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Circular 44

**GENERALIZED POTENTIAL FOR RADON EMISSION
BASED ON ESTIMATED URANIUM CONTENT IN
GEOLOGIC ROCK UNITS, SOUTH DAKOTA**

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INTRODUCTION

Purpose

The purpose of this paper is to describe the compilation methods and limitations of the relative radon emission potential map of South Dakota.

Overview of Radon

Radon-222, with a half life of 3.82 days, is a naturally occurring radioactive noble gas derived from the natural decay of uranium. In a complex decay chain, uranium-238 decays to form lead. One of the daughter elements of this transition is radon-222. Radon-222 (hereafter referred to as radon) may be found in relatively high concentrations in soils and rocks which contain uranium but cannot be seen, tasted, or smelled. In addition, because radon is chemically inert, it is highly mobile in permeable materials.

Radon is generally measured in units of picocuries per liter (pCi/L). A picocurie (pCi) is a unit of measurement of radioactivity; a curie is the amount of a radionuclide that undergoes exactly 3.7×10^{10} radioactive disintegrations per second; 1 picocurie is one trillionth of a curie.

The health risk from radon is proportional to exposure rates. Studies of hard-rock miners in this century show that inhaled radon-decay products cause lung cancer (Spencer, 1986). Radon does not react directly with tissue when inhaled; it is immediately exhaled. Radon daughter products, however, may become trapped in the lungs by adhering to dust or water molecules. These radon daughter products release bursts of energy, and continued bombardment of the cells by this energy may result in an increased incidence of lung cancer (U.S. Environmental Protection Agency, 1986a and b). Currently, the U.S. Environmental Protection Agency (EPA) recommends that radon levels in indoor air should be reduced to levels less than 4 pCi/L (U.S. Environmental Protection Agency, 1986b). It should be noted that this value was not selected based on health risk estimates, but rather because it represents a realistic level that can be achieved in homes by implementation of currently available control technology (Fortmann, 1988). A person living in a home with an average radon level of 4 pCi/L risks contracting lung cancer at a level which is equivalent to smoking almost half a pack of cigarettes daily (Spencer, 1986). The EPA estimates that 5,000 to 20,000 people in the United States die of lung cancer each year due to the inhalation of radon-decay products; in comparison, approximately 110,500 lung cancer deaths per year are attributed to smoking (U.S. Environmental Protection Agency, 1986b).

Outdoors, radon gas is rapidly dispersed in the atmosphere, therefore, it is not generally considered hazardous. Average

outdoor concentrations of radon range from approximately 0.05 to 0.75 pCi/L (Department of Water and Natural Resources, 1985; Bruno, 1983). The ambient outdoor air radon concentration in South Dakota is approximately 0.08 pCi/L based on limited testing conducted throughout the state from 1982 to 1984 by the Department of Water and Natural Resources (DWNR); (Department of Water and Natural Resources, 1985). Dilution by air is very important, as radon measurements in soil gas range from a few hundred to several thousand pCi/L (Bruno, 1983).

Indoor radon concentrations may accumulate to hazardous levels, depending on numerous factors. Radon, generally derived from natural soil and rock, enters homes and buildings primarily through fractures in basement walls and floors. However, radon may also enter structures through potable ground water supplies. Further discussion of the factors which affect radon concentrations is included in the section of this report entitled Factors Affecting Radon Emission Potential. For the nation as a whole, measured radon concentrations vary from house to house by a factor of several thousand (U.S. Environmental Protection Agency, 1986a).

In general, indoor radon concentrations are usually double that of the outdoor concentrations (Department of Water and Natural Resources, 1985), however, lack of adequate ventilation may enable radon levels to accumulate to more than two orders of magnitude above the average outdoor levels (Bruno, 1983). In South Dakota the mean indoor concentration is estimated to be 0.16 pCi/L. However, testing conducted by the state showed that this estimated concentration was much lower than what has been observed (Department of Water and Natural Resources, 1985). Wiblin and Garland (1988), collected 36 samples from home dwellers in South Dakota; of those 36, 15 (42 percent) had radon values of less than 4 pCi/L, and 21 (58 percent) had values between 4 and 20 pCi/L. No values greater than 20 pCi/L were observed.

Geochemistry and Geology of Uranium

Natural uranium (U) consists chiefly of the isotope U-238, which decays by a series of intermediate radioactive isotopes to form stable isotopes of lead. One of the daughter elements of this transition is radium-226, from which radon-222 gas is derived. Radon-222, with a half-life of 3.82 days, decays to polonium-218. Although several isotopes of radon are produced from the disintegration of radium, only radon-222 has a sufficiently long half-life to be considered a potential health hazard. Given the relatively short half-life of radon-222, it follows that radon must be continuously replenished by longer lived nuclides that precede it in the uranium-238 decay chain. This simple relationship between uranium and radon is the basis for the construction of plate 1.

Uranium has a low crustal abundance, therefore, it is generally present in low concentrations in most rock types (table 1). Chemically, uranium exists as a mobile cation under conditions present at the earth's surface. The principle factor influencing uranium geochemistry is its multiple valency; +4 under reducing conditions and +6 in oxidizing environments. In the +4 state it forms insoluble precipitates (for example, UO_2). It is soluble in the +6 state.

Table 1. Average abundance of uranium in common rocks and natural waters

	Concentration U in parts per million (ppm)	
	(1)	(2)
Igneous rocks:	2.7	
Granite		4
Basalt		0.5
Sedimentary rocks:		
Sandstones:	0.45	
Quartz arenite		0.45
Graywackes		2.1
Arkoses		1.5
Shales:	3.7	
Gray and green		3.2
Red and yellow		2
Black:		
Average		53
Chattanooga		79
Alum Shale		168
Ohio Shale		50
Carbonates:	2.2	
Limestone		2.2
Dolomite		1
Phosphorite		50-300
Natural waters:		
Sea water		1-4 *
Ground water		0.1-460 *
River water		0.026-40 *

(1) Values from Mason and Moore, 1982, p. 176-177.

(2) Values from Maynard, 1983, p. 149; Wedepohl, 1969, p. 92-I-1, 92-I-2.

