#4748

Health Physics Vol. 56, No. 4 (April), pp. 423–429, 1989
Printed in the U.S.A.

0017-9078/89 $3.00 + .00

Pergamon Press plc

● ***Paper***

INFLUENCE OF SUBSOIL GEOLOGY AND CONSTRUCTION TECHNIQUE ON INDOOR AIR ^{222}Rn LEVELS IN 80 HOUSES OF THE CENTRAL SWISS ALPS

R. Buchli and W. Burkart
Radiation Hygiene Division, Paul Scherrer Institute, CH-5303 Würenlingen, Switzerland

(*Received* 14 *March* 1988; *accepted* 7 *October* 1988)

***Abstract*—The indoor ^{222}Rn level depends mainly on the subsoil geology, the cellar floor permeability, the cellar aeration, the air-tightness of the homes, and the aeration habits of the occupants. These five parameters and the ^{222}Rn levels in the cellar and in the living room on the ground floor were compiled in 80 one- or two-family houses of the central Swiss Alps. The ^{222}Rn levels were measured with passive alpha track detectors.**

Houses located on a granite, ortho-gneiss or verrucano subsoil have a cellar ^{222}Rn level that is on the average 4.4 times higher than houses which are built on grey-schist or sediments. The cellar level is on the average 5.4 times higher if the cellar has partially a gravel or earth floor than if the whole cellar surface is covered with a concrete floor. Energy-efficient, highly air-tightened homes have a living room level that is on the average 1.8 times higher than normally insulated conventional homes.

In the cellars and the living rooms of the 80 houses considered, arithmetic mean ^{222}Rn levels of 724 Bq m^{-3} (20 pCi L^{-1}) and 178 Bq m^{-3} (4.8 pCi L^{-1}), respectively, were found. In the central Swiss Alps ^{222}Rn and ^{222}Rn decay products lead to an estimated mean exposure of 5.3 mSv effective dose equivalent per year.

INTRODUCTION

THE ^{222}Rn emanation power of a soil is mainly controlled by the ^{238}U concentration, the humidity, the porosity, and the fissuration of the rocks of the subsoil. The ^{222}Rn gas which emanates from the subsoil and the surficial bedrock is transported into the living space of homes through a combination of diffusion and Darcy flow. The transport of ^{222}Rn through diffusion (due to concentration gradients) and Darcy flow (due to pressure gradients) occurs via cracks, joints, and especially gravel or earth floors of the cellar. Darcy flow is believed to predominate, particularly in the winter period with its large temperature differences between the inside and outside (stack effect) and particularly for homes with above-average concentrations of ^{222}Rn. In the living space, the build-up of indoor ^{222}Rn gas was shown to be strongly influenced by the air-exchange rate (Burkart et al. 1984; Fleischer and Turner 1984). Other studies, however, did not find a significant correlation (Nero et al. 1983). The air-exchange rate is determined by the air-tightness of the house and by the aeration and heating habits of the occupants (Burkart et al. 1984).

In the central Swiss Alps the Rhine-Rhone line separates the Aar Massif in the north from the Gotthard Massif in the south. The Rhine-Rhone line is divided from west to east into three subregions: the Upper Valais, the Urseren valley, and the Upper Rhine valley (see Fig. 6). Because of the significant fluctuations of the ^{238}U concentration in the subsoil and because of the well-known radiogeological situation, the central Swiss Alps are very well suited for an investigation of the correlation between the subsoil geology and the indoor ^{222}Rn level.

Some of the ^{222}Rn gas diffusing into the cellar is transported into the living space. The transport mechanisms are quite different in old and new dwellings, in apartment houses and family houses. Because it is not possible to investigate the correlation between the construction technique and the indoor ^{222}Rn level for all types of homes, the chosen 80 homes are as similar as possible, all of them being quite recently built one- or two-family houses, provided with a cellar and having the living room on the ground floor. A by-product of the study is to get more information on the region and the house type where the highest Swiss indoor ^{222}Rn levels can be found (Buchli and Burkhart 1985).

MATERIALS AND METHODS

For the sake of simplicity, it is assumed that the ^{222}Rn emanation power of the rocks depends only on the ^{238}U concentration. The humidity, the porosity, and the fissuration of the subsoil are difficult to determine and would demand an analysis of rock samples in the laboratory. Categories of high, of medium, and of low ^{238}U concentration and therefore emanation power are defined (Lab-

Table 1. Parameters used for the classification of the 80 homes.

