Publication No. 05-021-058

PRODUCTION OF RADON-RESISTANT FOUNDATIONS

Prepared by American Atcon, Inc.

under a grant sponsored by the

Florida Institute of Phosphate Research

Bartow, Florida

January, 1988

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PRODUCTION OF RADON-RESISTANT FOUNDATIONS

FINAL REPORT

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September, 1987

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Perspective

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It has been known since the early part of this century that central Florida phosphate deposits contained higher levels of uranium, and consequently the radioactive decay products of uranium, than did most other soils and rocks over the earth. It was not until the mid-1970's, however, that interest in the subject began to pick up. In the 70's, both the U.S. Environmental Protection Agency and the Florida Department of Health and Rehabilitative Services performed limited surveys of indoor radiation in homes built in the central Florida phosphate district. Both studies showed that some persons in the area were exposed to levels of radioactivity higher than normal background levels, including a number of persons who lived in houses built on land reclaimed from open pit phosphate mining operations, where the soil was naturally enriched in uranium. In May of 1979 the Administrator of EPA wrote to the Governor of Florida, suggesting that remedial action was necessary in some existing homes, and that future new homes built in the region should incorporate construction techniques to resist the entry of radon gas. At that point, the Governor appointed a Task Force to consider the problem and possibly develop an environmental radiation standard.

Another consequence of this was that the Federal Department of Housing and Urban Development withdrew FHA and VA mortgage insurance for housing built on reclaimed phosphate mining lands, thus discouraging their development for low and moderate price housing. This did not prevent all construction, for some attractive areas were developed with conventional mortgage funds, and the housing sold to persons who did not need or qualify for FHA or VA loans. These actions by the federal government led the Task Force to consider regulation of house construction to encourage the use of "radon-resistant" foundation styles (ventilated crawl space, or an improved monolithic slab) in those areas where radon concentrations in houses were generally elevated. Although there was general agreement that the two construction techniques just mentioned should minimize entry of radon from the soil, there were no real data on the either the performance or the additional construction costs of such foundations. Without a demonstration that radon-resistant foundations could be built, and built economically, any regulation might well be premature.

The first steps taken to address the problem were accomplished in an earlier study, also sponsored by the Institute as project 82-05-012. These were obtaining the participation of public agencies and private groups with an interest in the project, and then designing a suitable study. Work done under the current study included testing of building sites to assure that soil radon levels were indeed elevated, actual construction of the homes, and finally testing of the finished homes for indoor radon. An agreement was reached with HUD to lift the ban on loan insurance for homes built by the demonstration techniques, if the project were successful. Also, if the project were successful, the researcher was to prepare a brief guidance booklet for builders, one that described the construction of radon-resistant foundations.

Three homes were built for the study - one on a ventilated crawlspace foundation, and two on monolithic slabs-on-grade, one with standard reinforcing and one with post-tensioned cable reinforcing. All three designs proved to be successful. Average indoor radon levels in all homes over a period of several months were shown to be about 2 pico Curies per liter (pCi/l) or less, well below EPA and state HRS guidelines of 4 pCi/l suggested as an upper acceptable limit. This was despite soil gas radon levels of 3000 to 5000 pCi/l, levels perhaps ten times background for most Florida lands. Especially encouraging was the finding that, while an elevated crawlspace could add perhaps 10% to the cost of a home, a monolithic slab home could be built for about the same cost as a conventional slab home.

Results of this study should prove useful to all citizens of Florida, and especially so to Florida homebuilders. Results of a recent statewide study, sponsored by the Institute, have shown that elevated indoor radon levels are not just a problem involving reclaimed phosphate lands, nor even a problem unique to central Florida. The potential for elevated radon indoors was found in parts of 18 counties, from Leon to Dade, and involving some 7% of the total land area in the state. A Peer Review Committee, authorized by the 1986 Legislature to recommend how the study might be used in implementation of a new state radiation rule, has suggested that radon-resistant construction techniques should be required statewide. This study has shown that two construction techniques do indeed work. Furthermore, they are the two techniques suggested by the Florida Department of Health and Rehabilitative Services early in 1986 as being radon-resistant and suitable for home construction on lands known to be elevated in soil radon.

This study was designed to investigate two other radon-resistant techniques - a sub-slab ventilation system and a plastic soil gas barrier installed under the foundation. The effectiveness of sub-slab ventilation could not be determined, as the slab itself was effective in preventing radon entry. Use of a plastic barrier, while seemingly effective to stop gas flow, is not condoned in the report because of the near impossibility of constructing a foundation without frequently puncturing the membrane.

This study is but a start in the development of radon-resistant building techniques. Hopefully homebuilders themselves will enter the field and develop other new and innovative techniques to provide Floridians with home foundations that minimize the entry of radon gas.

ACKNOWLEDGEMENTS

The assistance and cooperation of the United States Environmental Protection Agency, the United States Department of Housing and Urban Development, the Florida Department of Health and Rehabilitative Services, the Polk County Health Unit, USR Realty Development, and Central Florida Contractors is gratefully acknowledged.

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EXECUTIVE SUMMARY

Two houses with radon-resistant monolithic-slab foundations and a crawlspace house were built on a reclaimed phosphate mining area with soil radium concentrations of 5 to 12 pCi/g near Bartow. The houses also included a number of additional features suggested as methods for increasing the radon-resistance of foundations. These were a site membrane, an improved subslab vapor-barrier membrane, and passive subslab ventilation.

Construction of the foundations was monitored to identify field problems, and the costs of the individual features were identified. A six month measurement program found that the average radon concentrations in all three houses were less than 2 pCi/l, Conventional housing on reclaimed land of that radium content would have been expected to have average radon concentrations greater than 10 pCi/l.

As this program demonstrated that radon-resistant foundations could be produced, it is expected that HUD will resume FHA insured loan approval for housing on reclaimed phosphate lands, conditional on the use of radon-resistant foundations.

Radon-resistant slab-on-grade foundations can be produced cost-effectively by the use of monolithic concrete foundations with sealed plumbing openings in the slab and subslab barrier membrane, and improved concrete practice. The total cost of the radon-resistant monolithic foundation is estimated to be less than that of a conventional concrete block foundation.

The ventilated crawlspace effectively isolated a house from the ground, but at a cost of several thousand dollars higher than that of a house on a standard foundation,

The additional radon-resistant features did not appear to have any value in this study. The site membrane was found difficult to use, expensive, and not very effective. The improved vapor-barrier membrane was found to be as easily damaged as the standard polyethylene sheet.

Radon levels in the houses were too low to detect any effect of the passive subslab ventilation systems.

1. INTRODUCTION AND BACKGROUND

This is the final report on a program to demonstrate the production of houses with radon-resistant foundations carried out for the Florida Institute of Phosphate Research under contracts 84-05-021 and 84-05-021S by AMERICAN ATCON INC.

In the mid 1970's it was discovered that many homes in Central Florida had elevated levels of radon, The levels were highest in those houses built on land reclaimed from open pit phosphate mining operations, where the soil was naturally enriched in uranium. One consequence of this was that the Federal Department of Housing and Urban Development withdrew FHA and VA mortgage insurance for housing built on reclaimed phosphate mining lands, thus discouraging their development for low and moderate price housing. This did not prevent all construction, for some attractive areas were developed with conventional mortgage funds, and the housing sold to persons who did not need or qualify for FHA or VA loans. This state of affairs led to proposals at the State level to regulate house construction to encourage the use of 'radon-resistant' foundation styles (ventilated crawl space, or an improved monolithic slab) in those areas where radon concentrations in houses were generally elevated.

Although there was general agreement as to the need for such regulation, a practical difficulty was that there were no hard data on the expected performance or additional costs of these foundation styles. Similar foundations were in use in the State, but none of them had been designed specifically to be radon-resistant, and their performance had not been measured. As the foundations had not been modified for radon-resistance, there could be no data on the additional costs involved. Without a demonstration that radon-resistant foundations could be built, it was clear that any legislative prescription would be premature.

2. PROGRAM DESCRIPTION

As a first step towards breaking this impasse, a cooperative radon-resistant housing demonstration program was planned under a previous FIPR contract, 82-05-012. Discussions were held with the EPA, HUD, and FHRS as regulatory and technical agencies to obtain their opinions and assent to the goals of the program, and with local developers and builders to find out who might be willing to participate. When agreement was reached, a second program was started to carry out construction of the houses.

