about 3.5%. If tension in the concrete exceeds 2 MPa, it will crack, and the sides of the crack will be drawn apart with an initial force of about 2 kN per cm of crack, or 18 kN per strand of wire mesh. This force would extend a 20 cm length of the wire (2 meshes) about 0.5 mm. In practice the gap would be larger, as the stress is greater than the yield stress of the wire, and the high local stresses in the mesh would cause creep in the concrete gripping it.

The purpose of light mesh reinforcement in slabs is therefore not to resist torsion or tensile forces, but to hold the parts of the slab in approximate alignment after it has cracked. If these forces are to be resisted effectively, it is necessary to place the concrete under compression before the load is applied. This is called 'pre-stressing', and is performed by tensioning the reinforcement so that its reaction against the concrete produces compressive forces opposite in direction to those from the load. Before the concrete can crack, the load stresses must reduce the compressive stresses in the concrete to zero, and so the strength of the slab is greatly increased by the tensioned reinforcing.

The preferred field pre-stressing method is to use high strength steel cables which are cast into the concrete. These are tensioned and locked in extension, after the concrete has developed enough strength to withstand the resulting compressive forces. This method is not effective against tension produced by restrained shrinkage, for cable tensioning is delayed until shrinkage has taken place. If the cables were tightened earlier, creep and shrinkage would reduce the cable extension, and reduce the compressive force.

7.0 CONCRETE AND RADON RESISTANT FOUNDATIONS

Production of radon resistant foundations requires that all openings to the soil be known and sealed, and that there should be no uncontrolled openings, such as cracks in the foundation. To achieve a crack-free floor slab, we require that it should be unrestrained in shrinkage, the concrete used should have low shrinkage, moisture be retained in the slab as long as possible, and that temperature variations during the curing period be minimized. It is instructive to compare these requirements with the way that small building contractors actually handle concrete. The requirement that the concrete be unrestrained in shrinkage is mainly a design matter, and will be discussed separately.

7.1 Concrete Shrinkage

The Building Code requires floor slabs to be at least 3.5" thick, and the concrete to have a minimum strength of 2500 psi (9 cm thick, 17 MPa). To achieve this, the nominal strength of the concrete used is normally 3000 psi (21 MPa). The selection and combination of aggregates of different types and sizes, cement, and water to produce a concrete of satisfactory strength and workability is a difficult task, and rightfully occupies a large portion of any book on concrete technology. As a result, most constructors have eagerly sloughed off this task to specialist firms, who deliver concrete ready-mixed to the site in large trucks from a central location where local materials are proportioned to produce a concrete to suit the builder's requirements.

From a contractor's point of view, strength is not as important as workability, for he must place the concrete into its final position. To ensure that it is sufficiently workable, a quantity called 'slump' is often specified. This is the subsidence of a pile of concrete formed in a truncated cone mold 30 cm high, and is a fair indication of the general workability of a mix. In large industrial construction, where mechanical placement is common, slumps of less than 100mm are satisfactory, but in house construction where placement is by hand, slumps as high as 175mm to 250mm are used to reduce the effort involved in moving and levelling the mass.

Slump is a measure of the viscosity and thickness of the cement paste layer between the aggregate, and can be increased by either increasing the thickness of the paste layer, or reducing its viscosity. The thickness of the layer can be increased by adding more cement and water to the mix, while keeping the water/cement ratio constant (a rich mix). This would be expensive as cement is the most costly ingredient of concrete. The viscosity of the paste can be reduced by entraining air into the mix with a special additive, for small stable air bubbles act as a lubricant. The cost of the additive is a few dollars per m^3 of concrete. If additional water is added to a mix, the volume of paste is increased by the volume of water added, and the viscosity is also reduced by the dilution of the gel. Water is free.

Most ready-mix companies supply a standard concrete mix of about 21MPa and 100mm slump to small builders. This is generally satisfactory for most small building jobs. However, if a large slab has to be poured, it is likely that the workmen will regard this mix as too stiff for easy placement. It is unlikely that their complaints will be answered by provision of concrete where the slump has been increased by increasing the cement content, when the slump of standard concrete can be increased at the site in a matter of moments by adding a small amount of water. Increasing the water/cement ratio by about 5% will increase slump from 100mm to 150 or 175mm which is a very fluid concrete. The increase in water/cement ratio will decrease the concrete strength by about 6%, and increase the drying shrinkage by about 12%.

7.2 <u>Curing Conditions</u>

Floor slabs are usually poured on dry days, as rain makes production of a smooth surface on the slab difficult. On a well organized site, pouring will start in the morning, and the concrete achieve its initial set in early afternoon, and the surface will be trowelled smooth before the end of the work day. However, unexpected events often delay completion of the final trowelling until late evening when the rest of the crew have gone home. The slab is then left until the following morning, when it may be coated with a curing compound which retards evaporation, or kept wet with a lawn sprinkler. If the house is of frame construction, it is common for the carpenters to start laying out the walls the next day, for it is easy then to fix the wall sole-plates in position by nails driven through the wood into the weak concrete. Appliction of curing compounds and wetting the slab would interfere with the tradesmen, therefore it is not carried out.

As there is usually no effort made to prevent the evaporation of water from the slab, on a sunny day with a brisk breeze, the upper surface may dry much more rapidly than the rest of the slab. The local shrinkage stresses, combined with the thermal stresses caused by the temperature change from day to night, may cause fine cracks in the surface layer of the concrete. These cracks do not reduce the slab strength greatly, but their presence indicates poor curing of the slab, and early shrinkage. If the slab surface is wetted by rain, hydration of the unreacted cement can continue, and these cracks may heal.

The conventional practices of the small builder are therefore directly opposed to the production of crack-free concrete. The mix is often watered to increase slump, and curing is haphazard, as shown by the frequent presence of partially healed surface drying cracks. Despite this, most house-sized slabs are free of tension cracks, demonstrating that the restraining forces are routinely less than the tensile forces required to fail even these poor quality slabs.

7.3 Slab Restraints

Since all concrete shrinks, crack free slabs can only be produced if the restraints to shrinkage are minimized. The major restraints to floor slab shrinkage are frictional resistance against the ground, adhesion of the concrete to rigid structures at the edges, slab shapes that have projections at right angles to the long axis and thickened sections which are effectively keyed into the soil.

Slabs are poured on top of a plastic sheet which is usually laid over smooth compacted sand, so the frictional resistance to movement is small. In houses where the plastic sheet prevents the floor slab from adhering to the foundation walls, there is no evidence of cracking due to frictional restraints. The friction between slab and ground can be greatly reduced by using a double sheet of plastic, so friction is a problem that can be overcome.

If wet concrete is poured on a horizontal surface, it will form a bond with strength varying from near zero to close to the shear strength of the concrete, depending on the state of the surface. As the shear strength of concrete is at least equal to the tensile strength, bonding to rigid horizontal foundation members at the edge of the slab can be strong enough to produce restraining forces exceeding the tensile strength of the concrete. As the foundation walls for a monlithic slab are poured at the same time as the floor slab, this type of restraint cannot occur. It is only significant if a floor slab is poured on top of pre-existing footings, as is common in basement construction.

A simple rectangular slab without restraint can contract without generating large stresses, but if it is asymmetric, e.g. 'L'-shaped, the contraction of the longer portion of the slab will try to pull the smaller portion sideways. Resistance to this will produce tension forces at the inner corner of the 'L' and may crack the slab there. This type of cracking is found in many 'L' shaped houses, and is accentuated by the practice of placing the garage at the junction of the two arms of the 'L'. As the garage slab is separate from the house slab, the house slab resembles two separate rectangular slabs at right angles joined by a small concrete neck. The shrinkage stresses are concentrated there and are high enough to crack the neck, although the two rectangular slabs are without shrinkage cracking.

Floor slabs are often thickened to provide a footing beneath a support pillar, or to provide a grade-beam beneath a load-bearing wall. This keys the slab into the ground, which will resist sideways movement. The resistance is limited by the depth of the footing, the compaction of the sub-slab fill, and by sloping edges of the footing. If there are two footings, or two parallel grade-beams, the slab is then anchored at two points, and tensile forces will be generated as the concrete between them tries to shrink.

Monolithic slabs have peripheral grade-beams, and are therefore restrained at their edges. The resulting stresses are not enough to crack house-sized slabs, probably because the slab is poured on top of lightly compacted sand which only weakly resists the small sideways movement. However, large multiple dwelling units or commercial units may require large slabs with several footings beneath the slab. In that case, provision must be made for shrinkage movement. This could be done by placing compressible plastic beadboard adjacent to footings to allow sideways movement, or casting the floor slab in small unrestrained sections. The joints between sections can be closed either by application of sealants, or by placing a specially shaped heavy plastic strip (waterstop) in the concrete at each joint. Common types of waterstop and their application are shown in Figure 4.

8.0 SUMMARY

Concrete is not dimensionally stable, and the tensile stresses produced by restrained drying shrinkage can be large enough to cause it to crack. Small building contractors routinely use placing and curing techniques that maximize shrinkage and reduce strength, but despite this, many large floor slabs have been produced without cracking.

If monolithic slabs were designed to avoid shrinkage restraints, and better concrete placing and curing practices were encouraged among small builders, the production of crack-free monolithic slabs would be routine.

References

Figures, 1, 2, 3 after Troxell G.E. and Davis H.E., "Concrete", McGraw-Hill, 1956.