Name of parameter	Status of parameter	Percent	No.of homes
1. Subsoil geology	a) High emanation power	37%	30
	b) Medium emanation power	28%	22
	c) Low emanation power	35%	28
2. Cellar floor	a) Partially gravel/earth floor	56%	45
	b) Whole surface concrete floor	44%	35
3. Cellar aeration	a) Never/infrequently aerated	76%	61
	b) Permanently aerated	24%	19
4. Air-tightness	a) Air-tightened energy-efficient house	67%	54
	b) Non-air-tightened conventional house	33%	26
5. Aeration habits	a) Aerated less than 30 $min\ d^{-1}$	36%	29
	b) Aerated more than 30 $min\ d^{-1}$	64%	51

hart and Rybach 1971; Labhart 1976; Halm et al. 1962). Granite, ortho-gneiss (granitoid gneiss), and verrucano (permian sediments) have high ^{238}U concentrations reaching from 11 to 16 ppm. In mica-schist, biotite-gneiss, para-gneiss, and phyllite, 4 to 7 ppm ^{238}U are found. Greyschist (Bündnerschiefer), Mesozoic sediments (Lias, Cretaceous) and Quarternary sediments show concentrations between 1 and 3 ppm. The geology and the approximate subsoil ^{238}U concentration were determined at the location of the houses with the help of a geophysicist and with the most accurate geological maps available.

A detailed questionnaire provided information about the construction technique of the houses and the aeration habits of the occupants (Burkhart 1983). Concerning the cellar floor permeability, the distinction was made between the cellars having partially a gravel or earth floor and those having a concrete floor covering the whole cellar surface. Because the study was made during the winter season, most cellars were never or infrequently aerated and only few had a permanent aeration through an open cellar window of at least 0.06 m^2 surface in one or more cellar rooms. Nearly all investigated dwellings were built after the petroleum crisis. Therefore, many houses are energy-efficient, being air-tightened by means of caulking and weatherstripping; the other houses are non-air-tightened and of a conventional type. Finally, a high and a low aeration of the living space was defined (Schmid 1985). In most houses the mean daily aeration period including the mean daily use of an open fireplace exceeded 30 min; in the other houses the duration of the aeration and fire-

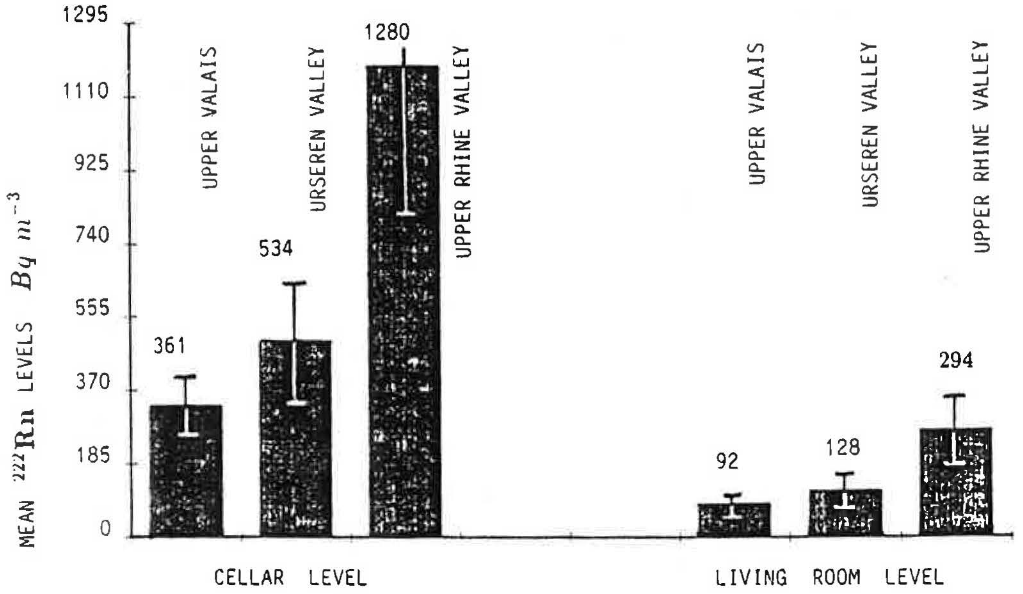

Fig. 1. Arithmetic mean ^{222}Rn levels in the cellars and the living rooms. The bars represent the arithmetic standard deviations of the mean ^{222}Rn levels.

