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Assessment of Potential 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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Readers of these reports are encouraged to inform the Office of Radiation Programs of any omissions or errors. Comments or requests for further information are also invited.

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Deputy Assistant Administrator
for Radiation Programs

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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ASSESSMENT OF POTENTIAL RADIOLOGICAL HEALTH EFFECTS FROM RADON IN NATURAL GAS

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

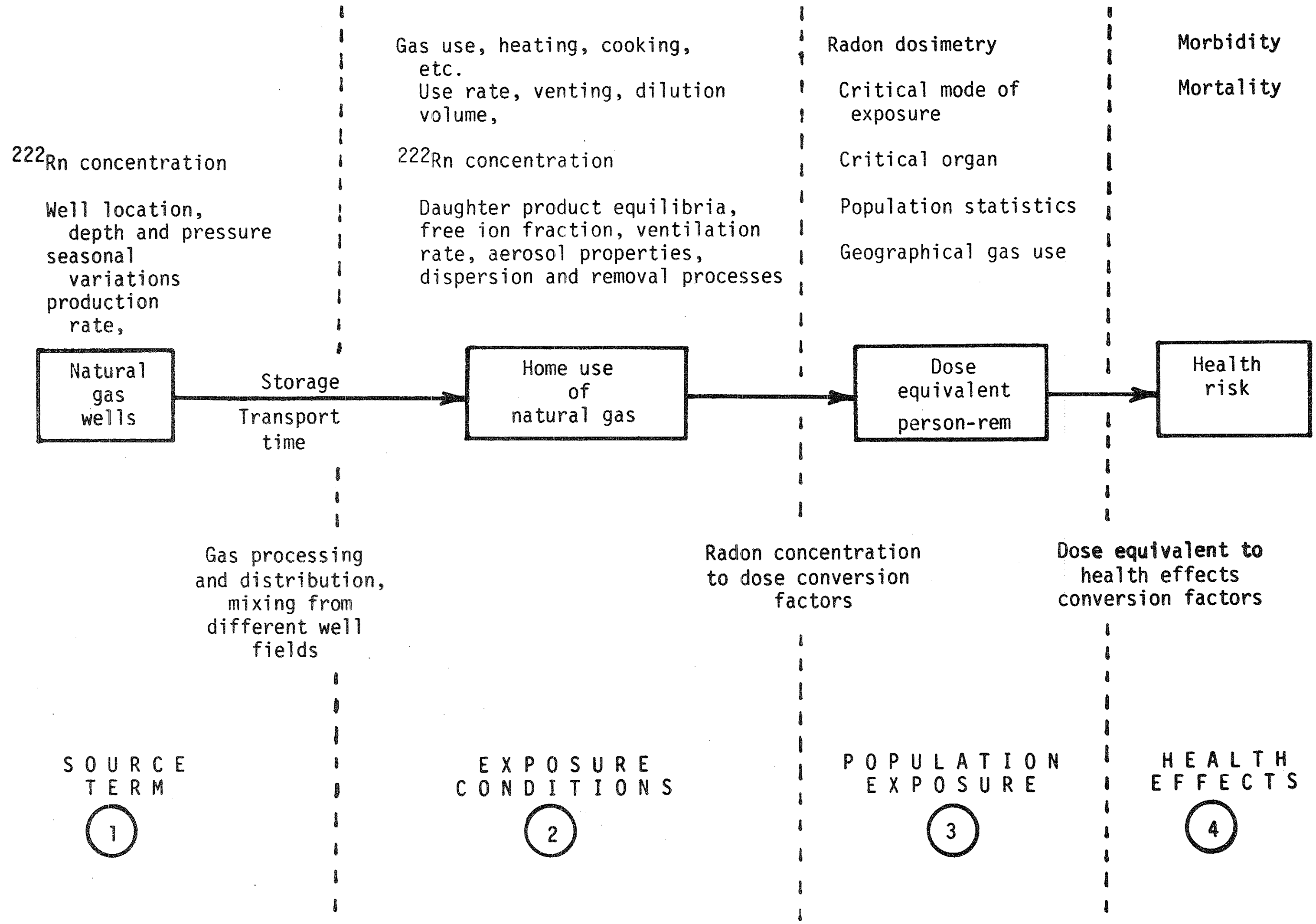

Figure 1. Model for estimating potential health effects from radon in natural gas

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/l. Individual wells were sampled with levels as high as 160 pCi/l and as low as 0.2 pCi/l. A review by Barton (2) showed that 1,250 wells in Texas, Kansas, and Oklahoma had average radon concentrations of 100 pCi/l or less. Concentrations in these wells varied from 5 to 1,450 pCi/l.

