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Assessment of Potenial Radiological Health Effects from Radon in Natural Gas

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Radiation Programs

ASSESSMENT OF POTENTIAL RADIOLOGICAL HEALTH EFFECTS FROM RADON IN NATURAL GAS

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FOREWORD

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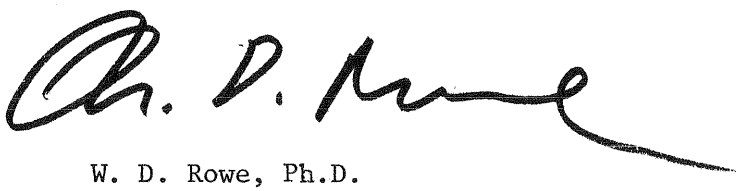

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ABSTRACT

Natural gas contains varying amounts of radon-222 which becomes dispersed in homes when natural gas is used in unvented appliances. Radon decays to alpha-emitting daughter products which can contribute to lung cancer when inhaled and deposited in the respiratory system. For the average use of unvented kitchen ranges and space heaters, the tracheobronchial dose equivalent to individuals was estimated as 15 and 54 mrem/yr, respectively, or 2.73 million person-rems/yr to the United States population. A review of exposure conditions, lung model parameters, dose conversion factors, and health effect factors indicated this population dose equivalent could potentially lead to 15 deaths a year from lung cancer. This represents only 0.03 to 0.08 percent of normal lung cancer mortality. Since control of radon levels in gas would cost over $100 million for each reduction of one health effect, it was concluded that a requirement for such controls would not be cost effective on a national basis.

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INTRODUCTION

Radon in natural gas

Radon-222 is a radioactive gaseous daughter product of radium-226 found in naturally occurring uranium minerals throughout the earth's crust. This heavy inert gas permeates porous geological formations and is collected along with methane in production wells for natural gas. When this natural gas is used in unvented appliances, such as kitchen ranges and space heaters, the combustion products and radon are released within the home. This radon constitutes an additional source of radiation in the home which has not been adequately evaluated for potential health effects.

Radon: Health effects

The hazard to persons working in radon-contaminated atmospheres was first associated with radiation exposure to uranium miners in the 1920's. Since then the correlation of radon daughter concentrations and the incidence of lung cancer among miners has prompted stricter controls on radon and radon daughters and many studies on radon dosimetry. These studies concluded that the primary concern for exposure to radon was from inhalation and deposition of radon daughters which release their alpha decay energy to tissues of the respiratory system.

The potential for health effects resulting from the use of natural gas containing radon was not recognized until about 1966. Even now, this source of radon exposure has had only limited evaluations. However, studies still in progress at the National Environmental Research Center-Las Vegas, Oak Ridge National Laboratory, and the University of Texas Health Science Center at Houston have provided information which can be used to place the question of health effects from radon in natural gas in perspective. Data from these studies will be reviewed here along with an analysis of radon dosimetry as a summary of present knowledge on potential radon exposure and consequences resulting from use of natural gas.

Approach

Estimates of potential health effects from radon in natural gas will be derived following a sequential analysis outlined in figure 1. This