The agreed goals of the demonstration program were to show that houses built on reclaimed phosphate mining lands with the proposed radon-resistant foundations designs would have low radon levels, to identify the construction problems that might occur in practice, and to document the extra costs involved. The final form of the plan was that three houses were to be constructed on reclaimed phosphate mine land, two with improved monolithic slabs, and one with a ventilated crawl space. The improvements to the slabs consisted of improved concrete handling practice, higher quality subslab membrane material, and airtight plumbing entries. For comparison, one slab would have standard reinforcing, the other would be heavily reinforced with post-tensioned cables, The crawl space house was to have an airtight precast concrete floor.

One item of major importance was to demonstrate that improved concrete handling practice could produce large monolithic foundation slabs without shrinkage cracking in the first few weeks after pouring. If this could be done, the slab with standard reinforcing would be expected to remain crack-free as long as the ground on which it stood was stable. A heavily reinforced slab was included in the program to indicate the cost premium for a slab that would not crack even if built on unstable ground.

The Federal Department of Housing and Urban Development agreed to lift the ban on FHA insured loans for new housing on reclaimed phosphate lands, conditional on the demonstration that the proposed construction techniques could produce concentrations of less than 4 pCi/l.

A constraint on the program was that the houses could not be purchased and then resold, A builder would have to be found who was willing to build houses to the suggested designs and recover his basic construction costs from the sale of the house. He would be compensated for additional construction costs, and for the time taken in testing the houses after they had been completed. Given this, the choice of sites for the project was limited to a few existing developments on reclaimed phosphate mining areas where houses might be sold. One possibility was Brittany Place, which had been under development in the mid 1970's, and still had vacant lots as a result of the HUD freeze on mortgage insurance.

The attractiveness of this area was increased from a commercial point of view by a small housing development underway nearby (on unmined land). The owner, USR Realty Development, agreed to extend the services to three lots, and sell them to any local builder who was willing to participate in this program.

The houses were to be built using locally available material and labor. The construction would be discussed with the builder by American Atcon staff, and observed by them, but apart from that they would only intervene if practices were observed that would reduce the radon-resistance of the foundations. Construction would take place under the usual field supervision.

During the construction planning stages two additional features were suggested for testing. The first was a passive subslab ventilation system, and the plans for each slab house was modified to include one. The second was a durable membrane to be placed underneath the house to isolate it from the soil. This might make conventional foundations radon-resistant. The crawlspace house would be a suitable test structure for this concept, as the radon-resistance of the house would not be affected if the membrane failed to reduce the rate at which radon left the ground. Installation of a membrane beneath the footings of this house was added to the scope of the project.

3. SITE DESCRIPTION

The Brittany Place subdivision is built on an old phosphate mining area, which was reclaimed by being used as a sand tailings disposal area. The sands were slurried out to the area, as shown by obvious layering and considerable vertical variation in particle size visible on the sides of excavations. The radiation field on contact with exposed sands is about 20 uR/h. The final layer of material on the site was a sand/clay/pebble mixture about 4 to 12 inches thick, with a radiation field in contact of about 14 uR/h. This has formed a firm crust on top of the sand, and all the plant growth on the site is confined to this layer.

Municipal sewer and water services had been installed along the roads on the east and south sides, and a single row of houses facing on to the road had been built and sold before the withdrawal of FHA insurance guarantees in the mid 1970's effectively closed off further development. There were a number of vacant lots along the south road, and the services could be easily extended to them. The owners of the land, USR Realty Development, were willing to extend the services to three lots, numbers 22, 23, and 24 on their plans.

The radiation field over the entire settling area reportedly varied from a few uR/h at the edges, which are probably unmined lands with minimal tailings cover, to as high as 40 uR/h at the west end, Because of the known variability of the site, the Polk County Health Unit carried out a radiological survey of these three lots to evaluate if they would be typical of reclaimed mining lands in Polk County.

The gamma field at one meter height over each lot was measured with a scintillation meter calibrated against a Pressurised ion chamber, and ranged between 14 to 18 uR/h over the area where the houses were to be constructed. Soil cores were taken to a depth of 1.8 m at the centre and 4 other locations on each site. The centre core was divided into 30 cm sections, the other cores were cornposited and analyzed for radium content. The cores showed considerable lateral and vertical variability in the radium content. The near surface radium content averaged 9 pCi/g at lot 322, 12 pCi/g at lot 23, and 4.7 pCi/g at lot 24. These values are typical of old reclaimed lands, which have gamma fields of 10 to 20 uR/h, and surface radium concentrations of 5 to 15 pCi/g.

The surface radon flux was measured with charcoal flux canisters at 12 locations on each lot on two different occasions, and ranged between 0.3 to 9.1 pCi/s.m^2, averaging 4.8 pCi/s.m^2 at lot 22, 4.3 pCi/s.m^2 at lot 23, but only 1.8 pCi/s.m^2 on lot 24.

Most houses in Polk County that have average radon levels greater than 4 pCi/l are built on ground with gamma fields of more than 10 uR/h,

and surface radium concentrations usually exceed 3 pCi/g. Average radon fluxes in excess of 1 $pCi/s.m^2$, as measured by the charcoal canister method, have been associated with radon concentrations greater than 10 pCi/l in existing Polk County housing. The measurements made on the sites all indicated that average radon levels of 10 to 15 pCi/l or more could be expected in conventional housing.

4. HOUSE DESCRIPTION

The houses to be built on the site were typical of moderately priced single story housing in the Polk County area of Florida, with expected sale prices in the $55 000 bracket. Each house had an attached garage, living room with attached dining room, a kitchen with a breakfast nook, three bedrooms and 1 1/2 bathrooms. The exterior walls were to be made of concrete block.

The first house (lot 22) had 1 300 ft^2 of living space plus an attached garage of 390 ft^2 on a single improved monolithic-slab. The house was generally rectangular in plan, about 46 ft long by 32 ft wide, and the garage projected 15 ft beyond the front wall of the house at right angles to the long axis of the slab.

The second house (lot 23) had 1 200 ft^2 of living space plus an attached garage of 220 ft^2 and a exterior patio of 70 ft^2 all on a single heavily reinforced monolithic-slab. The house was asymmetric in plan, about 40 ft long and 28 ft wide at the centre, but the garage slab projected 6 ft at the front, and the patio and bedroom portion of the slab projected 6 ft to the rear.

The third house (lot 24) had 1 230 ft^2 of living space over a ventilated crawlspace, plus an attached garage on a separate slab. The house was rectangular in plan about 40 ft long and 30 ft wide. The original design was to have concrete block exterior walls and a suspended floor of precast concrete slabs, supported by central pillars in the crawlspace. This design was subsequently changed by the builder to a wood frame house with vinyl siding, a conventional suspended wooden floor, and a carport instead of a garage.

5. SITE MEMBRANE SELECTION

At the project meeting held in Bartow on May 20, 1986, it was decided that the crawlspace house (lot 24) should be used as the location to test the effectiveness of a plastic barrier membrane to prevent the movement of radon from the soil. This house was particularly suitable for such a test, for if the membrane was ineffective, this would not have any significant consequences. The crawlspace would still effectively isolate the house from the ground.

The ideal barrier material should be:-

- impervious to air, flexible, unaffected by burial.
- tough enough not to be penetrated by construction debris and hand tools.
- available in large sheets.
- stable for handling in hot weather
- joined by adhesives rather than by heat welding so that patches can be applied for field repairs.
- cost less than 50¢/ft^2.

A number of sheet materials were identified, all of which would prevent the passage of soil-gas if they remained intact. The final selection depended largely on the expected ability of the membrane to withstand construction work taking place on top of it, and its availability from stock, for construction on the crawlspace house was scheduled to start July 1, only five weeks after approval of this additional program.

The material that appeared to best meet the requirements was a 30 mil PVC sheet made by DuPont. This was available in large sheets, was tough, and was the lowest priced at 30¢/ft^2, about half the price of some other candidate materials. The material was ordered from Staff Industries Limited, and to speed delivery it was paid for in advance. Priority treatment was given, for it took only five days from manufacture to delivery on the site.

6. CONSTRUCTION PHASE

At a meeting on May 20 1986, a schedule was agreed for the construction of the first two houses by Central Florida Contractors. The start date was set for June 2, 1986.

6.1. SITE PREPARATION

Central Florida Contractors initiated construction with an on site meeting on June 10, 1986. Initial preparation had been carried out in mid May with the removal of top soil and storage on site, and rough grading. Sand for the final leveling of sites 22 and 23 was dumped and spread on the first two sites on June 12, when the form work for the monolithic-slabs was started. Samples of the sand were taken and delivered to the Polk County Health Unit for measurement of the radium activity.