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/l 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/l. The later samples, in September and October, had levels of about 17.8 pCi/l. 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/l (range 11 to 45 pCi/l). McBride and Hill (7) reported that levels of radon-222 in preshot samples for project Gasbuggy had an average value of 19.4 pCi/l. 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/l with a range of 12 to 59 pCi/l. 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/l. Upper Texas, Kansas, Oklahoma, and California have average levels up to about 100 pCi/l. When all the data are averaged a level of 37 pCi/l 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 Average	Range	Reference
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-

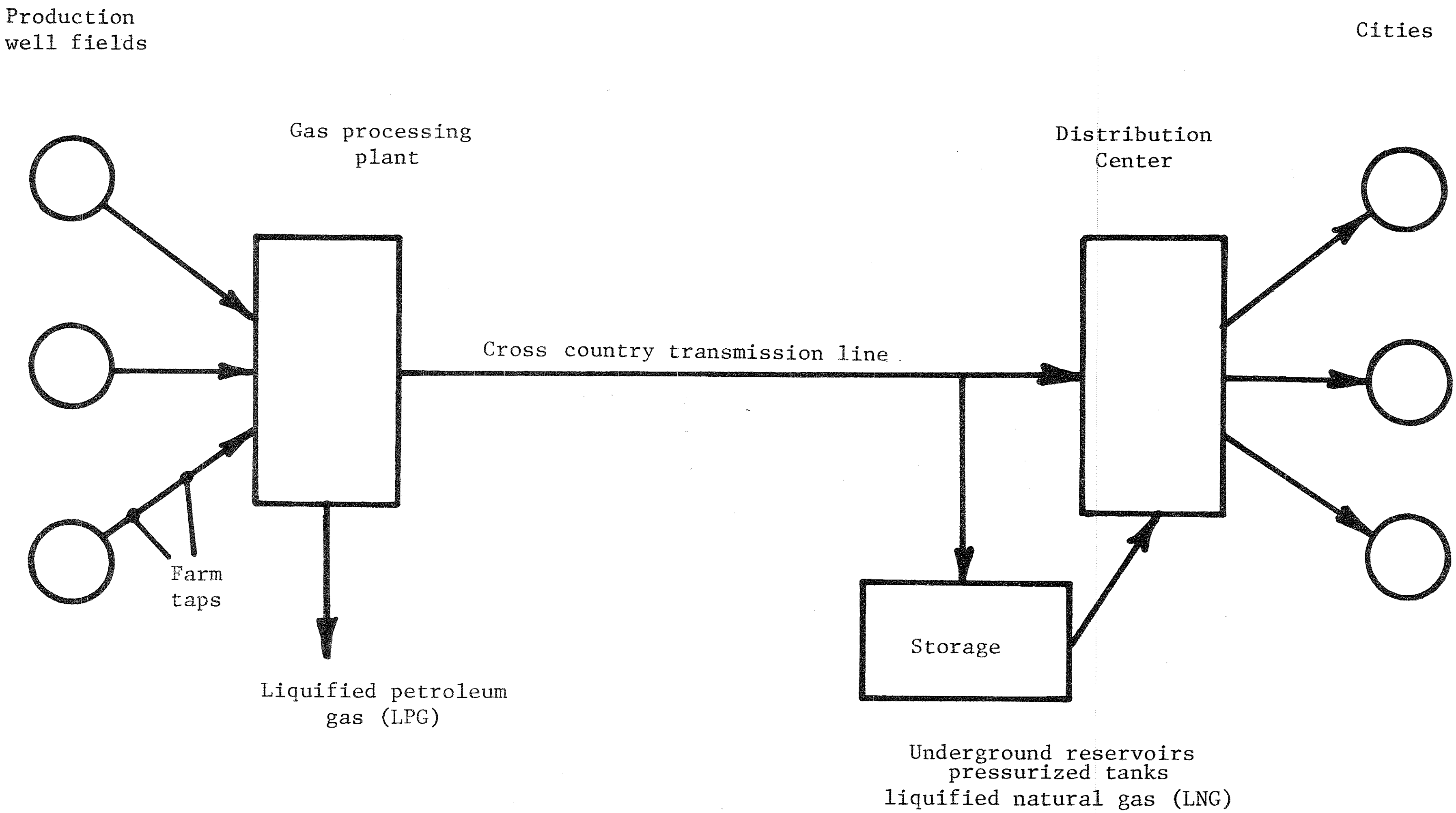

Figure 2. Normal operations on natural gas from production to consumption

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.

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[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

