ENVIRONMENTAL RADON: OCCURRENCE, CONTROL, AND HEALTH HAZARDS

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Chapter Three

THE INDEX HOUSE: PENNSYLVANIA RADON RESEARCH AND DEMONSTRATION PROJECT POTTSTOWN, PENNSYLVANIA, 1986-1988

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INTRODUCTION

During the closing days of December, 1984, there was brought to the attention of the Pennsylvania Department of Environmental Resources (DER), Bureau of Radiation Protection, a sequence of events which would have enormous impact on radiation protection programs at the state and national levels in the following years.

Until that time, the attention of the Bureau had been focused upon the accident at Three Mile Island and upon the many changes of policy and procedure required to respond to lessons learned from that event. In those years and in the twenty or so years of organizational life of the Bureau prior to that event, the business of the agency had dealt with a specific family of institutional and technical matters. The technical matters included interest in radiation-producing equipment such as X-ray generators and accelerators, discrete sources of radioactive materials and nuclear power stations. The institutional context of these radiation sources placed them, for the most part, in the hands of trained professionals with the knowledge to deal responsibly with the associated radiation hazard within an established structure of regulation, registration and licensure. The radiation protection community was well settled into a pattern suited to deal with controlled radiation sources used in a known setting. Procedures and standards had been worked out, authorities and responsibilities were established and the system was stable. Within this framework, natural radioactivity was viewed as a source of potential error in sensitive radiation measurements, and as a datum to which other radiation measurements might be referred (eg: "twice background"). It was a kind of neutral-to-benign environmental characteristic, ubiquitous and more or less constant. As a natural feature of the environment, "background" radiation was assumed to be harmless and beyond regulatory concern.

Under these circumstances, it is not surprising that in 1984 radiation protection agencies like the DER were unprepared to deal with natural radiation problems like indoor radon contamination. There was no existing system to identify radon sources, comparable to the registration and licensing of medical and industrial radiation sources. Neither was there any identifiable "user" who could be considered responsible and liable for remediation costs. The kinds of radiation-producing equipment and sources of radioactive materials then subject to regulation employed a common language and a familiar set of units; the language used in radon measurements, units, mechanisms and controls was to a large extent alien. In short, no radiation protection infrastructure existed to deal with the problem of radon contamination, and no one knew what to do about radon contamination once it was identified.

All of this was about to change.

DISCOVERY, DECEMBER 19, 1984

About noon of December 19, 1984, the Senior Health Physicist at the Philadelphia Electric Company's Limerick (Nuclear) Generating Station called the Department of Environmental Resources with a question which soon proved to be a profound, world-class problem. A contract engineer working at the facility had been tripping the newly installed exit portal monitor every time he had reason to leave the site. Because tripping the portal monitor for any reason caused an administrative burden to the facility and delays and inconvenience to the engineer, a thorough investigation was immediately undertaken. Inasmuch as the reactor had not yet achieved criticality, fission products could not be responsible for the contamination the engineer was carrying past the exist portal monitor. This conclusion was quickly confirmed by gamma spectrometric analysis of the engineer's clothing, which was found to be contaminated by beta- and gamma-emitting decay products of radon.

The engineer had already begun to suspect that he was bringing the contamination from his home. Earlier that week he had used the portal monitor on his way into work, at which time the contamination on his clothing and his person set off all the detectors in the array. (It is useful to point out that the detectors used were large-area thin window proportional counters which are exquisitely sensitive to beta radiation as well as gamma emission. This makes them good detectors for reactor-produced fission products, all of which are beta emitters. It also makes them excellent detectors for radon decay products, several of which are beta emitters as well.) No one could dispute the engineer's conclusion that the source of the contamination was his own home; he asked the utility to check it.

INITIAL INVESTIGATIONS

The utility arranged for its consultant to carry out 'radon' measurements in the engineer's house. The consultant employed a modified Kusnetz technique which uses airborne particulate alpha activity, with corrections, to determine the concentration of airborne radon decay products (Kusnetz, 1956). The unit of measurement is the "Working Level" (WL), which finds its origins in uranium mining. At first glance, a "Working Level" sounds innocuous, but in actuality continuous exposure to one Working Level delivers about 83 millirem per hour or 730 Rem per year to the bronchial epithelium.