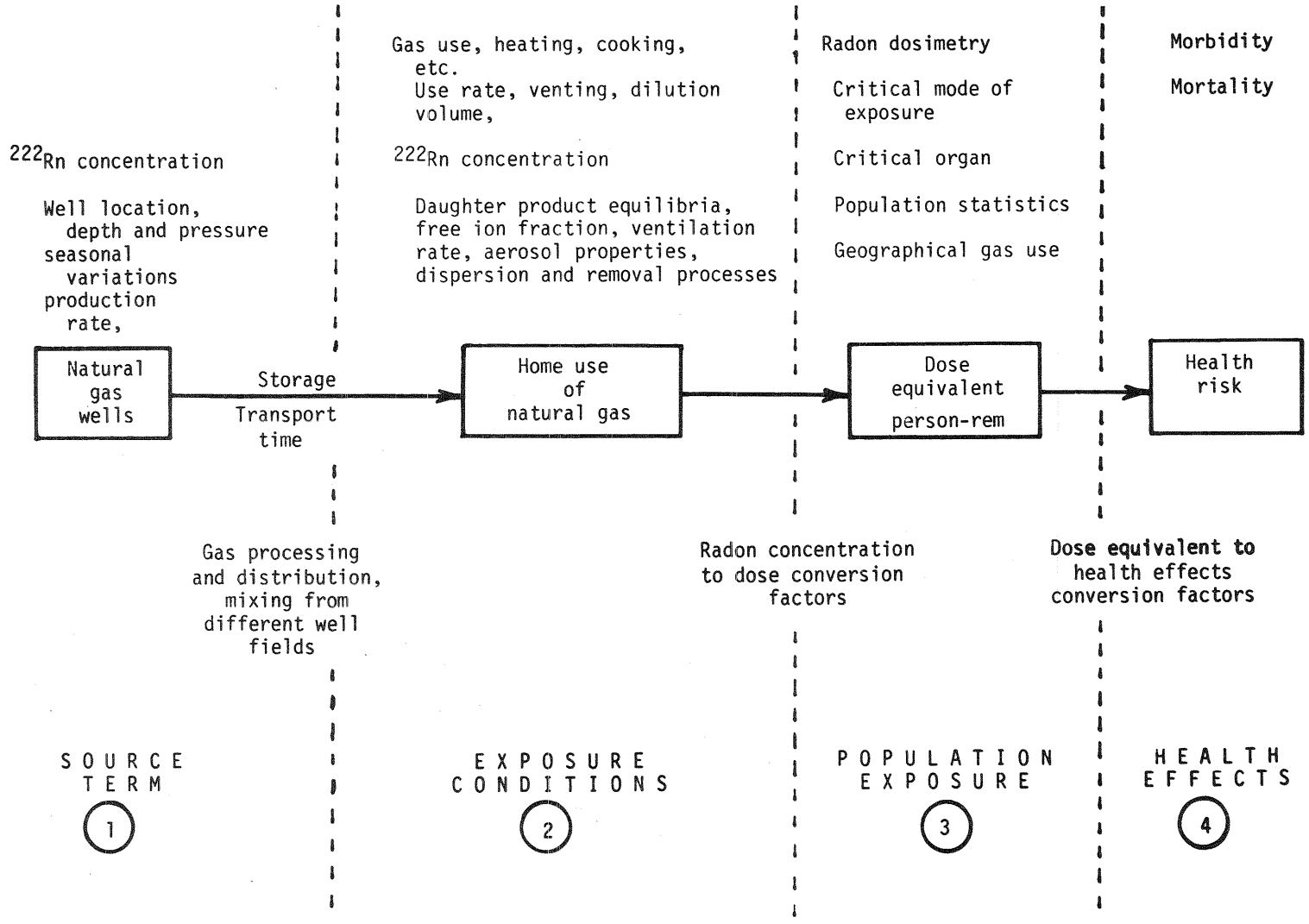

Figure 1. Model for estimating potential health effects from radon in natural gas

figure shows a generalized model for assessing health effects and some of the factors to be considered. Reference to this model will assist in relating these factors for a logical approach to calculating and interpreting the significance of potential health effects from radon.

Scope and objectives

This review will primarily cover the estimation of health effects from release of radon in dwellings through use of natural gas in unvented cooking ranges or space heaters. The significance of these estimates will be interpreted in terms of reasonable variations which could be expected in the assumptions used in the model for calculating health effects. Particular attention is given as to how conservative the various parameters may be which enter into the analysis.

This report is intended to provide information on the following items:

(a) radon-222 concentrations in natural gas,
(b) natural gas usage and exposure conditions,
(c) critical mode of exposure and radon dosimetry,
(d) population dose,
(e) potential health effects and interpretation of significance, and
(f) alternative radon controls and comparison of costs for reduction in potential health effects.

RADON CONCENTRATION IN NATURAL GAS

At production wells

Bunce and Sattler (1) conducted an extensive study in 1965 to determine the radon-222 concentrations in natural gas production wells in the San Juan Basin area of Colorado and New Mexico. They sampled over 300 wells and found an average radon level of 25 pCi/1. Individual wells were sampled with levels as high as 160 pCi/1 and as low as 0.2 pCi/1. A review by Barton (2) showed that 1,250 wells in Texas, Kansas, and Oklahoma had average radon concentrations of 100 pCi/1 or less. Concentrations in these wells varied from 5 to 1,450 pCi/1.

Faul and coworkers (3), with the United States Geological Survey, determined the radon content of about 500 producing gas wells in the Texas panhandle area. They observed levels from about 10 to 520 pCi/1 at standard temperature and pressure. They also noted that the radon content is nearly constant for a given well under normal production conditions. A significant change in radon concentration was measured in several wells on restarting after being shut down during the summer.

The radon values rose sharply with initial production and leveled off after removal of about twenty to fifty thousand cubic feet of gas (less than one hour's production for wells normally producing two to three million cubic feet daily). They interpreted this behavior, along with an analysis of transient gas flow and steady state conditions, as an indication that radon originates in the immediate vicinity of the bore in most wells.

Seasonal variations in radon content of natural gas were also observed by Bunce and Sattler (1). They measured radon in 11 wells in three geologic strata over 3-month intervals from May to October 1964. The earlier samples, corresponding to reduced summer production, had average levels of 22.5 pCi/1. The later samples, in September and October, had levels of about 17.8 pCi/1. They attributed these differences mainly to changes in the rate of gas production (or usage).

Many measurements have also been made of radon in gas in conjunction with tests for nuclear stimulation of natural gas. Data from Boysen (4), Gotchy (5), and NERC-LV (6) on studies of the Rulison and Rio Blanco gas stimulation projects indicate the average radon level for wells in the Rulison area during 1969-1970 was 25.4 pCi/1 (range 11 to 45 pCi/1). McBride and Hill (7) reported that levels of radon-222 in preshot samples for project Gasbuggy had an average value of 19.4 pCi/1. Postshot samples indicated that nuclear stimulation did not raise radon-222 concentrations in neighboring wells above the naturally occurring levels.