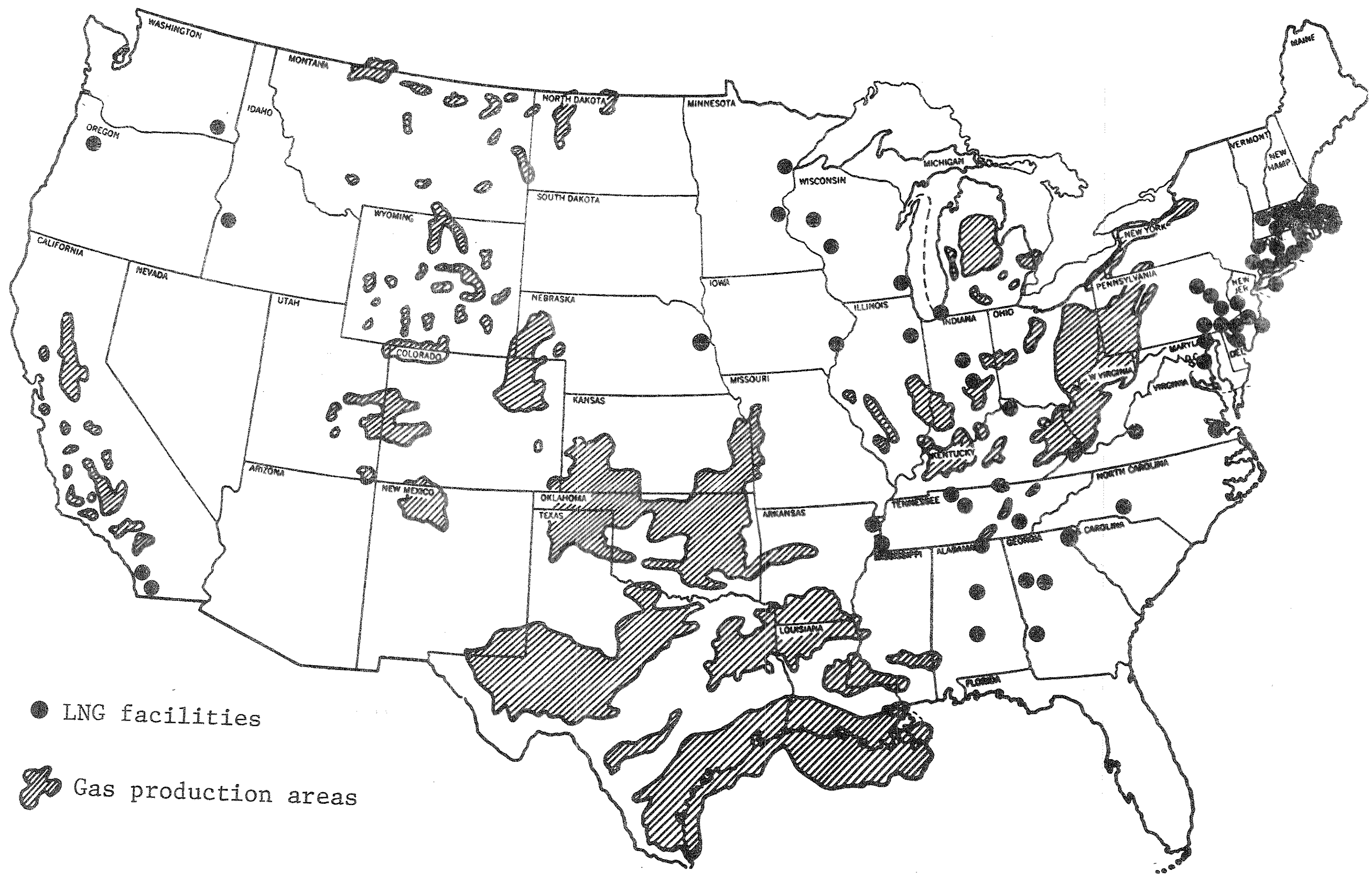

Figure 3. LNG facilites and gas production areas in the United States

Kansas to Denver which had a level of 95 pCi/1. Excluding this value, the average level was 10 pCi/1.

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/1. 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/1 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/1.

Gesell[2] measured radon in a distribution main in Houston weekly from November 1972 to January 1973. The average radon level was 8 pCi/1.

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/1 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/1 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/1 should be used. The value of 20 pCi/1 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:

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

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

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

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 occur as a result of ionization from alpha particles in the basal layer cells of the upper bronchial epithelium.

Some controversy still remains unresolved as to the most important mode of exposure within the lung. The issue in question is whether local, or "hot spot," doses are more effective in producing cancer in the respiratory system than is uniform radiation exposure to the entire epithelium (26). Lung cancers usually arise at bifurcations of the bronchial tree, which are areas of the pulmonary structure where radioactive materials could become lodged. Altshuler et al. (25) concluded that this contribution to lung dose could not be treated quantitatively because of insufficient knowledge of localized tissue exposures. However, recent animal studies by Grossman et al. (40) indicate that a higher localized dose from alpha particles was not more carcinogenic than the same amount of energy delivered uniformly to surfaces of the airways in the respiratory system. Consequently, today most investigators assume the most important mode of exposure is from uniform alpha irradiation of the epithelium. This lung exposure is modeled by a series of tubes of known dimensions containing a uniform concentration of radon daughters.