The results of that initial survey, presented in Figure 1, were disturbing even with our limited level of understanding at the time. Radon decay product concentrations well in excess of 10 Working Levels were found in the house. Duplicate measurements yielded equal or even higher results, in some cases approaching 20 Working Levels. Due to the limitations of the sampling and counting arrangements which had been assembled on short notice, some uncertainty could be assigned to the absolute values observed, but the order of magnitude was certainly correct.

Because the problem appeared to be serious but unrelated to the operation of the Limerick Generating Station, the Senior Health Physicist asked the Bureau of Radiation Protection to take up the problem and talk with the engineer. The Bureau suggested a one day delay to allow its staff to become familiar with the language of radon, to gain some understanding of the risks presented by the radon concentrations involved, and to determine what steps the agency might take to help correct the situation.

PREPARATION FOR THE FIRST VISIT BY DER/BRP

During the next twenty-four hours (December 20) the Bureau staff studied NCRP reports 77 and 78 (NCRP 84, 84-a), called federal agencies concerned with the issue, notified the DER management, estimated radiation doses due to radon exposure, and considered preliminary responses to the property owner's concerns.

On the following day, December 21, the problem was discussed with the property owner by telephone. He was justifiably concerned and asked whether

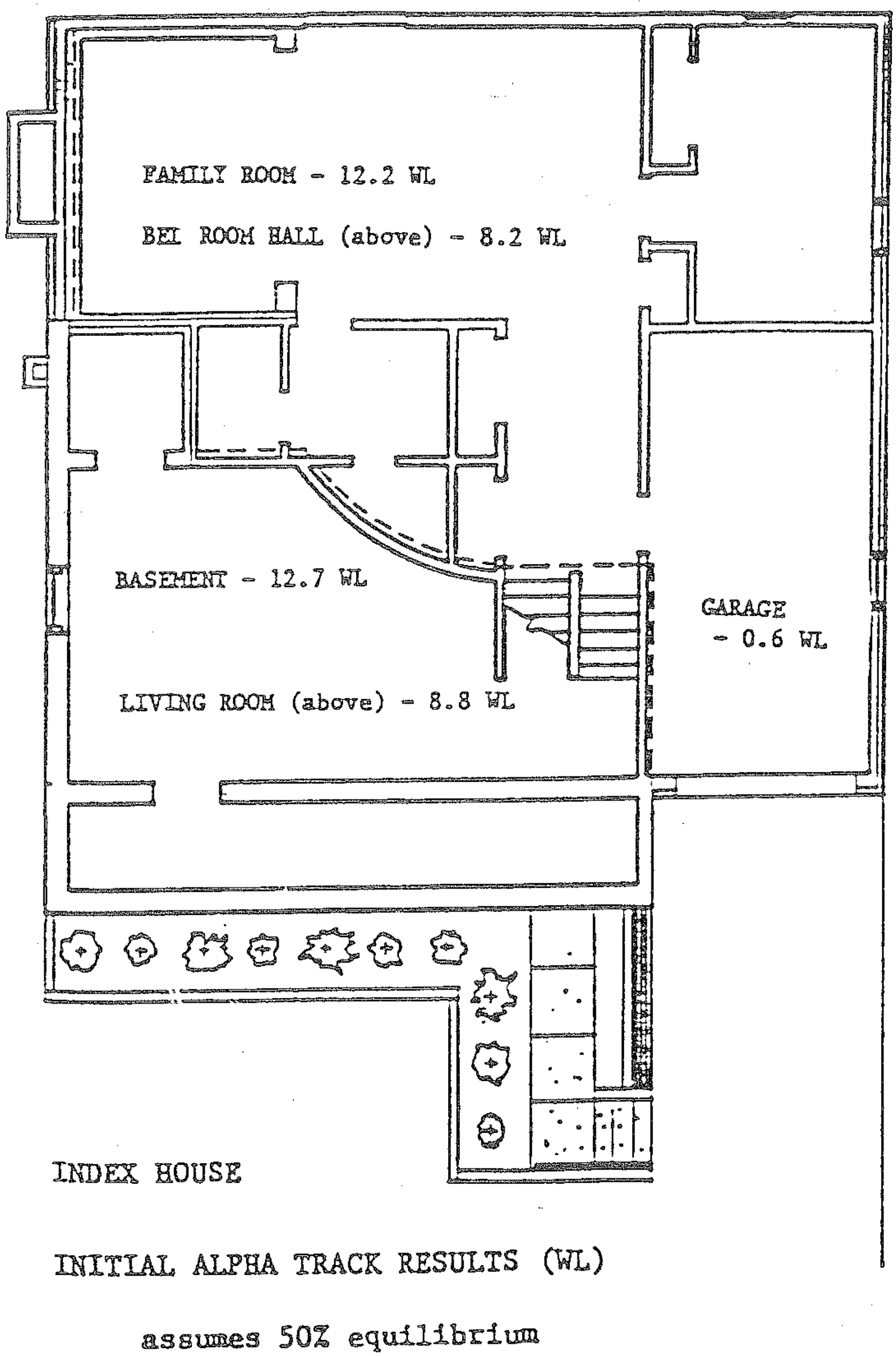

FIGURE 1. Floor plan of the Index House, showing initial alpha-track radon measurements expressed in Working Levels, assuming 50% equilibration.

he should get his wife and two small children out of the house. Since the dose equivalent to the bronchial epithelium from even 10 WL is about 0.8 Rem per hour, he was encouraged to do so. Arrangements were made for the Bureau staff to gain access to the house to make independent measurements on December 26th. The family spent the holidays with relatives in a neighboring state.

During the two business days between the initial contact and the first visit to the property, the focus of the Bureau's effort was on gathering and evaluating the available instruments, devices and methods with which to approach the problem. Among the radon sensors selected were alpha track detectors. These are passive film detectors which are exposed for several days (or longer), then developed chemically