The forms for the two foundation slabs were complete by June 16. A section was left open in each form to allow a small tractor and vibrator to enter the forms and grade and compact the sand fill inside the forms. Grading and compaction was completed that day, although it was subsequently found that lot 23 had been left five inches high. Trenching for subfloor plumbing was started when compaction was finished, with some lines being installed that day. By June 18, both sites had subfloor plumbing (drains and water lines) installed. Hand leveling and final compaction of the fill was completed on June 19.

After the plumbing installation was complete, the subslab ventilation system collector pipe was installed at each site. This was a corrugated 5 inch drainage pipe wrapped in a cloth sock and laid in a continuous loop in a 5 inch deep trench dug in the fill, The exhaust pipe connector was a solid PVC pipe “T”, set to pass vertically through the slab.

6.1.1. Comments

The plumbers used a mechanical ditcher for excavation and backfill of plumbing lines. The excavation penetrated the sand cover and brought mineralized material to the surface thus contaminating large areas of the sand subfloor fill. Even after removal of the worst of the mineralized material, the radiation field over the fill was 8 uR/h, an increase from the 6 uR/h found when the sand was first placed.

At lot 23, foam rubber collars were installed on all the copper water lines where they would pass through the slab. This is a common local practice to comply with the Building Code requirement that water lines should be protected from contact with concrete. As foam rubber would provide a passage for soil-gas, the plumber was asked to remove it and place an asphalt coating on the water lines at both sites. This was done on the 20 June.

6.2. MOISTURE BARRIER MEMBRANE

Central Florida Contractors had selected a polyethylene coated, fibre reinforced paper sandwich (Moistop) as a moisture barrier. This material had considerably higher tear resistance and greater thickness than the polyethylene sheet (Visqueen) normally used for this purpose. The joints were lapped and sealed with asphalt to form a continuous barrier, and all plumbing penetrations were effectively sealed to the membrane with asphaltic sealant, as shown by retention of rainwater in the depressions around each pipe.

Despite the reinforcing, and a generally higher standard of care than normal at a site, the membrane was repeatedly punctured during the installation of the metal reinforcing mesh and the post-tensioning cables, and a major patching job had to be carried out.

6.3. REINFORCEMENT

On June 19, the moisture-barrier membrane was laid and the perimeter reinforcing bars were installed at both sites, The wire mesh slab reinforcement was placed at lot 22.

On June 20, the sheathed cables that would be post tensioned to provide the reinforcement for the monolithic-slab at lot 23 were installed. When the first cable was unwound, the free end repeatedly struck the moisture-barrier, perforating it. The holes were patched with asphalt. Subsequent cables were unwound with two people controlling the cable to prevent further damage to the moisture-barrier. The cables were supported on plastic chairs to ensure adequate concrete thickness below each cable.

The garage slabs at each slab house were to be integral with the house floor slab, but at a lower level. The separate forms for the garage and the suspended forms for the step changes in level at the garage and patio were completed this day.

On the afternoon of June 20, a check was made at lot 23 on the height of the forms above the fill, and it was found that they were too low to produce the specified 4 inch slab thickness. The minimum slab depth recorded was only 1 3/4 inch. These discrepancies were attributed by the contractor to the forms sinking as a result of overnight rain wetting clays in the upper layer of the ground.

The contractor added a 2x2 inch (actual 1 1/2 inch) to the top of the forms. A grid check revealed that only two small areas at lot 22 were below 4 inches and these were measured at 3 l/2 inches, an acceptable tolerance.

As a result of this change in slab surface elevation, the plumber had to return to site to raise the top of the fixture connections by

1 1/2 inches to the new floor level, which involved cutting the membrane to join the new vertical pipe to the drain. At the same time, fill was removed around each plumbing fixture drainage pipe to ensure that at least 4 inches of bare pipe was in contact with the concrete. The moisture-barrier was resealed with asphalt.

6.4. CONCRETE PLACEMENT

Concrete pouring had originally been set for June 24, but labor to adjust the forms was not available on June 23. Pouring was postponed until June 25. The first concrete truck arrived on site at 7:30 am and the first slab was poured by 8:45 am. Work on the second slab started immediately and that slab was poured by 11:30 am. The first slab had set sufficiently by then for trowelling to start, and work on both slabs was finished by 3:00 pm.

The concrete used was a standard 3,000 psi mix with plasticiser to give a 10 inch slump added at the local concrete plant. A vibrator was used to consolidate the mix along the perimeter foundation beam and around the plumbing penetrations.

The concrete crew made an effort to pull the wire mesh reinforcing at lot 23 up into the middle of the slab as the concreting progressed, but it was obvious from the amount of foot traffic in the wet concrete that the mesh was continuously trodden down. The concrete placers had to walk on the mesh ahead of the mix, and walk in the wet concrete to level and screed, so it is likely that most of the mesh rested on the moisture-barrier beneath the slab, and provided no significant reinforcing at all.

No grade stakes or screed bars were used to control the surface level. A laser level and hand held receiving staff were used instead. Small areas of the concrete were trowelled to the correct elevation, and the concrete was leveled to these, Long handled floats were used to smooth the concrete.

As soon as the concrete was set, the stakes holding the suspended forms at the garage and patio step changes in level were removed. Asphalt caulk was placed into the bottom of each hole formed by the stake to seal the holes, even though these openings were outside the house. The top of the hole filled with concrete when the slab surface was trowelled smooth, and was invisible,

The temperature on the site was 85°F (but only a weak sun) while the concrete was being trowelled. With these high temperatures, the chemical reactions in the slab proceed three times more rapidly than at “standard” temperature of 70°F. By the time the concrete finishers had completed their work, some parts of the slabs had shrunk between 0.02 and 0.06 inch away from the forms.

The builder had proposed to cover the slabs with sand to retard moisture loss, but when the concrete crew finished, there was not enough sand on the site or a labor crew to do this. A centrally positioned circular jet spray sprinkler was placed on each slab before 5:00 pm to keep the surface covered with a film of water.

The water limited solar heating of the slab to only a few degrees above the air temperature. At 11:00 am on the following day, the air temperature was 85°F, and the thermometer read 88°F in the sun. On a dry portion of a slab it read 100°F, and 91-95°F on areas covered with a water film. The internal temperature of the slab, as measured down a water filled drain was 90°F. The temperature of the water delivered to the spray was 82°F. The sprays were kept on for two days, and limited additional shrinkage to less than 0.04 inch.

Concrete test cylinders of the mix used were taken from each slab (3 samples from lot 23, and 2 samples for lot 22). Samples were also taken of the material incorporated in the concrete mix and of the mix itself. These were delivered to the Polk County Health Unit for measurement of the radium content.

6.4.1. Comment

There were difficulties in producing changes in traditional practices. For instance. although the concrete contained a plasticiser to fluidise the mix and delay the set, when a concrete truck had to wait, the batch (9 cu.yds) was still “tempered” by three gallons of water to delay the set.

The following problems were noted:

1. The foamboard collars wrapped round the plumbing fixture pipes to provide a space between the connections and the concrete were not properly adjusted after the height of the forms was increased. The tape holding some of the short collars in position lost its grip, and they floated up in the concrete, leaving only shallow depressions around the pipe. One shower drain pipe was found to be too low by a l/2 inch despite the correction the plumber had made, and a recess had to be trowelled in the concrete for it.

2. The bath at lot 23 (post tensioned) had been reversed from the original drawings so that an access panel to the bath drain opening could be installed in a bedroom closet. The original drawings had been used to locate the post-tensioning cables, so this resulted in the bath drain and a reinforcing cable within a few inches of each other. The cable prevented the concrete block used to form the drain access opening from being placed over the drain. The moisture-barrier membrane material was opaque, so the drain pipe position could not be seen, and this error was not realised until after the concrete was poured and set.

6.5. POST-TENSIONING PROCEDURE

On Friday June 28 the forms were stripped from the slab at lot 23. Arrangements had been made to tension the cables on Saturday June 28, after a concrete test cylinder had been tested to ensure concrete strength was adequate, but no result was received from the testing laboratory. Tensioning was postponed until Monday, June 30.

On Monday morning the testing laboratory (Ardaman Associates) reported that the concrete cylinder crushing test showed that the concrete was strong enough for tensioning (>2 000 psi), and sent two technicians to witness and record the tensioning.

