The plotting of radon measurement data on computer generated maps of South Central Pennsylvania indicate hot spots and regions of uniform chronic exposure.

Radon Measurements and Analysis for Central Pennsylvania Counties Having Elevated Radon Levels

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Abstract: *The U.S. EPA identified South Central Pennsylvania as a region having elevated radon levels. The thrust of this paper is to examine in some detail the TCS Industries, Inc., data base for eight Central Pennsylvania counties having a combined population of about 1.7 million people, which is 14% of the state population.*

TCS has been making and analyzing radon measurements since 1986. During the period 1986 to 1999 more than 125,000 measurements were recorded in the TCS data base. The data consisted of analyzed results from four subsets. Results were from mail order charcoal canisters, bulk orders from RMP certified companies for their placement, wholesales to retail vendors, and also direct home placement of canisters, track detectors, and continuous radon monitors. The data base for the eight South Central Pennsylvania counties for the 13-y period consists of more than 27,000 screening measurements from non-duplicated addresses.

The results were assembled into three studies. The locations of the measurements were converted into individual latitude and longitude values. The data were divided into four blocks of concentrations from 740 Bq m^{-3} to over 4,440 Bq m^{-3}. The data were plotted on computer generated maps for South Central Pennsylvania. The plots indicated both hot spots and regions of relatively uniform chronic levels of 740 to 1,480 Bq m^{-3}.

An average value of the basement to first floor concentrations ratio was constructed from measurements made by TCS for real estate purposes. The ratio represents 1,608 sets of simultaneous measurements of basements and first floor radon values above 37 Bq m^{-3}. The measurements were made by trained personnel performed under the EPA protocol for closed house conditions. The ratio was 2.3 at 1 standard deviation of 0.05 of the mean.

A third study assembled all of the data into first floor radon concentrations and separately for addresses with only basement values. The average concentration data within each of the eight counties were converted into the probability of fatal lung cancers and compared with occupational risk of fatal cancers for nuclear power plant workers. This study illustrates the importance of a continuing strong measurement program in South Central Pennsylvania. Health Phys. 80(Supplement 2):S55–S61; 2001

Key words: *operational topics; radon; health effects; monitoring, environmental*

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INTRODUCTION

Any environmental radiation safety program consists of four parts. The first is the development of a measurement program. Second is a data base to record measurement results. Third, the radiation environment is transformed into population radiation exposure, which is directly related to potential human risk, and the last is remediation or the means to reduce the risk. This paper addresses the first three parts for South Central Pennsylvania, an 8-county region roughly centered on the capital city of Harrisburg.

In 1985, TCS Industries, Inc., built a radon test chamber and developed two different open face activated charcoal detectors based on the work of George (1984). The TCS detector characteristics were outlined by Distenfeld (1995).

Beginning in 1986, TCS has provided activated charcoal detectors and associated laboratory services to mail order customers, to other firms including those certified by Pennsylvania for radon measurements, to retail outlets, and to a national mail order firm. TCS personnel also have placed activated charcoal, continuous radon, alpha track, and radon water test devices in private homes, commercial buildings, and county offices. All of the above comprise a data base of more than 125,000 U.S.-wide measurements.

On 22 November 1995, The U.S. EPA Region III published a radon potential chart by postal Zip code for the percentages of radon readings above 150 Bq m^{-3} (4 pCi L^{-1}). Perusal of the EPA data suggested 70 to 80% of central Pennsylvania dwellings contained radon concentrations above the U.S. EPA action level for remediation of 150 Bq m^{-3}. The purpose of this paper was to explore the risk potential to the inhabitants of part of central Pennsylvania within an eight county region centered on the capital city of Harrisburg, Pennsylvania. Finally risk comparisons to nuclear radiation workers are suggested.

DATA BASE

All radon screening data were entered into a dBase IV version 2, (dBase IV 1994). This DOS-based data base program was able to accept all of the information in a flexible, addressable form, but also allowed discard of measurements from duplicated addresses.