to make damage tracks in the plastic caused by the passage of alpha particles visible under the microscope. The number of alpha tracks, adjusted for the exposure time interval, is related to radon concentration in the air. The results are expressed in picocuries (of radon) per liter of air (pCi/L). Based on the sensitivity of the detectors used, it was expected that an exposure time of at least one week would be required. In an attempt to acquire earlier results, air samples were also taken using activated charcoal. This method depends on the adsorption of radon gas by the charcoal, with subsequent counting of ingrown decay products by gamma spectroscopy in the Radiation Measurements Laboratory in the DER laboratory at Harrisburg. Additional observations were made in the house using microR meters for measurement of low intensity gamma radiation, and a thin window alpha scintillation survey meter. Finally, thermoluminescent dosimeters (TLD's) for passive longer-term measurement of gamma radiation were annealed and packed.

During the same two days, geological aspects of the problem were investigated in an effort to identify possible source(s) of the radon gas. The house is situated on an edge of the Reading Prong, a physiographic province extending from near Reading, Pennsylvania, northeastward past Allentown, Bethlehem and Easton, into New Jersey and New York. The area occupied by the Prong in Pennsylvania is about 300 square miles, underlain by Pre-cambrian metamorphic rocks (mainly granitic gneiss) which contain moderate concentrations of uranium and thorium. The landscape is physiographically distinct, being somewhat hilly compared with the surrounding countryside, and is easily distinguished from an aircraft.

On December 26th, several of the BRP staff met the engineer and his wife, and visited the house. The house is a split-level style. The ground level garage with kitchen above constitutes one portion, and the balance of the house, basement and family room below and bedrooms, living room and bath above, the other. The house is heated by oil-fired hot water; domestic water is drawn from a private well; sewage disposal is by an on-lot septic system. The house is located in a neighborhood which until relatively recently had been an orchard. The site upon which the house is situated slopes steeply downward from the road to the north edge of the property. In 1984 the house was seven years old, and had had two previous owner-occupants. The engineer and his family had lived there for just under one year.