Post tensioning started at approximately 10:00 am on Monday June 30. The cable ends were embedded in the sand that had been used to level the site, and had to be dug out. The plastic cones were removed and replaced by serrated wedges, a portable electric/hydraulic jack threaded onto the cable and faced against the concrete. The cable was then stretched to the calculated strain plus an amount to allow for slippage as the cable retracted into the wedges when the jack was released.

After the jack was removed, the technicians measured the final cable extension (about 2 1/2 inch) and computed the tension in the cable, A nominal tolerance of -5% to +15% in stress was allowed, which translated into an extension tolerance of approximately -l/8 inch to +3/8 inch. This was readily measurable with the steel tape used. On these small slabs the actual tolerance is larger than indicated, for it is not feasible to retension for errors smaller than 3/8 inch. The cable length can be adjusted by less than that amount, but it is unlikely that the wedges will regrip the cables to the same accuracy. Once it was agreed that a cable was adequately tensioned, the end was cut off flush with the end of the wedges, and the recess in the edge of the concrete slab was filled with cement mortar for protection.

6.6. STRENGTH OF CONCRETE

The concrete specified was a mix with 3 000 psi strength at 28 days under standard conditions. Concrete was removed from the forms at each slab to make two test cylinders. They stood on the site and were wetted by the sprinklers for the first two days, so their curing history is similar to that of the slabs.

At 3 days after pouring the tested strengths of two cylinders were 2 400 psi and 3 150 psi, and at 28 days, the tested strengths of the other two cylinders were 3 940 psi and 3 850 psi. This is a high early strength at 3 days compared with standard conditions, and is probably the result of more rapid chemical reactions caused by higher temperatures in Florida compared with standard conditions.

7. SITE MEMBRANE INSTALLATION

The PVC sheet for the site barrier membrane was delivered to the Florida Phosphate Research Institute on Friday June 27. Arrangements were made with the contractor, and it was brought to site on Monday June 30, when excavation for the footings was started. The topsoil from lot 24 was stripped off, string lines and levels were set out, and hand excavation continued to the bottom of the footings. Material from the excavation was placed on sites 22 and 23.

The next day, July 1 the excavation for lot 24 was levelled with a small tractor mounted scraper. A hand operated mechanical compactor and watering was used to compact the excavation beneath the footing. A soil-gas collection system was installed, consisting of a 4 inch corrugated perforated plastic pipe with a solid PVC connector at each end to carry the line under the footing, Each end was capped and marked with a stake. A composite soil sample was taken from the excavation, and a gamma survey carried out over the site.

Once the excavation was compacted, the 35 ft x 70 ft PVC sheet was brought into the excavation by front-end loader (it was too heavy to move manually). Once unpacked on the prepared base it was relatively easy to pull into position. The sheet was accordion folded to its centre, and care had to be taken place it in a position that would allow the edges to reach the perimeter of the work. It turned out that one edge fell short, and the whole sheet had to be pulled in one direction. Two people could have done the job, but three were preferable.

In the original plan, the house floor was to be 2 feet above grade and the carport at grade. The builder felt that the appearance of the house would be improved by raising the carport to floor level by constructing it on compacted fill. This would place soil against the above grade block work. This change was discussed with the project manager, and it was agreed that the PVC sheet would be extended under the carport, and clean (low radium content) sand would be placed on top as fill.

The size of sheet purchased was larger than needed to allow for unforseen eventualities, so there was spare material to place underneath the carport. The sheet was 25 ft longer than the excavation. The excess was cut off before the sheet was unfolded and was rolled back to the edge of the excavation.

The sheet was unfolded in the long direction of the excavation and cut to be 18 inches beyond the footing line. The sheet was then unfolded across the width of the excavation. One hole was found near the edge that looked as if it had been rubbed by packing binding.

On July 2, the footing formwork was placed on top of the PVC sheet. The exterior forms were set up and supported by wooden stakes driven through the sheet on the outside of the forms. The inner forms were to be supported by cross supports from the outer forms. The footing reinforcing bars were put in position before the cross supports were in place, then the inner forms were set up and a wooden member nailed across the top of both forms. The reinforcing bars were hung from this cross member to place them near the middle of the footing. For economy, the forms were made from the 2x10 timber that would be used for the floor joists. A screed line was placed 8 inches high inside the form.

Two horizontal 2 inch PVC pipes open at each end were to be placed on top of the membrane passing through the footings to act as drains to each half of the divided foundation. Unfortunately only one pipe was installed, and this was not noticed until after the concrete had been poured. Only one half of the foundation was drained.

Although the PVC was tough at room temperature, it became very soft and easily damaged when exposed to the mid-day sun. The temperature on the surface of the sheet was an average of 120°F with a maximum of 127°F. Since the soil surface was 100°F, the black color of the PVC had raised the temperature an additional 20°F.

Only three holes were found in the barrier; two stake holes at the east end of the house and a small hole caused by rubbing against a stone by the south form. These were patched with a patch cut from the rest of the sheet and adhesive.

Sand was dumped into the area inside the forms and placed against the inner form. This provided a restraint to form movement and prevented concrete running out from small openings between the forms and the sheet. Sand was spread to a depth of 1 1/2 to 2 1/2 inches over the entire sheet to protect it.

Great care was taken by those involved in the work to avoid damaging the PVC barrier. Material was carefully moved and deposited; wire pieces and nails were thrown clear of the work, It is unlikely that this would be done on most construction sites. A sand cover was a necessity to protect the PVC from the sun.

Once the forms for the footings were in place the contractor started excavation of the carport area with the front-end loader. Once the area was leveled, a section of PVC sheet was cut to fit under the carport area. The junction areas between the house and the carport extension were swept clean of sand and 2x10's were placed underneath to provide a firm working surface. The sheet was overlapped by approximately 2 inches in accordance with the manufacturer's suggestions, and then folded clear and swept again. The joining faces were stretched to smooth them, laid joining side up and adhesive was then poured on the joint area and brushed out. The two faces were placed together on the joist and rolled with a sheet flooring roller. Full adhesion was not obtained the first time. A second application with a 8 inch lap had to be made to obtain continuous adhesion. Once the lap was properly joined, sand was placed over the top of the entire PVC sheet to protect it.

A concrete pump was used to deliver concrete to the forms since it would have been difficult to move concrete from a truck to the central footing except by wheelbarrow. This traffic could damage the barrier despite the sand protection. The concrete truck arrived at 4:45 pm, and concreting was complete by 5:30 pm. The mix used was a 3 000 psi concrete with a pea gravel aggregate. The slump was in excess of 12 inches and flowed readily round the forms. It was float finished as soon as the correct level was reached.

On the morning of July 4, the forms were stripped off the concrete footings and the sand within the footings was spread to an average depth of 4 inches. Samples of pea gravel that had been used in footing mix were obtained from the Ready Mix plant. It was not known which of two pea gravels had been used so a sample of each was obtained. A composite soil sample was taken from the sand within the footings (on a 10 ft grid) and all samples taken to the Polk County Health Unit in Winter Haven for radium measurements.

On Monday July 7, after a weekend of heavy rain, the footings were filled with water to the top of the concrete. The drain was blocked by silt washed out of the sand. The drain was unblocked and the area drained slowly. The undrained half of the footing remained filled with water showing that the barrier/concrete interface was watertight. After discussion with the project manager a 8x8 inch drainage hole was cut in the sheet at the centre of the west half. Drainage from the west half was very slow even after the hole was cut.

7.1. EVALUATION

Although this exercise showed that it was possible to place a membrane beneath a building, and that the junction between the membrane and the concrete footings would have a very small leakage area, it required considerable extra work and pointed out a number of significant problems that would have to solved before the procedure could be generally adopted.

7.1.1. Additional Labor

The whole area has to be levelled, and the footing excavation has to be much larger than usual.

Placing the sheet in position requires 2 or 3 people, and equipment on site.

7.1.2. Other Problems

As services have to pass above the barrier, obtaining the required minimum cover for services may be a problem.

The footing forms must be supported only by stakes driven through the membrane outside the building.

If the house will not fit on a single sheet of material, joints will be needed. Satisfactory joints are hard to install in the field with a non-specialist crew.

PVC is not a suitable material, despite its relatively low cost. It is too easily damaged when exposed to solar heating during installation.