The data included radon concentration, dwelling street address, county, 5-digit postal ZIP code, and measurement location information. The data were comprised of results from exposures made by property owners, Pennsylvania individuals certified for measurements, and real estate transaction tests by TCS personnel. The latter includes simultaneously exposed charcoal canisters in the basement as well as in the first and usually the second floor of a dwelling. The multi-location program allowed a determination of the basement to first floor ratio as a case controlled type of study. For radon values above 37 Bq m^{-3} (1 pCi L^{-1}), the ratio was 2.29 with a 1 sigma standard deviation of the mean of 0.05 for 1,608 measured ratios. This may be contrasted to an environmental study of basement and first floor values of different addresses. This ratio was 2.69 for 25,731 basement and 14,928 individual first floor readings from the TCS data base. For dosimetry purposes, the former value of 2.3 should be used.

MAPPING PROGRAM

To assess the potential risk to the inhabitants, it was important to map the radon concentration data to search for clusters, or regions of higher radon concentration, hot spots, and to test for extent and uniformity of the radon concentration. A commercial mapping program was used to plot location information.† This WINDOWS 95/98 program was based on 7.5-min U.S. Geological Survey topographical charts. DeLorme repackaged the chart data in a more convenient form: three compact discs, CD-rom discs, for Pennsylvania. Nearly 4,000 data points were plotted by entering latitude and longitude for each point. Different plotting symbols in different colors allowed radon concentration information to be added to the location markers. The mapping program was not limited to the 4,000 points plotted and was continuous for the 8 South Central Pennsylvania Counties, with any part or all accessible by varying the scale.

The U.S. Postal Service has assembled latitude and longitude data for 9-digit zip codes for the U.S. These data were available as TIGER ZIP CD rom discs for each state.‡ The TCS data base, which originally contained 5-digit zip codes, was amended to 9-digit zip codes. The TCS and TIGER ZIP data bases were compared. Latitude and longitudes were copied to the TCS data base for each matched 9-digit zip code in TIGER ZIP. According to the U.S. Postal Department, the resulting latitude and longitude would be within one-half of a city block of the exact location. One-half block uncertainty did not invalidate analysis drawn from the plotted information, but the location uncertainty was desirable to protect the privacy of individual homeowners.

The TCS eight county data base consists of about 18,803 non-duplicated short term screening basement values, which varied from about 3.7 to > 4,440 Bq m^{-3} (0.1 to > 120 pCi L^{-1}). Only values above 740 Bq m^{-3} (20 pCi L^{-1}) were plotted. This reduced the available data points to about 4,294 locations. Not all of the TCS 9-digit zip code data were included in TIGER ZIP. Post office box addresses, rural delivery boxes, new construction, and invalid addresses amounted to about 26% of the TCS eight-county data base for radon values above 740 Bq m^{-3}. Street Atlas§ was used to derive latitude and longitudes for new construction and other addresses that could be found in Street Atlas. This recovered an additional 89% of the omissions in TIGER ZIP for a total of about 97% of the total available data points plotted as shown in Table 1. As can be seen from Table 1, the fraction of unidentified locations varied with radon concentration; the higher the radon concentration, the greater the location uncertainty. For values above 4,440 Bq m^{-3}, only about 75% could be located. Higher values may have reflected new construction in the more

† 3-D TopoQuads, Pennsylvania Region 3; DeLorme, Two DeLorme Drive, Yarmouth, ME 04096; www.delorme.com; 1999.

‡ TIGER ZIP. Topigraphical Integrated Geographical Encoded referencing, National Customer Support Center, U.S. Postal Service, 6060 Primacy Parkway, St. 201, Memphis, TN 38188, 1999.

§ Street Atlas for U.S.A., Version 7.0 Delorme, 2 Delorme Drive, Yarmouth, ME 04096; www.delorme.com; 1999.

Table 1. Numbers of plotted basement locations.[a]

Radon Bq m^{-3}	Total locations	Plotted locations	Recovered[b] locations	Fraction plotted
>4,440	177	128	31	0.72
2,960 to 4,440	256	208	55	0.81
1,480 to 2,960	1,212	1,104	302	0.91
740 to 1,480	2,649	2,573	602	0.97
Total	4,294	4,013	990	

[a] Data for 8 Central Pennsylvania Counties.
[b] Included in plotted locations.

distant suburbs with locations not yet included in TIGER ZIP or in the 1999 version 7 of Street Atlas.