FIRST VISIT, DECEMBER 26, 1984

During the visit of December 26th, duplicate alpha-track detectors and duplicate TLD's were posted in the on-grade garage, in the below-grade family room, in the living room, and in the bedroom hall. Since the couple expressed some concern that the source of the radon might be the structural materials of the house, a single alpha-track detector was placed in a standpipe serving the septic system. The rationale for the standpipe alpha detector was that if a detector exposed to soil gas but outside the house showed high readings, the source of the radon was probably soil gas rather than building materials. Both TLD's and alpha-track detectors were to be exposed in place for seven days.

Air samples collected on activated charcoal were analysed by gamma spectroscopy using an intrinsic germanium detector. Since values for collection efficiency of radon gas were not available from the manufacturer, the results could not be used for direct measurement of radon gas concentration. The gamma spectrum analyses did show, however, that if thoron was present, its concentration was vanishingly small compared to radon. If thoron (^{220}Ra) were present, it would seriously complicate subsequent measurements and dose estimates. Several gamma measurements were made using the microR meter. The highest measurement was 140 microR per hour in the service area of the basement. The gamma exposure rate in the house was a combination of gamma 'shine' from the airborne radon decay products plus gamma 'shine' from uranium and its decay products in the bedrock beneath the floor. Measurements in the back yard ranged from 40 microR per hour, presumably all from ground 'shine' from radon decay products in the native soil. The alpha survey meter was not directly useful in making measurements in the house since the plateout of alpha-emitting radon decay products on the window of the detector yielded a background which ingrew significantly with time. (It should be noted that radon decay products produced by alpha decay, particularly polonium-218, are born with a net positive static charge due to the stripping off of orbital electrons from the atom during decay recoil. This charge drives the daughter atom to attach to any surface which satisfies the charge requirement. Common attachment surfaces include airborne dust particles, clothing, detector windows, lung epithelium and television screens.)

Arrangements were made to return to the house on January 2, 1985, to collect the passive detectors and to take samples of soil, well water, and other materials. During the drive back to the rendezvous point a microR measurement indicated a gamma intensity in the vehicle of 70 microR per hour. At the rendezvous point, up to 100 microR per hour was recorded on staff clothing. Normal background in the area is 10-12 microR per hour. Staff exposure time in the house had been less than two hours. It was now quite clear that the radon decay products adhering to the engineer's body and clothing would have been sufficient to activate the portal monitors at the Limerick plant.

SECOND VISIT, JANUARY 2, 1985

On January 2nd staff members from the Bureau of Radiation Protection returned to the house to collect the passive radon samplers set out inside the house on the visit of December 26th. Well water and outside soil samples were collected at the same time. Alpha-track detectors and TLD's placed in the house during the earlier visit were collected for analysis. The observed radon concentrations and TLD results are presented in Tables 1 and 2, and Figure 1, respectively. The same data, normalized to one year, are shown in Figure 2 by location in the house. Analysis of the well water sample by gamma spectroscopy showed a radon concentration of 15,000 picocuries per liter. Although high, this value is not disproportionately high when compared to well water samples collected from other households in the region. The soil samples were analysed for radium by gamma spectroscopy and found to range from 1.7 to 16.9 picocuries (radium) per gram. These values appear to be significantly higher than the national average (approximately 1 picocurie per gram).

During the visit on January 2nd, the staff observed that the family had returned to live in the house. This was not unexpected, since they had so simple alternative available, but it appeared inadvisable. On January 5th a letter from the Secretary of DER was hand-delivered to the family recommending their vacating the building. They moved out shortly thereafter.

TABLE 1

*Index House, Radon Concentrations, Expressed as Radon Concentration, and Working Levels (Average of Duplicates)**

Location	Radon Concentration pCi/L	Working Levels**
Garage	114.2 ± 10.2%	0.57
Basement	2535.2 ± 4.3%	12.68
Family Room	2441.3 ± 4.4%	12.21
Living Room	1753.1 ± 5.2%	8.76
Hall - Bedroom	1642.7 ± 5.4%	8.21
Septic Standpipe	2666.8 ± 4.2%	13.33

* Exposure time: 7 days.