Lung models

Since tissue dose cannot be measured directly, the rad dose to the critical cells of the tracheobronchial tree is derived from the lung models. Such models allow calculation of dose as a function of environmental conditions, anatomy, respiratory physiology, and radon dosimetry as follows:[6]

(a) Characteristics of the ambient atmosphere affecting deposition of radon daughters in the respiratory system (25, 35, 36):

1. Degree of equilibrium between radon and daughter products.
2. Relative concentrations of radon daughters.
3. Adsorption of radon daughters to aerosols.
4. Fraction of unattached daughter products or free ions.
5. Abundance of dust particles or aerosol carriers for attached daughter products, and their size distribution.
6. Ventilation rate or air change rate.

Of these characteristics, numbers 3 and 5 are probably the most important.

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[6]The reader is referred to the literature for detailed discussion of these variables which is beyond the intended scope of this paper.

(b) Biological factors influencing site and deposition of radon daughters in the lung include (25, 35, 38, 39, 41):

1. Method of breathing, i.e., mouth breathing vs. nose breathing.
2. Rate and depth of respiration, tidal volume.
3. Diameter and surface area in different regions of the lung.
4. Changes in diameter of the tracheobronchial tree during respiration.
5. Angles and irregularities in the tracheobronchial tree.
6. Fraction of daughter products deposited in different regions of the respiratory system.
7. Clearance rates of deposited dust and other materials.
8. Retention, translocation by ciliary transport, mucus flow, and elimination.
9. Pile-up or collection of mucus impregnated with radon daughters at bifurcations in the tracheobronchial tree.
10. Effect of fumes, smoke, and other aerosols on lung clearance rates.
11. Medical status of the individual, e.g., some pneumonias and perhaps smoking can cause radical changes in clearance rates and lung retention of dust.

Factor numbers 2 and 11 are especially important.