* Parts per billion (ppb)

During magmatic differentiation uranium crystallizes in late-stage residual solutions. Therefore, it is generally observed in felsic minerals in igneous rocks.

Metamorphic processes may redistribute uranium if the metamorphic intensity is sufficiently high. Under extreme metamorphic conditions, rocks may be converted to magma which subsequently forms uranium-rich differentiates. Under other metamorphic conditions the uranium may be distilled from large volumes of weakly uraniferous rocks concentrating it in favorable geologic settings (Klepper and Wyant, 1957).

In sedimentary rocks, uranium is usually concentrated by secondary, diagenetic processes; specifically by changing oxidizing and reducing conditions (Eh). Ground water leaches uranium under oxidizing conditions, moving it downward and laterally along fractures and through permeable layers. The solubility of uranium, and thus its transport potential, can be greatly enhanced by the formation of complexes with other ions in solution, especially carbonate and phosphate (Maynard, 1983).

Primary deposits of uranium are generally precipitated under reducing conditions. For example, black shales which are rich in organic matter, are deposited slowly in strongly reducing marine environments. Evidence indicates that the concentration of uranium in black shales is probably related to the presence of organic matter in these sediments. Mason and Moore (1982) state that ground water and organic carbon react to produce hydrogen sulfide and organic acids; both reducing agents which promote precipitation of uranium. However, Maynard (1983) suggests that deposition occurs by sorption of uranium onto organic matter rather than precipitation, because low-organic beds can be rich in pyrite (which indicates reducing conditions), but lack appreciable amounts of uranium.

Economic Uranium Deposits

Economic reserves of uranium are typically found as secondary deposits in a variety of rock types and frequently a strong age-dependence is observed. For example, large uranium deposits are found in Proterozoic quartz-pebble conglomerates. The origin of these ores is usually attributed to early atmospheric conditions of low oxygen (Maynard, 1983). In the United States, secondary diagenetic roll-front type deposits in sandstones are typically Mesozoic-Cenozoic in age. The source of uranium in these deposits is usually volcanic ash, from which uranium has been leached soon after deposition, then precipitated at redox interfaces (Maynard, 1983).

Occasionally uranium is observed as a primary, marine, sedimentary deposit. For example, the unusual bituminous Alum Shale in Sweden averages 0.035 percent U_3O_8 [99 ppm U] (Cheney, 1981).

As of December 31, 1971, more than 99 percent of the identified recoverable uranium resources in the United States were in peneconcordant deposits in sandstones and related rocks, and they averaged 0.22 percent U_3O_8 (622 ppm U) (Finch and others, 1973). In the early 1980's most of the large economic uranium deposits contained above 0.03 percent U_3O_8 (85 ppm U) (Cheney, 1981). Only the Witwatersrand deposit contained less, however only one section of one mine was the primary producer and it had a tenor of 0.031 percent U_3O_8 (Cheney, 1981).

ESTIMATED RADON EMISSION POTENTIAL IN SOUTH DAKOTA

Overview

At the request of the Division of Air Quality and Solid Waste, South Dakota Department of Water and Natural Resources, the South Dakota Geological Survey (SDGS) has prepared a generalized relative radon emission potential map of South Dakota (pl. 1). It is intended only to aid in selecting areas to be studied for an EPA sponsored state-wide study of radon. It should not be used to predict radon concentrations in individual homes or buildings. The map is based solely on the distribution and lithology of geologic materials, specifically on the average amount of uranium found in various rock types throughout the world (table 1). Maps similar to plate 1 have been generated by other states (for example, Hall and others, 1987; Muessig, 1988) for use as a first step in identifying areas of possible or existing radon hazards. These studies emphasize the point that many other factors are just as important, or more so than the uranium content in bedrock in determining the potential for elevated radon levels in individual buildings (refer to the section entitled Factors Affecting Radon Emission Potential).

Methods

The current state geologic map (Petsch, 1953) was used as a base map for delineating radon potential boundaries. However, the outline of the Missouri River (U.S. Geological Survey, 1984) was superimposed on Petsch's map to reflect the change in surface-water distribution since the Missouri River dams were constructed. Five relative groups are proposed based on the likelihood that uranium and its daughter products, specifically radon, would be present in near surface rocks. Group one indicates a higher relative radon potential than group five. The relative radon emitting potential between ranks is not necessarily consistent and the order of magnitude of radon emitting potential between two adjacent ranks is uncertain. The first group represents localities where uranium has been found and the uranium content of some rock samples is known to be greater than 0.005 percent U (50 ppm). Uranium mines are often present in these areas. Group two includes stratigraphic units and localities with a high probability of containing uranium. Group three includes

stratigraphic units with abundant volcanic materials, immature sands, and coaly or organic-rich beds which have a moderate probability of containing uranium. Group four contains black shale units which have a lower probability of containing uranium. Group five consists of all other lithologies and they generally have a very low probability of containing uranium. The radon potential ranking of each stratigraphic unit designated by Petsch (1953) is given in table 2.

The uranium values in common rock types given in table 1 are averages. In actuality, a wide range of values exist for most lithologies. For example, based on table 1, all carbonates have been given a "low" ranking for radon potential in South Dakota. However, soil gases from limestones in several places in the United States have surprisingly high radon contents. For example, one of the caves in the Mammoth Cave system in Kentucky has a radon concentration level of 3,600 pCi/L (J. Duval, U.S. Geological Survey, personal communication, 1988).

Group 1

Areas ranked 1 on the relative radon emission potential map (pl. 1) indicate that the probability of uranium occurring in the rock is very high, and of these rocks which have been analyzed for uranium content, the value is known to be greater than 0.005 percent U (50 ppm). Generally these areas have been mined for uranium, or in a few cases sampled for uranium and found to be of ore-grade quality (table 3). The source of radon in this group is attributed directly to the decay of uranium contained in the rocks.