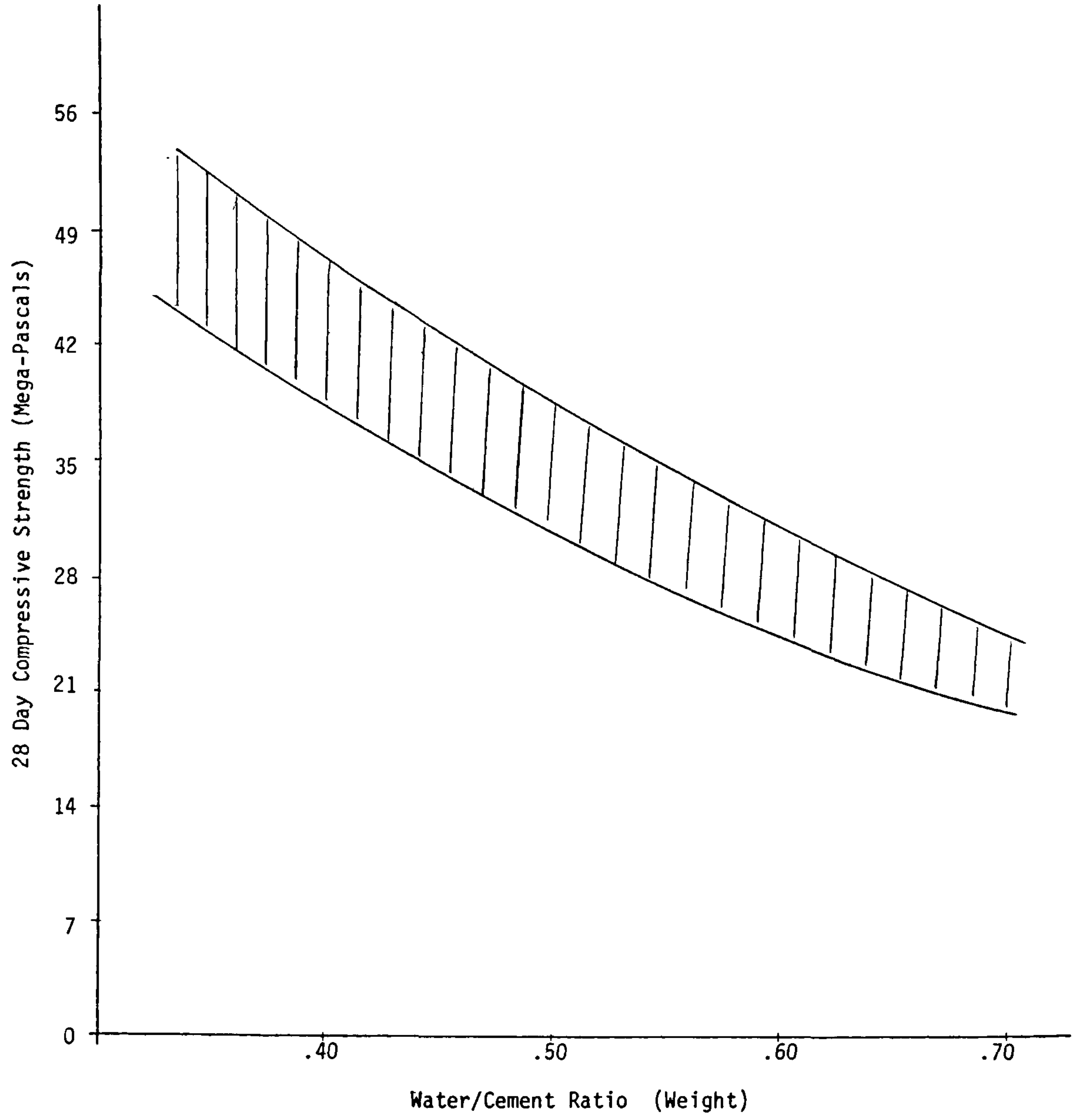


FIGURE 1 VARIATION OF CONCRETE STRENGTH WITH WATER/CEMENT RATIO

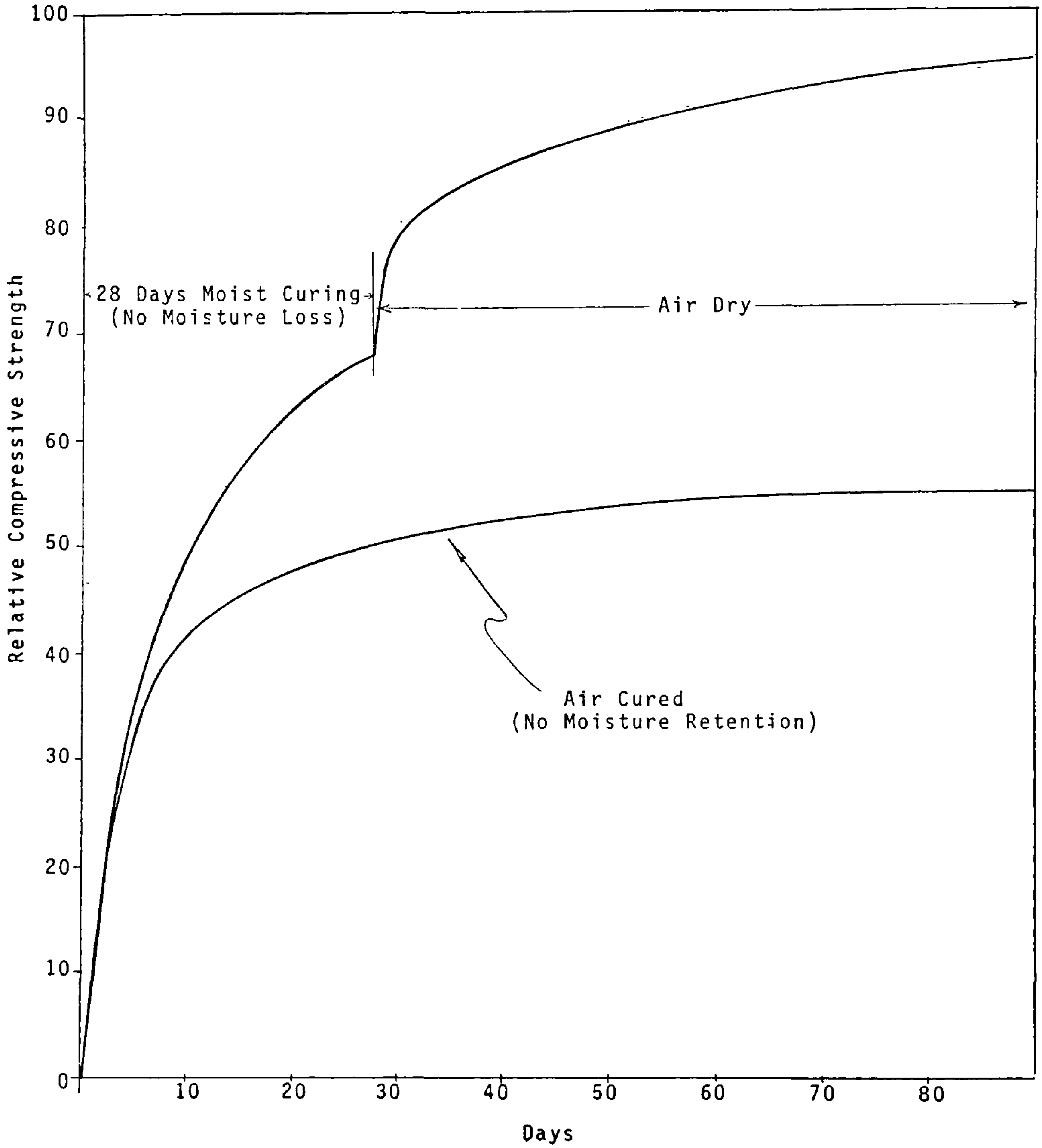


FIGURE 2 INCREASE OF CONCRETE STRENGTH WITH TIME AND CURING

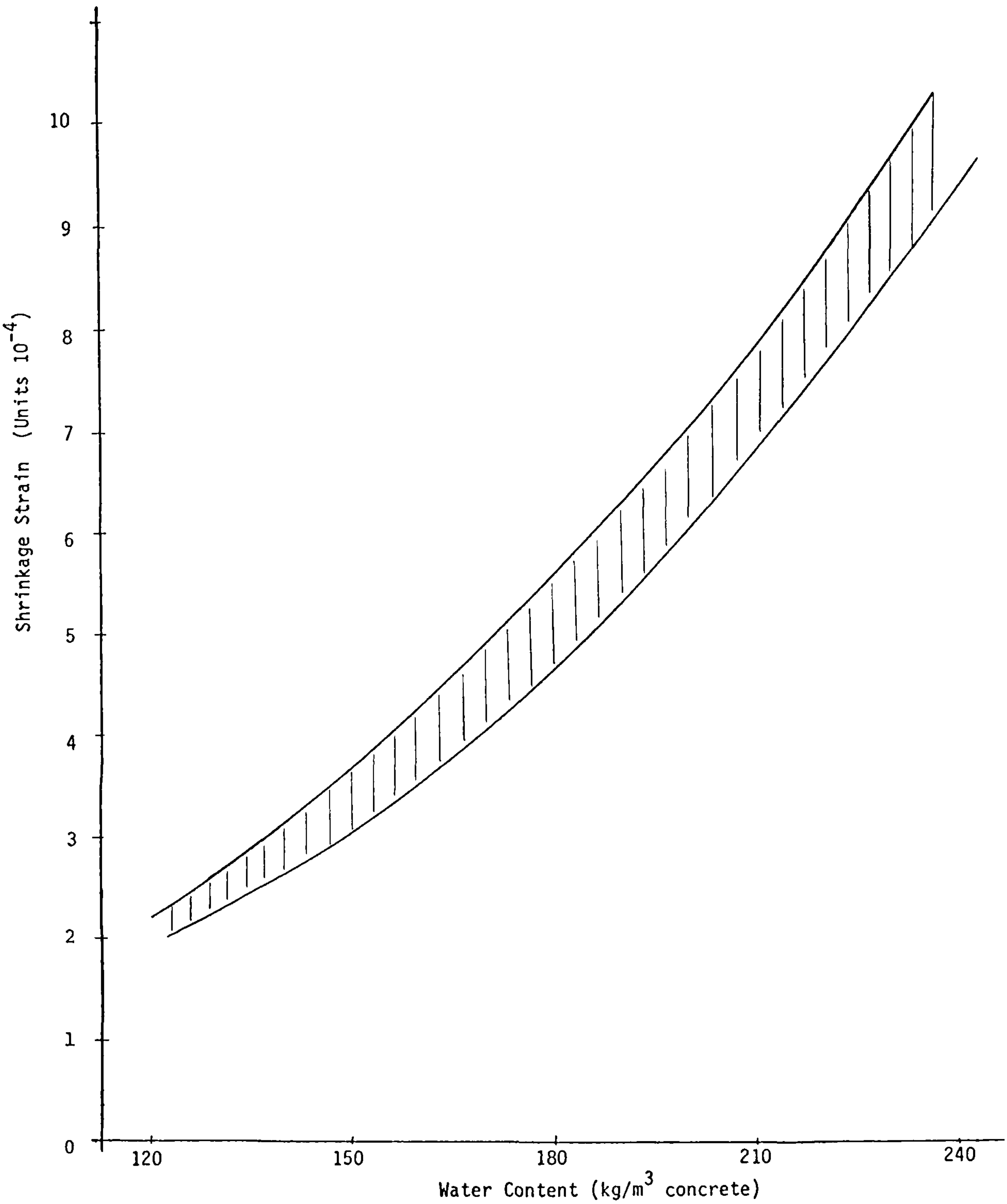


FIGURE 3 VARIATION OF CONCRETE DRYING SHRINKAGE WITH WATER CONTENT

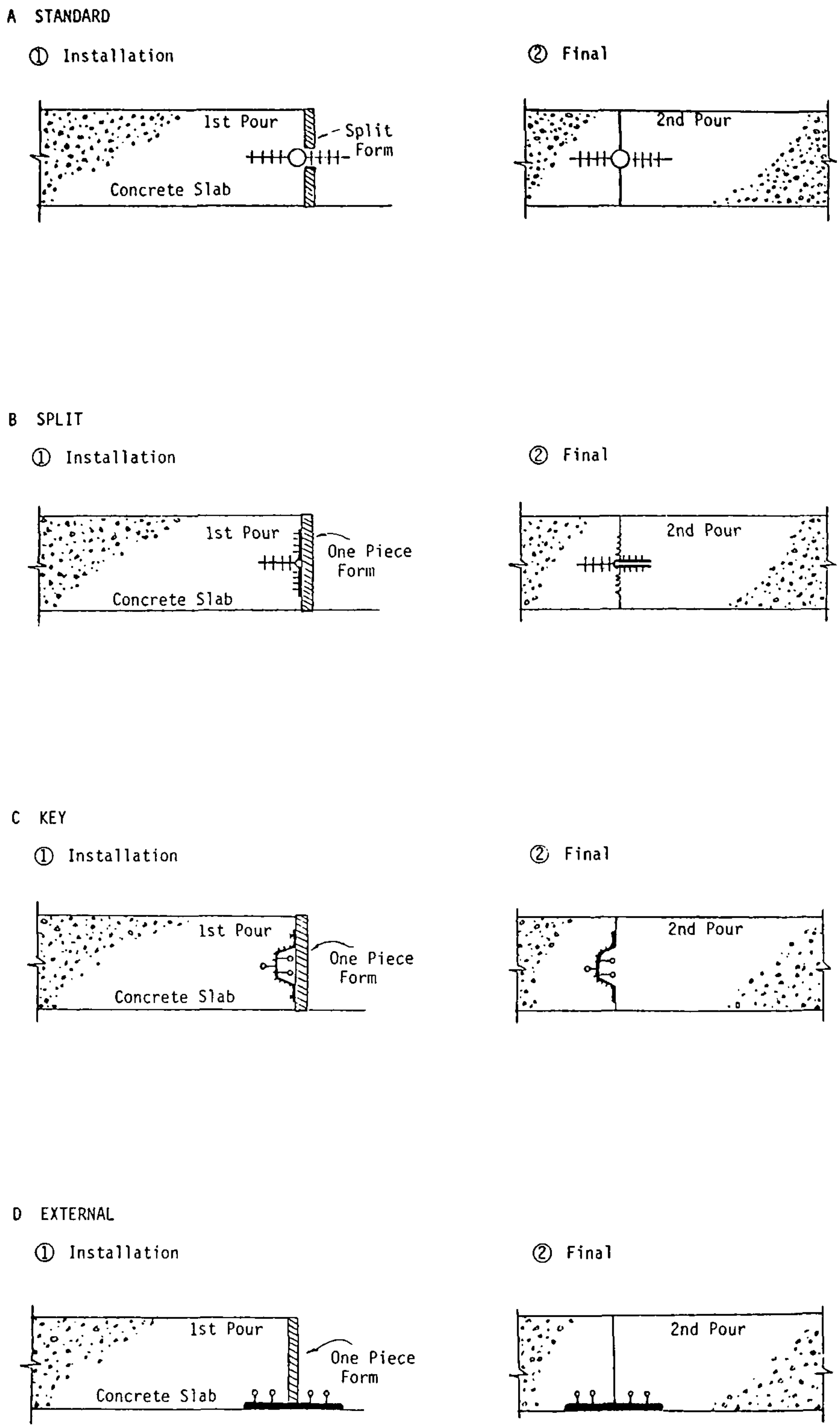


FIGURE 4 WATER STOPS

SECTION V

A SOIL STRUCTURE SURVEY
IN
POLK COUNTY, FLORIDA

Report No. 1168/1216

1.0 INTRODUCTION

This report is to document the results of part of a program to demonstrate means of controlling indoor radon levels in structures built on Florida phosphate lands. The work is being carried out by AMERICAN ATCON INC. with the support of Acres American Incorporated.

The radon arises from the presence of naturally ocurring uranium and its radioactive decay product radium in the soil of the area, which results in significant radon concentrations in the soil gas. When the building construction provides pathways between the interior of the building and the soil, this radon-bearing soil gas enters the building, producing elevated indoor radon levels.

This report describes the geological factors that produced soils with differing uranium and radium concentrations in this area, and examines the soil grain size distribution of each type of soil. All soils were found to be very porous, with relatively low resistance to the movement of soil gas through them. As a result, soils of equal radium content have similar potential to produce elevated radon levels in buildings.

2.0 THE PROBLEM

The average radon supply rate into a building from the soil is limited by the radon production rate of the soil near the building, which can be estimated from the following information. The water table in Polk County lies within 2 to 3 metres of the surface, and the movement of radon through soil passages filled with water is so slow, that virtually none of the radon produced in the soil beneath the water table can escape into the soil gas above the water table. As a result, only the soil above the water table is effective in producing radon that can enter a house. Lands reclaimed from phosphate mining have bulk densities of about 1.4, and contain around 1 pCi/g of emanating radium (1), so a vertical column of 1 m^2 cross section extending from the soil surface to the water table would contain 4.2×10^6g of soil, with a radon production rate of 3.2×10^4 pCi/h. Accordingly, if all the radon produced in the soil beneath a house entered the house, the resulting average concentration would be about 25 pCi/L. Some houses on reclaimed lands have radon concentrations averaging 10 pCi/L or 50 mWL (2), so a large fraction of the radon produced near these houses is transferred to the house.

Attempts have been made to correlate soil radioactivity with house radon levels by the EPA, the University of Florida, and the State of Florida. The parameters measured were respectively surface exposure rate; total soil radium both near the surface and at depth by laboratory high resolution gamma spectroscopy; and total soil radium by spectroscopy plus surface radon flux by the charcoal accumulation method. None of these studies demonstrated a strong correlation between the parameters and the house radon level. While radon was supposed to enter buildings at a rate determined by its diffusion through soil and foundations, this lack of correlation was surprising, and could only be explained by the high spatial variability of radium concentration in reclaimed soils making it difficult to estimate an average concentration from a few measurements.

With the realisation that radon could also enter a building as a component of a mass flow of the soil gas, alternative explanations were available. These were that houses varied in the ease with which soil gas could enter, and that soils of similar radium content differed in the ease with which soil gas could flow through them. The ease of soil gas entry into a house is influenced by the type, extent, and area of the connections from the interior of the house to the soil, and has been examined and reported on for both houses under construction (3) and existing housing known to have high radon concentrations (4). The variability was high, and could explain much of the lack of correlation.

The ease of soil gas movement is affected by soil structure, so this study was not directed toward soil radioactivity, which has been extensively examined by many investigators, but rather toward the physical properties of the soil, which have been largely ignored.

3.0 GEOLOGY

Sixty five million years ago, at the start of the Paleocene epoch, the present Florida peninsula was part of a broad limestone plateau, separated from the mainland by the Suwanee Straits. The plateau was generally submerged, and carbonates leading to the deposition of limestone, were produced by the vast numbers of marine organisms which flourished in these warm shallow waters. About 20 million years ago during the early part of the Miocene epoch, the land rose slightly, and the Florida peninsula was rejoined to the mainland. Stream-borne sediments from the north formed deltas over the northern part of the peninsula, and the Gulf shore currents transported sands and clays southward.

These two sedimentary environments (carbonate and clastic) produced the Hawthorne Formation, which underlies the northern three quarters of present day Florida. In its lower layers the formation is composed of limestone mixed with sands, silts, and clays, while the upper layers are more clastic, with multiple lenses of limestones, sands and clay. The total thickness averages 65m. Despite the variability of the depositional environments, grains of calcium fluorophosphate (apatite) are present fairly uniformly throughout the formation. They are thought to have been produced by precipitation from phosphate-rich off-shore marine waters that entered the shallow seas. The same processes also resulted in co-precipitation of uranium, which replaces the calcium in the apatite, and is found in concentrations of up to 400 ppm (140 pCi/g) in the phosphate.

A continued rise in land level finally brought the Hawthorne Formation out of the sea, and the upper surface was weathered and eroded, producing a surface layer of calcareous clays and sands. The weathering also produced large phosphate pebbles by a disolution/redeposition process. In the northern part of Florida, this weathering continued uniterupted for most of the Pliocene epoch, producing what is now called the Alachua formation.

About 20 million years ago, in the early part of the Pliocene epoch, the southern part of the Hawthorne Formation was submerged. Wave action eroded the upper surface of the formation, and reworked the sand, clay, and phosphate sediments that resulted. This mechanical sorting concentrated the heavier phosphate grains preferentially in what is now known as the Bone Valley Formation. This process took place in at least two stages, and the lower part of the formation contains most of the phosphate modules in sandy clay. This is called the 'matrix' by the phosphate miners. The upper part contains much less phosphate, and consists of clayey sands. These sediments cover the Hawthorne Formation to an average depth of 8m over an area of several hundred square kilometres in west central Florida. In the northern part (Polk and Hilsborough Counties) phosphates comprise as much as 30% of the lower formation mass, and in the southern part (Manatee, Hardee, and Desoto Counties) the concentration falls to about 10% by mass.

In the late Pliocene, the land rose again, exposing the upper surface of the Bone Valley formation to weathering. Acidic groundwater percolating through the upper layers reacted with the clay removing silica and bases to transform montmorillonite clay into kaolinite clay. As kaolinite swells much less than montmorillonite when wetted, this increased the permeability of the upper layers, and increased the leaching rate. The final result of this acidic leaching was to remove the clays to produce a layer of white quartz sand at the top of the formation, and transform the phosphate in the upper layer of the formation from calcium phosphate to aluminum phosphate. This weathered layer is called the 'leach zone' by the miners.

About two million years ago, during the Pleistocene epoch, the sea level fell and rose in response to the removal and addition of great amounts of water from the oceans during the ice ages. Parts of Florida were submerged seven times in this period, and clean quartz sands were deposited over much of Central Florida to a average depth of 5 m. Most of the existing surface topography was formed during this epoch. The most recent deposits are still visible as wind blown dunes, silt and sand deposits from tidal flows, and old beach ridges. Since the last inundation, a further 50 cm of fine windblown quartz sands have been deposited on top of the Pleistocene deposits. This section was based mainly on references 5, 6, 7, 8.

4.0 PHOSPHATE MINING

The phosphate deposits of the Bone Valley Formation have been mined to produce chemical fertilizers since the turn of the century, and this has had a major effect on the near-surface soil structure and radioactivity over a large part of western Polk County. The effect produced varies with the technology available at the time of mining. As the phosphate grains are insoluble they have to be treated to produce soluble phosphates for fertilizers. The calcium phosphate can be dissolved by sulphuric acid to produce phosphoric acid, but the aluminium phosphate from the leach zone cannot be treated in the same way. As a result, it has no commercial value, and the leach zone is regarded by the miners as part of the overburden, and is discarded with it.

Until the mid-30's, the only process available to separate phosphate grains from the matrix was screening and washing (1,5). Virtually all the sand grains in the matrix are smaller than 1 mm, but about 30% of the phosphate grains are larger than that. Due to both the small size of mechanical earth moving equipment available then, and the high water table, hydraulic mining was the usual extraction process and mining was confined to those areas when the overburden was thinest. The overburden (including the leach zone) was washed away with high pressure water jets, and the slurry pumped to another part of the mine area for disposal. The matrix was then washed away, and pumped to a screening plant, where the +1 mm phosphate pebble was removed. The reject stream (debris) containing about 60% of the original phosphate mass was disposed of on the mine site, often in the same area as the removed overburden.

In the late 30's, a flotation method was developed to separate those phosphate grains in the 1.0 to 0.1mm range from the sands and clays in the matrix, and so about 65% of the phosphate mass could then be recovered. Larger draglines also became available, and these two factors effectively extended the areas that could be economically worked. The flotation process is applied to the reject stream from the screening plant, and first separates the clays from the quartz sands and the small phosphate grains, and then a second flotation separates the sands from the phosphate grains. The mining operations now produced three reject streams; overburden, sands, and clay. These were originally dumped at the mine site, but mining practice since the late 50's, is to store the clay slimes and sands separately in designed storage and settling areas. (1,9)

The result of these early mining practices was to cover large areas with Bone Valley formation material, thereby reversing 20 million years of geological evolution, and at the same time produce large open pits, filled with water. The older mining areas were close to transport centres, which are now population centres. The reject areas from hydraulic mining tend to be flat, and even if draglines were used, a little work with earthmoving equipment could soon "reclaim" the area by leveling the spoil piles, and landscaping the edges of the flooded mine pits to produce scenic lakes. As a result many of these mining areas have been used for housing, particularly those close to the towns of Lakeland, Mulberry and Bartow.

5.0 RADIOACTIVE CONTENT OF SOILS

The phosphate grains contain up to 400 ppm Uranium, and are the major source of soil radioactivity in the central Florida area. The concentration varies from place to place in the formation, and with the size of the grain, and so the average concentration in the matrix is lower, typically 100 to 200 ppmU. The phosphate concentration in the upper part of the formation is lower, and so average uranium concentrations are about 30 ppm in the leach zone (1). From the point of view of radon production, the important nuclide is Ra 226, and concentrations will be quoted in terms of its activity (pCi/g).

The Pleistocene and recent deposits consist almost entirely of quartz sands, and have very little inherent radioactivity, typically less than 0.3 pCi/g. As these deposits were laid down by wave and wind action, their thickness can vary considerably from location to location. Although they average 3 m, in the flat lands away from the ridges the thickness can be much less, and the Pleistocene deposits can even be absent, or mixed with the upper layers of the Bone Valley Formation (7,8). As a result, the radium content of undisturbed near-surface sands can vary considerably. In low lying areas, the uranium and possibly radium concentrations of near surface soils can be raised considerably by biological concentration in swamp plants.