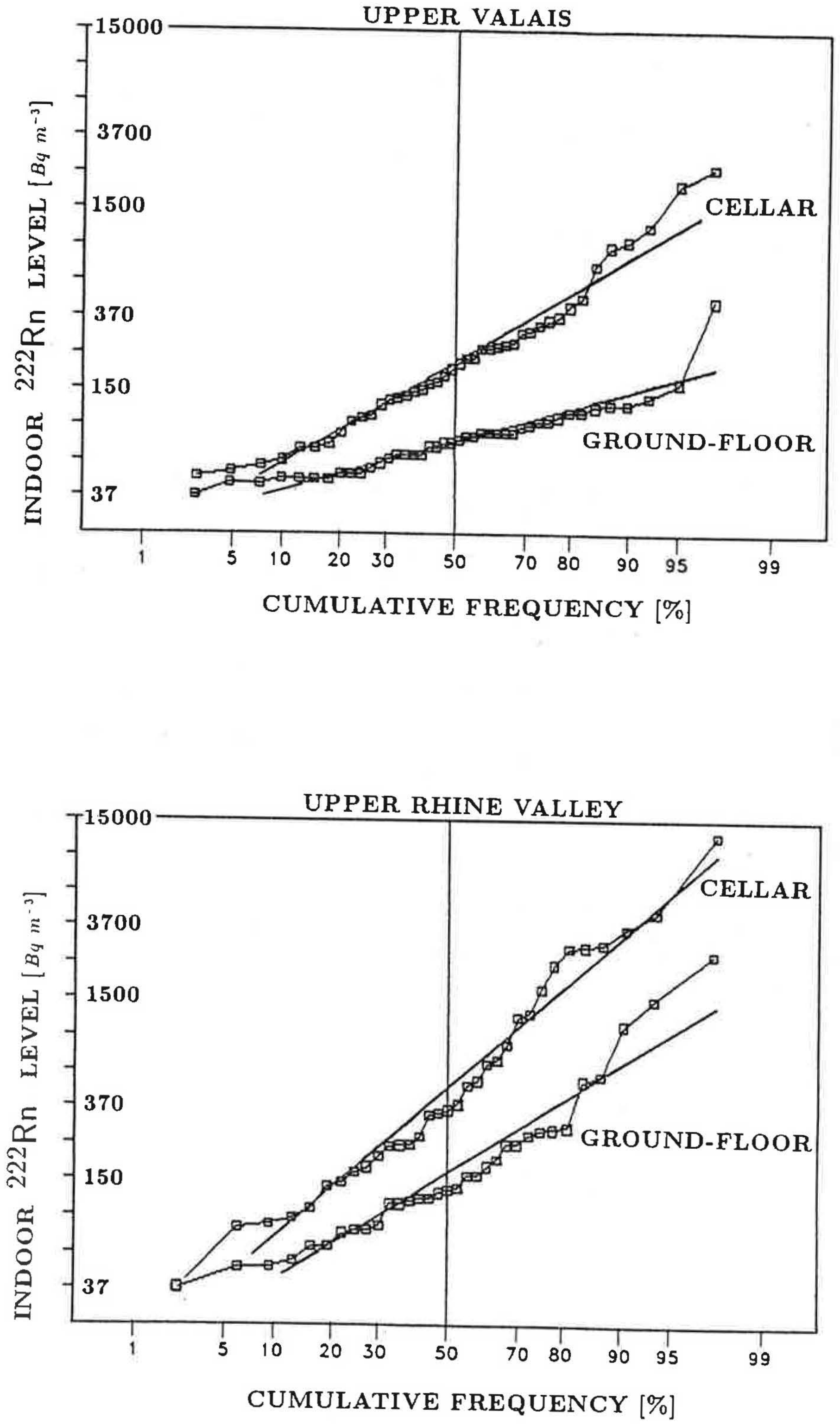

Fig. 2. Frequency distribution of the indoor ^{222}Rn levels in 42 houses of the Upper Valais and in 33 houses of the Upper Rhine valley. In the Upper Valais the geometric mean levels in the cellar and the ground-floor are 213 Bq m^{-3} and 80 Bq m^{-3}, respectively. In the Upper Rhine valley these values are 483 Bq m^{-3} and 162 Bq m^{-3}.