The NERC-LV Technical Support Section (8) also sampled natural gas from two trunk lines serving all 28 producing gas wells within 5 miles of Project Gasbuggy from November 1969 to November 1970. The average radon level was 29.4 pCi/1 with a range of 12 to 59 pCi/1. These results were essentially the same as before Project Gasbuggy and confirmed that nuclear stimulation does not increase radon levels. Some seasonal variation was apparent with the higher levels occurring between March 31 and September 15, 1970.

A summary of data on radon-222 concentrations in natural gas at production areas is given in table 1. The Gulf Coast region of Louisiana and Texas has the lowest average radon concentration at about 5 pCi/1. Upper Texas, Kansas, Oklahoma, and California have average levels up to about 100 pCi/1. When all the data are averaged a level of 37 pCi/1 is obtained. However, many individual wells could have radon levels 10 to 20 times this value. In addition, the average level calculated here does not account for the relative gas production volumes from different regions of the country (see table 2).

Table 1. Radon-222 concentrations in natural gas at production wells

Area	Radon-222 level, pCi/l		Reference
	Average	Range	
Colorado New Mexico	25	0.2-160	1
Texas, Kansas, Oklahoma	<100	5-1450	2
Taxas Panhandle	---	10-520	3
Colorado	25.4	11-45	5-7
Project Gasbuggy Area	15.8-19.4	---------	7
Project Gasbuggy Area	29.4	12-59	8
California	---	1-100	10
Gulf Coast (Louisiana, Texas)	5	--------	11
Kansas	100	--------	11
Wyoming	10	--------	11
Overall average	37		

Table 2. Gas wells, marketed production, and use of natural gas by regions and states (9)

Division and State	Producing gas wells	Net marketed production	Approximate gas consumption
United States[a]	117,300	19,532,622	20,268,303
		Percentage of United States	
New England	0	0	1.11
Connecticut	0	0	0.27
Maine, New Hamsphire, Vermont	0	0	0.05
Massachusetts	0	0	0.68
Rhode Island	0	0	0.11
Middle Atlantic	14.58	0.35	8.28
New Jersey	0	0	1.46
New York	0.52	0.01	3.22
Pennsylvania	14.06	0.34	3.60
East North Central	7.47	0.47	18.14
Illinois	0.01	0	5.74
Indiana	0.04	0	2.48
Michigan	0.25	0.11	3.65
Ohio	7.17	0.36	4.77
Wisconsin	0	0	1.50
West North Central	7.37	4.11	8.96
Iowa	0	0	1.52
Kansas	7.32	3.94	2.84
Minnesota	0	0	1.51
Missouri	0	0	1.87
Nebraska	0.02	0.02	0.92
North Dakota	0.03	0.15	0.16
South Dakota	0	0	0.14
South Atlantic	17.82	1.05	6.79
Delaware	0	0	0.12
Florida	0	0	1.45
Georgia	0	0	1.52
Maryland, District of Columbia	0.01	0	0.83
North Carolina	0	0	0.70
South Carolina	0	0	0.68
Virginia	0.12	0.01	0.64
West Virginia	17.69	1.04	0.85
East South Central	6.21	0.85	5.19
Alabama	0	0	1.20
Kentucky	5.89	0.32	1.15
Mississippi	0.31	0.53	1.67
Tennessee	0.01	0	1.17
West South Central	35.84	82.2	34.83
Arkansas	0.74	0.77	1.52
Louisiana	8.16	35.93	9.31
Oklahoma	6.94	7.49	3.01
Texas	20.00	38.01	20.99
Mountain	9.60	7.70	5.71
Arizona	0.01	0	0.93
Colorado	0.76	0.48	1.27
Idaho	0	0	0.22
Montana	0.45	0.15	0.43
Nevada	0	0	0.29
New Mexico	7.67	5.19	1.44
Utah	0.07	0.19	0.54
Wyoming	0.64	1.69	0.59
Pacific	1.11	3.26	10.97
Alaska	0.04	0.54	0.31
California	1.07	2.72	9.53
Hawaii	0	0	0
Oregon	0	0	0.44
Washington	0	0	0.69

[a]Total gas wells, production and consumption in millions of cubic feet. Consumption was derived from net interstate receipts and deliveries of natural gas including foreign imports and exports.

The relative numbers of gas producing wells by regions and states are also shown in table 2. It is worthwhile to note that about 36 percent of the gas wells are located in the West South Central region (Arkansas, Louisiana, Oklahoma, Texas) which produces over 82 percent of this country's natural gas. Furthermore, most of this gas is consumed outside of this region. Therefore, the low radon concentrations reported for the Gulf Coast may be especially significant when one considers the large contribution (40-60 percent) which this region produces for the national supply of natural gas. Likewise, the production regions of higher radon concentration in Texas, Kansas, Oklahoma, and California may produce only 15 to 20 percent of this country's natural gas. At the present time, however, insufficient radon measurements have been made in these states to correlate radon levels and production volumes. Therefore, it is not possible to determine an average radon level for the country that is weighted for production volumes from different regions of the country.