When mining has taken place, the surface radium content depends greatly on the mining practices of the time. The activity of stripped overburden, which consists of the overlying sands and the leached zone, depends on the relative thickness and activity of these layers and the accuracy of the stripping, and varies from background to 10 pCi/g. Debris lands are generally in the range of 7 to 15 pCi/g. The flotation sands typically contain 5 pCi/g, and the clays 30 pCi/g. (1) As the clays contained large amounts of water, it was usual to mix them with or cover them with sands or overburden in an attempt to stabilise them. This practice, plus remining of some areas as the techology improved, and redistribution of material as part of the reclamation process, makes it very difficult to estimate the average soil radium content at a site from a few measurements. Not only does the radium concentration vary from place to place, but soil cores show that it also varies with depth. The average concentration can be either higher or lower than the surface concentration.

The gamma radiation at 1 metre above soil containing 1 pCi Radium/g is about 2 micro R/h, (10) so it would seem possible to estimate the near surface radium concentration by a gamma survey. The main obstacles to this are that in reclaimed areas the near surface radium concentration varies from place to place, and that in mineralised but undisturbed areas there is a general layer of quartz sands between 10 to 30 cm thick over most of the surface. This layer of inactive sand will shield the underlying material, and reduce the effective sensitivity of the method by at least a factor of 2. As a result, given the general background of 4 to 5 uR/h, and the variability of survey meter readings, it would be difficult to tell the difference between low activity Pleistocene sands and sands containing up to 3 pCi Ra/g. This is shown in Figure 1, where the observed radiation fields are generally less than that expected from the measured soil radium concentrations. (2)

Not all the radon produced in a soil grain escapes to the air. This escape fraction or emanating power has been measured (1) at about 15% for the phosphate material, and at about 10% for the Pleistocene quartz sands.

6.0 SOIL STRUCTURE

To investigate the variation of soil structure over the Polk County area, near-surface soil samples were collected at the locations listed in Table 1. In addition to a sieve analysis to determine the size distribution by mass, the radon production rate (emanating Radium/g) of most samples was measured. The results are summarized in Table 2, and the size distributions shown in Figures 2 to 5.

6.1 Sample Collection

A 400 to 600 g sample was collected by trowel at a depth of 10 to 20 cm beneath the surface and placed in a plastic bag. This provided a sample that had not been affected by biological processes in the surface soil layer, and was below the surface layer of recent windblown sands.

6.2 Emanating Radium Measurement

The sample was dried at 105^{o}C for 24 hours, and then a 350 g aliquot was sealed into a 4.5 litre can and left for 28 days. The radon concentration in the can was then determined by withdrawing an air sample with an evacuated 140 cm^3 scintilation cell. The cell was then counted for 30 minutes. The minimum emanating radium concentration measurable by this method is 0.01 pCi/g. Total radium was not measured, as it is only an indirect measurement of the radon production rate of the soil.

6.3 Sieve Analysis

The entire dried sample was shaken for 15 minutes through #20, 50, 70, 120, 200 U.S. Standard sieves in series. Grains of diameters less than 0.84, 0.297, 0.210, 0.125, 0.074 mm respectively will pass those sieves. The mass retained on each seive was measured on a laboratory beam balance to the nearest 0.1 g, and the cumulative mass/size distribution calculated.

6.4 Discussion

A group of samples was taken at the Pleistocene beach ridges both on and remote from the Bone Valley formation, and their size distribution is shown in Figure 2. The emanating radium content of all these samples was very low. Pleistocene deposits are exploited for building sand, and so a low activity building sand sample of unknown origin is included on Figure 2 for comparison, together with the reported size distribution (5) of Pleistocene sands collected at 2 m depth at a mine site. These samples all have similar dispersions but fall into 3 size groupings. They are the Lakeland Ridge samples plus the Frostproof sample, the other two ridge samples, and the two sand samples. The difference between the first two groups probably results from differences in the ridge building processes in the past. Sands often become coarser with depth, so the generally larger grain sizes of samples 13, 16 are not unexpected.

A group of samples was taken from reclaimed lands, and their size distribution is shown in Figure 3. The emanating radium content of these samples was in the range of 0.5 to 1.2 pCi/g. The samples contain very little fine material, and with the exception of the "overburden" sample, they fall within the size range of the Pleistocene/Recent sands of Figure 2.

A third group of samples, shown in Figure 4, is active sands. Although sands containing phosphate are generally avoided for masonry and concrete work, sand is also used to level building sites and fill the space beneath the floor slab. Sample 14 was taken from beneath the floor slab of a 10 year old house, sample 12 was taken from a 30 cm layer used to level the site for a house under construction, and sample 10 was taken from a sandy debris area in Lakeland. The emanating radium concentrations are in the range 0.2 to 0.5 pCi/g, and size distributions are almost identical, which suggests a common origin. It could be that old sand tailings are being used to level building sites, but the size distribution is also very similar to that of the Pleistocene deposits from the Lakeland Ridge. Small amounts of phosphate (1 to 2 % by mass) are found in the Pleistocene sands near the contact with the Bone Valley Formation, so the size distribution and the low radium concentration are equally compatible with slightly phosphated sands from the Lakeland Ridge or old sand tailings.

Figure 5 compares the extreme size distributions of the samples with that of typical glacial-aluvial gravel and silt deposits found in Northern Canada. The Florida sands are much more uniform in size, and contain only slightly more fine material than the gravel sample. The porosity of soil depends on both compaction and on the size distribution of the soil particles, and the more uniform the size, the greater the porosity. The gravel sample has an in-situ porosity of about 38% open volume. The Florida sands are more uniform in size, so their porosity will be at least that, and in addition, reclaimed lands are less compacted.

7.0 CONCLUSIONS

The variation in soil particle size distribution between undisturbed surface sands of low radioactivity, radioactive sands, and various reclaimed lands is small, and the largest variation is between surface samples from different locations in Polk County. The relatively large mass median soil grain size, and the small mass percentage of fine material in these samples indicates that the porosity of all these soils is high, and that the resistance to soil gas movement will be low. As a result,both undisturbed virgin lands and reclaimed lands of similar average radium content can be expected to have similar potential to produce elevated radon concentrations in buildings. The actual concentration in the building will depend on the ease of soil gas entry, and the pressure differences involved.

The average soil radium concentration from the surface to the water table is known to vary widely in the Pleistocene sands that cover the Bone Valley Formation, and can only be investigated by taking a soil core sample. Rather than attempt to quantify lands as acceptable or unacceptable by an extensive soil radium measurement program, it would be more cost-effective to adopt radon-resistant foundations for structures in this area. Buildings could then be sited whenever desired, rather than only where allowed.

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TABLE I

Soil Samples

Sample Number	Location	Description
1	Lakeland Ridge -15 km N. of Lakeland	Pleistocene or recent
2	Lakeland Ridge -10 km N. of Lakeland	near surface deposits
3	Winterhaven Ridge - Lake Eloise	unmixed
4	Lake Wales Ridge - Near Dundas	with Bone Valley
5	Lake Wales Ridge - Near Frostproof	Formation Material
6	Lakeland Ridge - 5 km South of Lakeland	

		Description
7	Bartow	- sand fill area
8	Lakeland	- debris area (house #6)
9	Lakeland	- reclaimed land -sandy debris
10	Lakeland	- reclaimed land -sand fill
11	Lakeland	- reclaimed land -overburden
12	Lakeland	- Building Sand -Grey (contains phosphate)
13	Lakeland	- Building Sand -White
14	Lakeland	- Building Sand -removed from beneath floor slab (house #21)
15	Lakeland	- Overburden -Saddle Creek Mine (2)
16	Canada	- Glacial Sandy Gravel
17	Canada	- Glacial Silt

TABLE 2

Soil Sample Summary

Sample Number	Emanating Radium pCi/g	Mass Median Diameter micrometres	Geometric Standard Deviation of mass
1	0.03	220	1.7
2	0.04	200	1.7
3	0.01	360	1.5
4	0.05	310	1.5
5	0.03	220	1.5
6	0.03	200	1.6
7	0.50	370	1.7
8	0.65	260	1.9
9	1.23	430	1.9
10	0.3	240	1.5
11	1.0	440	2.2
12	0.21	220	1.8
13	0.01	500	1.7
14	0.52	250	1.7
15	-	560	1.6
16	-	900	2.6
17		27	6.0

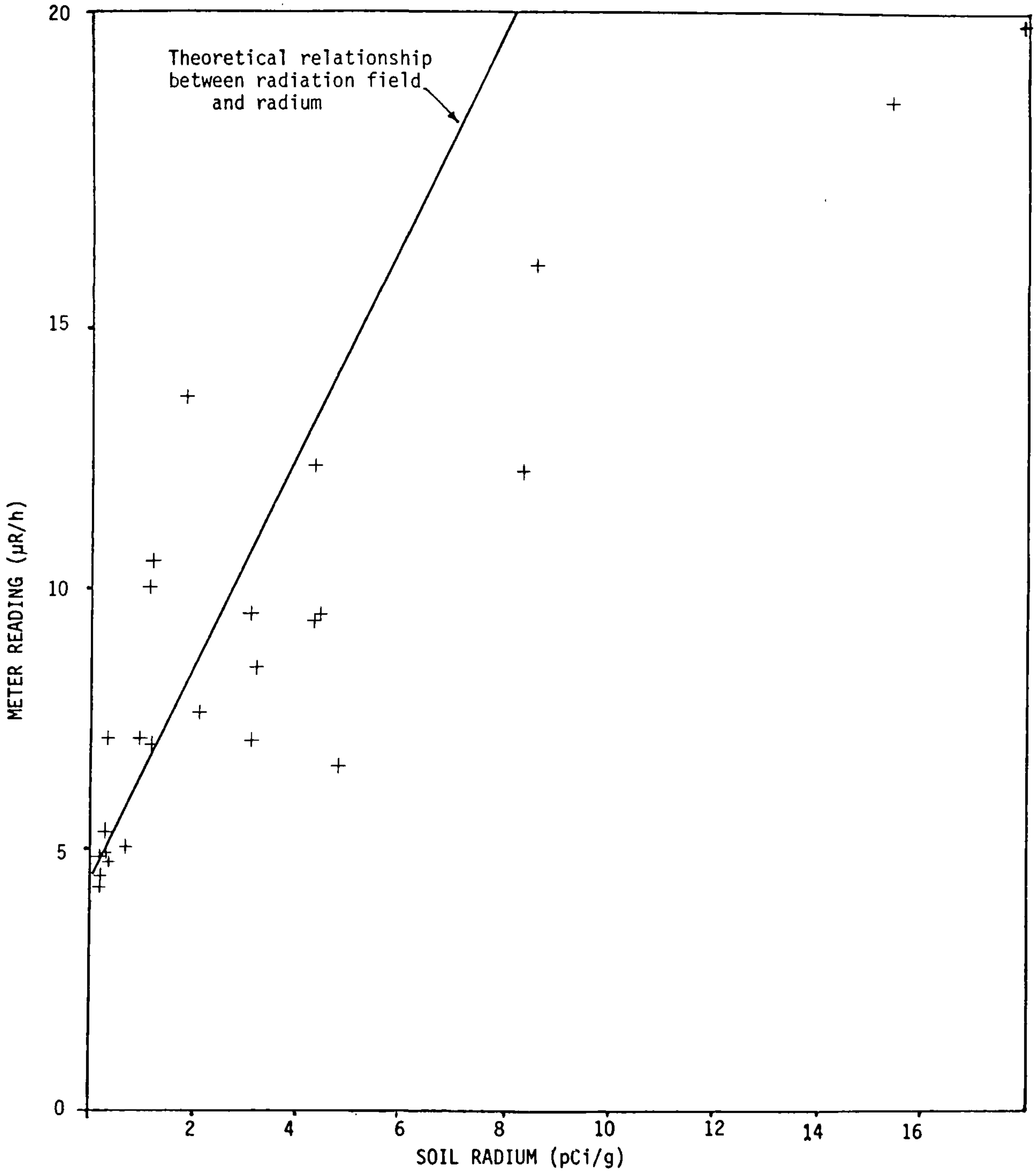

FIGURE 1

OBSERVED VARIATION OF RADIATION FIELD
WITH SOIL RADIUM

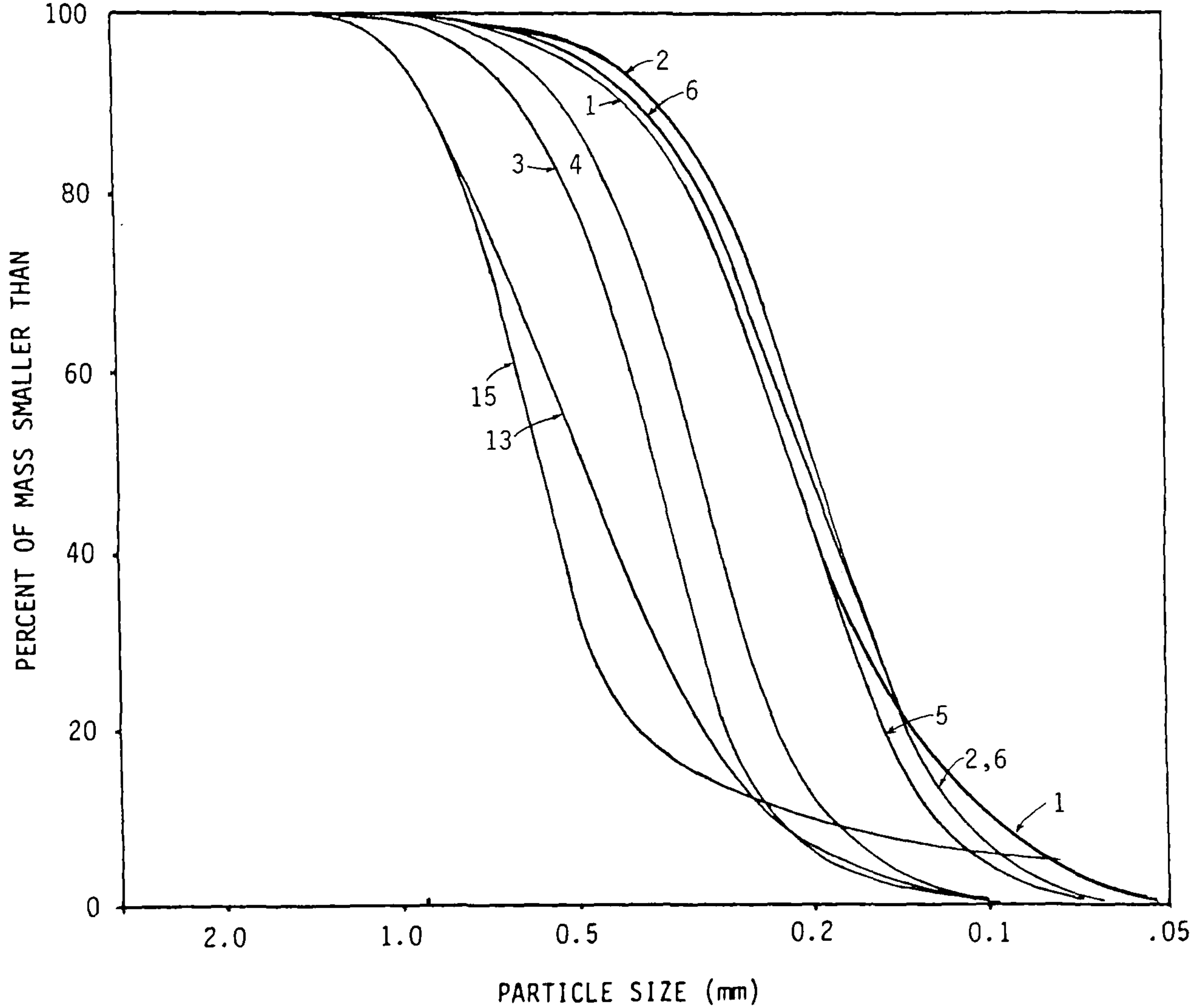

FIGURE 2 SIEVE ANALYSIS
PLEISTOCENE AND RECENT DEPOSITS (SAMPLES 1 TO 6,13,16)