7.2. CONCLUSIONS

The ideal site membrane material must be low cost and tough enough not to be penetrated by construction debris and practices such as dropping tools, nails, wire ties, etc., and walking over them. A more resistant material than PVC is required, The short screening investigation carried out was not sufficient to identify more than a few readily available materials. A more complete series of tests would be needed to find materials better able to resist penetration during construction.

8. MONOLITHIC-SLAB HOUSE MEASUREMENT PROGRAM

8.1. GENERAL

Long term alpha-track measurements were made continuously in the houses on a 6 week cycle. Short term measurements and tests were made when the houses were visited to change the alpha-track dosimeters.

8.2. OCTOBER

The two monolithic-slab houses were almost complete in October. The exterior doors and windows were installed and caulked, and the block walls were painted or stuccoed. The interior walls and ceiling were painted. The baths and showers were in place but the toilets, wash basins, and vanities were still to be installed. The kitchen cabinets were still to be installed in House #1. No interior doors were attached. The floors were uncovered with the bare concrete exposed. The air conditioning system was in place, but the light fixtures and sockets were not connected. No electrical power was available. The passive subfloor exhaust in each house was connected.

The formed opening for the bath drain in house #2 was incorrectly located at the time of pouring the slab, and was not over the drain pipe. The plumber extended the opening 6 inches by chipping away concrete. A tensioned cable ran through the opening, so care had to be taken to avoid damaging the cable. The walls of the opening had been chipped smooth and the debris had all been removed from the pit. These bath pits were supposed to be left unsealed, but the plumber had followed his usual routine in house #1, and poured in asphalt to seal the opening. A borescope was used to examine the opening. The asphalt layer was seen to be continuous over the bottom of the hole, but there was a small area between the drain pipe and the slab that was filled with debris, and was apparently not sealed with asphalt. The asphalt was still fluid, and so it was left to harden until an opening could be made through it to the soil that would stay open.

8.2.1. Shrinkage Cracking

The exposed floor slab in each house received a close visual examination. No cracks were observed, either in the house slab or in the garage where the shrinkage stresses would have been the highest. This showed that the placing and curing procedure used was adequate to prevent shrinkage cracking in this size of slab.

8.2.2. Short Term Measurements

Radon measurements were made in each house with a Pylon AB-5 radon monitor which took a measurement of the radon concentration once an hour. As AC power was not available the units operated on their internal batteries.

The houses were closed up about 9:00 am on the 16 Oct. and the AB-5 units were started about 11:00 am. By that afternoon it was obvious that the radon concentration in both houses was low. It was decided to obtain 24 hours of measurements with the houses and then to disconnect the passive subfloor ventilation systems which had been connected during construction. This would make the houses equivalent to conventional slab houses in their radon-resistance. The increase in radon concentration would be a measure of the effect of the subslab system.

The subfloor ventilation system in each house was disconnected by cutting the exhaust pipe in the attic and covering the open end with two layers of duct tape. The short section of the pipe that passed through the roof was also taped closed, and an empty paint can was inverted over the roof fixture to prevent rain from entering the fixture and wetting the ceiling. This was completed by 10:30, 17 Oct.

In house #1, concentrations during the day ranged from 0.0 to 1.1 pCi/l, averaging 0.6 pCi/l, and at night were 1.1 to 4.1 pCi/l, averaging 2.3 pCi/l. The average concentration before the subfloor system was turned off was 1.5 pCi/l, and was 0.6 pCi/l afterwards, suggesting that the system had no affect on the indoor radon concentration.

In house #2, concentrations during the day ranged from 0.3 to 1.1 pCi/l averaging 0.6 pCi/l, and at night ranged from 1.1 to 3.7 pCi/l, averaging 2.7 pCi/l. The average concentration before the subfloor system was capped off was 1.5 pCi/l, and did not change afterwards, suggesting that the system had a minor effect.

8.3. NOVEMBER

8.3.1. Depressurisation test

The houses were depressurised by a large window fan run on low speed, which showed the air conditioning system and vents to be relatively airtight. The major air leakage paths were at the bottom of the frame walls and openings in the wallboard around plumbing pipes. In both houses the frame wall at the head of the bath was doubled and provided a chimney directly into the attic. Blown attic insulation had fallen down inside this chimney and was lying in the bath pit area. When the inspection door was removed, a considerable airflow was drawn through this route by the fan. There was no visible air movement into the house at any of the closed slab penetrations.

The sanitary fixtures with their water traps had not yet been installed in these houses. The sewer pipe openings had all to be taped closed to prevent sewer gases being drawn into the house.

8.3.2. Short term measurements

House #1 (conventional slab)

In November, the concentration ranged from 1.6 to 2.3 pCi/l, averaging 1.8 pCi/l, with the subslab radon vent system capped and inoperative. When the house was depressurised the average radon concentration fell to 0.7 pCi/l, indicating that the ventilation rate had increased more than the radon supply, and that the pressure-driven radon supply into the house was low.

The 24-hour average radon concentration was measured at a number of locations with charcoal packets. The average concentration in the bath pit and beneath enclosures placed over toilet connections in the floor was between 1.3 to 2.0 pCi/l. These measurements indicated that there was no significant radon entry by those routes. The average concentration in the capped subfloor ventilation stack was 1 300 pCi/l, showing that the radon concentration in the soil directly beneath the house was at least that high.

A hole was dug in the asphalt in the bath pit. Despite the length of time since the pit was filled (60+ days), the asphalt was still semi-liquid. To prevent the asphalt from creeping back into the hole, a 2 inch diameter pipe was placed in the hole through to the fill beneath. Access to the bath pit was poor, and the work had to be carried out using a trowel in one hand and the borescope in the other hand to view the work.

Under conditions of natural ventilation the radon concentration in the house prior to asphalt removal ranged from 0.7 to 2.4 pCi/l, averaging 1.7 pCi/l, and afterwards ranged from 0.9 to 4.2 pCi/l, averaging 2.5 pCi/l.

House #2 {Post-tensioned slab)

The radon concentration in the house ranged from 0.6 to 2.6 pCi/l, averaging 1.4 pCi/l with the bath pit open and the subslab radon vent system capped and inoperative. When the house was depressurised, the average radon concentration ranged from 1.4 to 7.0 pCi/l, averaging 3.2 pCi/l, indicating that there were pressure-driven routes of radon entry, such as the open bath pit.

The 24 hour average radon concentration was measured with charcoal packets. Under conditions of natural ventilation the concentration in the bath pit was 15 pCi/l, and with the house depressurised was 33 pCi/l, confirming that it was a route. The 24-hour average radon concentration in enclosures placed over toilet connections in the floor was between 1.5 to 2.0 pCi/l, indicating that there was no significant radon entry by those routes.

8.3.3. Comment

The plumber visited the house during the tests to install sinks and toilet flanges. The original floor level in this house was about 2 inches too low, When this was corrected prior to pouring, the Styrofoam collars on the sewer pipes were readjusted upward, but they were displaced further upward during the pour, and left only shallow annular depressions around the pipes. The depression was too shallow to fit a standard external toilet flange flush to the floor, but the plumber used a flange that fitted inside the pipe, and needed only a shallow depression around the pipe. General use of this type of flange would eliminate the need for deep collars to provide clearance round the sanitary pipes, and consequently the need to seal round them.

8.4. DECEMBER

8.4.1. Short Term Measurements

The average overnight radon concentrations were measured by charcoal packets. At house #1, the house air concentration was 2.3 pCi/l, the concentration in the opened bath pit was 21 pCi/l, and the concentration in the capped subslab exhaust stack was 3 400 pCi/l. In house #2 the average overnight concentration was 2.5 pCi/l, and the concentration in the unsealed bath pit was 9.4 pCi/l.

Radon fluxes from surfaces were compared by placing a charcoal adsorption detector in a 10 l enclosure with a 0.0576 m^2 opening. The average radon concentration in an enclosure left overnight on the concrete floor of house #1 was 2.5 pCi/l, on the soil adjacent to the house was 4.8 pCi/l, and at 10 m from the house on undisturbed soil the concentration was 11.3 pCi/l. The sand fill that underlies the site was exposed in an utility pit. The radon concentration in an enclosure placed on the sand fill was 25.9 pCi/l.

8.5. FEBRUARY

8.5.1. Short Term Measurements

Short term radon concentration measurements were made in both the houses with AB-5 continuous radon monitors.

In house #1, all measurements were made with the subfloor ventilation system disabled. With the house under natural ventilation (closed), and an opening in the asphalt seal in the bath pit, the concentration ranged from 1.8 to 7.3 pCi/l, averaging 3.6 pCi/l. Asphalt was poured into the pit to close the opening and following this, the concentration ranged from 2.4 to 6.4 pCi/l, averaging 4.1 pCi/l.