In distribution systems

The concentration of radon in distribution systems near points of consumer use is determined by a number of factors which include (12):

(a) concentration at the wellhead,
(b) production rate,
(c) pipeline dilution,
(d) gas processing,
(e) pipeline transmission time, and
(f) storage time

The relationship of these factors is shown in figure 2. The normal operations on natural gas which may affect radon concentrations will be reveiwed briefly in the following sections.

Gas processing

Natural gas processing facilities receive gas from the well fields which contains from 55 to 98 percent methane and various percentages of other heavier hydrocarbons (ethane, propane, butane), as well as carbon dioxide, nitrogen, helium, and water vapor. This gas is processed to give a marketable fuel with the following average properties (volume percent):

Methane	Ethane	Propane	Butane	CO_2	N_2
84	6	2	1	1	8

Primarily, the processing plant removes water vapor, propane and longer chain hydrocarbons as fractionated liquid products. The heavy hydro-

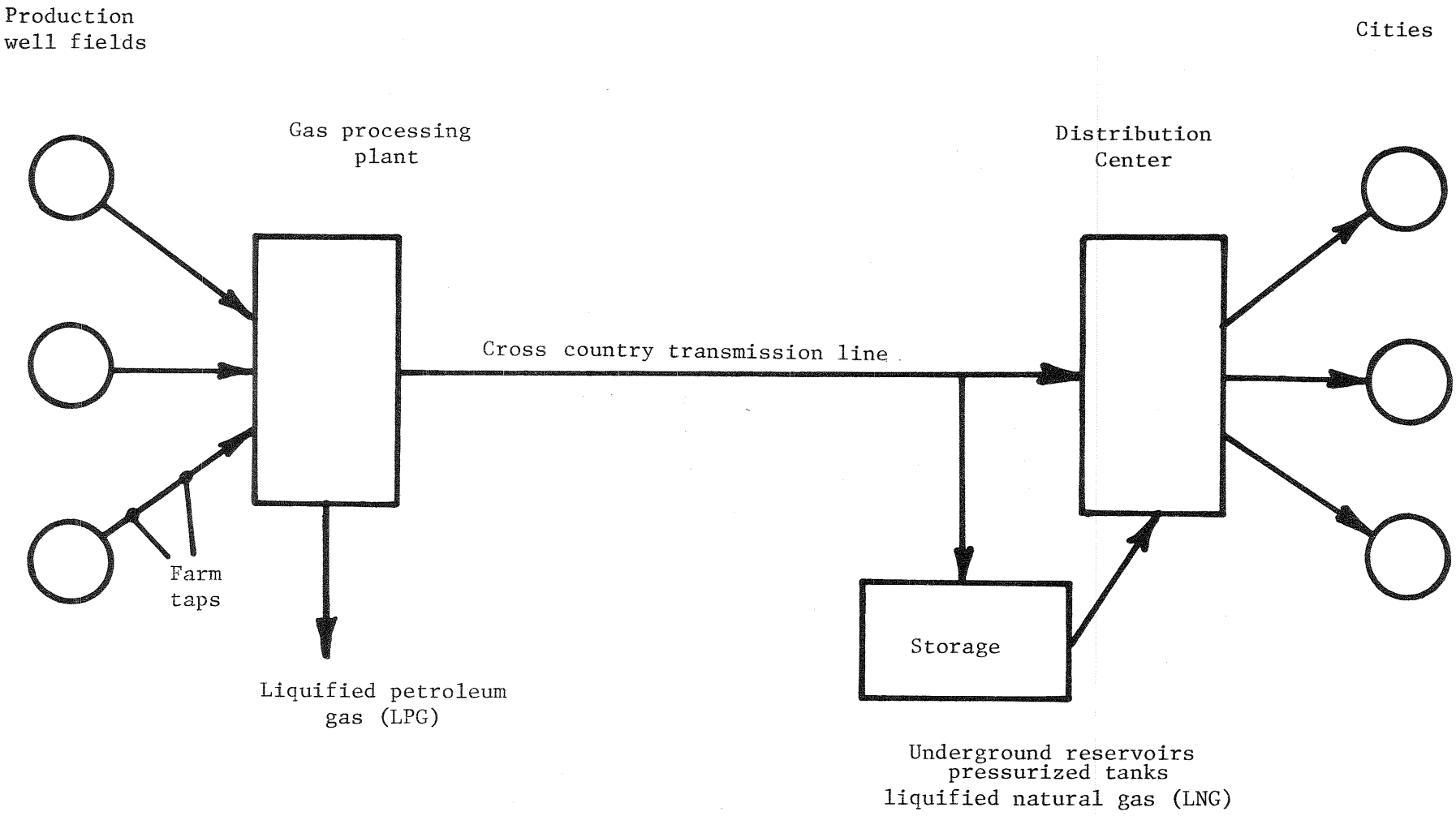

Figure 2. Normal operations on natural gas from production to consumption

carbons are then bottled under pressure for sale as liquified petroleum gas (LPG) with properties shown in table 3.