All uranium mines in South Dakota are located in the western half of the State. The Inyan Kara Group sandstones near Edgemont, in the southern Black Hills, have been the most productive ore-producers in the State (Gott and Pipiringos, 1964). The Inyan Kara Group is, in older terminology, equivalent to Petsch's Lakota and Dakota-Fuson Formations (pl. 1). In Harding County, ore-grade carbonaceous siltstones and lignites are present in the North and South Cave Hills area, and sandstone-type uranium deposits are present in the Slim Buttes area. In Perkins County, ore-grade uraniferous lignite ash and extensive deposits of uraniferous lignite are present. The average content of uranium in South Dakota sandstone ores is 0.18 percent U_3O_8 [509 ppm U] and 0.47 percent U_3O_8 [1,329 ppm U] in lignite ores (Gott and Pipiringos, 1964).

Group 2

Group 2 indicates stratigraphic units or areas which have a high probability of containing uranium. These include the Inyan Kara Group and the conglomeratic metasedimentary rocks near Nemo in the Black Hills (J. Redden, South Dakota School of Mines and

Table 2. Radon emission potential ranking assigned to individual stratigraphic units

STRATIGRAPHIC UNIT (Petsch, 1953)	RADON POTENTIAL RANKING	LITHOLOGY	COMMENTS	REFERENCES *
Psh sand hills	3	Sand	-----	-----
Pl lake deposit	5	Clay and silt	-----	-----
Pd delta deposit	5	Sand and silt	-----	-----
Pg gravel	5	Gravel	-----	-----
Py younger drift	5	Shale-derived till with granitic clasts	-----	-----
Po older drift	5	Shale-derived till with granitic clasts	-----	-----
Ph Herrick gravel	5	Gravel	-----	-----
MPb Bijou	3	Arkosic sandstone	-----	Stevenson, 1958
OM Oligocene-Miocene	3	Silt and clay, volcanics	Contains U	Gott and Pippingos, 1964, p. 56 Denson and others, 1959

STRATIGRAPHIC UNIT (Petsch, 1953)	RADON POTENTIAL RANKING	LITHOLOGY	COMMENTS	REFERENCES *
Oa Arikaree	3	Clay and silt	Contains U in Harding County	Curtiss, 1955, p. 78, 85, 100
Om White River	3	Clay, sandy silt	-----	Denson, 1952, p. 10-11
Paf Ft. Union	3	Clay and sand, thin coal beds	Contains U, mined in north- western South Dakota	Curtiss, 1955, p. 78 Schnabel, 1975, p. 176
Palc Ludlow-Cannonball	3	Phosphatic green-gray shale, some sandstone and lignite	Contains U, mined in north- western South Dakota	Curtiss, 1955, p. 78 Schnabel, 1975, p. 176 Gott and Pipirinos, 1964, p. 55
Kh Hell Creek	3	Brown shale, gray sandstone, contains lignite in upper part	May contain U	Curtiss, 1955, p. 97
Kf Fox Hills	5	Glauconitic sands, shale	-----	Curtiss, 1954 Lange, 1962
Kpe Elk Butte	4	Black shale	-----	-----
Kpm Mobridge	4	Black shale	-----	-----
Kpv Virgin Creek	4	Black shale	-----	-----
Kps Sully	4	Black shale	-----	-----

STRATIGRAPHIC UNIT (Petsch, 1953)	RADON POTENTIAL RANKING	LITHOLOGY	COMMENTS	REFERENCES *
Kpgs Gregory-Sharon Springs	3	Black shale	Most uraniferous member of all Pierre Formation	Schultz and others, 1980
Kp undifferentiated	4	Black shale	-----	-----
Kn Niobrara	5	Limestone, marl	-----	Stach, 1972
Kc Carlile	5	Gray, black shale not very organic	-----	-----
Kg Greenhorn	5	Limestone	-----	-----
Kgs Graneros	5	Gray, black shale not very organic	-----	-----
Kd-f Dakota-Fuson	2	Sandstone	Mined for U in southern Black Hills, also U minerals in Newcastle Formation	Curtiss, 1955, p. 99, 70 Schnabel, 1975, p. 176
Kl Lakota	2	Sandstone	Mined for U in southern Black Hills	Gott and Pippingos, 1964, p. 53
Jm-s Morrison-Sundance	5	Silt, clay, limestone green sandstone, thin green nonorganic shale	-----	-----

RADON

STRATIGRAPHIC UNIT POTENTIAL

(Petsch, 1953) RANKING

LITHOLOGY

COMMENTS

REFERENCES *

Trs Spearfish 3 Red sandy siltstone and anhydrites Contains U minerals Schnabel, 1975, p. 176

Pm-o Minnekahta-Opeche 3 Red beds, anhydrites, limestone -----

Pm Minnelusa 3 Sandstone, limestone, dolomite, anhydrite, variegated nonorganic shale Contains U minerals Schnabel, 1975, p. 176

Pma Madison 5 Dolomitic limestone -----

OC Ordovician-Cambrian 5 Sandstone, limestone, green nonorganic shale

Schnabel, 1975, p. 176
J. Redden, South Dakota School of Mines and Technology, personal communication, 1988

Deadwood Formation contains U minerals, anomalous locality

Tertiary intrusives 5 -----

Curtiss, 1955, p. 68, 93
Page and others, 1953, p. 11

Contains U in some pegmatites

pCm, pCs, pCg 5 Precambrian, igneous, and metamorphic rocks

Page and others, 1953, p. 11
Curtiss, 1955, p. 98

Contains U in some pegmatites
Milbank granite may be uranium-ferrous

* All stratigraphic unit lithologic descriptions include Agnew and Tychsen (1965) as a reference.