Fig. 1 depicts the basement radon concentration data plotted in the greater Harrisburg metro region. The map scale was 1 in 56,200. Each flag represents a location with concentration between 740 to 1,480 Bq m^{-3}. Inspection of Fig. 1 suggests a pervasive dispersion of radon with clustering in certain locations. Clustering, or regions containing greater concentration of 740 to 1,480 Bq m^{-1} locations, are observed in a few areas. For example, higher concentrations of measurement points were found along a horizontal center line through Fig. 1: two west of center and two others east along the line. Fig. 1 represents about 2% of the 8-county area. Figs. 1 and 2 are provided as a sample of the 8-county area.

Fig. 2 is similar to Fig. 1 except the radon results for concentrations above 1,480 Bq m^{-3} are shown for a lower map scale. The 3-D TopoQuad program allowed good control of image scale and

Figure 1. 1,740 to 1,480 Bq m^{-3}.

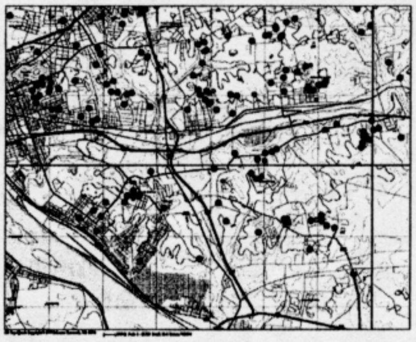

Figure 2. Harrisburg, PA, 1,480 to above 4,440 Bq m^{-3}.

color. Inspection of the data with a color computer monitor or a color printout showed the same kind of detail seen in Fig. 1 for three additional bands of radon concentration. Concentrations >4,440 Bq m^{-3} were plotted as red discs, 2,960 to 4,440 Bq m^{-3} were yellow-filled red-rimmed discs, and 1,480 to 2,960 Bq m^{-3} data were shown as blue-filled red-rimmed discs. Unfortunately, the gray scale figure image is difficult to interpret for concentration. Generally, it was shown that radon readings above 1,480 Bq m^{-3} occur in many of the same locations as the under 1,480 Bq m^{-3} data shown in Fig. 1.

RADON DOSIMETRY AND RISK

The act of breathing draws radon gas and, more importantly, radon progeny into the respiratory system. The progeny decay by ejecting alpha particles that potentially deposit 6 and 7.7 million electron volts of energy to respiratory tissue per decaying ^{218}Po and ^{214}Po atom. Radon gas is exhaled, and since radon has a relatively long half life, few decays take place in the respiratory tract between breaths. The irradiated tissue has some probability of developing lung cancer. This process of acquiring risk is similar to the damage caused by radiation exposure to nuclear power plant workers, x-ray technicians, medical isotope workers, or anyone occupationally or otherwise exposed to ionizing radiation. Federal and state regulatory organizations limit the amount of radiation exposure to workers. The limits were selected to reduce the workers' risk of developing observable short term bodily damage or later developing cancer at a rate greater than the natural rate that people expect working in a safe industry.

Most radiation workers are exposed to radiation over much of their whole body; whereas radon and radon progeny only expose the respiratory system. Standard dosimetry practice adjusts the energy deposited in a reference organ, such as the lung, to include radiosensitivity, organ size or cells at risk, and how vital the organ is to the life of the host. This item is the weighting factor, which is used to balance risk for all parts of the body. The weighting factor is formally defined as the stochastic risk arising from a given tissue to the total risk when the whole body is irradiated uniformly (ICRP 1978). The final value is expressed as the effective dose equivalent and, since it is risk related, is additive for different radiations affecting different organs (ICRP 1978; NUREG 1993). When summed over all organs and body parts, the result is termed the total effective dose equivalent, TEDE. The U.S. Nuclear Regulatory Commission, NRC, collected and reported on all classes of radiation workers under their control (NUREG 1998). For the year 1998, the NRC listed 65,070 persons with a measurable radiation exposure with an average total effective dose equivalent of 3.6 mSv (0.36 rem).