Table 3. Liquified Petroleum Gas (13)

Component	Percent of LPG	Boiling Point (°C)
Methane	0.2-2.0	-161.5
Ethane	2.4-9.5	- 88.3
Radon	-------	- 61.8
Propane	88-96	- 42.2
Butane	0.5-1.5	- 0.5

This processing is of particular interest because radon tends to separate with LPG due to its boiling point which is between that of propane and ethane (table 3). Removal of LPG (primarily propane) can remove 30 to 75 percent of the radon from natural gas (10). Since virtually all natural gas receives this processing before distribution to customers, significant reductions in radon concentrations may be effected by this aspect of routine gas industry operations.

On the other hand, the transfer of radon from natural gas into LPG may result in a shift of potential health effects (from radon) to users of LPG as the critical population at risk. The significance of radon in LPG is presently under study by Gesell (14). As part of this study, weekly measurements of radon in LPG have been made in the Houston, Texas area which indicate annual average concentrations from 25 to 180 pCi/l for six LPG retailers. Similar measurements in other parts of Texas and California gave maximum radon concentrations in LPG from 287 to 1,288 pCi/l. The maximum levels for other southern states ranged from 1.9 to 119 pCi/l. Other data at a gas processing plant in New Mexico indicate that the inlet natural gas radon level of 56 pCi/l was increased to 1,100 pCi/l in the separated propane.[1] These high levels of radon indicate a need to evaluate the use of LPG in the same manner as presented here for natural gas.

[1]Bernhardt, D.E., "Radon in Natural Gas Products--San Juan Plant," Memorandum to C.L. Weaver. August 31, 1973.

Transmission lines

As the natural gas moves from the production wells through processing plants and through trunk line systems, it becomes mixed with gas from many wells. For example, Jacobs, et al. (12) estimated that gas leaving San Juan Basin of New Mexico came from over 6,000 wells. Consequently, the production from wells with higher radon levels becomes diluted. The mixing and dilution process becomes more significant as the gas is piped over longer distances and is combined with gas from widely separated production areas.

In addition to mixing and dilution, as the gas is moved cross-country through transmission lines, the transmission time allows radon to decay away. Pipeline transit rates apparently vary from 10 to 12 miles per hour (15). Thus, a transit distance of about 1,500 miles would allow time for radon decay by 1 to 2 half-lives (half-life 3.83 days). This distance is typical of many transmission lines from Texas and Louisiana production well fields to eastern distribution centers in New York, Pennsylvania, Ohio, West Virginia, and west to California.

According to the American Gas Association these main transmission lines are normally intended to be operated at full capacity. This requires that well field production rates and gas processing be maintained nearly constant. Pipeline pumping varies only about 3.5 percent during the year. The constant production rate is balanced with seasonal demands for gas by storage operations.

Storage

Storage reservoirs are located close to market areas to meet peak demands of the winter season which could require more gas than normal transmission line capacity. These storage reservoirs are usually former depleted oil or gas wells. At present there are 330 storage reservoirs with a total capacity of 5.6 trillion cubic feet or about 29 percent of the 1971 net marketed production of 19.5 trillion cubic feet (9, 16).

The possible extent of storage is significant because the additional time could allow more radon to decay away. Within the storage reservoirs additional mixing would also tend to reduce fluctuations in the radon levels. On the other hand, the reduction in radon with storage time may be partly offset by further accumulations of radon from storage in depleted well reservoirs. However, there is no information available to evaluate this possibility.

Furthermore, it should be noted that most of the depleted well storage capacity is presently being utilized, and the costs for developing

additional underground reservoirs are leading to more economical storage by liquefaction of natural gas.

The construction of liquified natural gas (LNG) facilities is rapidly increasing. There are presently 46 LNG facilities operating or under construction in the United States with capabilities for liquefaction, LNG storage, and regasification as noted in figure 3 (17). These facilities in conjunction with 46 satellite facilities, which only have storage and regasification capability, are operated for "peak shaving," i.e., supplementing the normal supply of pipeline gas during periods of peak winter demands. The liquefaction of natural gas results in a volume reduction of nearly 600 fold thus allowing economical storage. The stored LNG must be regasified prior to introduction into regular natural gas lines for distribution. Liquefaction does not alter the chemical properties of the gas; however, LNG storage could allow a significant reduction in radon by radioactive decay. As of June 1973, LNG storage capacity existing or under constructions in the United States is about 6.6×10^{10} ft^3 or 0.34 percent of the annual net marketed production (9, 17).

While the bulk of the gas may be transported over long distances and undergo a significant delay in transmission and storage times, there are many users close to production areas where these times could be short. Some closed systems do not use storage but vary production and processing rates to meet seasonal demands. Then high winter demands result in short times. This situation is partially compensated by shorter times for radon accumulation in the production wells at higher production rates.

Short pipeline times may also be significant for another group of gas users near production fields. Apparently gas companies allow farms through which gas lines pass to tap into the pipeline. These "farm taps" allow use of natural gas directly from the wells with no processing and a minimum delay time (12).

Radon data

Barton (2) and Klement et al. (18) noted that very little data are available for radon levels at consumer use points. However, radon has been measured in gas distribution lines and that data will be reported here as estimates of concentrations at points of gas usage.