In house #2 (lot 23), all measurements were made with the subfloor ventilation system connected. The house was under natural ventilation (closed) and with the bath pit open the concentration ranged from 0.3 to 5.0 pCi/l averaging 2.4 pCi/l. The open pit beneath the bath was filled with 2 gallons of asphalt, and following this concentrations ranged from 0.9 to 4.1 pCi/l, averaging 2.2 pCi/l.

The passive soil-gas vent system in house #1 was reconnected after the measurements were completed. While this was being done, a strong draft was observed blowing out of the pipe before the junction was sealed, The roof vent pipe was on the upwind side of the house at this time. This illustrates the difficulty of ensuring consistent depressurisation with a passive system.

8.6. MARCH

8.6.1. Efflux Testing

Sealing the bath pits with asphalt did not make any appreciable change in the radon concentration, strongly suggesting that these known open soil connections were not the only route of radon entry in these buildings. All other potential entry routes in the sanitary and water systems had received special attention during construction to ensure that there was at least 4 inches of concrete in contact with the pipe, and the pipes were all sealed to the underlying plastic moisture/soil-gas barrier membrane with asphalt. A number of the toilet locations were tested before the fixtures were installed, and soil-gas leakage was not detected at that time.

To recheck these potential entry routes, extensive efflux testing was carried out in both houses. Plastic enclosures were placed round toilets and over openings into walls enclosing plumbing penetrations and the subfloor ventilation system stack. Average radon concentrations over 24 hours in these enclosures were measured with charcoal packets. The night was cool, and heating was maintained in the houses overnight. All concentrations were 1 to 2 pCi/l range, comparable to the general air concentrations in the house, and confirming that there were no large routes of radon entry in the areas tested.

8.6.2. Short Term Radon Monitoring

The radon concentrations in each house were measured with AB-5 monitors under conditions of natural ventilation (closed), and with the floor slab openings sealed and the subslab ventilation system connected. In house #1 the radon concentration ranged from 0.8 to 2.3 pCi/l, averaging 1.5 pCi/l. In house #2 concentrations ranged from 0.2 to 2.5 pCi/l, averaging 1.4 pCi/l.

The highest radon concentrations had always been measured at night, which perhaps was due to inversions raising the radon concentration of the outside air. To check this, the radon concentration of the external air was measured, and found to increase from essentially 0.0 pCi/l during the day to peak concentrations of 1.3 pCi/l at 6:30 pm with another peak of 0.9 pCi/l at 1:30 am. The average concentration for the night time was 0.7 pCi/l. The weather conditions were not favorable for a strong inversion, for there was a breeze present all night, so higher peak radon concentrations are probable. Concentrations in house #1 over the same period ranged from 1.2 to 2.2 pCi/l, averaging 1.5 pCi/l, suggesting that the radon contribution from building materials and soil-gas leakage was about 1 pCi/l.

This may be the explanation for the radon peaks measured on previous visits. The radon levels in each house increased at about the same time, so the radon concentration in the outside air may have increased due to an inversion.

8.7. APRIL

The house slabs received a final inspection. Although the house floors were covered with carpet or tile, the garage slab was still exposed. The shrinkage stresses would be higher here than in other parts of the slab, and this area was examined for signs of cracking. No cracks were visible in either slab, confirming the validity of the recommended improvements in concrete practice.

8.8. LONG TERM MEASUREMENTS

To provide an estimate of the long term average radon concentration, alpha-track dosimeters were placed in each house. As low radon concentrations were expected, close to the detection limit for the exposure times used, unexposed control dosimeters were included with each set sent for processing, The difference between the readings on the exposed dosimeters and controls averaged less than 1 pCi/l, and the radon concentration in the exterior air may have accounted for 50% of the difference. The results are shown in Tables 1 and 2.

9. CRAWLSPACE HOUSE MEASUREMENTS

9.1. GENERAL

The footings for the house were poured in July 1986, but actual construction of the house was delayed until September, when the block foundation wall was laid. The plan had been for the house to have an airtight floor made from precast concrete sections with a thin concrete topping to level it, but this was changed to a conventional suspended wood floor at the request of a purchaser.

9.2. OCTOBER

The joists and plywood subfloor had been laid, the external frame walls were covered with sheathing, and the internal frame walls had been erected. The roof trusses were being moved into place. The crawlspace was examined, there are 14 ventilation openings each of 1 ft^2, with at least 2 openings on each side of the house. The internal centreline supports are provided by pillars, so the ventilation flows are unobstructed.

9.3. DECEMBER

The house was closed in, but work was still in progress, and since doors and windows were routinely left open few measurements could be made. The work had nearly progressed to a stage where the house would be closed and locked to prevent vandalism, so alpha-track dosimeters were placed in the house and crawlspace to provide an indication of the ratio of radon concentrations in the house and crawlspace. A short term measurement with charcoal packets found the average overnight concentration in the crawlspace was 1.7 pCi/l.

The radon flux from the sand placed over the plastic membrane in the crawlspace was estimated by placing a charcoal packet overnight in a 10 l enclosure with a 0.0576 m^2 opening. The average concentration was 5.7 pCi/l. The concentration in the crawlspace air itself was 2.0 pCi/l.

9.4. FEBRUARY

The final finishing touches of painting internal and external trim were under way, The alpha-track dosimeters placed in the living space of the house on the previous visit were collected and replaced. They had been in position when the house walls were painted, and had both been sprayed with paint. The filter was not clogged, and so this is not expected to affect the measurements. The dosimeters in the crawlspace itself were left in position to accumulate a larger exposure, as the anticipated exposure was close to the background value. The purchasers moved into the house in March 1987.

9.5. APRIL

A direct test of the value of the ventilated crawlspace as a radon-barrier was carried out by closing the ventilation openings in the crawlspace. Plastic sheets were tacked to the internal wood frame that supported the vermin grilles over each ventilation opening. This greatly reduced the ventilation area in the crawlspace. The radon concentration was measured in the crawlspace and in the house with Pylon AB-5 radon monitors.

A stiff breeze was blowing on the first day of tests, and the crawlspace was well ventilated even after plastic was placed over the openings. The breeze blew the plastic sheets away from the frames, and there was a draft into the crawlspace from each upwind opening. The radon concentration was low (less than 1 pCi/l) and remained low for several hours after the ventilation area was reduced at 17:00. In the early hours of the morning, when wind speeds were at their lowest, the concentration rose rapidly to range between 10 to 14 pCi/l, and then dropped to 1 pCi/l as the wind speed increased during the morning. The concentration in the house was initially 0.5 pCi/l, and rose in synchrony with the increase in crawlspace concentration to 5 pCi/l. A similar rise was observed the following night.

This shows that about 30% of the house ventilation air enters the house from the crawlspace via openings in the wooden floor. The crawlspace is only effective as a radon-barrier as long as the ventilation openings are unobstructed.

This house is underlain by a 30 mil PVC sheet. A single drain hole was cut in one half of the membrane during construction, and there are no other known holes. All holes detected during installation were patched, and the sheet covered with a layer of sand for protection. The sand was generally damp, with very damp patches, but with dry areas close to the ventilation openings in the walls. This suggested that the source of the moisture was not rain driving in through the ventilation openings, but rather to soil moisture entering from below via punctures or openings in the PVC sheet. The sand used to cover the membrane had many small stones in it, so perhaps the membrane was extensively punctured by them after installation by the extensive foot-traffic that took place when the floor was built and the plumbing installed.

9.6. LONG TERM MEASUREMENTS

Alpha-track dosimeters were placed in the house to provide an estimate of the long term average radon concentration. The difference between the readings of the exposed dosimeters and the controls averaged less than 1 pCi/l, and the radon concentration in exterior air may have accounted for 50% of that difference. The results are shown in Table 3.

10. OTHER MEASUREMENTS

10.1. RADON IN SOIL-GAS MEASUREMENT

Alpha-track soil-gas dosimeters were installed in December at 12 inches depth adjacent to each house, in accordance with the protocol used in the State wide survey. A fourth was installed in undisturbed soil at 30 feet from house #1, and a fifth in the sand that underlies the site. Four cups were recovered in February. The site had received final grading, and the excavation into the underlying sand that contained the fifth dosimeter had been filled in.