(c) Dosimetric factors influencing the dose due to deposited daughters (24, 25, 39, 42):

1. Location of radiation-sensitive epithelial basal cells or precancerous cells at risk.
2. Variable thickness of mucus blanket covering bronchial epithelium.
3. Thickness of bronchial epithelium.
4. Variation in distance of daughters from epithelial surface.
5. Energy loss characteristics of alpha particles of different energies, depth of penetration.
6. Dose rate effect, if any, for alpha particles.
7. Appropriate quality factor to use.

The location of the precancerous cells at risk is the most important factor. A review of radon daughter exposure and respiratory cancer effects indicates that the epithelial basal cells in the walls of the bronchi are the biological target (39). The integrity of the basal cells determines the continued integrity of the epithelial tissue (42). Of these cells, 70 percent are considered near enough to the epithelial surface to be within the range of alpha particles of radon daughters (39).

The range of alpha particles in soft tissue for RaA is about 47 microns and about 71 microns for RaC' (25). The distance from the upper mucus layer (the area of initial deposition of radon daughters) to basal target cells is from 36 to 63 microns for minimum to median epithelium thickness (25, 42). The average distance from source to biological target is believed to be about 60 microns (21). This means that few of the basal cells receive any alpha radiation from RaA. Studies reported by Morken (43), however, indicate that much of the deposited radon daughters becomes dissolved in the mucus layer and absorbed in the epithelial tissue. This means more basal cells are within the range of alpha particles from RaA but the dispersion within the epithelial tissues of both RaA and RaC' results in a lower dose to the basal cells than when these daughters are retained in the narrow zone of the mucus layer.

The International Commission on Radiological Protection (ICRP) Task Group on Lung Dynamics noted that the estimated average whole lung dose for radon and daughters is also a measure of dose to specific areas, such as the trachea (38). This was taken as justification for the concept of calculating dose to the lung based on a lung model.

It was concluded by ICRP (38) that the properties of the carrier aerosol are the major determinants for deposition of radon daughters in the lung. However, these properties do not appear to be important in determining the clearance of radon daughters, mainly, because radon daughters appear to be weakly attached to dust particles which become solvated in the lung thereby enhancing removal processes. Even short half-lived daughters are rapidly removed from the lung with removal half-times of 10 to 30 minutes.

Free ions

The fraction of daughter ions which remain free, or unattached to surfaces or aerosols, is defined for RaA ions in particular as (44):

$$f = \frac{\text{RaA atoms uncombined}}{\text{RaA atoms in equilibrium with radon}}$$

This fraction is related to the aerosol content of home atmospheres such that f increases as the ventilation rate increases or as the aerosol content decreases.

ICRP (38) took particular note of the work of Chamberlain and Dyson (45) which regarded the radiological importance of free ions of RaA. The uncombined fraction of RaA, f, was found to preferentially deposit in the upper passages of the respiratory system where uranium miners' lung cancers develop. This factor was taken into account in the ICRP formula for occupational radon MPC_a,

$$MPC_a = \frac{3 \times 10^{-6}}{1 + 1000f} \quad \frac{\mu Ci}{cm^3}$$

The listed 40 hour per week MPC_a for radon-222 was given as 30 pCi/l on the basis of an uncombined RaA fraction of 0.1 as determined by Chamberlain and Dyson (45). George et al. (44) measured f values for New Mexico uranium mines and found an average of about 0.03. They concluded that higher values of 0.05 to 0.10 were found only in relatively clean air (particle concentrations of 1×10^4 cm^{-3} or less). Hague et al. (24) estimated that the f value is 0.35 for an aerosol spectrum of 0.006 to 0.1 microns and a concentration of 3×10^4 cm^{-3}, typical of a country atmosphere. This value was then used to calculate radon daughter doses in living accommodations and industrial premises. Jacobi (35) plots f versus aerosol concentration and this curve gives an f value of about 0.25 for air with 10^4 particles per cubic centimeter, which he concludes is a reasonable mean value for ordinary room and city air.