Barton et al. (19) concluded that a nationwide natural gas sampling program would be impractical, presumably on the basis of analytical costs and the priority need for the information. Instead they sampled the gas supplied to several large metropolitan areas including Chicago, New York City, and Denver. Two sources supplying each of the market areas were sampled and the average pipeline concentration was 20 pCi/l. This average included measurements on radon in a high pressure line from

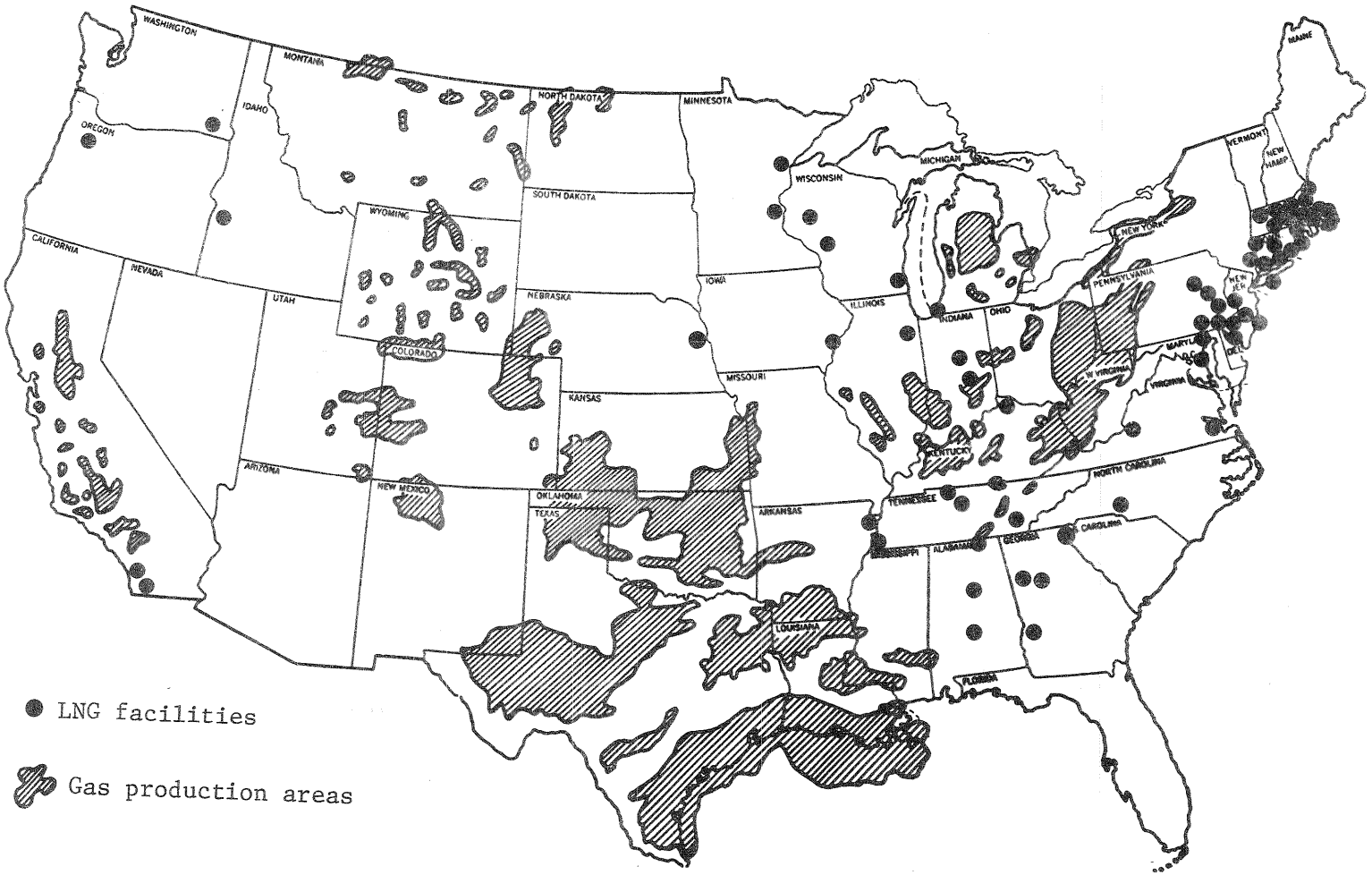

Figure 3. LNG facilites and gas production areas in the United States

Kansas to Denver which had a level of 95 pCi/l. Excluding this value, the average level was 10 pCi/l.

The Rocky Mountain Natural Gas Company (RMNG) has measured radon in its city main pipelines in the Colorado towns of Aspen, Glenwood Springs, and Delta. Average levels were about 25 pCi/l. The RMNG distribution system is closed, i.e., it neither supplies nor obtains gas from other systems.

McBride and Hill (7) reported radon levels of about 8 pCi/l at two metering stations on the way to Las Vegas and Los Angeles. Levels were also measured in natural gas at the Farmington Laboratory in New Mexico, and the average radon content was about 45 pCi/l.