The concentrations were:-

house #1	3 700 pCi/l
house #2	3 100 pCi/l
house #3	5 300 pCi/l
undisturbed soil	9 800 pCi/l

These concentrations are well above normal for Florida, and are close to the maximum value of 6 600 pCi/l measured in the State-wide survey. Only 1% of the house sites measured in that survey had soil-gas concentrations in excess of 1 350 pCi/l, so there is no doubt that this site is much higher in soil-gas radon than most areas in Florida.

10.2. SHORT TERM MEASUREMENTS

Charcoal canisters from the State-wide survey were exposed in the houses for 3 days in January 1987. The results were :-

house #1	0.8 pCi/l
house #2	1.0 pCi/l
house #3	0.9 pCi/l

The Polk County Health Unit ran a Radon Progeny Integrating Sampler Unit in the houses for 4 days in March 1987. The results were :-

house #1	0.012 WL
house #2	0.012 WL

Electrical power was not available in house #3.

These results agree well with the other measurements made in the houses, and confirmed that the radon concentrations were low.

10.3. GAMMA RADIATION

10.3.1. House #1

Radiation fields around the house were 11 uR/h at the front of the lot, 8 uR/h at the sides and 13 to 14 uR/h at the rear. The spoil pile of surface material removed from the sites read about 20 uR/h. The last material on the pile would be the most radioactive material from the deepest excavations, and so the higher field is to be expected. The field inside the house was 5 to 6 uR/h.

10.3.2. House #2

Radiation fields around the house were 14 uR/h at the front and side of the lot, and 10 uR/h at the rear. The field inside the house was 5 to 6 uR/h.

10.3.3. House #3

Radiation fields around the house were 15 uR/h at the front, and from 9 to 10 uR/h at the rear and side. A sand pile on the site gave 6 uR/h. The "low activity" fill used to build up the carport area gave 7 to 8 uR/h. This was a disappointment, as a premium price had been paid to get fill from outside the immediate area, in the expectation that it would have a lower radium content than that locally available. However, the last fill placed would have been from the bottom of the pile, and may have contained some active material from the site, so the bulk activity of the sand could be lower than indicated by this measurement.

The field in the crawlspace was 9 uR/h, and at 1 m height above the house floor the field was 6 uR/h.

10.3.4. Comment

These measurements confirm the general picture that the site is relatively high in gamma activity, and the building materials low. The concrete floor slabs and block walls are thick enough to effectively screen the house occupants from most of the site radiation.

10.4. VENTILATION RATE MEASUREMENTS

The average ventilation rate was estimated in these houses over the period February to March 1987 using passive perfluorocarbon tracers and adsorbers. The ventilation rate in all three houses was approximately 0.5 air changes per hour. The presence of occupants would lead to higher ventilation rates, and lower radon concentrations.

10.5. BUILDING MATERIAL RADIOACTIVITY

Samples of building materials and fill were sent to the Polk County Health Unit for radium analysis, The results were :-

Sample	^{226}Ra (pCi/g)
Concrete Aggregate from houses #1,#2	3.7
Concrete Sand from houses #1,#2	0.3
Portland Cement from houses #1,#2	0.9
House #3 (lot 24)	
Crawlspace fill	0.6
Footer concrete	0.7
Pea gravel footer concrete aggregate	0.9
surface soil beneath liner	3.1

11. ADDITIONAL COSTS

The additional costs of each of the features incorporated in these buildings were estimated with the assistance of the builder, who provided access to his records and subcontractor billings. He was recompensed for his additional costs as determined by this analysis. A breakdown of costs is provided in APPENDIX A - BUILDER COSTS.

In summary, addition of the recommended radon-resistant features to a standard monolithic-slab would add about $260 to the cost of the slab.

A heavily reinforced post-tensioned radon-resistant slab, such as might be needed in areas of unstable ground conditions, cost $2 125 more than a standard slab to construct. In addition to the direct construction costs, there were additional charges totaling $725 for soil bearing tests to determine the amount of reinforcing needed, the design of the reinforcing cable pattern, and a concrete strength test to confirm that the concrete was strong enough to stand the stress of tensioning the cables. This charge would not apply to every foundation if the same builder were to build several houses in the same development.

A crawlspace with a wooden floor cost $5 170 more than a radon-resistant slab.

A passive subslab ventilation system cost about $480 to add to a house.

The site membrane cost about $2 100 to add to a house.

12. DISCUSSION OF RESULTS AND RECOMMENDATIONS

12.1. PERFORMANCE

The average radon level in these three houses built on reclaimed phosphate mining land with elevated radium content was consistently low, less than 2 pCi/l. This shows that houses can be built to resist the entry of soil-gas. There was no significant cost penalty for this if a monolithic-slab foundation was used. In fact, the estimated cost of a radon-resistant monolithic-slab was several hundred dollars less than that of a conventional concrete block foundation of a comparable size, and only $260 more than a standard monolithic-slab.

The radon levels in these houses even with the secondary anti-radon measures defeated (bath pits unsealed, subslab vents capped) are very low, considering that the measured near-surface radium content of the mining debris beneath them ranges from 3 to 10 pCi/g, well above the normal level of less than 1 pCi/g in Florida soils. This might be a result of local soil conditions, but the sand/clay layer over the sand tailings was disturbed and perforated by site grading and installation of the plumbing and sewer services, and is certainly not impermeable.

This suggests that it may not be necessary to have an absolutely airtight slab to achieve radon-resistance. If low radon concentrations are achieved with the 8x16 inch bath pit open to the soil, then floor cracks of one or two square inches open area are not likely to be major entry routes. As the elevated radon concentrations seen in existing houses with concrete block foundation walls are mainly due to soil-gas entering the house via the very large area peripheral gap between the edge of the floor-slab and the outer skin of the top block in the foundation wall, this also suggests that small modifications in conventional block construction to close this opening might provide adequate radon-resistance. For example, the open area could be greatly reduced by ensuring that the floor-slab was poured completely over the top voids of the foundation walls, or else by using a solid or closed block at the top of the foundation walls. These modifications could reduce the total area of soil connections to be in the same range as these unsealed monolithic-slab houses. As the floor-slab in conventional housing rests on fill, the source strength could also be reduced by using fill of low radium content. Taken together, these steps might allow concrete block foundations to provide low radon housing even in areas of elevated soil radium.

12.2. RADON-RESISTANT FEATURES

These houses contained a number of different radon-resistant features for test and costing purposes. Not all features proved effective.

12.2.1. Concrete Improvements

Higher strength concrete, the addition of a plasticiser, and use of sprinklers for curing were features suggested to improve the resistance of the slab to shrinkage cracking. They worked very well, for the slabs did not crack even in the areas of greatest stress, and cost a relatively small amount. As the soil at the site is stable, the expectation is that the slabs will remain crack-free indefinitely.

12.2.2. Subslab Membranes

A higher quality moisture-barrier membrane material than usual was used beneath the slabs, and the joints were all sealed with asphalt. Despite considerable care, the membrane was repeatedly punctured by the ends of the reinforcing mesh. In matters of performance there did not seem to be any improvement over the standard polyethylene sheet. The opaque sheet also made it difficult to check the position of plumbing piping before the pour.

As the membrane was repeatedly punctured, there does not seem much point in sealing the junctions between sheets in an attempt to produce a completely airtight membrane. Simply lapping the sheets by a foot will provide adequate airtightness. On the other hand, sealing round the plumbing penetrations in the membrane is easy and cheap, and as they are the locations of deliberate openings in both the slab and membrane, is a cost-effective action.

Experience with the use of a heavy PVC membrane to cover the site suggested that even substituting that material for the conventional polyethylene moisture-barrier sheeting, at an additional cost of about one thousand dollars, would not guarantee an unperforated membrane. The economics of transforming the moisture-barrier into a soil-gas-barrier are not favorable.

12.2.3 Collars round Plumbing

The collars applied round the sanitary fixture pipes were all displaced upwards by the concrete, leaving only shallow depressions for the plumber to connect the traps and flanges. All the pipes were sealed to the plastic membrane and there was at least 4 inches of concrete in contact with the pipes. Testing showed that soil-gas and radon did not leak into the house at the junction between pipe and concrete even though there was no additional sealant between the concrete and the pipe. The plumber had no difficulty in attaching the traps and flanges. The use of short collars in conjunction with sealant on the membrane is an alternative to long collars with sealant in the gap between pipe and concrete.