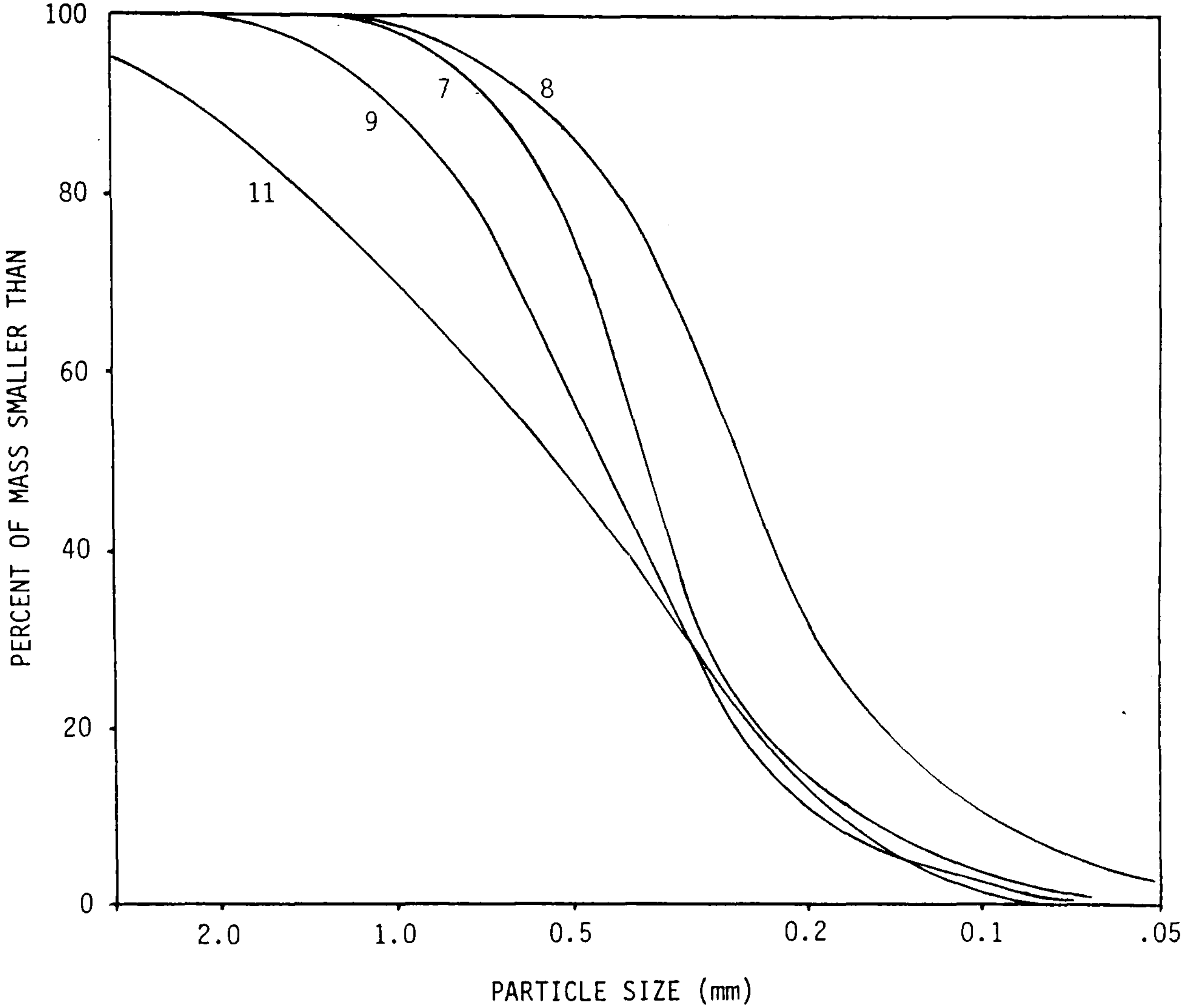

FIGURE 3 SIEVE ANALYSIS
RECLAIMED LAND SAMPLES (SAMPLES 7,8,9,11)

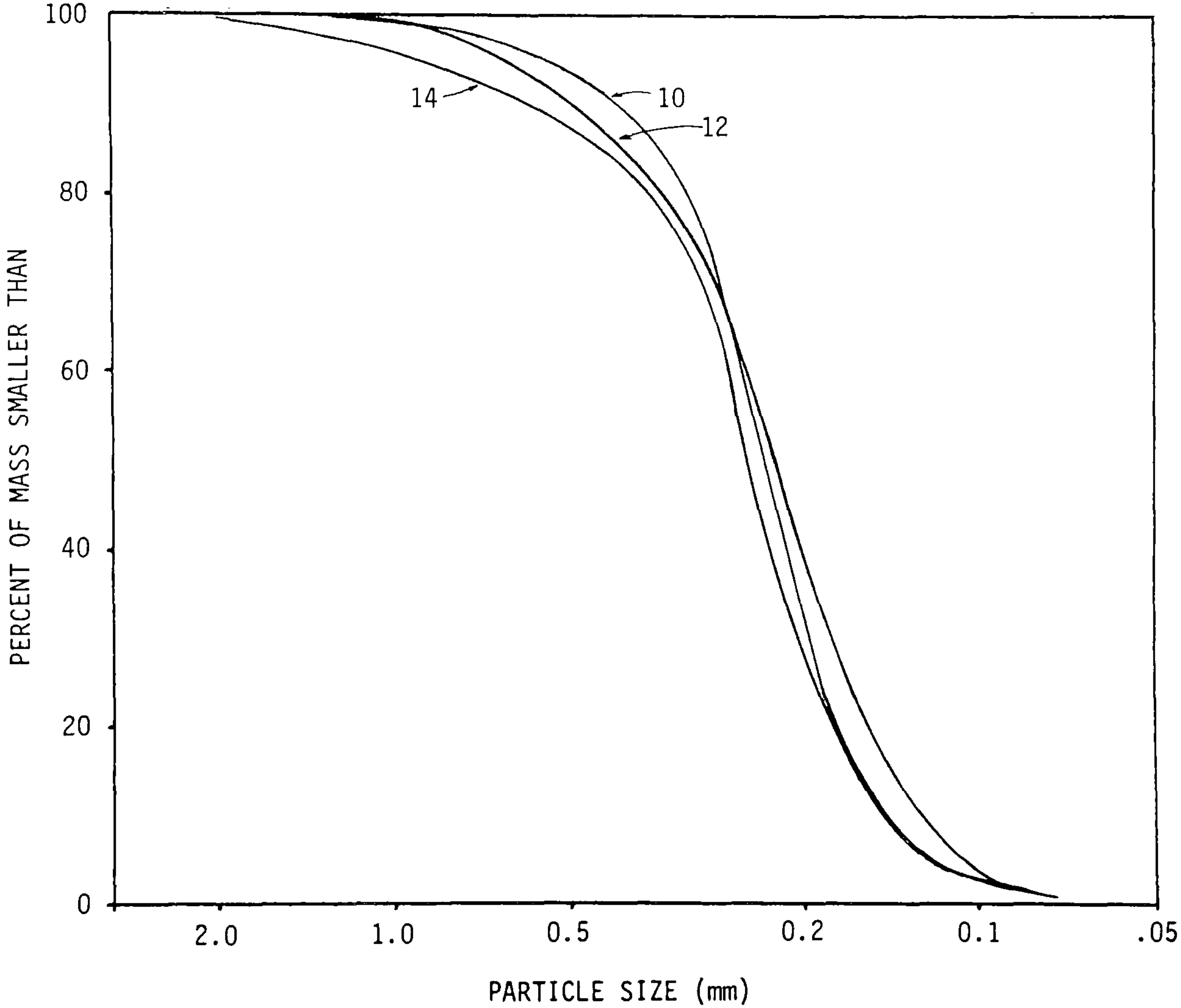

FIGURE 4 SIEVE ANALYSIS

ACTIVE SANDS (SAMPLES 10,12,14)

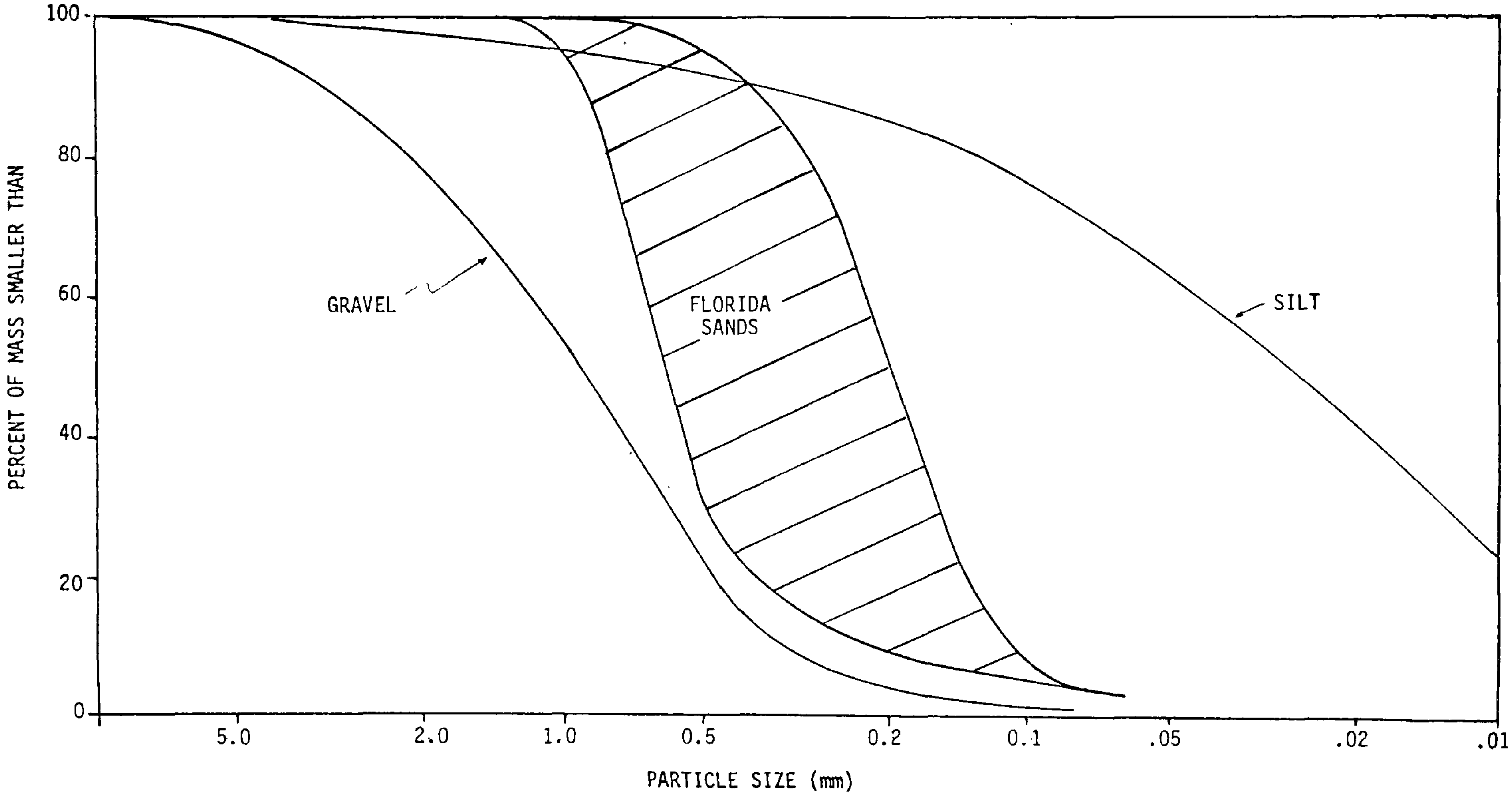

FIGURE 5 SIEVE ANALYSIS
COMPARISON OF GLACIAL DEPOSITS WITH FLORIDA SANDS

SECTION VI

EXPERIMENTAL INVESTIGATION
AND
REMEDIAL ACTION PROGRAM

1.0 INTRODUCTION

This report is to document the results of the experimental investigative and remedial action programs carried out to reduce radon and radon daughter concentrations in structures built on Florida phosphate lands. The work was carried out by AMERICAN ATCON INC. with the support of Acres American Incorporated.

The program was carried out in two parts. The first part was to reduce the entry rate of radon by closing the major foundation openings associated with the plumbing. The second part was to reduce radon daughter concentrations by removing them from the air by filtration.

2.0 REMEDIAL PROGRAM SUMMARY

2.1 Closure of Radon Entry Routes

Most houses built in Central Florida over the past 25 years have been constructed on concrete block foundations with a poured concrete floor slab. Usually the exterior walls are of concrete block, with frame walls used for internal walls and as an architectural feature. A review of current building practices found that large openings were left in house floor-slabs to allow the plumbers to connect the drains from toilets, baths, and showers as described and illustrated in Section 1. The first stage of the remedial program was to close these large openings to the soil. If this was effective in reducing the radon entry rate, then homeowners would be able to carry out remedial work without elaborate investigation, or special equipment. The location of the opening could be deduced from the location of the bathroom fixtures, and access to the openings was expected to require only hand tools and minimal skills.

There are also many openings from the soil into concrete block walls, and many openings from the wall into the house as shown in Section 1. As these openings are virtually inaccessible, a secondary study was carried out in the same houses to determine if radon entered concrete block foundation walls to any significant extent. This provided a guide to the general feasibility of preventing radon entry in houses with concrete block foundations.

2.2 Removal of Radon Daughters

If it is not economically feasible to prevent the entry of radon into an existing house, then the only other possible remedial action is to remove the radon daughters from the air by filtration. Electrostatic air cleaners (EAC) have been found to be effective in laboratory experiments, but field experience was lacking. Accordingly, if closing routes of entry was ineffective in reducing radon concentrations in these houses, an EAC would be installed for evaluation.

2.3 Program Results

Experimental remedial work was carried out in 11 houses. Major openings in the floor slab associated with the plumbing were sealed, and significant reductions in radon concentration were achieved in 8 houses. The conclusion was that although sealing of plumbing openings could produce significant reductions, it was not an universal remedial measure, and that other remedial measures such as electronic air cleaners should be investigated. Electrostatic air cleaners were installed in 5 of the houses where radon concentrations remained high, and reduced the WL close to, or below, 15 mWL when in operation.

3.0 SELECTION OF HOUSES FOR REMEDIAL WORK

Houses were selected on the basis of cooperative studies carried out in the area by the United States Environmental Protection Agency (EPA) in 1975-1977 and the Florida Department of Health and Rehabilitative Services (DHRS) in 1977-1978.

3.1 EPA Study (Gu 79)

3.1.1 Survey Procedure

The primary measurement system used in this study was the Integrating Radon Daughter Sampler (IRDS). The intention was to estimate the average WL in about 200 structures located mainly on reclaimed lands by sampling with an IRDS four to six times per year for approximately one week each time. It was difficult to achieve this standard in many structures. Although the IRDS were usually placed in unused rooms, some occupants still objected to the noise of the silenced air pump and refused further sampling. In other locations, environmental particulates, particularly those from smoking, rapidly clogged the filter, automatically stopping the unit before one week of sampling was completed. The units do not re-start after a power interruption, so brief power failures caused by thunderstorms made it difficult to obtain long duration samples in some seasons. As a result, data collected at a structure was regarded as valid only if at least three samples were obtained, totalling more than 125 hours, and no sample of less than 24 hours' duration was included.

A pilot study was also carried out with bare track-etch[1] detectors in about 160 structures. The detectors were usually placed in unused rooms, bedrooms, or closets, and exposed for a complete year. At that time the track-etch system was not well-developed so an empirical calibration factor from track density to average WL was obtained from regression analysis of measurements with IRDS and track-etch detectors in 23 houses.

3.1.2 Survey Results

Valid IRDS data was obtained from 133 structures, of which 20 were identified as having annual averages greater than 0.03 WL.

Track-etch detectors were recovered from 153 structures, of which 43 were identified as having annual averages greater than, 0.03 WL.

Both surveys together identified 57 different structures with averages greater than 0.03 WL.

3.2 DHRS Study (FI 78)

3.2.1 Survey Procedure

The primary measurement system used in this study was the bare track-etch detector. Detectors were installed in 997 structures in Polk and Hillsborough Counties for a complete year. Additional measurements were made in 176 of those structures with IRDS. Many of the structures measured in the EPA study were included in this study.

The procedure, equipment, problems were similar to those of the EPA study. An empirical calibration factor for the track-etch detectors was obtained from regression analysis of concurrent measurements with IRDS and track-etch detectors.

3.2.2 Track-Etch Calibration

The DHRS calibration procedure differed from that used by the EPA in that the regression analysis did not force zero track density at zero exposure. In addition, most of the houses in the calibration group had low average WLs, so the statistical uncertainty in both the track density and the IRDS measurements was high. As a result, different calibration factors were obtained for different housing types and different soil types, all with large uncertainties. To provide a conservative estimate of the average WL, despite these uncertainties, results were reported as "less than x", where x was the calculated 2 sigma upper limit of WL.

The major effect of this procedure is at lower values of WL, for at higher values the result does not differ greatly from the mean derived using the EPA procedure. In addition, in 12 houses where the IRDS measurement was greater than 0.03 WL, the average difference between the IRDS and the track-etch detector was less than 10%. Accordingly, the "less than" value quoted in the DHRS survey was interpreted as an estimate of the mean WL for values greater than 0.03 WL.

3.2.3 Survey Results

Track-etch detectors were recovered from 905 structures, of which 75 were identified as having the upper limit of WL greater than 0.03 WL - equivalent to annual average greater than 0.03 WL.

Valid IRD measurements were obtained in 134 structures, of which 12 were identified as having annual averages greater than 0.03 WL.

Both surveys together identified 79 different structures with annual averages greater than 0.03 WL.

3.3 Measurement Accuracy

The standard deviation of a series of IRDS measurements in a structure averaged 70%, suggesting that the annual average WL in a structure is measured by an IRDS survey to no better than 35%.

The standard deviation of the difference in track densities between pairs of track-etch detectors exposed together is about 30%, and the detectors were calibrated using IRDS data, so the annual average WL in a structure is measured by those track-etch surveys to no better than 45%.

Given these uncertainties, a survey reading in excess of 0.03 WL is necessary to ensure that average WL in a house is greater than the proposed EPA standard of 0.015 WL.