** Assumes 50% equilibrium with Rn concentration divided by 200 to yield radon decay product concentration in Working Levels.

JANUARY-MARCH, 1985

Following the January visit, efforts of the BRP staff were concentrated on the many problems associated with devising a remediation plan. The issue was extremely complicated. No existing government agency was authorized to carry out remediation of the property, even if funds were available to defray the cost. Only two engineering firms in North America had any experience in dealing with indoor radon contamination, and that experience was confined to correction of the problems resulting from the use of uranium mine and mill tailings in house construction. There was some question whether that experience could be applied directly to the present problem.

APRIL-JUNE 1985

In early April, the Philadelphia Electric Company, owner of the Limerick Generating Station where the problem was first discovered, decided to undertake the remediation of the house as a research project to determine whether a house with such a profound indoor radon problem could be corrected at reasonable cost, and to evaluate the effectiveness of various remediation procedures. The Company contracted with ARIX, of Grand Junction, Colorado, one of the two North American firms experienced in radon remediation, to conduct the demonstration project. The project was conceived and planned as a multi-phase effort.

Phase One: The first phase consisted of excavating around the three below-grade foundation walls to the footing. The house is set into the hillside in such a way that the fourth foundation wall is wholly above grade. After sealing all foundation cracks with hydraulic cement, a sealant membrane of TROCAL (registered trade mark) was fastened to the outside of the wall using sheet metal flashing at the top edge. A four inch perforated drain tile was installed on compacted roadbase crushed stone at the level of the footing, draining downhill

TABLE 2

*Index House, TLD Results (Average of Duplicates)**

Location	mrad/std. month**	mrad/year
Garage	42.4	509
Basement	82.4	989
Family Room	74.1	890
Living Room	71.6	859
Hall - Bedroom	63.0	757

* Exposure time: 7 days.
** Standard month: 30.4 days.