The usual approach to radon dosimetry is to convert the absorbed dose to the dose equivalent and apply a weighting factor. At least three uncertainties exist. First, the deposition site within the branchial tubes of the radon progeny depends on a number of factors including variable aerodynamic diameters of dust particles laced with radon progeny. Second, a mucus layer coating the branchial tubes absorbs a fraction of the potential alpha energy. Smokers are thought to have thicker mucus layers. Last, energy transfer beyond the range of the alpha particles has been observed. This was attributed to migrating chemically active molecules produced by interaction of alpha particles and lung fluids, which make the number of cells at risk uncertain. What is best known is the lung cancer risk due to radon exposure (Lubin and Boice 1997).

Alternately, occupational exposure is better characterized as radiations of lower linear energy transfer (LET) and irradiation of a larger fraction of the whole body. The dosimetry aspects are taken to be reasonably well known. What is uncertain is the cancer risk. In 1990, BEIR V reported significantly more conservative risk values over BEIR III, which was published 10 years earlier. One of the reasons was a reduction in the average dose equivalent for Hiroshima and Nagasaki people making the observed cancer risk higher. The effects of near instantaneous irradiation and poor hygiene for the people living in the damaged cities are hard to assess. In summary, radon risk is better known than dosimetry, and risk due to occupational exposure is not as well characterized as the dosimetry. For these reasons, risk comparisons between radon and occupational exposure will be based directly on radon risk as compared with occupational exposure risk defined in BEIR V.

It is revealing to compare the fatal cancer risk acquired by radiation workers during employment to the risk of contracting a fatal lung cancer from radon and radon decay products in 8 South Central Pennsylvania Counties.

For illustration, the annual lung cancer risk due to an exposure of 46 Bq m^{-3} (1.24 pCi L^{-1}) at home is as follows:

Assumptions:

1. Over a 365-d year, a person spends 18 h a day at home with an average radon concentration of 46 Bq m^{-3} (U.S. EPA 1992);
2. Remaining time is spent outdoors with a median radon concentration of 14.4 Bq m^{-3} (0.39 pCi L^{-1}) (U.S. EPA 1992). Average radon exposure is 38.1 Bq m^{-3} = $46 \times 0.75 + 14.4 \times 0.25$;
3. The number of working hours per month is defined as 170 h (U.S. EPA 1992);
4. For an equilibrium of 50% the working level is 0.02/148 = 0.000135 WL/Bq m^{-3} (U.S. EPA 1992);
5. In 1995, 15,400 to 21,800 extra lung cancer deaths were projected due to radon exposure in U.S. homes (BEIR VI 1999);
6. The 1995 U.S. population was 262,803,000 (U.S. Census Bureau 1990 to 1999); and
7. The fatal cancer risk due to radiation exposure to a nuclear industry worker was 0.04 per Sv (0.0004 per rem), TEDE (BEIR V 1990).

Then:

Per year, working level months (WLM) = $38.1 \times 0.000135 \times 365 \times 24/170 = 0.265$. The annual lung cancer risk due to exposure of 0.265 WLM is

- Lower limit: 15,400/(262,803,000×0.265) = 0.000221 lung cancer risk per person per WLM;
- Equivalent risk per WLM: TEDE WLM^{-1} = 0.000221/0.04 = 0.00553 Sv WLM^{-1} or 5.53 mSv WLM^{-1};
- Upper limit: As above for 21,800 lung cancer deaths = 0.000313 per WLM;
- TEDE WLM^{-1} = 0.000313/0.04 = 0.00783 Sv WLM^{-1} or 7.83 mSv WLM^{-1}.

Table 2 represents radon measurement data taken from nonzero and non-duplicated addresses between 1986 and 1999. The radon concentration data were converted to WLM by assuming 75% indoor and 25% outdoor exposure. The annual TEDE was calculated as the product of projected average working level months and the TEDE per WLM for each county considered and for the overall.

It was apparent every value is greater than the average annual nuclear industry worker exposure.

Federal and state regulatory bodies require occupationally exposed workers to be exposed to a effective dose equivalent of less than 50 mSv (5 rem) per year. Many scientists began to feel exposures near the annual limit for many years would cause the cancer risk to exceed that of a safe industry. Partly for this reason the federal agencies adopted the principal of As Low As Reasonable Achievable (ALARA) (ICRP 1977)

Table 2. Projected home owner radiation exposure.