Table 3. Location of uranium mines or high concentrations of uranium

Group 1	Source of U	References
1. Edgemont area, Fall River and Custer Counties	All mines in the Lakota and Dakota Formation near Edgemont	Curtiss, 1955, fig. 8
2. North and South Cave Hills, Harding County	Curtiss identified Ludlow and Tongue River = Palc and Paf on Petsch's (1953) map	Curtiss, 1955, p. 71
3. Short Pine Hills, Harding County	Curtiss identified Arikaree and White River, both are Oligocene, Petsch mapped as OM	Curtiss, 1955, p. 71
4. Slim Buttes, Harding County	Curtiss identified Arikaree and White River, both are Oligocene, Petsch mapped as OM and Palc	Curtiss, 1955, p. 71, 79
5. Anomalous U value near Belle Fourche, Dakota Formation from Belle Fourche, Butte County, South Dakota to Wyoming border	No specific location given	Curtiss, 1955, p. 70
6. Anomalous U value southwest of Scenic, Pennington County	White River in Curtiss and on Petsch's map. NE 1/4 sec. 31, T. 3 S., R. 13 E., south side of Hart Table	Curtiss, 1955, p. 87
7. Anomalous U value Bald Mountain, Lawrence County	At contact between Whitewood and intrusive rhyolite porphyry, NE 1/4 sec. 1, T. 4 N., R. 2 E., NE 1/4 sec. 3, T. 4 N., R. 2 E.	Curtiss, 1955, p. 92
8. Anomalous U value near Lodgepole, Perkins County	Curtiss identified Tongue River = Paf on Petsch's map. Secs. 9 and 10, T. 21 N., R. 11 E; sec. 19, T. 21 N., R. 12 E.	Curtiss, 1955, p. 97
9. Nemo area	Conglomeratic metasedimentary rocks	J. Redden, South Dakota School of Mines and Technology, written communication, March 21, 1988

Technology, written communication, March 21, 1988). A high probability has been assigned to the Inyan Kara because it is the principal uranium ore-producing sandstone deposit in South Dakota. It should be noted that the Skull Creek Shale member is

included in the Inyan Kara Group on the base map (Petsch, 1953), and that it has a much lower radon emitting potential (rank 4) than the remaining parts of the Formation (J. Redden, South Dakota School of Mines and Technology, written communication, March 21, 1988).

Groups 3-5

Stratigraphic units defined by Petsch (1953), were grouped and ranked 3, 4, or 5 based on estimated uranium content (table 1). Ranks were adjusted where additional information was available which contradicted values given in table 1 (see table 2).

Group 3 contains those stratigraphic units which have a relatively large percentage of volcanic material, are immature nonmarine feldspathic sandstones, or are coaly or organic-rich. These units have also been considered as good prospects for elevated uranium concentrations. The source of radon is inferred to be from the decay of uranium often concentrated in these types of sediments. Group 3 includes most of the state's Tertiary age rocks: Bijou Facies, Oligocene-Miocene deposits, Arikaree Group, White River Group, Fort Union Group, Ludlow-Cannonball Formations, and Hell Creek Formation. In addition, the Sand Hills Formation of southwestern South Dakota, the organic-rich Sharon Springs Member of the Pierre Shale, the Spearfish Formation, Minnekahta-Opeche Formations, and Minnelusa Group are also included (J. Redden, South Dakota School of Mines and Technology, written and personal communication, March, 1988).

Group 4 includes all members of the Pierre Shale Formation except the Sharon Springs Member. The source of radon is inferred to be from the decay of uranium in the organics which are ubiquitous to these black marine shales. Uranium is generally more abundant in shales than most other sedimentary rock types as a primary deposit.

Group 5 consists of stratigraphic units which are considered to have relatively low potential for radon emission. It generally includes the remaining carbonates, sandstones, redbeds, anhydrites, variegated (generally organic-poor) shales, igneous and metamorphic rocks and glacial drift. It should be noted that inclusion of the variegated shales and igneous and metamorphic rocks into this group is controversial. In general, glacial drift (which essentially covers the eastern half of the state) is uranium-poor, however in places it may contain enough pulverized shale to elevate radon concentrations. The following stratigraphic units are ranked as 5: most Pleistocene deposits; the Fox Hills Formation; the Niobrara Formation; the Carlile Shale; Greenhorn Limestone; Graneros Group; Morrison-Sundance Formations; Madison Group; Ordovician-Cambrian deposits; Tertiary intrusives and Precambrian igneous and metamorphic rocks.

Additional Data

Average uranium values for most rock units in South Dakota are not known. Limited radon data have been collected from soils and within homes in South Dakota and very few have been published. These data are not compiled by the state, and therefore, were not used when constructing plate 1. Some useful indirect methods of evaluating the uranium content of the state's rocks are available. These include the National Uranium Resources Evaluation (NURE) program conducted by the U.S. Department of Energy and the South Dakota Geological Survey.

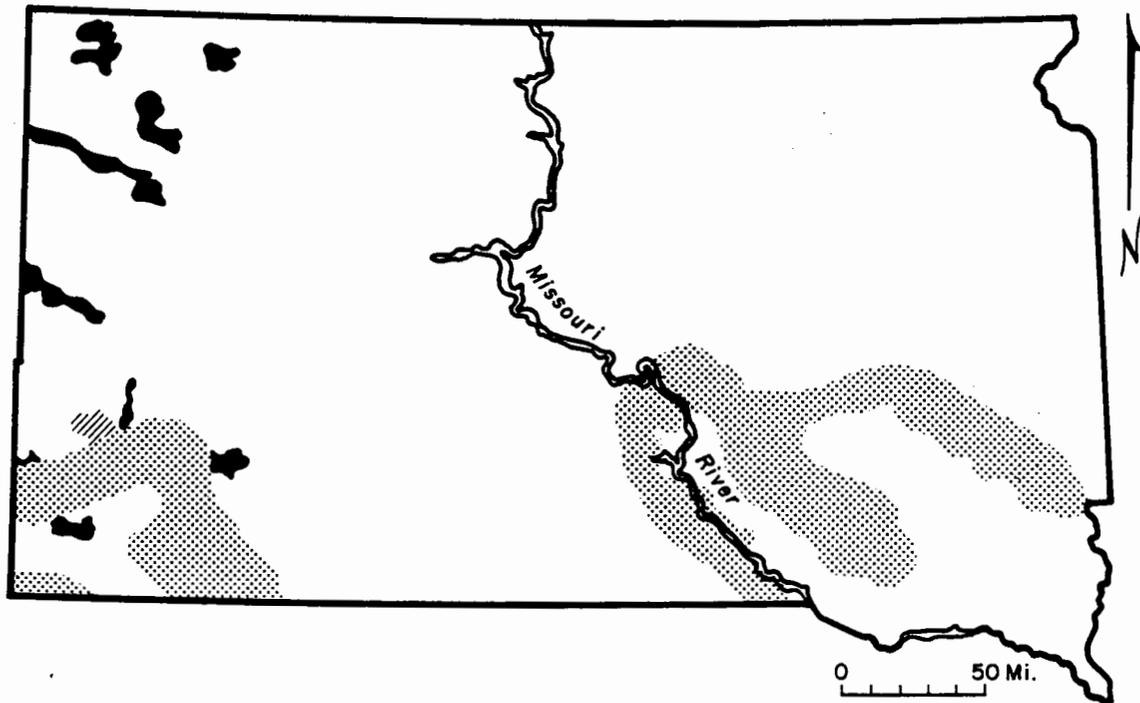
NURE Data

The purpose of the NURE program was to evaluate the regional uranium potential of the United States. Currently, the data are being reevaluated and processed into a digital data base format (J. Duval, U.S. Geological Survey, personal communication, 1988). The revised airborne radiometric survey data will be available in 1989.