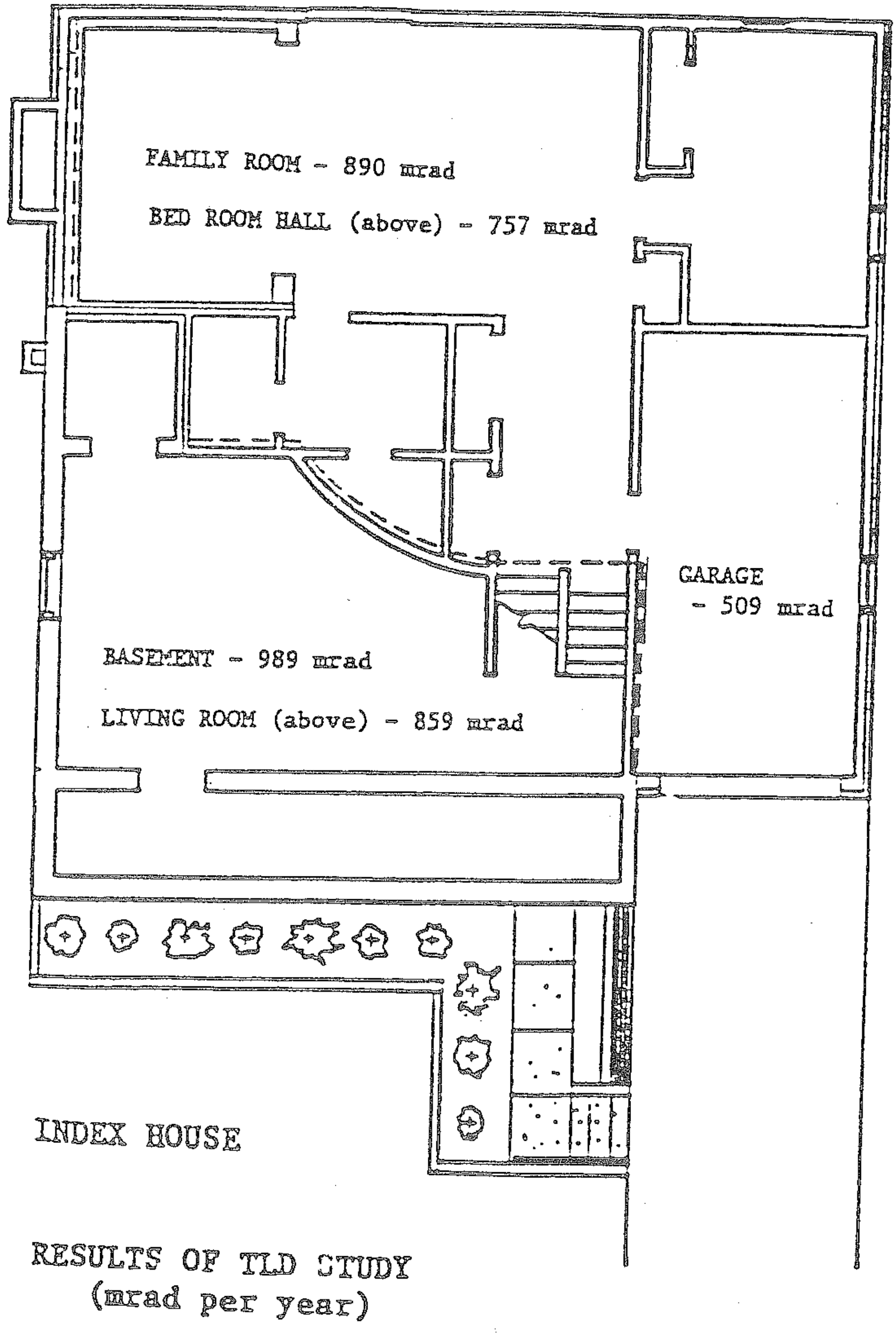

FIGURE 2. Floor plan of the Index House, showing TLD results, normalized to one year exposure in millirads.

to daylight at existing grade at the rear of the house. The purpose of the TROCAL membrane was to prevent the infiltration of radon-bearing ground water through the foundation walls as well as to act as a barrier against radon gas itself. (Note: Working drawings for remediation procedures developed in the course of the demonstration project are included in the DER/BRP publication, "General Remedial Action Details for Radon Gas Mitigation" which had been reprinted (with permission) in the Appendix of this volume. See also: Henschel, 1988).

The drain tile was covered with drainage fabric to inhibit future clogging of the tile. The excavation was then back-filled with washed limestone gravel to within a foot of existing grade. The original plan to backfill with the native soil which had been excavated was abandoned because it was feared that angular fragments in the excavated material might puncture the TROCAL membrane. The limestone fill was covered with drainage fabric, again to prevent clogging, and the excavation filled to grade with topsoil and relandscaped.

The net effect of this phase was a 39% reduction in the concentration of radon decay products inside the house.

Phases Two and Three: The second and third phases of the project sought to attack the problem from inside the house by sealing recognized existing penetrations.

In Phase two, an interior stub foundation wall separating the basement from the family room was sealed with two coats of epoxy paint, fitted with a soil-gas accumulator of perforated pipe, and exhausted to a roof vent.

In Phase three, all openings in the basement floor slab and all joints and cracks in the floor slab and foundation walls were sealed. The unused penetration for a sump was filled with soil and capped with concrete, and the joints between the concrete and the floor slab were sealed with silicone sealant. A ¾" French drain at the joint between the floor slab and the foundation wall was sealed with silicone, and all existing cracks and joints were dressed by power hammer, cleaned and filled with flowable silicone.

The combined effect of phases one, two and three was a reduction in indoor radon decay products of 78%.

Phase Four: The final remediation phase was originally conceived as the installation of a relatively simple sub-slab passive ventilation system. However, problems encountered in attempting to dress and seal floor cracks in Phase three drove the final phase of the project to a treatment which was more drastic than would be practicable in most other homes with a profound radon problem. The basement slabs in the Index House had apparently been poured directly on the native rock substrate, with no gravel ballast beneath. Further, the slab thickness ranged from two to six inches. This condition combined with the absence of ballast would foster crack development in the future. The original plan to cut a two-foot wide perimeter drain inside the basement wall and to install a perforated tile sub-slab ventilation system in an assumed gravel ballast layer, was obviously impossible.