County	Houses total[a] No.	Measured houses %	1-floor avg. Bq m^{-3}	1-floor TEDE mSv y^{-1}	Basement avg. Bq m^{-3}	Basement TEDE mSv y^{-1}
Adams	33,730	1.5	93	2.8–3.9	252	7.4–10.4
Cumberland	81,024	10.1	244	7.2–10.1	533	15.5–21.9
Dauphin	94,452	8.4	241	7.1–10.0	525	15.3–21.7
Franklin	49,543	1.4	170	5.1–7.2	337	9.9–14.0
Lancaster	176,937	2.8	322	9.5–13.4	633	18.4–26.1
Lebanon	45,329	1.9	218	6.5–9.2	696	20.3–28.7
Perry	17,031	4.3	422	12.3–17.4	895	26.0–36.8
York	144,841	2.2	226	6.7–9.5	440	12.9–18.2
8-county summary	642,887	4.2	248[b]	7.6–10.4	533[b]	15.6–22.1

[a] County households taken as 2.6 people per house from http://www.census.gov/population/estimates/county/co-99-1/99C1_42/txt.
[b] Average weighted over numbers of measurements.

Since 1975, the consequences of a vigorously applied ALARA program reduced the average annual occupational dose equivalent to a U.S. radiation worker to an average of 3.6 mSv (0.36 rem) (NUGEG 1998).

DISCUSSION

The work was performed to reveal the radon risk potential for South Central Pennsylvania. As such the data base was filtered to eliminate duplicate addresses. Thus, lower values due to remediations of previous high values were filtered out. It was inappropriate to include values due to remediations when the data sets represent a very small fraction of all households, since the people that test are more likely to remediate and retest. Including all the data would force county average radon values down without significantly changing the actual average thereby creating false optimistic impressions of the radon risk.

A graphical presentation of radon concentration data illuminates hot spots and reinforces the EPA recommendation that every household should test for radon. This is particularly true for South Central Pennsylvania. Based on an aggregate measurement of 4.2% of all the homes in the 8-county region, the average radiation exposure to adults occupying the first floor is more than 2 times greater than the average worker occupationally exposed to radiation. Many Central Pennsylvania families use their basements for living space. Based on inspection of homes during radon measurements, TCS estimates about a fifth of the homes built in the last 20 y have finished areas in the basements. Of older homes, possibly one in ten to fifteen have bedrooms in the basement. Central Pennsylvania is experiencing a home building boom. Many of the larger new construction have high ceilings with walk-out basements, which may encourage owners to convert to family rooms. In time, this would trend toward more people using basements as living space and more radon exposure.

It may seem clusters represent a higher concentration of testers rather than higher frequency of elevated values. Considering Fig. 2, the radon concentration shown is sufficiently elevated to be a concern whether clusters exist or not. Further, comparing the measurement distribution shown in Fig. 1 with the higher values of Fig. 2 tends to argue against clusters of testers. Only about 4,000 measurement locations out of 27,000 were plotted. The 3-D TopoQuads program was not written to allow batch data entry. Four-thousand latitude and longitude entries were sufficient to allude to the regions of higher radon risk.

Adams County had the lowest first floor average radon exposure value. The value was similar to the average national radiation worker exposure. It is useful to note that about 122 Bq m^{-3} (3.3 pCi L^{-1}) in a home is equivalent to the risk borne by the average U.S. radiation worker exposure.

From Table 1 for basements, more than 433 first floors exceed 1,295 Bq m^{-3} (35 pCi L^{-1}). The first floor value was calculated by dividing the basement number by 2.3, which is the TCS measured basement to first floor ratio. The lower limit of 2,960 Bq m^{-3} in basements divided by 2.3 was about 1,295 Bq m^{-3}. Accounting for six daily hours spent outdoors, the minimum first floor exposure for the group was projected to be about 962 Bq m^{-3} (26 pCi L^{-1}) averaged over a year. This corresponds to a TEDE of 35 to 50 mSv y^{-1}. Some of the basements were also occupied. Assuming about 15% of basements contain child play areas, bedrooms, and finished family rooms, and taking into account only the 1,480 to 2,960 Bq m^{-3} group, an additional 182 households project annual exposures of 43 to 61 mSv y^{-1} TEDE. Assuming 2.6 people per household, more than 1,414 people living in eight Central Pennsylvania counties may receive yearly exposures above the federal and international limit of 50 mSv TEDE. None of the more than 57,339

U.S. wide nuclear power plant workers, which had measurable radiation exposures, received an over limit exposure for the 5-y period 1994 to 1998, inclusive (NUREG 1998). The 1,414 person group was based on measured households from only 4% of households in 8 of 67 Pennsylvania counties.