3.4 Candidate Houses

In cooperation with the EPA and the DHRS, the results of both studies were used to develop a list of houses that were candidates for remedial work. Because of the large uncertainties in the average WL, a candidate house had to have a track-etch estimated average greater than 0.03 WL, be located on reclaimed or mineralized land, and be in an area where there were other houses with elevated averages. A total of 53 houses fulfilled these requirements, located in five areas around Lakeland, two areas in Bartow, and one area in Mulberry.

3.5 Selection Procedure

It had previously been agreed with the EPA that because of the known variability of building techniques, at least 10 structures would be selected to demonstrate remedial techniques. Candidate houses were first given an external visual inspection to eliminate atypical structures, such as those with basements or extensions. This reduced the list to 46 houses. Homeowners were then contacted, highest average houses first, and were invited to participate in a one-year experimental remedial program at no cost to themselves. It was necessary to contact 23 homeowners before the consent of 11 could be obtained. The 11 structures included five houses in four different areas of Lakeland, three houses in two different areas in Bartow, and two houses in one area of Mulberry. The final structure was a house trailer with a crawl space located in the fifth area of Lakeland. All owners were concerned that carrying out remedial work in their houses might affect the saleability of the house if it were generally known, and most of those who participated did so only on the understanding that their names and addresses would not be divulged. Agreements with all the participating homeowners were completed by March, 1981.

4.0 INVESTIGATION

4.1 Gamma Radiation

All these structures were located on lands that had been altered by phospate mining activities in some way, or were believed to have phosphate mineralization beneath the surface. Gamma-ray exposure rate measurements at 3 feet height had been made at these sites by DHRS/EPA, and those measurements are shown in Table 1. At those sites where the exposure rate is not uniform over the site, a range is given.

Measurements were made by American Atcon (AA) at some sites with a portable 5 channel spectrometer[2] to confirm that the predominant activity was from uranium decay chain. The same instrument was used to estimate the exposure rate at 3 feet height at some sites and at other locations in the general area for comparison. These results are also shown in Table 1.

The terrestrial radiation field in areas unaffected by phosphate mining activities is about 5 uR/h. Lands disturbed by phosphate mining typically have radiation fields in excess of 7-9 uR/h. Phosphate rock and mining residues have been used extensively throughout the area as fill material, and many building sands contain some phosphate rock. In some areas of Polk County, sub-economic deposits of phosphatic materials are present at small depths beneath the soil surface.

4.2 Soil Measurements

Measurements were made of the emanating radium content of soil at a few of the sites selected for remedial action and at a number of other places for comparison. The results of these are shown in Table 2. The particle size distribution of these samples was determined by sieve analysis. Measurement methods and discussion are contained in Section V.

Soils and sands containing phosphate residues were found to have emanating radium contents in the range of 0.2 to 1.2 pCi/g emRa, which is 5 to 50 times higher than the typical value of 0.04 pCi/g emRa found outside the phosphate area. There was no significant difference in soil particle size distribution between different areas.

Measurements were made of the radon content of soil gas at a few of the sites selected for remedial action and a number of other places for comparison. A 45cm tube was driven into the soil to a depth between 10 to 30cm dependent on soil conditions, and approximately 500cm^3 of soil gas was withdrawn from the tube by a bulb suction pump through a 125cm^3 scintilation cell, protected by an in-line filter. The results of these measurements are shown in Table 2A.

Radon concentrations in soil gas depend on a number of factors in addition to the emanating radium content of the soil, but concentrations in excess of 1000 pCi/L were measured at depths of 25cm or less over reclaimed lands. The movement of as little as 1 or 2m^3 an hour of this soil gas into a typical house would produce working levels in excess of the proposed EPA standard.

4.3 Visual Inspection

Prior to performing any work, each house was given a visual investigation. As all interior surfaces are finished with gypsum board, wood panelling and floor coverings, it is not usually possible to inspect the building fabric itself without removing the finish. To avoid disturbing the owners, a boroscope with a high power fibre-optic light source was obtained. This could be passed through a 6mm diameter hole, and so could be used to view the interiors of walls by passing it through those openings made in the finish to install electrical outlets and switches, or water pipes.

A summary investigation report on each house is given in Appendix I.

4.4 Pre-remedial Measurements

The investigation program started in late March 1981, when temperatures were not high enough to require the use of air-conditioning, and the houses were cooled by keeping the windows open. As a result, radon concentrations in house air were usually so low as to be undetectable and so measurements were not made routinely.

5.0 REMEDIAL WORK

5.1 Choice of Sealant

The intent of the remedial work program was to find and seal the accessible routes of soil gas entry associated with the plumbing. Local builders have used asphalt roofing cement (a 50/50 mixture of asphalt and solvents) as a sealant against the entry of insects through floor slab openings for many years. The solvent slowly evaporates, leaving a hard, durable layer of asphalt that adheres well to concrete. Laboratory tests showed that the asphalt would flow readily through a 12mm diameter pipe (especially if warmed slightly), adhered well even to unprepared concrete surfaces, and took many months to harden fully. These desirable properties, plus local availability and low cost, made asphalt the sealant of choice for this project.

5.2 Openings to be Sealed

The openings through the floor slab present in most houses are a pit beneath the bath about 20 x 40cm to allow the bath drain to be connected to the sewer systems; and annular spaces about 3 to 5cm wide around the sewer pipe to each toilet and the shower drain pipe to allow sealing flanges to be attached.

A description of the work carried out in each house is given in Appendix I.

5.2.1 Bath Drain Pits

Access to the bath-drain pit is usually possible from an adjacent room by cutting through an internal wall. Some houses have a removable inspection panel for this area, but not any of the houses in our sample. The internal walls are usually wood frame covered by 16mm gypsum board, and so a hole can easily be cut with a small saw. In general, access was easy, but in some cases, an access opening had to be cut in the plywood back of a kitchen or bathroom cabinet before an opening could be cut in the dividing wall.

In one house the adjacent wall was tiled, as part of a shower stall. Rather than attempt to cut through and repair the tiled wall, access to the bath-drain pit was gained through a hole made in the adjacent external wall by removing two concrete blocks. A mason was required to remove and replace the blocks.

As the bath is not installed until the roof is on the house, it is not surprising that many of the pits contained building debris-broken pieces of block, mortar, bits of wood, etc. which had to be removed before the pit could be filled with sealant. In one case, the pit had the appearance of an afterthought - the slab had apparently been broken with a hammer in that area to make the pit, and most of the concrete fragments had been piled back into the pit. A number of pits had been filled with sand alone to within an inch or so of the floor level, and only two pits had a continuous layer of asphalt over the sand to form a barrier against the entry of insects.

It had been hoped that it would be possible to fill the bath-drain pits with asphalt by simply drilling an 18mm hole through a wall, and pouring asphalt into the pit through a flexible tube. The procedure would be monitored with the boroscope, inserted through a second hole. The holes could be drilled just above floor level, and subsequently concealed by the skirting board.

Although this procedure was feasible, and was tested in the laboratory and in the field at one house, the amount of debris usually present in the pit made it impracticable. A large access hole was required to remove debris, and it was then much faster to ladle sealant into the pit through that opening, than to drain it through a tube. Experience with the boroscope found that the limited angles of view available when it was inserted through a single hole made it difficult to reliably detect the presence of debris, particularly at the far side of the pit, whereas debris was easily detected by direct observation through a large access hole.

Sealing the pit beneath the bath would be well within the skills and tools of most homeowners. A small sabre saw can easily cut an opening through cabinet plywood or wallboard, a domestic vacuum cleaner would be adequate to remove debris and sand, and asphalt can be used to fill the pit using waxed paper cups as bailers. The opening can either be repaired by the owner, or by a professional plasterer for about $70.00.

5.2.2 Toilet Connections

Access to the opening around the sewer pipe leading to each toilet is obtained by simply unbolting the toilet and lifting it away. This exposes the sealing flange and gasket. The original intention was to fill the opening by removing the gasket from the flange and then running sealant into the opening through the bolt holes in the flange. However, this was not possible as the spacing material (paper or cardboard) used to keep the concrete away from the pipe was often left in place, with parts of the material closing the bolt holes. Even where the holes were open, the sealant drained down the many voids in the material, preventing the formation of a seal. For these reasons, it was usually necessary to remove the spacing material to produce a gap between the sewer pipe and the concrete floor that could be sealed. To do this, the flange had to be removed so that the material could be pulled out. In many cases, the hole through the slab was smaller at the top than at the bottom, and the material had to be cut into small pieces before it could be removed.

Fortunately, the plumbing in these houses was cast iron with leaded joints, so the flange could be removed from the pipe and a new flange fitted after the spacing material was removed. To do this with modern plastic plumbing, which has solvent welded joints, would have required cutting off the flange and part of the pipe with a special internal expanding tube cutter. Fitting a new flange would have required a solvent welded extension to compensate for the length of pipe cut off.

Although it would be quite simple for a homowner to lift a toilet, it would not be practicable for him to pick out the spacing material without removing the flange. The skills and tools needed to remove and replace the flange for both cast iron and plastic piping put the task beyond the usual scope of homeowner projects. The assistance of a plumber would therefore be required to remove and replace the flange at a cost of about $100 per toilet.

5.2.3 Shower Connections

The opening around the drain pipe to a shower is virtually inaccessible without major work. The floor of a shower stall is constructed inside a heavy plastic liner which is attached to the shower enclosure walls and clamped to the shower drain head. The interior of this liner is covered with cement to act as a base, and then the shower walls and floor are tiled. As the liner is not sealed to the floor, soil gas can move from the pipe opening through small gaps between the concrete floor and the shower liner.

The proposed remedial method was to drill through the shower drain pipe from the inside, inject sealant into the annular space through the drill holes, and subsequently close the holes by solvent welding a sleeve inside a plastic pipe, or epoxying a sleeve inside a metal pipe. This was tested in the laboratory, and found practicable, but it would only work reliably if there was no spacing material around the pipe. The discovery that spacing material was generally left in place around the sewer pipes suggested that this procedure would be impracticable. The probability of successfully sealing the shower drain opening by any means short of removing the shower unit entirely was felt so low that this work was not attempted in the program.

6.0 POST-REMEDIAL MEASUREMENTS

6.1 General

As mentioned earlier, most of the sealing ws performed in the early spring of 1981, while temperatures were low enough for people to cool their houses by opening windows rather than running the house air conditioning system. As a result radon levels were low, and post-remedial measurements were therefore delayed until early summer, when the air conditioning systems were in operation.

6.2 Spot Measurements

A limited number of spot radon and radon daughter measurements were made in the houses to check the effectiveness of the remedial work and to determine an average value for the equilibrium ratio of WL to radon. Radon concentrations were measured with Eberline[3] 500cm^3 scintillation cells and counting equipment. Radon daughters were collected on 25mm glassfibre filters at a flow rate of 33 litres/minute and counted with an Eberline scintillation probe. Individual daughter concentrations, or RaA and WL were estimated by the MRK method (Sc81).

The equilibrium ratio of WL to radon varied from house to house, depending on the operation of the house air conditioning system, but the average ratio was 0.44.

6.3 Integrating Measurements

The original intention had been to carry out post remedial measurements with both IRDS and track-etch detectors for comparability with the pre-remedial measurements. Accordingly, IRDS were installed in the first two houses where work was carried out. The owners turned the units off at night to reduce the noise, and this, plus power interruptions caused by lightning storms prevented the units from running for more than a few hours at a time. The owners of the third house did not want an IRDS. The use of IRDS for post-remedial measurements was regarded as impractical, and was abandoned after the first month.

The track-etch system had been extensively developed since the original EPA survey, and it had been found that the response of bare detectors was more a function of radon concentration than of WL. A more reliable estimate of radon concentration was now available from Track-Etch[4] detectors mounted in diffusion cups. Accordingly, to obtain post-remedial radon concentrations averaged over several months, a Track-Etch radon detector cup was placed in each home after completion of remedial work or after the start of the air conditioning season, and removed in August, near the end of the season. Windows were generally closed during this period, so the values represent near maxima. Detectors were generally located in unused rooms or in master bedrooms. As the air in the house is circulated through the air conditioning system several times per hour, the radon concentration is uniform from room to room, and so the choice of detector location is not of major importance. Owners had no objection to these detectors.

6.4 Measurement Accuracy

The average radon concentration over the exposure period was calculated by Terradex. Their reported estimate of the standard deviation of the concentration was about 15%.

6.5 Estimated Annual Average WL

The pre-remedial measurements were expressed in WL, and based on measurements over a complete year. The post-remedial measurements were expressed in radon concentration, and based on measurements over the summer. To compare the pre and post-remedial measurements the post-remedial annual average WL was estimated in the following manner.

The EPA study (Gu78) had found that average WL's in the winter half of the year were similar to those in the summer half, so it was assumed that average radon concentrations were the same in the house whenever the windows were closed in either the heating or cooling season. House windows were estimated to be open and radon concentrations zero in the spring and fall - about 40% of the year. This gives an estimated annual average radon concentration of 60% of the summer average radon concentration. The estimated annual average WL was calculated from this on the basis of the average equilibrium factor of 0.44 measured previously.

In view of the variation in average radon concentration and hence average WL that could be produced by manipulation of ventilation conditions by the owner, and the uncertainties in the pre-remedial measurements, more detailed conversion factors did not appear justified.

The average radon concentration over a year is dependent on the weather and the living habits of the occupants, mainly how willing they are to ventilate rather than run the air conditioning. As the cost of electricity to run the air conditioning has increased considerably since 1977, most house occupants in the area have increased their use of natural ventilation. As radon concentrations are low when the windows are open, the annual average radon concentration in most houses is probably lower now than in 1977.

Table 3 shows for each house the pre-remedial estimates of annual average WL, based on the track-etch film detector exposed in the house for 1 year, plus IRDS measurements where available, the post-remedial radon concentration averaged over the summer estimated from a Track-Etch radon cup detector, and the post-remedial annual average WL estimated from that radon concentration.

6.6 Results

The estimated post-remedial annual average WL was decreased to less than 25% of the pre-remedial average and to less than the proposed EPA standard of 15 mWL in houses #2, 5, 10, 14, 15. In houses #11, 12, 21 the post-remedial average WL was decreased to 50% of the pre-remedial average. No significant reduction was observed at houses #6, 7, 9. The occupants of house 10 kept their windows open virtually all summer, which they did not do in 1978, and only minor remedial work was done there, so it is likely that changes in living habits alone are responsible for the reduction at that house. Changes in living habits in the other houses were much less marked, and so the reduction in WL is attributed to the remedial work.

Table 3 summarises the measurements and the work performed.

6.7 Effect of House Ventilation Systems on Radon and Radon Daughter Concentrations

6.7.1 Radon Concentration

A series of measurements made in one house during the EPA survey found that operation of the house heating and air conditioning (HAC) system reduced both radon and radon daughter concentrations (Wi78). The cause of the reduction in radon concentration was not determined at that time. When the HAC installation in houses under construction was examined as part of this program, it was found that the air distribution ducts in the attic often had large gaps at their joints and seams. The ducts are wrapped in fibrous insulation, which conceals these openings, but will not significantly reduce the leakage. Construction standards for the industry (Sm76) expect system leakage with good workmanship to be less than 5% of the operating air flow, but local air conditioning contractors size the system on the basis of 10% duct leakage. In typical houses, this amounts to a forced ventilation rate in the range of 50 to 100 cfm (80 to 170m^3/h). The ventilation rate with the air conditioning system running normally (fan on auto) was measured in 5 of the program houses and was less tha $0.3h^{-1}$ in 2 houses, and between 0.5 to $1.0h^{-1}$ in the other 3 houses. The higher ventilation rates indicate major leakage from the air distribution ducts.

The significance of this leakage is twofold. The ventilation rate is increased, but as the air which leaks out of the ducts is outside the house pressure boundary of walls and ceiling, the pressure in the house must be lower than outside. The lower pressure will not only draw air into the house, but will also draw soil gas into the house through soil connections. The final radon level in the house will depend on the ratios of the increased ventilation rates and the radon supply rates. Generally the ventilation rate increases more than the radon supply, but this is not inevitable. At one house, continuous operation of the system fan increased the ventilation rate from $0.15h^{-1}$ to $0.63h^{-1}$, but the radon concentration did not change over a period of several hours. The radon supply rate had increased by a factor of four.

6.7.2 Radon Daughter Concentrations

Low equilibrium ratios between radon and WL of less than 0.2 were observed in two houses where both air conditioning and floor fans were in use. These ratios are much lower than the "normal" value of about 0.4, and can only be explained by the presence of major removal mechanisms other than ventilation. The effect of air circulation on the equilibrium ratio was investigated in a joint study with the EPA. Operation of the HAC fan continuously gave ratios in the region of 0.2, and operation of a floor fan lowered the ratio to around 0.1 to 0.15. In southern houses at the height of the cooling season the HAC fan runs nearly continuously, and floor and ceiling fans are common, so ratios in the region of 0.2 or lower can be expected.

7.0 RADON CONCENTRATIONS IN WALLS

7.1 Measurements

Spot samples of air from hollow concrete-block walls found some radon concentrations in excess of the radon concentration in the house air, and air was observed moving out of wall openings into the house. To verify that radon concentrations in walls were generally elevated with respect to the building, bare track-etch detectors were inserted into the wall cavities through the openings made to accommodate the electrical outlet boxes and switches. The detector strips were attached to strips of stiff card and inserted into the middle of the cavities, more than an alpha particle range from the wall, so that radioactivity in the blocks would not produce tracks on the detector. A number of detectors were inserted into wood frame walls to act as controls.