Phase four, then, required the complete removal of floor slabs on the basement and family room levels to provide space for the actual sub-slab system. About eight inches of the underlying rock had to be hammered out. Because the bedrock beneath the house was, in effect, a low grade uranium "ore", it was considered essential to provide some form of gamma shielding against bedrock ground "shine". This shielding requirement was addressed by substituting diabase gravel for the limestone gravel originally specified as sub-slab ballast. The radiologically inert diabase, with a 15% iron content, has a higher effective atomic number than does limestone, and consequently offers greater gamma protection. Suitable crushed diabase was available locally.

The eight inch deep excavation under the entire house was filled with crushed diabase. A four inch perforated drain tile line, imbedded in the gravel, was installed around the perimeter on both levels of the ground floor. Each of these perimeter systems was attached to a solid tile riser which extended up through the house to the roof. A slightly negative pressure, on the order of a few Pascals, was maintained in the system by a combination of convection and suction from wind-driven turbines on the top of each riser. The gravel was covered by two layers of 30-pound felt, a sealed TROCAL membrane, and two inches of sand. The felt and sand were provided to protect the TROCAL membrane against accidental puncture during or after construction. Finally, a new four inch, wire-reinforced slab was poured over the entire floor on each level.

The combined effect of the entire effort (Phases one through four) reduced radon decay products in the basement level from 12.8 WL to 0.003 WL, or 99.9%. The residual gamma intensity was 17 microR per hour, only slightly greater than regional background. These results are summarized in Table 3.

Waste Materials: During the course of the project, substantial quantities of waste rock and soil were generated by the excavation of the below-grade foundation

TABLE 3

Radon concentrations and radon progeny concentrations at four locations in the Index House, at the time of discovery, and following each phase of remediation.

Location	Initial*		Post-phase I		Post-phases II & III		Post-phase IV	
	pCi/L	WL	pCi/L	WL	pCi/L	WL	pCi/L	WL
Basement	1765	12.8	1360	9.2	365	2.8	0.41	0.003
Family Room	2026	15.2	1579	10.3	532	3.1	0.88	0.004
Living Room	1701	14.0	943	7.2	361	2.5	0.38	0.003
Bed Room	1453	12.0	1058	6.1	476	2.4	0.52	0.004

* These values differ slightly from those of Table 1 because they were made at a different time, and under slightly different conditions.

(Data from McKelvey, 1989)

walls (Phase one), the original basement floor slabs and the rock from under the old basement floor (Phase four). The original plan called for disposal in a commercial landfill. Concerns arose about possible future controversy, however misled, about hazards posed by these materials. To avoid any possible problem, plans were changed and the debris was deposited in the backyard of the property, which fortunately was large enough to accommodate it. The material was covered with topsoil and landscaped.

The project was completed in late June, 1985. The family returned to their home in time to celebrate the fourth of July.

CONCLUSION

In retrospect, it is reasonable to speculate that the whole national interest in the hazards of indoor radon would not have materialized had not several things happened at the right time and in the right sequence. Firstly, it was required that this house with extremely high radon concentrations be purchased and occupied by someone who worked at a nuclear power station. Second, it was necessary that the facility have beta-sensitive portal monitors. (This type of equipment was not in universal use at the time.) Thirdly, it was required that the engineer have reason to enter the restricted area of the facility from which he could exit only through a portal monitor. (Many contractor engineers have no reason to go on-site). Finally, it was essential that the portal monitors be installed and in operation before the engineer's transfer to another site. (The engineer was originally scheduled for transfer to another state about the time the radon problem was found.)

In the years since the discovery of the Index House an infrastructure to address the problem of indoor radon has evolved. Exposure criteria have been set, assessment techniques and remediation methods have been developed and evaluated. Specialists within the private sector have been trained and have subsequently gained experience and insight. The regulatory structure to control the quality of testing and remediation services is in place. Public concerns about the problem have driven the establishment of some sound commercial practices which are very effective in mitigating the problem. These include radon screening for real estate transactions and the adopting of new construction techniques which protect against radon.

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