GPU Nuclear operated two nuclear power plants in Dauphin County about 10 miles south of Harrisburg on an a tract of land named Three Mile Island (TMI). On 29 March 1979, an accident occurred that damaged Unit 2 and released radioactivity into the environment. Due to radioactive releases from the accident, the U.S. Department of Energy found an average individual exposure for people residing within 1 mile from the Unit 2 was 0.79 mSv (Hull 1989). This was potentially delivered between 29 March and 3 April 1979. Both measurements and calculations showed the exposure rate on 3 April was about 1% of the initial value, and this declined by another factor of 10 to 0.1% in another 7 d (Hull 1989). The average exposure for residents within 1 mile of TMI Unit 2 was estimated to be less than 1.0 mSv for the entire duration of the accident. Taking the first floor radon equivalent exposure for Dauphin County to be 7.1 mSv y^{-1}, the TMI Unit 2 accident represented less that 2 mo worth of equivalent risk of living at home with no release from TMI. On 29 March 2000, the incremental risk from TMI was less than 0.7% of the minimum accumulated household radon risk for the 21-y period.

The High-Radon Project run by the Lawrence Berkeley National Laboratory, United States Geological Survey, posted a radon map for the 48 contiguous states on their web site (LBNL 2000). The color-coded map indicates Iowa has the highest radon concentration, which Berkeley expresses as a geometric mean of 101 Bq m^{-3} (2.72 pCi L^{-1}). Pennsylvania is posted as having a geometric mean of 68 Bq m^{-3} (1.83 pCi L^{-1}). Assuming a geometric standard deviation of 78, the Iowa arithmetic average radon concentration is about 130 Bq m^{-3}. This may be compared to the average derived from TCS first floor data of 248 Bq m^{-3}.

It is instructive to compare Central Pennsylvania to Iowa. Since radon reflects harm to people, any comparison must be people-driven and not land-area-driven. In 1990, the population of the state of Iowa was 2.76 million people (U.S. Census Bureau 2000). In 2000, with projected growth, the total Iowa population should be about 2.97 million people. In July 1999, the eight South Central Pennsylvania counties had a total population of 1.67 million people. Since lung cancer risk is taken to be directly proportional to the TEDE, which is also directly proportional to the radon concentration, the 8-county region may have about 1.08 times more radon-related lung cancer risk than the state of Iowa. This analysis was based on projecting the average of 4.2% of the households to the whole population of the 8 counties. It must be remembered, South Central Pennsylvania is not the only high-population, high-radon-risk area in the state. The state of Iowa reported an annual lung cancer rate of 54.0 fatalities per 100,000 population for 1996, and 53.6 for 1997 (IPH 1996). The corresponding rate for the eight South Central Pennsylvania counties was 56.9 fatalities per 100,000 for 1996, 54.2 for 1997, and 54.5 for 1999 (PBHS 2000). It is believed that only case-controlled studies that take smoking and other items into account are useful to define the lung cancer risk due to radon. Regardless, a higher radon related risk for the sub-set of Pennsylvania is not contra-indicated by the higher lung cancer fatality rate of the eight South Central Pennsylvania counties. A case-controlled study may be indicated for Pennsylvania.

A degree of uncertainty is present in all of the published risk projections. For radon-related risk, a meta-analysis of eight residential case-control studies found excessive lung cancer risk at an average indoor radon concentration of 148 Bq m^{-3} (4 pCi L^{-1}) (Lubin and Boice 1997). Thus, semi-direct evidence existed for excess risk at or below average radon levels found in Central Pennsylvania. For radiation exposure of nuclear workers at or below occupational limit values, no direct evidence of risk was ever observed (BEIR V 1990).

CONCLUSION

The risk portion of this paper can be summarized in two thoughts. The radiation industry is extremely safe, and the risk due to radon in South Central Pennsylvania is significant. The latter is supported by the latest results of 4 y of comprehensive study by a committee of the National Research Council. They found no reasons to significantly change the previous radon risk values (BEIR VI 1999).

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