Gesell[2] measured radon in a distribution main in Houston weekly from November 1972 to January 1973. The average radon level was 8 pCi/l.

A summary of available data on radon in natural gas distribution lines in gas consumption areas is shown in table 4. These data indicate that average radon levels at points of use are about 50 pCi/l or less. It should be noted, however, that the highest levels occur in the Colorado and New Mexico areas which are closest to sources of natural gas. The coastal regions farthest away from natural gas sources have the lowest radon levels. This can be attributed to pipeline transmission time and storage which allows significant radon decay. Also, gas may be mixed and diluted with that from several supply systems while in transit to areas such as New York City or Chicago.

It should be noted that variations in radon levels at consumer use points could also be attributed to production rates as a function of seasonal gas use. For example, the highest levels occurred in the winter during peak use periods, presumably due to shorter transport times.

For dose calculations, Barton et al. (19) selected a value of 20 pCi/l for radon concentrations at consumer use points. However, this figure does not adequately reflect the higher levels found near the natural gas fields in Kansas, Colorado, New Mexico, and the Texas panhandle regions. For these areas a level of 50 pCi/l should be used. The value of 20 pCi/l could be used as a reasonably conservative estimate for radon levels in natural gas for the remainder of the United States.

More definitive information will be available in the future from three studies now in progress. One study is being sponsored by the

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[2]Gesell, T.F., Unpublished data, University of Texas, School of Public Health, Houston, Texas, 1973.

Table 4. Radon-222 concentrations in natural gas distribution lines

Area	Radon-222 level, pCi/l		Reference
	Average	Range	
Chicago	14.4	2.3-31.3	19
New York City	1.5	0.5-3.8	1
Denver	50.5	1.2-119	19
West Coast	15	1-100	10, 19
Colorado	25	6.5-43	--(a)
Nevada	8	5.8-10.4	7
New Mexico	45	10-53	1
Houston	8	1.4-14.3	--(b)
Overall average	23		

(a) Bernhardt, D.E., Radon-222 concentrations in natural gas, Memorandum to D.T. Oakley, April 2, 1973.
(b) Gesell, T.F. op. cit.

Colorado Interstate Gas Company (CIG) to investigate radon concentrations in its own system and that of the Rocky Mountain Natural Gas Company.[3]

ORNL is also conducting a related study in cooperation with several gas transmission companies to analyze monthly samples for several metropolitan areas (19). A similar study is being performed by Dr. Thomas Gesell[4] of the School of Public Health, University of Texas, for a consortium of gas companies.

Radon concentrations in the home

Determining the radon-222 concentrations in natural gas at the point of use is only part of the analysis. The next step is to determine radon concentrations within the home resulting from use of natural gas in various appliances. Measurements on this source of radon have not actually been made in homes, however, estimates may be made by determining the quantity of gas consumed, the fraction of combustion products vented inside the home, and the home dilution factor (based on house volume and ventilation or rate of exchange with outside air).

When natural gas is burned in the home, the radon and daughter products are released within the dwelling. Mixing is not instantaneous but, as inhabitants move about, it is assumed they are exposed to the average concentration level. This level is affected by the quantity of gas consumed and the fraction of combustion products vented inside the home. These factors, in turn, depend on what the gas is used for, i.e., heating, or ranges, water heaters, refrigerators, clothes dryers, and other non-heating appliances. Gas furnaces are normally vented outside the home, although Jacobs et al. (12) have assumed non-ventilated heating to represent a "worst" case for assessing nuclide concentrations in gas from nuclearly stimulated wells. On the other hand, gas ranges are normally vented into kitchen areas and initial studies by Barton (19) take this source as the main contributor of radon-222 from natural gas usage in homes. Data compiled by Gesell[5] indicate that in addition, there is also widespread use of unvented space heaters. These heaters are commonly used in the warmer states where permanent heating systems are not necessary.

Dilution by air within the home is another factor affecting radon concentrations. This factor is a function of house volume and the rate at which the air is changed by ventilation with outside air. A conservative assumption is that the air inside the dwelling unit will be changed once per hour. Barton et al. (19) have calculated the accumulation of radon and daughters for air change rates of 0.25 to 2.0 per hour.

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[3]Bernhardt, op. cit. (April 2, 1973).
[4]Gesell, op. cit.
[5]Gesell, op. cit.

Kaye (20) determined after consultation with home ventilation experts that present information does not justify choice of a single value for annual average air change rates for United States homes. He did indicate that the rate probably was between 0.5 and 1.5 changes per hour. The same range of air changes per hour was derived by Handley and Barton (22) from a literature survey of studies on home ventilation rates. United Nations data (21) suggests that air change rates are typically from 2 to 5 changes per hour. Yeates, et al. (23) measured ventilation rates in several single family dwellings as part of a study on radon-daughter concentrations in the urban environment. They observed air change rates from 1 to 3 per hour for basements and from 2 to 6 per hour for upper levels in homes. Multiple family dwellings had air change rates from 5 to 9 per hour.

Since no measurements have been made on radon concentrations resulting from use of natural gas in homes, there are no data to report here. However, the preceding parameters will be used to calculate radon concentrations later in the section on postulated exposure conditions.