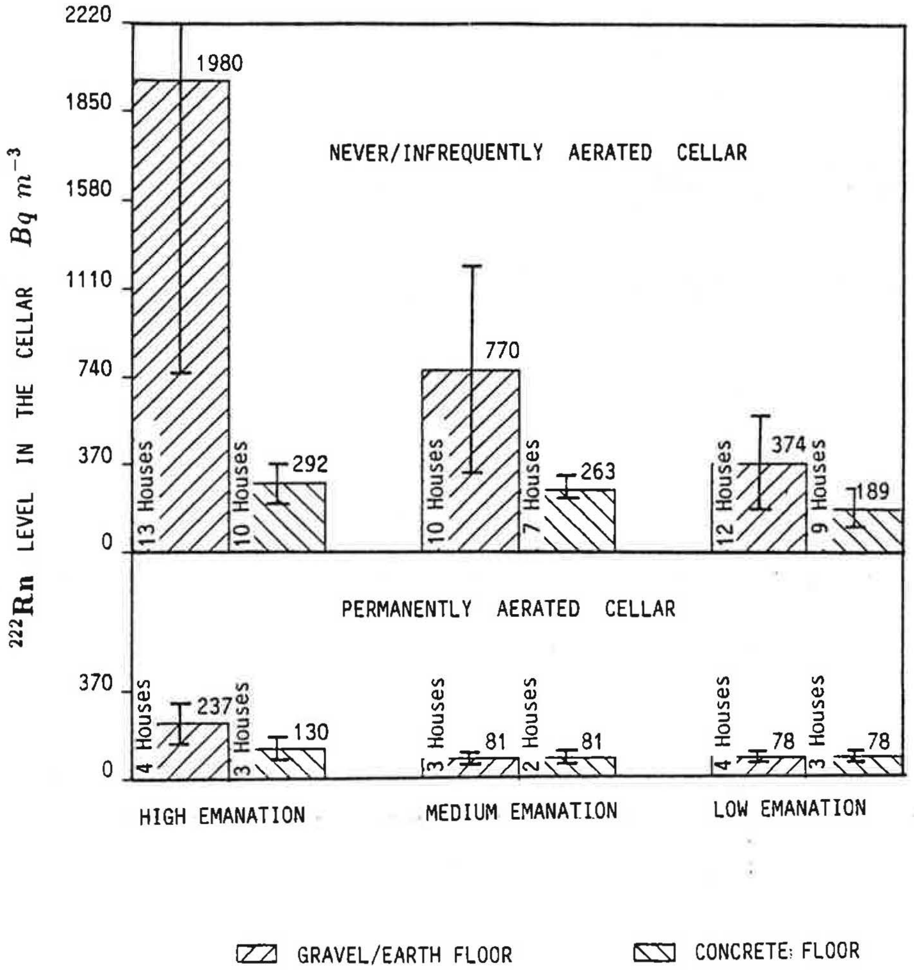

Fig. 3. Dependence of the cellar ^{222}Rn level on the cellar aeration (upper/lower part), the cellar floor (left/right column), and the emanation power of the subsoil (3 groups).

place use amounted to less than 30 min d^{-1}. At least one window per room was fully opened during the aeration period. Table 1 shows the five compiled parameters.

Time-integrating passive alpha track ^{222}Rn detectors were used for the measurement of the indoor ^{222}Rn level (Wernli 1982). The dosimeters are diffusion chambers of the Karlsruhe type (Federal Republic of Germany) using solid state nuclear track detectors (polycarbonate). After the exposure the detectors were electrochemically etched and track counting was performed. The duration of the exposure was 3 mo (December 1984 to March 1985). Ten villages were investigated in the Upper Valais, two in the Urseren valley, and seven in the Upper Rhine valley. Two to seven homes were measured per village.