Each wall of a house has the cavities of the top course of blocks and the vertical corner cavities filled with reinforced concrete as part of the hurricane reinforcement. As a result, there are no connections from the cavities in one wall to the other, so if soil gas leaks into a wall through openings in the block foundation, the radon concentration can be expected to be higher in that wall.

Detection strips were inserted into the walls in April 1981. One group was removed in June, and the remainder removed in August at the same time as the radon cups were collected. The reported average radon concentrations are shown in each house in Appendix I. Although the exposure conditions are different from those for which the strips were calibrated, the reported radon concentrations in frame walls are similar to those in the house, suggesting that the errors are not large.

7.2 Results

As expected, concentrations varied from wall to wall. Many walls had average concentrations in excess of 20 pCi/L, with a number in excess of 50 pCi/L. Leakage rates into a house of a few m^3/h of this wall air are possible, and could give radon daughter concentrations close to the EPA suggested standard of 15 mWL. This suggests that remedial work to meet that standard by excluding soil gas from the building may not be practicable in houses with concrete block foundations and walls unless the foundations are sealed also.

7.3 Sealing Concrete Block Foundations

Experience at other remedial action projects is that sealing hollow concrete block foundation walls is difficult and expensive. If the block cavities are empty, it is possible to drill holes into them and pour in a fluid cement grout, but cracks in the mortar between blocks can still provide entry paths for soil gas around the grout. In addition, to ensure a seal, the grout would have to extend to near or above the upper edge of the concrete floor slab. As grout flows through any large crack in the blocks or the mortar, and weeps water through small cracks and pores in the blocks, there is high probability that if the grout is accidentally taken above the floor level, the interior fininsh will be damaged.

In many houses the block cavities have been filled with sand to the underside of the floor, and in these cases the only possibility of sealing the foundation is to pour sealant into the wall cavities above the floor. Unless the interior wall-board was removed from the lower portion of the wall so a barrier membrane could be applied to the inner face of the block wall, sealant would leak out of the wall and damage both wall and floor finish. The cost of removal of the interior finish, the barrier membrane, and replacement and redecoration of the finish must be added to the cost of placing sealant in the walls. The total costs would be very high.

8.0 SEALANT PROGRAM EVALUATION

8.1 Program Aims

The aims of the program were to:

a) develop simple methods of closing the major openings in house floor slabs.

b) determine the costs of those methods

c) evaluate the effectiveness of the remedial measures.

8.2 Remedial Methods and Costs

8.2.1 Bath Drain Pits

In most houses access to the space beneath the bath is best gained by cutting through a plaster-board wall from an adjacent room. A hole about 25 x 50cm gives ample room to remove debris from the drain pit, and to bail in enough asphalt to fill the pit to a depth of several cm. The piece of plaster-board is then replaced, and the sawcut repaired. The cost of this action ranges from a few dollars if the homeowner does all the work himself to about $100 if a tradesmen is used to carry out the repair and refinishing.

8.2.2 Toilet Connections

Access to the space around the toilet connection is gained by unbolting the toilet and moving it off the flange. In most cases it is necessary to remove the flange from the drain pipe, so that the material used to keep the concrete away from the drain pipe can be removed, leaving a recess into which the sealant can be poured. Removal and replacement of the flange requires specialized tools and skills, so this is not a task that can be carried out by most homeowners. The cost for a plumber to carry out these tasks is in the range of $100 to $200 per toilet. A number of cast iron fittings are no longer in production, so they must be removed intact for re-use, producing costs at the upper end of the range.

8.2.3 Shower Connections

As shower drain connections are cemented over and then tiled, access to the space around the drain and removal of any packing material is not possible without major work. Estimated costs were as high as $1,000 for tradesmen to break out the shower floor, remove the packing material, replace the drain, and retile the shower. This work was not attempted as the homeowners would not agree to such a major disruption.

8.3 Sealing Program Effectiveness

Although the major openings in the floor slab of a typical house (bath-drain pit, toilets) can be sealed against the entry of soil gas for a cost of less than $500, alternate major routes of radon entry in many houses, reduces the overall effectiveness of this measure. Significant reductions in radon levels were produced in only 6 of 10 houses where sealing was carried out.

8.4 Evaluation of Alternate Routes of Radon Entry

The large reduction in the WL produced in some houses suggested that sealing plumbing openings could be a worthwhile remedial action if it were possible to identify in advance those houses without alternate major courses of entry. Accordingly, houses #6, #7, #9, #12 where the remedial work had least effect received additional investigation to determine if they were detectably different from the other houses.

House #7 was atypical with HAC return air duct beneath the floor, changes in floor level, and the floor poured inside the walls. These potential entry routes had not been sealed, and were inaccessible without major work, so it was not surprising that partial sealing was ineffective in this house.

The other three houses #6, #9, #12, did not differ in construction techniques from other houses in the area where sealing was apparently effective. The foundation construction was standard with the floor slab partially entering the hollow concrete block walls. There were direct soil connections into the walls of #6, #12, as shown by the presence of insects, but average radon levels in the walls were no higher than in other houses where sealing appeared to be successful. There was a crack in the "L" shaped floor slab of #6, but the rectangular floor slabs of #9, #12 are believed to be crack-free. The floors in all these houses are covered with permanently installed vinyl sheet or carpet, so only limited areas could be inspected without major work to remove and replace the covering.

8.5 Summary

Even with the benefit of the experience gained in carrying out this program, plus the use of investigation tools not available to the general public, it was not possible to identify house construction features to indicate when simple sealing would be successful. The high radon concentrations found in many walls suggest that the hollow concrete block foundations are major radon entry routes, and as a result, it is not certain that an expenditure of a few hundred dollars on sealing the plumbing openings will be successful in excluding soil gas and radon.

9.0 CRAWL SPACE VENTILATION EVALUATION

9.1 General

The DHRS study (F178) found that the average WL in mobile homes was less than half of that of slab-on-grade houses in the same area. As all mobile homes are placed over crawl spaces, this indicates that crawl spaces are effective in isolating structures from the soil. The effectiveness depends on the crawl space ventilation rate.

9.2 Remedial Methods and Costs

Increasing the crawl-space ventilation area is an effective remedial measure for those structures with crawl spaces, as shown by the fourfold reduction in WL produced at house #2 by increasing the ventilation area to about 2% of the wall area.

Crawl spaces require ventilation to prevent the growth of molds and fungus. The Building Code (SB79) specifies vents equal to about 4% of the total wall area, with openings on at least two sides to provide cross ventilation, so adequately vented crawl spaces should be an effective barrier to radon entry. The cost of enlarging ventilation openings would be only a few dollars in the case where the owner of a prebuilt home makes openings in the aluminium skirting around the crawl space, to at most a few hundred dollars if a mason was required to make new openings in an existing concrete block foundation.

9.3 Summary

Improving crawl-space ventilation is cheap, and effective, and so it is an attractive remedial measure in those cases where it can be applied (older housing and pre-built or mobile homes).

10.0 ELECTRONIC AIR CLEANER PROGRAM

10.1 Introduction

Electronic Air Cleaners (EAC) have been suggested as a remedial measure in the past (Fi76). In those cases where it is not possible to prevent the entry of radon, filtration of the air will reduce the daughter concentrations, and hence the WL. Large reductions in WL have been produced in laboratory conditions (Rn81), but field experience is lacking concerning their effectiveness. Accordingly, EAC's were installed in houses #6, #9, #12 as a remedial measure after sealing had been found to be ineffective. In addition, the occupants of houses #7, #11 agreed to participate in a similar joint program with EPA/DHRS, and EACs were installed in those houses.

10.2 Installation

EACs are available in two mounting packages. The simplest is an insert which fits into the air return duct, and replaces the standard fibreglass filter. As the unit is 20cm thick, it can be fitted into ceiling grilles, but not into wall grilles where the duct runs in the thickness of the wall, and is usually only 15cm deep. As it comes in a limited range of sizes, there are some ducts that cannot be fitted with this unit. For these cases, an in-line unit can be placed in the return air duct. A skilled workman is needed to cut and join the duct to fit the in-line unit, whereas any handy-man can install the insert unit with a few sheet metal screws.

The high voltage used in the EAC will produce ozone if the air movement through the unit stops. To prevent this, the manufacturer requires that the EAC be interlocked with the HAC blower so that power is only supplied when the fan is running. This is usually done either by wiring the unit in parallel with a 110V blower motor, or using a sail switch in the return air duct to control 110V to the EAC if a 220V blower motor is used.

The cost of an EAC and installation is about $750 in the Lakeland area.

Although the general standard of mechanical installation was high, difficulties were experienced with the electrical hook-up. One installer omitted the airflow interlock and this was not discovered until the occupants complained of symptoms similar to those produced by ozone. Interlocks were installed. Another installer obtained 110V from a 2 phase 220V motor by connecting the EAC between one phase and ground (not neutral). This is contrary to good practice, as any interruption in the ground circuit will put 110V on all grounded equipment. They also left wire bare in the HAC control and junction box so that a 24V thermostat wire was in contact with a 220V line. When the owner turned on air conditioning the thermostat and transformer were destroyed. These faults were rectified by the contractor, who then obtained the 110V supply for the EAC from the garage-ceiling light, so the EAC could only operate when the light was on. This was corrected.

10.3 Performance Measurements

As the EAC removes radon daughters from the air but does not affect the radon concentration, the performance of an EAC is most simply discussed in terms of the change in equilibrium fraction (100WL/Rn) produced by its operation.

It had been observed that air circulation alone, eg. by a floor fan, could lead to low values of equilibrium fraction. To separate the effect of circulation from filtration, radon, radon daughters, and WL were measured at each house under 3 standard sets of conditions. These were "baseline" where doors and windows had been closed for several hours and the HAC system had not been operated for at least two hours; "fan-on" - where the HAC system blower had operated continuously for some time but without power to the EAC or the heating or cooling coils; and "EAC on" - where the HAC blower had operated continuously for some time with power to the EAC, but not to the heating or cooling coils. Some additional measurements were made with the cooling coils in operation. Steady state conditions were not reached in some experiments due to variations in radon concentration. The steady state values are shown for each house in Table 4.

10.4 Results

The average steady state equilibrium fractions were "baseline" 0.59, "fan on" 0.29 and "EAC on" 0.07, showing that continuous air circulation alone would reduce WL by a factor of two. In practice, people operate their HAC systems on "auto", where the blower operates only when the system is heating or cooling, so the circulation or filtration rate depends on the exterior temperature and the setting of the interior thermostat. The equilibrium fraction in a typical house therefore lies between that for "baseline" and that for continuous circulation.

Estimated values of the average equilibrium fraction under summer conditions are 0.44 for the system on auto, and 0.15 for the system on auto with EAC. Addition of an EAC to the system can therefore be expected to reduce WLs by a factor between 3 to 4 compared with those obtained with normal operation of the system. Allowing for the portion of the year that windows are open, houses with average summer radon concentrations less than about 18 pCi/L, if fitted with an EAC will have average annual WLs less than the proposed EPA standard of 15 mWL. The EAC installations effectively brought our houses below this limit except at #9, where the average radon concentration was 30 pCi/L. Table 3 shows the calculated annual average WL in these houses on the basis that the average equilibrium fraction is reduced to 0.15.

If the blower motors were altered to give 2 speed operation on auto rather than on/off operation, the average equilibrium fraction would be lowered to nearer the steady state values found above, for filtration would not stop completely when the HAC system was neither cooling nor heating. An EAC would then give a reduction factor of about 5, and house #9 would then be close to 15 mWL annual average. Many HAC blower motors are actually 2 or 3 speed motors, but for control simplicity are wired for only on/off operation at one speed or occasionally two speeds. A lower speed is sometimes used for the heating cycle so that warmer air is discharged. In these cases the cost of multiple speed operation would be only the cost of additional control wiring ($100), rather than controls and a motor installation ($350).

10.5 Costs

As simply running the HAC system blower continuously will nearly halve the average WL in a house for only the cost of electricity to drive the blower, this would be a low cost remedial measure. If a larger reduction is required, an EAC could be installed in the system for an expenditure of about $700. With continuous blower operation, the average WL would then be reduced to about one-fifth of its previous value. As indoor radon concentrations are only significant when the windows are closed, which is when the HAC system is in operation, the use of an EAC with continuous blower operation would be sufficient to reduce the annual average WL in almost all houses to below 15 mWL.

10.6 Radon Daughter Ratios

Operation of the EAC's selectively removes the longer lived radon daughters. Typical ratios of radon to RaA, RaB, RaC in houses without AECs are 1:0.9:0.75:0.5, but operation of an EAC markedly reduces RaB and RaC concentrations, giving ratios of 1:0.6:0.06:0.03. As the WL depends mainly on the RaB and RaC concentrations, large reductions in WL are produced, despite the small change in RaA concentration.

11.0 OTHER REMEDIAL MEASURES

Although filtration reduces the concentration of radon daughters, the most positive remedial measures are those that reduce the radon concentration. This can be achieved by (a) increasing the resistance to soil gas movement from the soil to the house; (b) reducing the pressure differential between the house and the soil; (c) reducing the radon concentration of soil gas adjacent to the house; or (d) increasing the ventilation rate of the house. Only the first of these is a passive measure, the other three each require a continued energy input. This program attempted only passive methods of excluding radon, for no long-term arrangements could be made with the homeowners.

Two systems that have been effective at other remedial projects are house ventilation/pressurization and soil ventilation. The first is truly site-independent, but has the highest running costs, since the supplied air must be conditioned. Soil ventilation requires the installation of perforated pipes in the soil around and beneath a building, which are then connected to an exhaust fan. The reduced pressure in the pipes causes air to flow from the building to the soil, reducing the soil gas supply rate and the radon concentration in the soil gas adjacent to the building. The running costs are low, but the installation costs can be high. Since the system is affected by soil conditions and house designs, it is not site-independent.

As active remedial measures may be more effective than the passive measures examined for existing housing in Florida, they should be investigated further. The extensive work involved with installation of either active system makes it unlikely that individual homeowners would cooperate unless special arrangements were made.

12. FINAL CONCLUSIONS

Radon concentrations in many Florida houses can be reduced by sealing only the major openings in the floor slab against the entry of soil gas. The effectiveness of this limited sealing is reduced by concealed and inaccessible openings in concrete block foundations, which would be very expensive to close. It is only in new housing, where the number of openings can be controlled and openings can be sealed during construction, that sealing can be expected to be fully effective.

Soil gas and radon can be diverted cheaply from structures with crawl spaces by increasing the ventilator area, and providing cross-ventilation in the crawl space.

The WL in all structures can be decreased without reducing radon concentrations by increased air circulation or the use of electronic air cleaners.

Active measures to reduce radon concentration in houses were not attempted in this study because of their long term costs. As they may be the only site independent remedial measures in existing houses, further work should be carried out to discover their ability to reduce radon concentrations, and their associated costs in Florida housing.