POPULATION EXPOSURE

Exposure conditions

Several factors have to be considered when assessing the exposure conditions resulting from release of radon within a home, such as (24):

(a) the amount of daughter products dispersed in the air, which is a function of radon concentration and the extent of decay product equilibrium, and
(b) the proportion of daughter products present as free ions or attached to various size aerosol particles.

Evaluation of these parameters provides a model for estimating the radon daughter product mixture of the atmosphere in terms of radioactive decay, dispersion, and removal processes (25).

Each of these factors will be reviewed in further detail preparatory to a discussion of the critical mode of exposure to radon.

Daughter products

Radon-222 decays to daughter products according to the following scheme:

$$^{222}Rn \xrightarrow[3.823\ days]{5.49\ MeV\ \alpha} {}^{218}Po\ (RaA) \xrightarrow[3.05\ min]{6.0\ MeV\ \alpha} {}^{214}Pb\ (RaB)$$

$$\xrightarrow[26.8\ min]{0.7\ MeV\ \beta} {}^{214}Bi\ (RaC) \xrightarrow[19.7\ min]{3.3\ MeV\ \beta} {}^{214}Po\ (RaC')$$

$$\xrightarrow[164\ \mu sec]{7.687\ MeV\ \alpha} {}^{210}Pb\ (RaD) \xrightarrow[21\ yr]{0.02\ MeV\ \beta} {}^{210}Bi\ (RaE)$$

The radon daughters of primary concern in determining radiation exposure are RaA, RaB, RaC and RaC'. However, the total dose is due mainly to alpha emissions from RaA and RaC'. For dose estimates, the alpha energy contribution of RaC' follows almost instantaneously from RaC. Also RaB, as a beta emitter, does not contribute significantly to the total dose, but it is included in decay calculations to determine the activity of RaC (RaC').

Working level

The concentration of radon-222 and daughters is customarily given in terms of a working level (WL). One WL is the total potential alpha energy from any combination of the short-lived radon daughters (through RaC' that will impart 1.3×10^5 MeV per liter of air (26). This level was intended to be one, "which appears to be safe, yet not unnecessarily restrictive to industrial operations (27)." This was the philosophy of the United States Public Health Service when establishing the working level as a standard for the uranium mining industry in 1957. Since that time a better understanding of radon dosimetry and health effects has led to development of stricter recommendations by the Federal Radiation Council and the Environmental Protection Agency (28-31).

A standard of 4 working level months per year (WLM) is now recommended by EPA (30). One WLM is the exposure resulting from inhalation of air containing a radon daughter concentration of 1 WL for 170 working hours. The same exposure for 2,040 hours gives one working level year (WLY). Continuous exposure for a full year of 8,760 hours gives 8,760/2,040 = 4.3 times the exposure for 1 WLY.

The working level is often related to radon activity by calculating the number of radon daughter disintegrations required to impart 1.3×10^5 MeV of alpha energy. The relationship is defined by Evans (32) as:

1 WL = 100 pCi/l of radon-222 in secular equilibrium with daughter products RaA, RaB, RaC (RaC').

The working level definition is often misunderstood as a unit of radon concentration. However, it is a concentration of only the short-lived daughters RaA, RaB, RaC (RaC'). It can be applied to any mixture of these decay products. The conversion of 1 WL per 100 pCi/l of radon-222 applies only for secular equilibrium of radon and daughters.

Degree of equilibrium

When radon is dispersed into a clean air atmosphere, it will reach radioactive secular equilibrium with the above daughters after 3 hours (27). However, the extent of decay product equilibrium in the usual home is markedly affected by the rate of ventilation. Exchange with outside air results in removal of daughter products from the atmosphere within the home. Removal will also occur by deposition of daughter products on surfaces. Jacobi (33, 34) noted that these removal processes prevent the establishment of radioactive equilibrium between radon and its daughters. He therefore includes a factor for degree of nonequilibrium in calculating the potential alpha energy concentration from daughter products in air according to the WL definition.

Attached daughter products

A fraction of the daughter products will also become attached to dust particles and condensation nuclei in the air. For example, radon decay to RaA results in a single polonium ion which moves like an electrostatically charged gas molecule until it collides with an aerosol particle, where it remains attached (35, 36). The attached RaA no longer follows the diffusional behavior of a gas but moves with other aerosol particles. The proportion of ions attached to aerosols and those which remain free or uncombined will reach an equilibrium for each decay product (24).

Studies by Raabe (36) showed that the attachment rate of radon daughters to aerosols is proportional to the surface area of the particles. Increased humidity also affects the proportion of daughter ions which become removed by attachment to water molecules. Measurements by Wachsman, et al. (37) show a dramatic decrease in radon daughters in home atmospheres following rainy weather.

Critical mode of exposure

The primary concern for exposure to radon is from inhalation and retention of radon daughters which release their alpha decay energy to tissues of the respiratory system. The specific respiratory areas most susceptible to damage have been determined by evaluating the areas showing injury (lung cancer) in uranium miners (38, 39). Such cancers predominantly appear in the area of the large bronchi. These are believed to