Data compiled during the NURE surveys included gamma spectrometer counts of bismuth-214, thallium-208 and potassium-40. Bismuth-214 is a decay product in the uranium-238 decay series and can be used to estimate concentrations of uranium, or radon, if radioactive equilibrium is assumed (Muessig, 1988). Hansen (1986) has used NURE data in Ohio as a general guide to radon potential.

Plate 1 was compared with NURE airborne gamma-ray spectrometer survey summary reports for South Dakota. Environments that were recognized as favorable for uranium deposition based on NURE data included Upper Cretaceous strata and lignite-type deposits in Paleocene strata in the general vicinity of the Black Hills and northwestern part of the State. In general, these data agree with the data used in constructing plate 1. Data from ground sampling studies and home radon testing in a variety of geologic terranes in New Jersey show that NURE data reliably detect areas of rock containing elevated uranium and radon content Muessig (1988). However, Castren and others (1985) found that uranium concentrations in bedrock generally show a poor correlation with measured indoor radon concentrations.

Plate 1 was also compared with an EPA map (fig. 1) of areas with potentially high radon levels in the United States (U.S. Environmental Protection Agency correspondence dated July 31, 1987; Fortmann, 1988). The data used in constructing this map were reportedly based on geological reports, NURE data, and some indoor radon data (J. Duval, U.S. Geological Survey, personal communication, 1988). In general, the data suggest that radon concentrations may be elevated in parts of the western one-fourth of the state, and in areas of black shale outcrops in the entire state. Black shale outcrops are rare in the eastern part of South



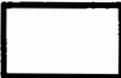
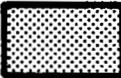
-  Areas which may have the least chance of producing high radon levels.
-  Granitic rocks with $> 4\text{ppm}$ uranium.
-  Black shales.
-  Near-surface distribution of NURE potential uranium resources.

Figure 1. EPA map of South Dakota depicting areas with potentially high radon levels. (Adapted from Fortmann, 1988).

Dakota, and those shown on figure 1 are actually covered by 50 to 1,000 feet of glacial drift (R. Hammond, SDGS, personal communication, 1988). Otherwise, it appears that the relative radon emission potentials of figure 1 and plate 1 are fairly consistent.

Gamma-Log Data

The SDGS routinely collects gamma logs from test holes after drilling. These data, as well as logs from many private wells, are on file at the SDGS in Vermillion. Gamma logs may provide a relative measure of uranium content. In South Dakota, black shales have a high to medium gamma response. Till and lake deposits as well as outwash, sandstone, and chalk have a moderate to low gamma response (R. Hammond; J. Lehr, SDGS, personal communication, 1988). It follows that the relative radon emission potential of the respective units may be high and low.

Gamma logs collected from drill holes in igneous and metamorphic rocks in South Dakota generally have a low gamma response and; therefore, probably a relatively low radon emission potential (R. Hammond; J. Lehr, SDGS, personal communication, 1988). Occasionally, however, the conglomeratic Sioux Quartzite Formation in eastern South Dakota may locally have a high gamma response (R. Hammond; J. Lehr, SDGS, personal communication, 1988).

Factors Affecting Radon Emission Potential

Many factors affecting the potential for radon emission cannot be isolated and analyzed individually. For example, permeabilities are intimately intertwined with rock and soil composition as well as moisture content. A zircon sand with several ppm U may not be hazardous because the radon cannot escape from the mineral grains, but a limestone with 2 ppm U with high permeability and high emanation power may result in several thousand pCi/L of radon in the soil gas (J. Duval, U.S. Geological Survey, written communication, May 12, 1988). The amount of soil moisture present affects both radon generation as well as transport. Radon emanation is inhibited at higher levels of moisture content because the radon atoms are trapped in the pore liquid coating on soil grains (Schumann and others, 1988). Increased amounts of soil moisture also block pore spaces thereby reducing gas migration (Sextro and others, 1988).

Generally only soil permeabilities are discussed as a variable in predicting indoor levels of radon. A South Dakota soils permeability map is not currently available. However, relative data are being computerized and such a map will be available from the Soil Conservation Service in 1990. It should be noted that such a map would reflect the soil permeability response to moisture, not gas.

Radon is primarily transported in one of two ways: (1) by diffusion in low permeability soils and (2) by convective transport in more permeable (intrinsic permeability generally greater than 10^{-7} cm²) soils (Sextro and others, 1987). A radon atom may travel approximately 1 or 2 meters in dry soil by diffusion during its mean life span (5.5 days), and only 1 to 2 centimeters in saturated soils during the same time period (Tanner, 1964). A radon atom may move up to several tens of meters from its source by convective transport in a relatively dry, permeable soil (Tanner, 1964; Schumann and others, 1988). In finer grained materials, especially those with high clay content (for example, till) less moisture is necessary to inhibit radon migration because (a) the pore spaces are smaller, (b) water molecules are bound to the clay particles, and (c) expandable clays swell in the presence of moisture, further reducing pore space (Schumann and others, 1988).

Capping effects (such as saturated soils or frozen moisture) inhibit the release of radon to the atmosphere. They also isolate the soil from the air, suppressing barometric, thermal and wind effects (Schumann and others, 1988).