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TABLE I
TERRESTRIAL EXPOSURE RATES IN CENTRAL FLORIDA

	Exposure Rate (uR/h)			
	DHRS/EPA measurements		AA measurements	
House #	External	Internal	External	Internal
2	24	22	37 (max)	-
5	7-12	7	11	7
6	10-13	9	18	13
7	11	8	13	-
9	38	20	43	19
10	28	17		-
11	9	9	-	-
12	11-19	10	-	
14	9-12	7		
15	8-12	9	9	7
21	7	7	-	-

Other Locations (measured by AA)	Exposure Rate (uR/h)
Bartow	
Sand tailings area (W)	12
Spoil pile at tailings area	20
Orange grove (NE)	8
Concrete sidewalk	8
Flower bed	35
Agricultural soil (E)	6
Highlands Area	
House site in orange grove	4
S.E. Lakeland Area	
White building sand	4
Grey building sand	18
Agricultural soil	5
Building site (reclaimed land)	21
Building sand on site	13
Building site	29
Orange grove	9
Mineralised area	21
Undeveloped building lot	5
Lake Parker area	27
S.W. Lakeland Area	
Reclaimed land Building sites	20
Phosphate rock on unpaved road	83
Concrete floor in office building	9
Concrete apartment building	11
Tampa	
Tampa Airport Concrete	5
Soil	5

TABLE 2

COMPARISON MEASUREMENTS

Emanating Radium Content of Various Soils/Sands

Sample description		pCi/g emanating Radium
Garden soil house #6		0.65
Sand fill beneath house #21		0.52
Sand tailings area West of Bartow		0.5
Overburden-mineralised area		1.0
Reclaimed land-building sites		1.2
House site soil-Highlands area		0.03
White building sand	<	0.02
Grey building sand		0.21
Crushed lime		0.15
Soil samples from the		
Haines City-Dundee		0.03
-Waverly-Lake Wales area		0.04
(outside the phosphate	<	0.02
zone.)		0.05
		0.03

TABLE 2A
COMPARISON MEASUREMENTS

Radon content of near-surface soil gas

Sample area	Comment (depth)	pCi/L Radon
House #6	garden (25cm)	1500
House #7	sample taken in ant hill (30cm)	1000
House #11	clay settling area, very hard to penetrate (15cm)	100
House #15	garden (20cm)	250
Orange grove NE of Bartow	wet, sandy, soil (25cm)	2300
Christina Recreation Area	reclaimed land (20cm)	1000
Reclaimed land building sites	very hard soil (15cm)	300
Office building lawn	wet organic soil (15cm)	250
Sand pile	loosely compacted (30cm)	80
Compacted sand cover	reclaimed area (30cm)	400
Building sand pile	on reclaimed area (30cm)	200
Spoil pile	clays and sand at sand tailings area	2000

TABLE 3

PRE-REMEDIAL AND POST-REMEDIAL RESULTS

House #	Pre-Remedial Annual Average (mWL)		Remedial Work March-June 1981	Post-Remedial		
	Track etch	IRDS		Average Radon (pCi/L) June-August, 1981 pCi/L	Estimated Annual Average (mWL)	Estimated Annual Average (mWL) with EAC
2	35	--	Ventilated Crawl Space	3.1	8	--
5	48	--	Sealed Bath & Toilet Openings	1.8	5	--
6	65	--	"	16.9	45	15
7	98	55,51	"	18.3	48	16
9	--	105,142	"	30.1	79	27
10	62	60	Sealed Toilet Openings	4.1	11	--
11	42	--	Sealed Bath & Toilet Openings	6.9	18	6
12	58	--	"	11.9	31	11
14	29	35,38	"	3.2	8	--
15	46	--	"	2.7	7	--
21	30	--	"	6.1	16	--

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TABLE 4

EFFECT OF HAC SYSTEM BLOWER AND ELECTRONIC AIR CLEANER ON EQUILIBRIUM FRACTION

House #	Equilibrium Fraction		
	No circulation	Fan on continuously	EAC on continuously
6	0.55	0.28	0.08
7	0.38	0.10	0.05
9	0.65	0.21	0.08
11	0.82	0.32	0.07
12	-	0.12	0.06

APPENDIX I

HOUSE SUMMARY REPORTS

HOUSE #2 SUMMARY REPORT

External gamma	24 uR/h (37 max)
Internal gamma	22 uR/h
Equivalent surface radium concentration	6 to 10 pCi/g
Estimated annual average (HRS survey)	35 mWL
Summer average Radon concentration (Track Etch cup)	3.1 pCi/L
Estimated post-remedial annual average	8 mWL

Investigation

This building is a "double wide" pre-built home located on reclaimed land east of Lakeland. It consists of two separate structures bolted together side by side along the centre line, and raised about 60 cm off the ground. The crawl space beneath the building is concealed by matching siding carried down to ground level. The joint between the two halves of the structure is not airtight, and services pass through openings in the floor. These entry routes allow crawl space air containing elevated radon concentrations to enter the trailers.

Remedial Work

The owner of the house had improved the ventilation in the crawl space prior to this program by removing parts of the skirting on one side of the building to build an elevated patio. An opening of $1 m^2$ was left in the skirting, which would increase the ventilation rate, and reduce the radon concentration. Although the estimated WL has fallen to 8 mWL, the summer average of 3.1 pCi/L radon is still surprisingly high for a building that is out of contact with the ground. More effective ventilation (cross ventilation) in the crawl space would be required to reduce the levels still further.

Measurements

An IRD unit was placed in this house in April 1981, but a satisfactory period of continuous running was not achieved. Finally the unit could not be restarted and was removed. No results were obtained. Although the unit was placed in a storage room, the owners commented on the noise it made.

HOUSE #5 SUMMARY REPORT

External gamma	7-12 uR/h
Internal gamma	7 uR/h
Equivalent surface radium	2.4 pCi/g
Estimated annual average (HRS survey)	48 mWL
Summer average Radon concentration (Track Etch cup)	1.8 pCi/L
Estimated post remedial annual average	5 mWL

Investigation

This house is about 15 years old and is located on reclaimed land in the south east of Lakeland. The plan is generally rectangular with an attached garage. The foundation is concrete block, with painted concrete block walls. Two exterior wall sections are wood framed as an architectural feature. The floors are covered with carpet over terrazo. A crack was visible in the bathroom floor. In addition, the exterior walls were extensively cracked, and the joints between the ceiling plaster board had opened up in several places.

A possible cause of this cracking is that the ground along the centre line of the house has settled less than at the edges. In some mining areas reclamation consisted of filling in the spaces between the mining windrows, and so the compaction of the ground can vary rapidly from place to place. If this house were built on the edge of a windrow, it could cause sufficient differential settlement to cause the structural damage observed. On the other hand, the roof is of asbestos-cement roman tiles, and their weight may have caused movement in the rafters supporting the ceilings, so it is by no means certain that the floor and ceiling cracks are related.

Boroscope examinations of the exterior walls suggested that the floor slab was poured up to the foundation wall, for there was no indication of the floor slab extending into the foundation wall cavities. The boroscope also showed that the kitchen and bathroom water pipes were of galvanized iron, and concrete was poured against them to form a good joint. The sink and shower in the master bedroom were supplied by pipes which ran from beneath the slab into the wall cavities, ran vertically to the fixture, and then left the wall through a hole in the inner face of the hollow block wall. The bath drain access pit was filled with asphalt. A small crack extended from the pit to the outside wall. Spot radon measurements were made at this time but the general level was less than 1 pCi/L as the owner kept the windows open. Efflux measurements on the floor crack showed that radon was leaving the crack but very slowly. Radon levels in the walls were also low.

Remedial Work

An opening was cut through the rear of a kitchen cabinet and through the wall to give access to the space beneath the bath. The asphalt filling had excellent adhesion to the concrete, and there was no sign of cracking. This indicated that there was every prospect that asphalt would be a satisfactory sealant in both the short and long term. To ensure that the rear of the pit was completely sealed, an additional layer of asphalt was poured into the pit, filling it level with the top of the concrete slab.

A local plumber provided labour to raise the two toilets. The plumbing consisted of cast iron pipe with a cast iron flange sealed to the pipe with poured lead. The paper that had been packed around the pipe to keep the concrete away was still in place. The cast iron flange was broken off, the packing removed, and the terrazzo topping at the edge of the hole cut back slightly to enable asphalt to be poured around the pipe after a new flange was attached. The first opening required about 2 litres of asphalt to fill it, suggesting that the asphalt drained into a sub-slab void. To prevent this, the bottom of the second hole was filled with molten lead. This worked well, as less than 0.5 litres of asphalt was required. The toilets were replaced without incident.

Comment

This house is occupied by a retired single man who played golf every morning, and was often out of the house during the rest of the day. If the weather was not too hot he would leave windows open rather than run the air-conditioning in his absence. It is possible that the average radon concentration would be higher with a different occupant.

An IRD unit was placed in this house in May 1981 while the occupant was away on holiday, leaving the house shut up, but a satisfactory period of continuous running was not achieved. No results were obtained.

Measurements

Date	Location	Results: Radon(pCi/L)	RaA(pCi/L)	mWL
81 03 25	Kitchen (windows open)	1.7		
	Sidewall cavity	1.7		
	Beneath bath	0.7		
81 04 01	Bedroom #1(windows open)	0.0		
	Bedroom #2(windows open)	0.9		
	Bedroom #3(windows open)	1.1		
81 04 02	Floor crack bagged overnight	56		
81 04 10	Living room(windows open)	0.0		
	Bathroom	0.0		
81 04 15	Living room (A/C off but house closed)	3.6	2.0	15
	Garage wall cavity	4.2		

Ventilation period variable 0.63 to 1.6 h

Track Etch

Average radon in house	1.8
In walls	
Front	20
Side	10
Rear	37
Garage	28
Bay windows (Frame wall)	1

HOUSE #6 SUMMARY REPORT

External gamma	10 - 13 uR/h
Internal gamma	9 uR/h
Equivalent surface radium	4.5 pCi/g
Estimated annual average (HRS Survey)	65 mWL
Summer Average Radon concentration (Track Etch cup)	16.9 pCi/L
Estimated post remedial annual average	45 mWL

Investigation

This house is about 7 years old and is located on reclaimed land to the south-west of Lakeland. The plan is 'L' shaped, with an attached garage. The foundation is concrete block, with concrete block walls. The front wall is stuccoed with Quik-brick, the other walls are painted. The floors are completely covered with carpet and sheet vinyl flooring. A crack in the floor slab was observed in the garage laundry area, and ran beneath the kitchen flooring in the direction expected for a shrinkage tension crack at the narrowest part of the slab. There were no other visible cracks.

Boroscope examination of the exterior walls suggested that the floor slab was poured across the top of the foundation wall, generally closing the foundation cavities. The area beneath the bath was examined via holes drilled in an adjacent closet wall. The bath drain access pit was found to be open, with the sub-slab leveling sand visible at the bottom. The water pipes in this area were of galvanized iron, and passed through the floor slab with the concrete poured right against them. The kitchen and master bedroom plumbing is run through the wall cavities and so was not examined. Spot radon measurements were made at this time, but house windows were open, and radon concentrations were low, including the wall cavities.

Remedial Work

A local plumber provided labour to fit and replace the toilets in both bathrooms. The toilet connection was cast iron with a 4" flange on a 4" line. The flange was removed, the opening around the pipe cleaned, and concrete chipped out to allow sealant to be poured in. A new flange was placed and asphalt poured in.

In the bathroom attached to the main bedroom, there were two cracks in the floor slab radiating from the waste pipe opening, and there was a large void in the sub-slab fill adjacent to the waste pipe. The void was filled with sand, and the accessible portions of the cracks filled with the soft wax used for the toilet seal. The asphalt was then poured into the opening around the waste pipe.

There were no cracks in the concrete in the main bathroom, but there was a void in the sub-slab fill. This was smaller than the other, and was filled with sand before the sealant was poured.

As the sand in the bath pit was well below the top of the concrete, and appeared level through the boroscope, it was decided to fill the pit remotely as a trial of a minimum disturbance remedial technique. Asphalt was drained from an elevated can into the pit via a hose passing through a 2 cm hole in the wall. This was supervised using the boroscope passed through a second hole. Approximately 6 litres of asphalt (2 cans) were needed to cover the sand to a depth of 5 cm or so.

Later in the year the plasterboard wall between the closet and bath was cut away to inspect the results of this technique, as there had been no apparent reduction in WL. Nearly 8 litres of asphalt had been poured into the pit, equivalent to a thickness of 5 cm. Evaporation of the solvent had caused the asphalt layer to decrease in thickness to about 3 cm, as would be expected for a 50% solvent material, leaving a 'high tide' mark on the walls of the pit. The asphalt in this surface layer was still flexible, and adhesion was excellent, even though the concrete had not been prepared. The bulk of the asphalt had a surface skin, but was still a viscous liquid underneath.

Unfortunately, the amount of asphalt poured in it did not fill the pit completely. A line of debris about 5 cm from the rear of the pit rose nearly to the top of the pit, and prevented the asphalt from reaching the rear wall. In addition, in the far rear corner of the pit was a small wad of fibreglass insulation. As asphalt will not readily saturate this material, it would have created a hole through the asphalt layer even if the asphalt had reached the rear wall of the pit. Neither of these obstacles were in the range of vision of the boroscope inserted through the two holes that were drilled.

The fibreglass and debris were removed, and an additional 4 litres of asphalt were poured into the rear of the pit, effectively closing the openings.

The conclusion drawn from this was that the restricted view available through the boroscope when it is inserted through only one or two holes is not sufficient to reliably identify the presence of debris, and that access to the pit area is required to remove debris that would otherwise impede the flow of asphalt.

The radon concentration remained high despite the additional sealing, and so an EAC was installed in the air return in the attic. The initial electrical instalation was unsatisfactory, as the 110V required for the EAC was derived from the 220V circulating fan supply by connecting between one phase and ground (not neutral). The unit was then rewired so that the 110V was derived from the garage ceiling light, and would only operate when the light was on. A constant 110V supply was finally obtained from a wall plug in the garage. Operation of the EAC markedly reduced the WL.

Measurements

		Results		
Date	Location	Radon(pCi/L)	RaA(pCi/L)	mWL
81 03 26	Bedroom (A/C off)	2		
	Beneath Bath	3		
81 05 15	Kitchen (A/C on)	17		
	Dining room wall cavity	33		
81 06 16	Kitchen (A/C on)	11	7.9	34
	Small bedroom	16		
	Beneath Bath	28		

Ventilation Period 1.9 hours

81 09 08	Kitchen (windows open)	5		
	Soil gas (25 cm)	1500		

Measurements - continued

Track Etch		Results
		Radon (pCi/L)
	Average radon in house	16.9
	After additional sealing	20
	In walls	
	Front	0
	Rear bedroom	10
	Kitchen	lost } Paper support
	Rear bedroom	lost } strips eaten
	Dining room	lost } by insects
Soil Sample	Garden soil	0.65 pCi/g emanating Radium

EAC Measurements

	Conditions	Equilibrium Fraction
82 04 08	House closed, no circulation	0.55
	Fan on continuously	0.28
	EAC on continuously	0.08

HOUSE #7 SUMMARY REPORT

External gamma	11 uR/h
Internal gamma	8 uR/h
Equivalent surface radium	2.6 pCi/g
Estimated annual Average (HRS Survey)	98 mWL
Summer Average Radon Concentration (Track Etch cup)	18.3 pCi/L
Estimated post remedial annual average	48 mWL

Investigation

This house is about 12 years old and is located on mining debris land to the east of Bartow. The plan is rectangular with an attached garage. The foundation and walls are of concrete block covered with stucco. The floors are all covered with carpet or vinyl sheet flooring. There are no visible cracks in floors or walls.

Construction drawings of this house were available and showed that the floor slab to be poured inside the walls. This was confirmed by boroscope examination, which found no sign of the floor slab inside the block walls. Boroscope examination via holes drilled in bathroom vanities found that the bath pit was open, with sub-slab leveling sand visible in the bottom, and the water pipes were of galvanized iron, with the concrete poured up to them. The kitchen and laundry plumbing was run through the block walls, and as a result was not examined. The construction drawings also showed that the air return duct to the HAC blower unit ran beneath the floor slab, not through the attic as usual. As the sub-floor duct appeared to be airtight, it was decided to seal only the major openings in the floor slab.

Radon concentrations on one day when the air-conditioning was running were about 10 pCi/L, including a sample from one wall. On a second day when the air-conditioning was off, concentrations were low. A 'wall air' sample also had a low radon concentration that day despite a marked 'soil gas' smell.

Remedial Work

An opening was cut through the rear of a bathroom cabinet and through the wall to give access to the space beneath the bath. A hot water pipe entered the pit at the rear, and sand was piled up around it. At the front of the pit, the sand was about 10 cm below the lower edge of the concrete slab. The piled sand was removed using a vacuum cleaner, and the pit leveled up to the underside of the slab with about 5 litres of sand collected from outside the building. About 8 litres of asphalt were bailed into the pit, covering the sand to a depth of about 5 cm.

A local plumber provided labour to lift the toilets. In the main bathroom the toilet connection was cast iron with a 4" flange on a 4" pipe reducing to a 3" pipe. There was a large opening around the pipe. The flange was removed, the area opened up to receive sealant, the flange replaced, the sealant poured, and the toilet replaced.

In the bathroom off the main bedroom, the toilet connection was a 4" flange tapering to a 3" pipe with an offset. This is a non-standard unit, which could not be replaced. It was therefore left in place, and the top of the large opening around the pipe chipped out so that sealant could be poured into the gap. A hole was drilled through the rear of the flange to provide access to the rear of the opening. Sealant was poured into the opening and the toilet replaced without further problems.

As radon levels were still elevated in this house, an EAC was installed as part of a joint EPA/Polk County Health Department Study. Operation of the EAC markedly reduced the WL.

Measurements

		Results		
Date	Location	Radon(pCi/L)	RaA(pCi/L)	mWL
84 04 03	Bedroom (A/C on)	32		
	Beneath bath (draft out of hole)	12		
	End wall cavity	36		
81 04 04	Bedroom (A/C off, closed)	4		
	Laundry room	4		
	Beneath bath	4		
	End wall cavity	27		
	Bedroom (A/C on, doors open)	0.5		
81 04 14	Bedroom (A/C on)	16		
81 06 18	Bedroom (A/C on)	13	12.2	76
	End Wall Cavity	34		
81 09 09	Kitchen (A/C, ESP on)	30	12.2	18
	Soil Gas	1000		

Measurements - continued

Track Etch

	Results Radon (pCi/L)
Average radon in house	18.3
In walls	
Front	57
End	24
Rear	5
Garage	4

EAC Measurements

	Conditions	Equilibrium Fraction
82 11 03	House closed, no circulation	0.38
	Fan on continuously	0.10
	EAC on continuously	0.05
	EAC and A/C on 'auto'	0.16

HOUSE #9 SUMMARY REPORT

External gamma	38 uR/h
Internal gamma	20 uR/h
Equivalent surface radium	12 pCi/g
Estimated annual average (HRS survey)	100 mWL
Summer Average Radon Concentration (Track Etch cup)	30.1 pCi/L
Estimated post remedial annual average	79 mWL

Investigation

This house is about 12 years old and is located on reclaimed land in a county subdivision to the south of Lakeland. The plan is rectangular, with an attached garage. The foundation is concrete block, with concrete block walls. The front wall is finished with Quik-brick, and the other walls are painted. The floors are covered with carpet or sheet vinyl.

Boroscope examination of the exterior walls suggested that the floor was poured across the top of the foundation wall, generally closing foundation cavities but open block cavities could be seen. The shower backed onto the bath, so the area under the bath was examined via a hole drilled through the mortar joints of an outside wall. There was no asphalt in the pit, and it appeared to contain an uneven layer of gray sand.