RESULTS

Figure 1 shows the arithmetic mean indoor ^{222}Rn levels. In the 42 houses of the Upper Valais the mean levels are 361 Bq m^{-3} in the cellar and 92 Bq m^{-3} in the living room. In the five homes of the Urseren valley, mean cellar levels of 534 Bq m^{-3} and living room levels of 128 Bq m^{-3} were measured. The highest mean levels were found in the 33 homes of the Upper Rhine valley: 1280 Bq m^{-3} in the cellar and 294 Bq m^{-3} in the living room. The cellar levels (left side) are on the average 4.2 times higher than the living room levels (right side). The highest ^{222}Rn levels were found in the village of Siat in the Upper Rhine valley: 12,200, 2800, and 2300 Bq m^{-3} were measured in the cellars and 2500, 1400, and 500 Bq m^{-3} in the living rooms. Using the UNSCEAR 82 conversion factors for non-occupational exposure to ^{222}Rn and ^{222}Rn decay products, the dose rate is 0.0295 mSv y^{-1} effective dose equivalent per Bq m^{-3} indoor ^{222}Rn. For the population living in a family house in the central Swiss Alps, the mean exposure to ^{222}Rn and its progeny amounts to 2.7 mSv y^{-1} in the Upper Valais, 3.8 mSv y^{-1} in the Urseren valley, and 8.7 mSv y^{-1} in the Upper Rhine valley.

Figure 2 shows the frequency distribution of the ^{222}Rn levels in the cellar and in the living room for the Upper Valais and the Upper Rhine valley. Because the distribution is approximately logarithmic-normal, it can be predicted that the ground-floor ^{222}Rn level for the most affected one-percentile of the houses in the Upper Rhine valley is higher than 1900 Bq m^{-3}. This would lead to annual exposures due to ^{222}Rn and its decay products which clearly surpass the limit for occupational exposure of 50 mSv y^{-1}.

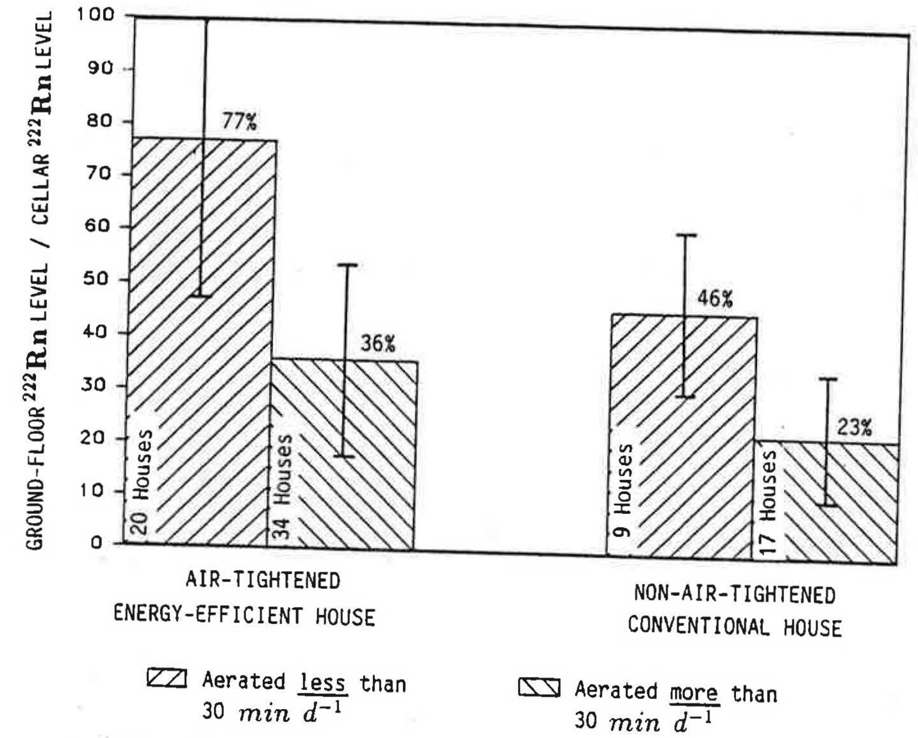

Fig. 4. Decrease of the ^{222}Rn level from the cellar to the ground-floor in percent. The ratio *ground-floor level to cellar level* depends on the air-tightness of the house (left/right group) and on the aeration habits of the occupants (left/right column).