Concentrations of radon soil-gas fluctuate at a site depending on meteorological factors. Soil-gas radon concentrations are highest in late winter and early spring and lowest in the fall, with variations as large as an order of magnitude (Schumann and others, 1988). In a seasonal context, an approximately direct correlation can be assumed between the wet and dry weather periods and moisture levels in the vadose zone. Changes in barometric pressure influence soil-gas radon concentrations up to a meter in depth during most of the year. A decrease in pressure draws soil gas into the atmosphere, whereas an increase in pressure forces air into the soil which dilutes the near surface concentration of radon soil-gas (Schumann and others, 1988). Relatively good correlations between soil-gas concentrations and changes in weather associated with discrete storms have also been observed (Schumann and others, 1988). Superimposed on seasonal changes are diurnal changes. One of the largest forces driving diurnal variations is the indoor-outdoor temperature contrast, radon concentrations generally increase twofold during the nighttime (Scott, 1988).

Building construction and materials may affect indoor radon concentrations. Masonry materials are the primary sources of radon among building materials; for all practical purposes, wood and wood-products do not contribute to indoor radon levels (Bruno, 1983). Levels vary depending on whether or not a basement or crawl space is present, whether the foundation is of poured or block cement, the leakiness of the substructure (presence of cracks, sumps), and the type of heating and cooling system used. The amount of soil disturbed between a building foundation and adjacent undisturbed soil may also affect indoor radon concentrations.

Occupant use of a building also affects the indoor radon concentrations. Ventilation rates will vary depending on whether or not open windows or air conditioners, forced air or electrical heat are used. Turning down a thermostat at night, or even the presence of an attached garage may influence indoor radon levels (Hubbard and others, 1988; Scott, 1988).

Aeration of radon-laden water (i.e., washing machine, driers, showers) is another potential source of elevated indoor radon concentrations. It has been estimated that 1 to 7 percent of the total indoor air radon concentration is due to aeration of drinking water sources (Cothorn, 1987). South Dakota does not analyze public water supplies for radon content and health standards have not been set for radon levels in potable water. Hall and others (1987) state that there is a general consensus among workers that 10,000 to 20,000 pCi/L of radon gas in ground water is cause for concern and that remedial action is probably required for concentrations greater than 100,000 pCi/L. Results from one study included three ground-water analyses of private well ground water in South Dakota. These radon concentrations ranged from 118 to 2,779 pCi/L (Vitz, 1988).

In an extreme example of occupant induced variability, an average wintertime basement measurement of radon was doubled (from 17 pCi/L to 35 pCi/L) when water use doubled (Scott, 1988). In that study the source of radon was primarily through aeration of the water supply. The family used more water after a baby joined the household, so presumably the radon levels increased as a function of how fast the family's clothes got dirty.

MAP LIMITATIONS

Plate 1 is a tentative map based on several assumptions and has several restrictive limitations because many important variables could not be considered. Nevertheless, the ultimate source of radon is uranium so it is expected that the occurrence of radon should, to a first approximation, be correlated with the uranium content of the bedrock (Hall and others, 1987).

Listed below are the assumptions which were made in constructing plate 1.

1. The worldwide average uranium content of various lithologies are consistent with South Dakota lithologies.
2. South Dakota bedrock lithologies are homogeneous units.
3. The textural and mineralogical characteristics of South Dakota lithologic units are representative of surficial materials (including soils).

4. Lithologic units have not been disturbed by natural (deformational) or manmade processes which may form pathways for more rapid transmission of soil gases (including radon) to the land surface.
5. Because radon has a short half-life (3.82 days) and most radon decays before it can move very far, only surficial rock units were used in constructing this map.
6. All surficial materials are unsaturated. If pore spaces in shallow materials contain water, radon emissions would tend to be reduced because the radon must diffuse through the water before it can escape into the atmosphere (J. Duval, U.S. Geological Survey, written communication, May 12, 1988).

Plate 1 must be used with several limitations kept in mind. All groups defined in this report are approximate, and boundaries between groups should not be considered definitive. Within any grouping, indoor radon levels may not be the same because of many contributing factors. This map cannot be used to estimate or determine the radon level of a specific neighborhood or building. In order to determine if a particular structure has a radon problem, it is necessary to measure the radon level in that structure. Finally, this map should not be used as the sole source for predicting indoor radon levels. It is imperative that this information be used in conjunction with other factors.

Many important variables could not be included in the construction of plate 1 because data were not available. Generally a site specific radon hazard is dependent on a combination of radon supply factors (such as permeabilities, local rock and soil composition, and moisture content) and ventilation rate factors (such as meteorological conditions, building construction and materials, and occupant use). Thus the concentration inside a building is set by the balance between radon supply and the ventilation rate (Scott, 1988).

SUMMARY

In general, this map illustrates that the western part of the State may have a higher relative radon potential because of outcrops of volcanic debris, immature sandstones and organic-rich shales and siltstones which are rare in the east. The highest relative radon emission potentials are estimated to be at localities which have been mined for uranium.

Additional information about radon, radon detection and radon mitigation methods may be obtained from the Division of Air Quality and Solid Waste, South Dakota Department of Water and Natural Resources, at the following address:

Air Quality and Solid Waste
South Dakota Department of Water and
Natural Resources
Foss Building
Pierre, SD 57501

The EPA may also be contacted for additional information:

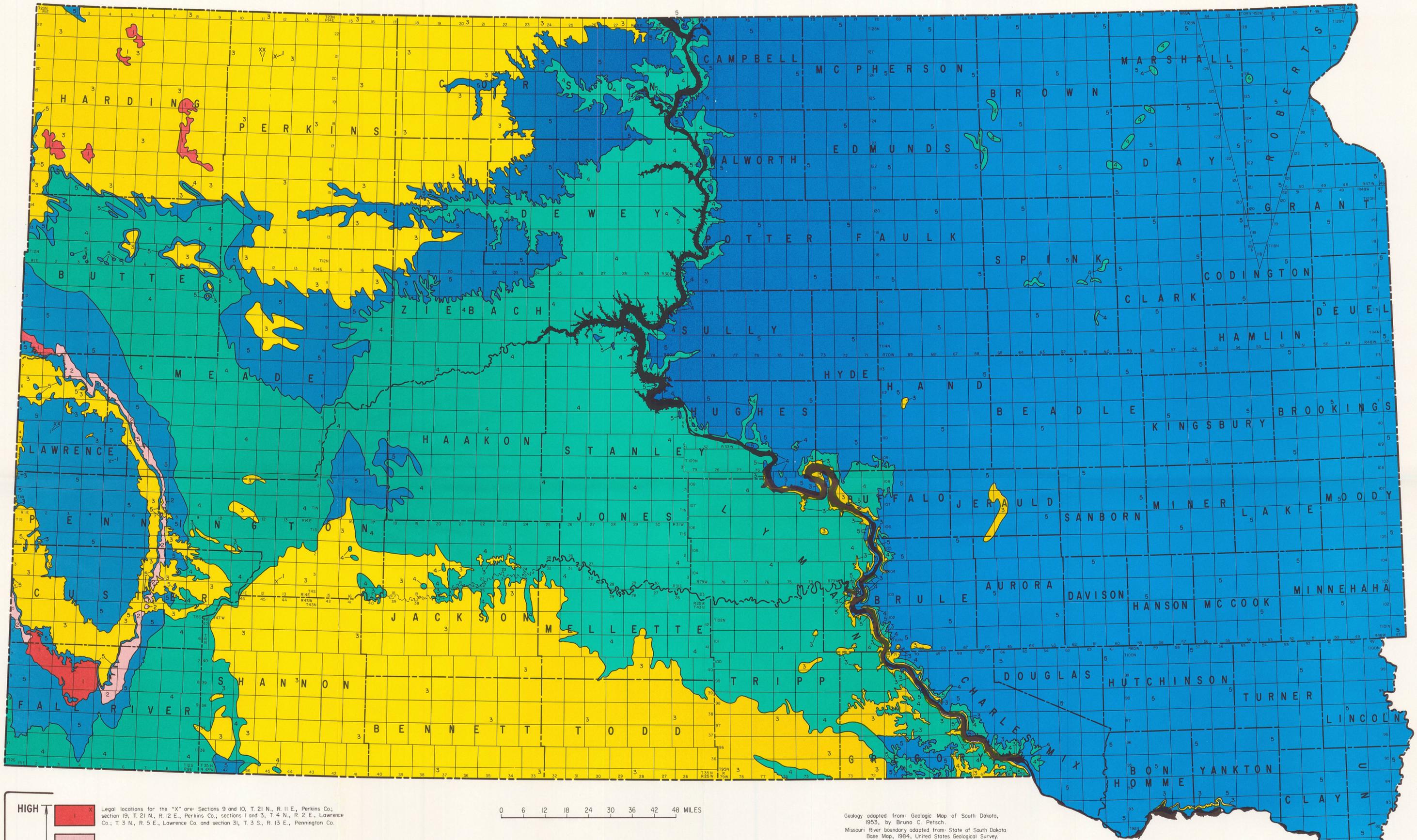
U.S. Environmental Protection Agency
Office of Research and Development
Washington, D.C. 20460

REFERENCES

- Agnew, A. F., and Tychsen, P. C., 1965, A guide to the stratigraphy of South Dakota: South Dakota Geological Survey Bulletin 14, 195 p.
- Bruno, R. C., 1983, Sources of indoor radon in houses: A review: Journal Air Pollution Control Association v. 33, no. 2, p. 105-109.
- Castren, O., Voutilainen, A., Winqvist, K., and Makelainen, I., 1985, Studies of high indoor radon areas in Finland: The Science of the Total Environment, v. 45, p. 311-318.
- Cheney, E. S., 1981, The hunt for giant uranium deposits: American Scientist, v. 69, p. 37-48.
- Cothorn, C. R., 1987, Development of regulations for radionuclides in drinking water, in Graves, Barbara, ed., Radon in Ground Water: Chelsea, Michigan, Lewis Publishers, p. 1-11.
- Curtiss, R. E., 1954, Areal geology of the Firesteel Creek quadrangle, South Dakota: South Dakota Geological Survey Geologic Quadrangle Map, scale 1:62,500, text.
- 1955, A preliminary report on the uranium in South Dakota: South Dakota Geological Survey Report of Investigations 79, 102 p.
- Denson, N. M., 1952, Summary of uranium-bearing coal, lignite, and carbonaceous shale investigations in the Rocky Mountain region during 1951 with description of deposits by Bachman, G. O., Gill, J. R., Hail, W. J. Jr., Love, J. D., Masursky, Harold, Denson, N. M., Moore, G. W., Pipiringos, G. N., Vine, J. D., and Zeller, H. D.: U.S. Geological Survey Trace Elements Memo. Report 341A, 44 p.
- Denson, N. M., Bachman, G. O., and Zeller, H. D., 1959, Uranium-bearing lignite in northwestern South Dakota and adjacent states: U.S. Geological Survey Bulletin 1055-B, p. 11-57.
- Department of Water and Natural Resources, 1985, Radon-222 and daughter concentrations in conventionally constructed and energy efficient structures in South Dakota, November 1982 - December 1984: Pierre, South Dakota, Department of Water and Natural Resources, Office of Air Quality and Solid Waste, 24 p.