Examination of interior walls found the bathroom plumbing to be galvanized iron, with the concrete poured tight to form a good joint. The kitchen and laundry plumbing is run through the block walls, and was not examined.

No radon measurements were made as the windows were open at this time.

Remedial Work

It was not possible to gain access to the pit underneath the bath in the usual way since the bath backed onto the shower of the main bedroom. Two blocks in the exterior walls were removed by a mason to provide access from outside the house. The pit was found to contain pieces of broken block, sand, and construction debris. These were removed and the pit filled by bailing in 10 litres of asphalt, after which the mason replaced the blocks.

A local plumber provided labour to raise the two toilets. There was a large opening, stuffed with paper, around each pipe. The toilet connections were cast iron 4" to 3" tapered flanges, which prevented removal of the paper. These are not a standard item, and it took some time to locate the last two flanges available in the Lakeland area. The old flanges were broken off, the paper removed, and the new flanges installed. The opening was then filled with asphalt, and the toilets replaced without incident.

As sealing did not reduce the radon concentration, an EAC was installed in the air return duct, replacing the filter behind the ceiling grille. The installation was satisfactory. Operation of the EAC markedly reduced the WL.

Measurements

		Results		
Date	Location	Radon(pCi/L)	RaA(pCi/L)	mWL
81 05 16	Living room	16		
	End wall cavity	9		
81 06 20	Kitchen (A/C just turned off)	13		
	Living room	15		
	Rear wall cavity	12		
	Kitchen wall cavity	16		
81 09 08	Kitchen (A/C on)	18	16.6	120

Track Etch

Average Radon in House	30.1
In walls	
Front	24
Side	49
Rear (1)	59
Rear (2)	lost
Kitchen	13

EAC Measurements

	Conditions	Equilibrium Fraction
82 04 08	House closed, no circulation	0.65
	Fan on continously	0.21
	EAC on continously	0.08
	EAC on plus ceiling fans	0.06

HOUSE #10 SUMMARY REPORT

External gamma	28 uR/h
Internal gamma	17 uR/h
Estimated annual average (HRS survey)	60 mWL
Summer Average Radon Concentration (Track Etch cup)	4.1 pCi/L
Estimated post remedial annual average	11 mWL

Investigation

This house is about 10 years old, and is located on what is thought to be a reclaimed clay settling area to the north of Bartow. The plan is generally rectangular, with an attached garage. The foundation is concrete block, with concrete block walls. The front wall is covered with Quik-brick, and the other walls are painted. The living room has a sunken floor, one step down from the rest of the house. All floors are covered with carpet or sheet vinyl.

Boroscope examination of the exterior walls found that in general the floor slab did not enter the walls. The kitchen and bathroom water pipes and drain pipes are both of copper, but they entered the concrete floor slab via holes drilled in the sole plate of the internal frame walls, so the seal between these pipes and the concrete could not be seen. The pit under the bath was already filled with asphalt.

Remedial Work

A local plumber provided labour to lift the toilets. The connection for the bathroom toilet was a cast iron 4" flange attached to a 3" pipe flush to the concrete. This is not a standard connection, and replacements were not available. The lead was removed from the joint, and the flange removed intact. It was found that the concrete floor slab had been poured right up to the sewer pipe leaving a surface recess to accomodate the flange. The flange was replaced, and asphalt poured into the recess through the flange bolt holes. The connection for the bedroom toilet, a non-standard cast iron 4" flange to 4" pipe was removed in the same manner. Since the concrete had been poured up to the pipe, the flange was replaced and sealed as above.

As the pit beneath the bath was filled with asphalt, no additional work was carried out there.

Comment

The low average radon concentration measured in the house is most likely due to the occupants making considerable efforts to use natural ventilation for cooling rather than run the air-conditioning.

The construction style with floor inside walls and a sunken living room ensures that there will be large connections to the soil, so it is unlikely that sealing just two toilet connections would cause any significant reduction in radon level.

Measurements

Date	Location	Results		
		Radon(pCi/L)	RaA(pCi/L)	mWL
81 06 18	Kitchen (window open)	3.9	3.3	22
	Front wall cavity (slight draft)	41		
	Side wall cavity (strong draft)	0		
	Kitchen (A/C on 7 hours)	1.3	2.8	8.8

Ventilation period (A/C on) 1.5 hours (approx.)

Track Etch

Average radon in house	4.1
In walls	
Front (1)	98
Front (2)	44
Side	8
Rear	26
Garage (frame wall)	4

HOUSE #11 SUMMARY REPORT

External gamma	9 uR/h
Internal gamma	9 uR/h
Estimated Annual Average (HRS Survey)	42 mWL
Summer Average Radon Concentration (Track Etch cup)	6.9 pCi/L
Estimated post remedial annual average	18 mWL

Investigation

This house is about 10 years old, and is located on what is thought to be a reclaimed clay settling area to the north of Bartow. The plan is generally rectangular, with an attached garage. The foundation is apparently a poured concrete strip foundation, with frame walls and real brick veneer. The floor slab is on one level throughout, and is covered with carpet or sheet vinyl. There are two full bathrooms.

Boroscope examination of the exterior walls was not informative, as the frame walls were filled with fibreglass insulation and nothing could be seen. The carpet was lifted at the sliding doors revealing that the floor was poured inside the concrete foundation. Examination of interior walls found the plumbing in the bathrooms to be copper water supply lines and galvanised waste pipes, both entering the floor slab through the sole plate of the frame wall. The seal against the concrete could not be seen. The kitchen plumbing ran through the walls, and was not examined. The pit beneath one bath was filled with asphalt, and the pit beneath the other was filled with sand alone.

Remedial Work

An opening was cut through the wall of the main bathroom to gain access to the pit beneath the second bath. The sand was removed by vacuuming, and the pit filled with 8 litres of asphalt.

An opening was cut through the wall of the second bathroom to gain access to the pit beneath the first bath. The existing asphalt sealant in the pit was in good condition. To ensure that the pit was completely sealed, 3 litres of additional asphalt was poured in.

A local plumber provided labour to raise the two toilets. The connection at each was a cast iron 4" flange on a 4" pipe, raised about 1 cm above the floor. The flanges were removed, the bead-board packing around the waste pipes taken out, grooves chipped in the surrounding concrete to enable sealant to be poured in, and the flanges replaced. The gaps were then filled with asphalt, and the toilets replaced.

As the radon levels were still elevated in this house, an EAC was installed as part of a joint EPA/Polk County Health Department Study. Operation of the EAC markedly reduced the WL.

Measurements

		Results		
Date	Location	Radon(pCi/L)	RaA(pCi/L)	mWL
81 04 16	Under bath	13		
	Bathroom (A/C off)	1		
81 06 18	Kitchen (A/C on)	10.3	8.2	56
	Rear wall cavity	8		
Ventilation Period	1.4 hours (A/C fan on)			
81 09 04	Kitchen	4.1	2.7	12
	Dining room	3.2		

Track Etch

Average radon in house	6.9
In walls	
Front *	5
Side *	3
Rear *	2
Garage *	5

*Frame wall

EAC Measurements

	Conditions	Equilibrium Fraction
81 11 05	House closed, no circulation	0.82
	Fan on continously	0.32
	EAC on continously	0.07

HOUSE #12 SUMMARY REPORT

External gamma	11 to 19 uR/h
Internal gamma	10 uR/h
Estimated Annual Average (HRS Survey)	58 mWL
Summer Average Radon Concentration (Track Etch cup)	11.9 pCi/L
Estimated post remedial annual average	31 mWL

Investigation

This house is about 15 years old and is located on reclaimed land in the north east of Mulberry. The plan is generally rectangular, with a carport. The foundation is concrete block, with painted concrete block walls. The floors are covered with carpet or vinyl sheet. There is some cracking of the block walls.

Boroscope examination of the exterior walls suggested that the floor entered the block walls, but did not close the cavities completely. Ants were observed inside the walls, indicating direct soil connections inside the blocks. Examination of interior walls found that kitchen and bathroom plumbing was copper for water and waste and their junction with the concrete slab was concealed by the sole plate of the walls. There was no sign of asphalt on the piping. The complete area beneath the bath was covered with sand. A probe indicated that there was no asphalt in the pit.

Remedial Work

An opening was cut through the bedroom wall to give access to the space beneath the bathtub. The area was found to be 1" deep in sand, which was removed by vacuuming. The pit under the bath was a formed opening approximately 8" wide by 12" long. On one side the sub-slab plastic sheet had been turned up and folded back into the concrete. Hairline cracks extended from the pit at right angles to the long axis of the bath. There were voids in the sub-slab fill underneath the waste pipe and at one corner of the slab.

The plastic sheet was removed and the concrete exposed. The voids were filled with sand and 6 litres of asphalt were bailed into the pit. The concrete around the water pipes was rough where they entered the slab. The area was cleaned off and the pipe joint was filled with sealant.

A local plumber provided labour to raise the only toilet. It was found that there was no flange on the top of the 4" line. The seal between the toilet bowl and the pipe was achieved only by means of the wax ring. The floor slab concrete had been poured to the pipe, and the joint appeared tight. In view of this, an extra wax ring was placed to seal the junction between the toilet and the floor, and the toilet replaced.

As sealing did not reduce the radon concentration an EAC was installed in the air duct, replacing the filter behind the wall grille. Installation was satisfactory, but incorrect assembly of a cover plate operated the safety switch, turning off the unit when the grille was closed. This was corrected, and operation of the EAC markedly reduced the WL.

Measurements

		Results		
Date	Location	Radon(pCi/L)	RaA(pCi/L)	mWL
81 04 21	Bathroom (windows open)	0		
	Beneath bath	15		
81 06 17	Kitchen (A/C on + floor fan)	3.2	2.1	5.3
	Front wall cavity	3		
81 09 03	Kitchen (A/C on + floor fan)	2.6	1.3	2.4

Track Etch

Average radon in house	11.9
In walls	
Front (1)	lost-paper backing eaten by insects
Front (2)	20
Side	28
Rear	41
Carport side	6

EAC Measurements

	Conditions	Equilibrium Fraction
82 03 31	House closed, no circulation	0.27
	Fan on continously	0.12
	EAC on continously	0.06

HOUSE #14 SUMMARY REPORT

External gamma	9 to 12 uR/h
Internal gamma	7 uR/h
Estimated Annual Average (HRS Survey)	38 mWL
Summer Average Radon Concentration (Track Etch cup)	3.2 pCi/L
Estimated post remedial annual average	8 mWL

Investigation

This house is about 15 years old and is located on reclaimed land in the north east of Mulberry. The plan is generally rectangular, with an attached garage. The foundation is of hollow concrete block, with painted concrete walls. There are brick panels beneath the front windows. The floor is covered with carpet or vinyl sheet.

Boroscope examination of the exterior walls found that the floor slab did not penetrate the block walls. Examination of the interior walls found that the plumbing was copper throughout, but the junction with the slab was concealed by the sole plate of the frame wall. The pit beneath the bath was apparently filled with grey debris.

Remedial Work

An opening was cut through the wall of the bedroom to gain access to the area beneath the bath. The pit had apparently been produced by breaking the concrete floor slab with a heavy hammer. The edges of the pit were broken and irregular, and pieces of concrete were in the pit.

The broken concrete was removed until solid concrete edges were exposed. Debris was removed and 8 litres of sealant were bailed into the pit.

The hot and cold water pipes were exposed at their junction with the concrete and openings were visible through the concrete alongside the pipes. The junction between the pipes and concrete was painted with asphalt.

A local plumber provided labour to lift the toilets. At both toilets, the connection between the cast iron waste pipe and toilet was without a flange but with a plastic reducer sitting on top of the wax seal. The bowl was held down with screws in lead inserts in the concrete. Concrete was poured up to the pipe. After the wax was removed, the junction between concrete and pipe was cleaned off and examined. The joint looked tight. Extra wax was placed in this area to seal the joint between the pipe and the concrete and the toilet. The toilet was then replaced in the same manner with wax ring and plastic reducer.

Measurements

Date	Location	Results		
		Radon(pCi/L)	RaA(pCi/L)	mWL
80 04 21	House air	1		
	Beneath bath	21		
80 06 17	Living room (1) (A/C on)	2.2	1.6	3.9
	Living room (2)	1.5		
80 09 04	Living room (A/C on)	2.7	1.8	10.8

Trach Etch

Average radon in house	3.2
In walls	
Front	21
Side	13
Rear	29
Garage	56

HOUSE #15 SUMMARY REPORT

External gamma	8 to 12 uR/h
Internal gamma	9 uR/h
Equivalent surface radium	4.7 pCi/g
Estimated Annual Average (HRS Survey)	46 mWL
Summer Average Radon Concentration (Track Etch cup)	2.7 pCi/L
Estimated post remedial annual average	7 mWL

Investigation

This house is 10 years old and is located in an area of reclaimed and mineralised land to the south east of Lakeland. The plan is rectangular with an attached garage. The foundations are concrete block, with concrete block walls. The front face is finished with Quik-brick. The floor is covered with carpet or vinyl sheet, and is on one level.

There are two bathrooms back to back. One has a bath, one a shower, both have toilet. The laundry room is internal to the house and has an open drain into which the laundry tubs and the hot water tank are connected.

Boroscope examination of the open exterior wall revealed that the floor slab did not enter the foundation blocks. Examination of interior walls found that the plumbing was of galvanised iron, and the junction with the slab was hidden from view by the sole plate of the frame walls. The pit beneath the bath was open, and two water lines ran across the bottom. The sub-slab plastic sheet was caught up in the concrete along one side of the pit.

Remedial Work

An opening was cut through the wall of an adjoining closet to gain access to the pit beneath the bath. The hot and cold water pipes passed through the slab at the edge of the pit, and then ran horizontally across the bottom of the pit. The sand fill under the slab was at least 5 cm below the lower edge of the slab. About 6 cm of sand was placed in the pit to reduce the volume of asphalt needed and 6 litres of asphalt bailed in. The concrete around the piping was in poor condition, and was broken away to expose good concrete. The exposed area and piping were painted with asphalt to seal them.

Measurements

Date	Location	Radon(pCi/L)	RaA(pCi/L)	mWL
		Results		
81 05 02	Bathroom	0		
	Beneath bath	9		
81 06 20	Family room (A/C on + floor fan)	1.0	0.7	1.2
	Front wall cavity	2		
	Garage wall cavity	0		
81 09 08	Soil gas	260		
81 09 09	Family room (A/C on + floor fan)	1.4	1.2	2.2
Track Etch				
	Average radon in house	2.7		
	In walls			
	Front	55		
	Side	29		
	Rear	20		
	Garage (frame wall)	1		

HOUSE #21 SUMMARY REPORT

External gamma	7 uR/h
Internal gamma	7 uR/h
Estimated Annual Average (HRS Survey)	30 mWL
Summer Average Radon Concentration (Track Etch cup)	6.1 pCi/L
Estimated post remedial annual average	16 mWL

Investigation

This house is about 10 years old, and is located in an area of reclaimed and mineralised land to the south east of Lakeland. The plan is 'L' shaped, with an attached garage. The foundations are concrete block, with concrete block walls. The front face is finished with Quik-brick. The floor is covered with carpet or vinyl sheet and is on one level. There are two bathrooms, the one attached to the main bedroom has a bath and the one in the bedroom wing has a shower.

Boroscope examination of the exterior walls was difficult, as the electrical outlets fitted the holes in the block wall very tightly, and the scope could only be inserted in two locations. The floor slab did not fill the wall cavities. The sub-slab plastic sheeting had apparently been drawn over the inner face of the foundation wall. Examination of the interior walls found that water supply lines were galvanised iron, with plastic waste pipes. The junction between the slab and the pipes was concealed by the sole plate of the walls. The pit beneath the bath was filled with sand with a layer of asphalt poured over the front half of the pit.

Remedial Work

An opening was cut in a bedroom wall to gain access to the pit beneath the bath. The pit was full of sand and a layer of cracked asphalt mixed with sand extended from the front of the pit to about 5 to 8 cm beyond the bath overflow line. The back half of the pit was filled to the top with exposed sand.

The asphalt layer was removed and the sand in the pit taken out to some 8 cm below the top of the slab. The pit was then filled with sealant. The concrete around the water piping was in good condition so the junction between the piping and the slab was coated with sealant.

A local plumber provided labour to raise the two toilets. The connection at each was a cast iron 4" flange on a 3" pipe. The flange was removed, revealing an opening through the slab. Paper was placed in the base of the opening to prevent the sealant running away into the sand. The upper surface of the concrete had been formed in a curve to accept the reducer flange, and it was necessary to chip away some of the concrete to provide a groove through which asphalt could be poured to seal the opening. The toilets were replaced without incident.

Comment

Part of the radon problem in this house may be due to the sub-slab sand fill, which has at least double the radium content of the local surface soil.

Measurements

		Results		
Date	Location	Radon(pCi/L)	RaA(pCi/L)	mWL
81 05 12	Kitchen (windows open)	0.5		
	Beneath bath	4		
81 06 16	Kitchen (A/C on)	2.6	3.7	24
Ventilation Period 3.5 hours				
81 09 08	Kitchen (A/C on)	7.2	6.2	70

Track Etch

Average radon in house	6.1
In walls	
Front (1)	39
Front (2)	42
Side	32
Rear	12
Garage	13

Soil Sample sand fill beneath bath 0.51 pCi/g emanating Radium.