Figure 3 demonstrates the influence of the parameters geology, cellar floor, and cellar aeration on the indoor ^{222}Rn level of the basement. The cellar ^{222}Rn levels are on the average 4.4 and 3.0 times higher in cellars built on soils with a high emanation power than in cellars built on soils with a low or a medium emanation power, respectively. The cellar ^{222}Rn level is on the average 5.4 times higher if the cellar has partially a gravel or earth floor than if its surface is entirely covered with a concrete floor. Infrequently or never-aerated cellars have a ^{222}Rn level that is on the average nearly 18 times higher than permanently aerated cellars.

Figure 4 depicts the influence of the parameters air-tightness and aeration habits on the ratio *ground-floor level to cellar level*. The decrease of the ^{222}Rn level from the cellar to the ground-floor is smaller for air-tightened houses than for conventional houses. If the living space is aerated less than 30 min d^{-1}, the decrease is also smaller than if the aeration exceeds 30 min d^{-1}. An analysis of the indoor ^{222}Rn levels shows that energy-efficient air-tightened homes have on the average 1.8 times higher living room levels than conventional non-air-tightened homes. Finally, the ^{222}Rn levels are on the average 2.1 times higher if the living space is aerated less than 30 min d^{-1} than if it is aerated more than 30 min d^{-1}.

Figure 5 shows the correlation between the measured and the calculated ^{222}Rn levels. Although the negative outcome was anticipated, the five parameters of Table 1 were combined in a semi-empirical model to predict the indoor ^{222}Rn levels on the ground-floor. The variation of the first three parameters leads to 12 combinations corresponding to the 12 columns of Fig. 3. As an example, a house located on a high emanation soil, having a gravel or earth cellar floor and being never or infrequently aerated, has a cellar level of 1980 Bq m^{-3} in the model. The ^{222}Rn level in the living room is calculated by multiplying the cellar level by the ratio *ground-floor level to cellar level*. According to Fig. 4 an air-tightened home, aerated less than 30 min d^{-1}, has a living room level that is 77% of the level in the cellar. Therefore, the model predicts a maximal living room level of 1980 Bq m^{-3} × 0.77 = 1525 Bq m^{-3}. The minimal living room level predicted would be 78 Bq m^{-3} × 0.23 = 18 Bq m^{-3}. The correlation coefficient of 0.64 clearly indicates that this semi-empirical model based on a limited amount of easily obtainable data cannot predict ^{222}Rn levels with reasonable accuracy.

CONCLUSION

The most affected valley of the central Swiss Alps is the Upper Rhine valley (Fig. 6). The logarithmic-normal distribution of the ground-floor ^{222}Rn levels predicts that