12.2.4 Passive Subslab Ventilation Systems

The low radon levels in these houses even with unsealed openings in the floor-slab made it difficult to evaluate the effect of the passive subslab ventilation systems. The effect, if any, was small. As installed, some wind directions would pressurise the system, which should lead to an increase in the pressure driven radon supply rate. The results from this study are insufficient to show that passive or active subfloor systems would be effective in excluding soil-gas if there was a failure in the slab. This may be due to site specific causes, and the concept cannot be rejected on the basis of these limited tests.

12.2.5. Subsite Membrane

The subsite membrane was relatively easy to place on the site, but significant changes to standard practice had to be made to install the footings on top without puncturing the area inside the building, Field joints were very difficult to make with adhesive, folded and mechanically seamed edges would be preferable for routine use. The concrete in the footings formed a good seal against the membrane, but this created difficulties in working when the footings filled up with water after rain.

For this system to be effective, not only must the membrane remain unpunctured while a house is built on top, but the subgrade portion of the foundation walls must be airtight too. The 30 mil PVC sheet was the type of material used to line waste pits, but it was not tough enough to resist punctures on a building site. Thicker, tougher and even more expensive material would be needed to assure a puncture proof membrane.

The subgrade part of the concrete block foundation walls was not airtight, as shown by the rapid rise in radon concentration in the crawlspace when the ventilation was reduced.

Bearing in mind the likely expense of a puncture proof membrane, and the modifications in building practice needed to make the system foundation walls airtight as well, a major effort would be needed to develop a building system to use a subsite membrane effectively. Currently, the subsite membrane does not seem to be a concept that could be used by the building trade in a cost effective manner.

12.2.6. Crawlspace Houses

There is no doubt as to the effectiveness of a ventilated crawlspace in isolating the house from the ground. Unfortunately it is the most costly solution. The cost of footings and foundation walls alone is nearly equal to the cost of a radon-resistant slab, and then there is still the cost of the floor. A suspended prestressed concrete slab floor would be cheaper than a suspended wood floor, but the cost would still be a few thousand dollars. This would be the premium paid for radon-resistance.

12.3. RECOMMENDATIONS

The ability of the suggested improvements in concrete practice to produce crack-free slabs has been questioned. The crack-resistance of concrete can be increased greatly at low cost by the use of micro-fibers dispersed in the mix. A small, long-term program to monitor the performance of a few test slabs using this and other techniques suggested by the building industry would provide a valuable reassurance that concrete slabs can be produced that will remain crack-free.

A specific test program is required to demonstrate that passive subfloor soil-gas collection systems will work in the housing styles common in Florida; and to determine how floor-slab construction methods should be modified for lowest cost and good performance of either active or passive systems.

The most common form of construction in Florida uses concrete block foundation walls. A small program to test methods to make this type of foundation radon-resistant would be valuable to the building industry over the entire State.

13. CONCLUSIONS

Radon-resistant slab-on-grade foundations can be produced cost-effectively by the use of improved monolithic foundations. The recommended improvements are use of sealed plumbing openings in the slab and subslab barrier membrane, use of stronger concrete with a plasticiser to discourage watering the concrete, and prompt watering of the slab for at least the first day to cure it wet. The total cost of the radon-resistant slab is estimated to be less than that of a conventional concrete block foundation.

Additional radon-resistant features, such as higher quality vapor-barrier material, or passive subslab ventilation systems, did not appear to have any value in this study.

A subsite membrane was found difficult to use, and not very effective. More work would have to be done to develop a building system to use a membrane effectively. The cost of the membrane material will be high, for it must be tough enough to resist the abuse of having a house built on top of it.

A ventilated crawlspace will effectively isolate a house from the ground, as long as the ventilation openings remain open. The cost of a crawlspace house is several thousand dollars higher than that of a house on a standard foundation, which is too high for these houses to compete on a price basis in the moderate priced housing market.

TABLE 1

ALPHA TRACK MEASUREMENTS IN HOUSE #1

	Average pCi/l
October-November: subslab system on, bath pit sealed	
Living room	2.0
bedroom	2.1
garage	2.3
control	2.3
November-December: subslab system off, bath pit open	
living room	3.5
bedroom	4.2
control	3.4
December-February: subslab system off, bath pit sealed	
living room	2.0
bedroom	2.3
bath pit	2.7
control	1.5
February-April: subslab system on, bath pit sealed	
living room	2.1
bedroom	2.5
bath pit	3.6
control	0.9

TABLE 2

ALPHA TRACK MEASUREMENTS IN HOUSE #2

	Average pCi/l
October-November: subslab system on, bath pit open	
Living room	2.5
bedroom	2.7
garage	2.8
control	2.3
November-December: subslab system off, bath pit open	
living room	3.7
bedroom	4.2
control	3.4
December-February: subslab system off, bath pit unsealed	
living room	1.8
bedroom	2.3
bath pit	6.6
control	1.5
February-April: subslab system on, bath pit sealed	
living room	1.9
bedroom	1.3
bath pit	1.6
control	0.9

TABLE 3

ALPHA TRACK MEASUREMENTS IN HOUSE #3

	Average pCi/l
December-February: house closed but work in progress	
living room	2.7
bedroom	3.0
control	1.5
February-April: house closed and occupied part of time	
main floor	1.1
crawlspace (December - April average)	1.3
control	0.9

APPENDIX A - FOUNDATION COSTS

ESTIMATED COST OF STANDARD CONCRETE BLOCK FOUNDATION

ITEM	COST$
Basic labor and material costs	
footings	1 530
concrete block foundation wall	1 200
sand fill inside foundation 90 cu.yd at $4.50/yd	405
labor to spread and compact fill	195
estimated cost of 4" concrete floor slab	1 600
Total estimated cost for 1 200 ft² standard foundation	4 930
Total estimated cost for 1 400 ft² standard foundation	5 340

IMPROVED MONOLITHIC-SLAB

ITEM	COST$
Estimated Basic cost of 1 700 ft^2 slab	3 200
Extra material or labor costs	
higher strength concrete 3 000 psi rather than standard 2 500 psi concrete	115
plasticiser in the concrete to avoid watering by the crew	105
"Moistop" reinforced vapor-barrier rather than "Visqueen" polyethylene sheet	130
labor and material to seal joints in barrier	255
labor for plumber to seal openings in the barrier around water and drain lines	30
labor for plumber to seal openings in slab round drains and traps	10
Total extra cost for radon-resistant features	645
Total cost of slab as built	3 845
Estimated cost of radon-resistant slab with standard barrier	3 460

POST TENSIONED MONOLITHIC-SLAB

ITEM	COST$
Estimated Basic cost of 1 425 ft^2 slab	2 910
Additional labor or material costs	
cost of extra reinforcing	1 225
plasticiser in the concrete to avoid watering by the crew	105
“Moistop” reinforced vapor-barrier rather than “Visqueen” polyethylene sheet	130
labor and material to seal joints in barrier	255
labor for plumber to seal openings in barrier at water and drain lines	30
labor for plumber to seal openings in slab at drains and traps	10
Ancillary costs	
reinforcing design	350
soil tests needed for design	475
lab tests	180
Total extra cost for post tensioned reinforcing and radon resistant features	2 850

PASSIVE SUBSLAB VENTILATION

ITEM	COST$
Basic material and labor to install subslab piping	330
additional labor to install plumbing 5” deeper than normal to make room for drain pipe to pass above	50
installation of above-grade piping and roof vent	100
Total cost of passive subslab system	480
(System could be made active for cost of fan plus labor to install and cost of electrical connection) estimated at	200
Total cost of active subslab system	680

SUBSITE MEMBRANE

ITEM	COST$
Membrane 2 000 ft^2 at 30¢/ft^2	600
Additional labor and material costs	
excavation to bring whole site to footer level	515
labor to place and join membrane	250
sand and labor to spread on membrane for protection	510
additional labor to place footing forms without damaging membrane	100
concrete pump to place footing concrete	100
Total cost of site membrane	2 075

CRAWLSPACE HOUSE

ITEM	COST$	
Basic labor and material costs		
footings 198 ft	1 530	
material		940
labor		590
concrete block foundation wall 198 ft	1 650	
material		980
labor		670
termite shield and anchor bolts for wooden floor	370	
material		165
labor		205
wooden floor	4 470	
material		3 300
labor		1 170
extra labor for plumber to hang plumbing from joists	320	
Total construction cost	8 340	
Estimated cost of 1 200 ft² radon-resistant monolithic-slab	3 170	
Additional cost for crawlspace and wood floor over slab	5 170	