- Finch, W. I., Butler, A. P., Jr., Armstrong, F. C., and Weissenborn, A. E., 1973, Uranium, in Brobst, D. A., and Pratt, W. P., eds., United States mineral resources: U.S. Geological Survey Professional Paper 820, p. 456-468.
- Fortmann, R. C., 1988, Radon in the indoor environment: American Society for Testing and Materials Standardization News, v. 16, no. 12, December 1988, p. 50-53.
- Gott, G. G., and Pippingos, G. N., 1964, Uranium, in Mineral and water resources of South Dakota: South Dakota Geological Survey Bulletin 16, p. 50-56.
- Hall, F. R., Boudette, E. L., and Olszewski, W. J., Jr., 1987, Geologic controls and radon occurrence in New England, in Graves, Barbara, ed., Radon in Ground Water: Chelsea, Michigan, Lewis Publishers, p. 15-30.
- Hansen, M. C., 1986, Radon, Ohio geology newsletter, fall 1986: Ohio Department of Natural Resources, p. 1-5.
- Hubbard, L. M., Balkar, B., Socolow, R. H., 1988, Radon dynamics in a house heated alternately by forced air and by electric resistance: Unpublished paper from the 1988 Symposium on radon and radon reduction technology, Denver, Colorado, U.S. Environmental Protection Agency, October 17-21, 1988.
- Klepper, M. R., and Wyant, D. G., 1957, Notes on the geology of uranium: U.S. Geological Survey Bulletin 1046-F, p. 87-148.
- Lange, A. U., 1962, Geology of the Signal Butte quadrangle, South Dakota: South Dakota Geological Survey Geologic Quadrangle Map, scale 1:62,500, text.
- Mason, B., and Moore, C. B., 1982, Principles of geochemistry: New York, John Wiley and Sons, 344 p.
- Maynard, J. B., 1983, Geochemistry of sedimentary ore deposits: New York, Springer-Verlag, Inc., 305 p.
- Muessig, K. W., 1988, Correlation of airborne radiometric data and geologic sources with elevated indoor radon in New Jersey: Unpublished paper from the 1988 Symposium on radon and radon technology, Denver, Colorado, U.S. Environmental Protection Agency, October 17-21, 1988.
- Page, L. R., Norton, J. J., Stoll, W. C., Hanley, J. B., Adams, J. W., Pray, L. C., Steven, T. A., Erickson, M. P., Joraleman, P., Stopper, R. F., and Hall, W. E., 1953, Pegmatite investigations 1942-1945 Black Hills, South Dakota: U.S. Geological Survey Professional Paper 247, 228 p.
- Petsch, B. C., 1953, Geologic map of South Dakota: South Dakota Geological Survey General Map, scale 1 inch = 9 miles.
- Schnabel, R. W., 1975, Uranium, in Mineral and water resources of South Dakota: South Dakota Geological Survey Bulletin 16, p. 172-176.
- Schultz, L. G., Tourtelot, H. A., Gill, J. R., and Boerngen, J. G., 1980, Composition and properties of the Pierre Shale and equivalent rocks, northern great plains region: U.S. Geological Survey Professional Paper 1064-B.
- Schumann, R. R., Owen, D. E., and Asher-Bolinder, S., 1988, Weather factors affecting soil-gas radon concentrations at a single site in the semiarid western United States: Unpublished paper from the 1988 Symposium on radon and radon

- reduction technology, Denver, Colorado, U.S. Environmental Protection Agency, October 17-21, 1988.
- Scott, A. G., 1988, Effect of indoor radon variability on the duration and interpretation of radon measurements: Unpublished paper from the 1988 Symposium on radon and radon reduction technology, Denver, Colorado, U.S. Environmental Protection Agency, October 17-21, 1988.
- Sextro, R. G., Moed, B. A., Nazaroff, W. W., Reuzan K. L., and Nero, A. V., 1987, Investigations of soil as a source of indoor radon, *in* Hopke, P. K., ed., Radon and its decay products: American Chemical Society Symposium Series 331, p. 10-29.
- Sextro, R. G., Nazaroff, W. W., and Turk, B. H., 1988, Soil permeability and radon concentration measurements and a technique for predicting the radon source potential of soil: Unpublished paper from the 1988 Symposium on radon and radon reduction technology, Denver, Colorado, U.S. Environmental Protection Agency, October 17-21, 1988.
- Spencer, J. E., 1986, Radon gas: a geologic hazard: Arizona Bureau of Geology and Mineral Technology, v. 16, no. 4.
- Stach, R. S., 1972, Mineralogy and stratigraphy of the Niobrara Formation, South Dakota: Unpublished Master's Thesis, Vermillion, South Dakota, University of South Dakota, 53 p.
- Stevenson, R. E., 1958, Geology of the Gregory quadrangle, South Dakota: South Dakota Geological Survey Geologic Quadrangle Map, scale 1:62,500, text.
- Tanner, A. B., 1964, Radon mitigation in the ground: A Review, *in* Adams, J. A. S., and Lowder, W. M., eds., The natural radiation environment: Chicago, University of Chicago Press, p. 161-190.
- U.S. Environmental Protection Agency, 1986a, Radon reduction techniques for detached houses: EPA/625/5-86/019, June, 1986.
- 1986b, A citizen's guide to radon: EPA-86-004, August, 1986.
- U.S. Geological Survey, 1984, State of South Dakota base map, scale 1:500,000.
- Vitz, E., 1988, Preliminary results of a nationwide waterborne radon survey: Unpublished paper from the 1988 Symposium on radon and radon reduction technology, Denver, Colorado, U.S. Environmental Protection Agency, October 17-21, 1988.
- Wedepohl, K.H., 1969, ed., Handbook of geochemistry: New York, Springer-Verlag.
- Wiblin, C., and Garland, R., 1988, A comparison of nationwide indoor radon measurements by home dwellers and by real estate testing firms: Unpublished paper from the 1988 Symposium on radon and radon reduction technology, Denver, Colorado, U.S. Environmental Protection Agency, October 17-21, 1988.



HIGH ↑

1 X
2
3
4
5

LOW ↓

Legal locations for the "X" are: Sections 9 and 10, T. 21 N., R. 11 E., Perkins Co.; section 19, T. 21 N., R. 12 E., Perkins Co.; sections 1 and 3, T. 4 N., R. 2 E., Lawrence Co.; T. 3 N., R. 5 E., Lawrence Co. and section 31, T. 3 S., R. 13 E., Pennington Co.

All ranks defined on this map are approximate and boundaries between groups should NOT be considered definitive. The estimated relative radon emitting potential between adjacent ranks is not necessarily consistent and the order of magnitude of radon emitting potential between ranks is also uncertain.

This map alone cannot be used to predict the radon level of a specific neighborhood because of differences in soil and rock permeabilities, water-table conditions, and construction methods. In order to determine if a particular structure has a radon problem, it is necessary to measure the radon level in that structure.

Plate I. Generalized potential for radon emission based on estimated uranium content in geologic rock units, South Dakota.

Geology adapted from: Geologic Map of South Dakota, 1953, by Bruno C. Petsch.
Missouri River boundary adapted from: State of South Dakota Base Map, 1984, United States Geological Survey.