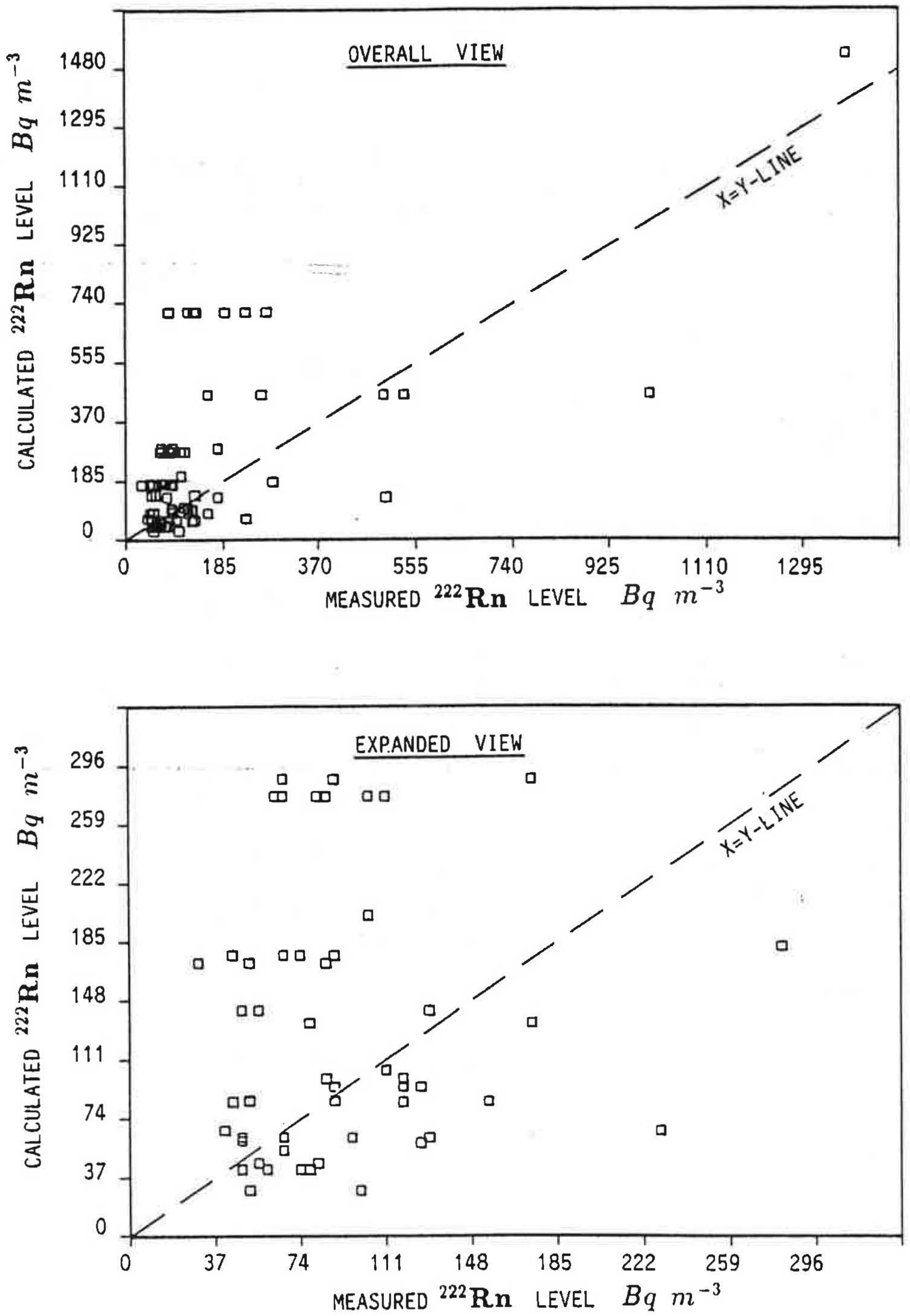

Fig. 5. Measured living room levels versus calculated living room levels. Every dot represents one of the 80 houses considered.

for the most affected 10-percentile of the houses in the Upper Rhine valley, an indoor ^{222}Rn level of 580 Bq m^{-3} and an exposure to ^{222}Rn and its progeny of 17 mSv effective dose equivalent per year are surpassed. For the most affected one-percentile these values are 1900 Bq m^{-3} and 56 mSv effective dose equivalent per year.

For the most affected 10-percentile of the homes in the Upper Valais, ground-floor ^{222}Rn levels higher than 120 Bq m^{-3} and exposures higher than 3.5 mSv y^{-1} are predicted. For the most affected one-percentile these values are 235 Bq m^{-3} and 7 mSv y^{-1}.

These facts lead to the conclusion that the soil of the Upper Rhine valley, which consists mainly of granite, ortho-gneiss, and verrucano, has a significantly higher ^{222}Rn emanation power than the soil of the Upper Valais, which consists mainly of mica-schist, biotite-gneis, para-gneis, phyllite, grey-schist, and mesozoic and quarternary sediments.

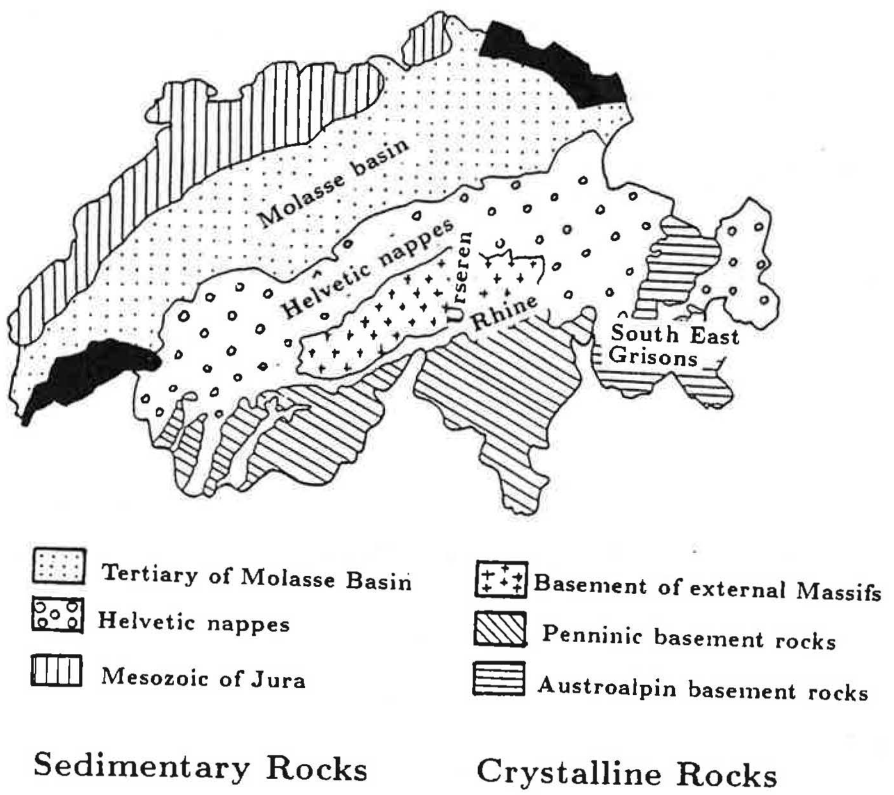

Fig. 6. Tectonic map of Switzerland.

Acknowledgments—This work has been partially supported by the Swiss Federal Office for Energy Research (Grant No. 0.805.391.02/6). The authors wish to thank Dr. R. Crameri and S. Schmolke for many helpful discussions, Prof. L. Rybach for geological and geophysical support, K. Heusi for technical assistance, and D. Stotz for manuscript review.

REFERENCES

Buchli, R.; Burkart, W. Main sources of indoor radon in the Swiss Central Alps. In: The science of the total environment. Proceedings of a seminar held in Maastricht, The Netherlands; Elsevier Appl. Science Publisher B.V.45; 1985:425–432.

Burkart, W. Assessment of radiation dose and effects from ^{222}Rn and its progeny in energy-efficient homes. Nuclear Techn. 60:114–120; 1983.

Burkart, W.; Wernli, C.; Brunner, H. Matched pair analysis of the influence of weatherstripping on indoor radon concentration in Swiss dwellings. Rad. Prot. Dos. 7:577–584; 1984.

Fleischer, R. L.; Turner, L. G. Indoor radon measurements in the New York capital district. Health Phys. 46:999–1011; 1984.

Halm, E.; Herbst, W.; Mastrocola, A. Messung des naturlichen Strahlenpegels in der Schweiz. Bulletin des Eidgenössischen Gesundheitsamtes; Beil.B; No.6; 1962 (in German).

Labhart, T. P.; Rybach, L. Abundance of uranium and thorium in the syenite of Piz Giuv (Aar-Massif, Switzerland); Chemical geology. Elsevier Appl. Science Pub.; 7; 1971.

Labhart, T. P. Die Radioaktivität alpiner Gesteine. Schweizer Strahler, Vol. 4, No.1; 1976 (in German).

Nero, A. V.; Berk, J. V.; Boegel, M. L.; Hollowell, C. D.; Ingersoll, J. G.; Nazaroff, W. W. Radon concentrations and infiltration rates in conventional and energy-efficient houses. Health Phys. 45:401–405; 1983.

Report to the UN scientific committee on the effect of atomic radiations; Ionizing radiation: Sources and biological effects. New York: United Nations; 1982.

Schmid, H. Combined stack effect in houses and eskers explaining transients in radon source. In: The science of the total environment. Proceedings of a seminar held in Maastricht, The Netherlands; Elsevier Appl. Science Publisher B.V.45; 1985:195–204.

Wernli, C. Radon in Wohnhäusern. Durchführung der Vorstudie 1981/82: Messtechnik, TM-81-82-6, EIR, Würenlinger; 1982.