Harley and Pasternack (46) also noted that unattached RaA ions deposit with 100 percent efficiency in the tracheobronchial region. Subsequent decay to RaC' gives rise to a substantial fraction of the total alpha dose. Jacobi (34) concluded that about half of the free ions of RaA which are inhaled become deposited in the nasopharynx region and the other half in the tracheobronchial region. Further studies by Jacobi (47) indicate that the uncombined fraction of the total potential alpha energy, fp, (for RaA + RaC') is a better parameter to observe. This is because the inhaled potential alpha energy deposited in the tracheobronchial region is directly related to fp and is independent of ventilation rates in the working or living area.

Dose conversion factors

The calculation of dose from exposure to a given concentration of radon-222 in pCi/l or WL requires that values be assumed for many variables as described in the preceding sections. A variety of values have been reported over the years as each investigator attempted to characterize particular exposure conditions. In addition, improvements in lung models and better understanding of the behavior of radon daughters have led to refinements in the calculations. Consequently, the literature contains a wide range of factors for converting radon concentrations to dose. A summary of these factors is presented in table 5 based on reviews by Bernhardt[7] and Barton et al. (19). This summary is presented here to show the range of values from which one may select according to assumptions on exposure conditions for a particular situation.

The dose conversion factors tabulated in table 5 are not directly comparable to each other for several reasons, the most important of which

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[7] Bernhardt, D.E., "Radon-222 Dose Caluclations," Memorandum to the Files, ABR-LV, March 15, 1973.

Table 5. Summary of dose conversion factors for radon and radon daughters

Radon-daughter equilibria	Exposure conditions	Lung model, critical tissue	Dose factor[a] rads/year	Reference
10,10,10,10[b] 4% free RaA	0.3μ particles Rn-100 pCi/l annual occupational exposure	Weibel model (A) 15 l/min, segmental bronchi	12	Harley and Pasternack (46)
10,6,3,2 4% free RaA	"	"	18.5	(46)
10,9,6,4 8.5% free RaA	"	Landahl model	86	(46)
Nonequilibrium, little free RaA	WLM = 170 hrs.[c]	Epithelial base cells of large bronchi	25.8-51.5	BEIR (26)
Nonequilibrium	500 hours per month in homes	Bronchial epithelium	34	Toth (48)
Nonequilibrium, 1-2% free RaA	Clean air MPAI of 4 WLM[c]	Revised ICRP model (38), bronchial region	19.3-51.5	Jacobi (34)
"	High aerosol conc. 0.05-0.2μm particles	"	15.5-25.8	(34)
10,10,6,4[d]	Normal room air change-1 hr^{-1}, 10,000 particles cm^{-3}, 0.09μm 10 pCi/l-Rn	Findeisen-Landahl model, bronchial epithelium, 14 l/min.	88	Jacobi (35)
10,10,10,10 25% free RaA	Natural radiation exposure, 0.09μm 0.1 pCi/l-Rn	"	140	(35)
10,9,6,4[d] 8.5% free RaA	0.3μm particles Rn-100 pCi/l, occupational exposure	Landahl model, segmental bronchi, 15 l/min., mouth breathing	103	Altshuler et al. (25) Lundin (39)
"	"	" Nose breathing	56	(25)
10,9,5,3.5	Adequately ventilated room, 6,000 hr/yr	Segmental bronchi, 15 l/min., mouth breathing	89-620	Hague and Collinson (24)
10,9,6,4	>0.1 μm particles Rn-100 pCi/l	Segmental bronchi 15 l/min.	111	Burgess and Shapiro (49)
			Range 12-620	

[a] Dose factor = rads/year for continuous exposure (8,760 hours) to one working level. One WL = any combination of short-lived radon daughters (through ^{214}Po, RaC') leading to a total emission of 1.3 x 10^5 MeV of alpha energy per liter of air (28). One WL is also defined as 100 pCi/l of radon in equilibrium with its dauthters.

[b] Relative concentrations of ^{222}Rn, RaA, RaB, and RaC (RaC').

[c] WLM, 1 working level month - 170 hours exposure at 1 WL. Jacobi (34) defines 1 WLM as 2.6 x 10^{10} MeV potential alpha-energy inhaled at 20 l/min. for 166.7 hours/month. MPAI = maximum permissible annual intake.

[d] These conditions represent typical dwellings.

is that each exposure situation has involved different radon-daughter equilibrium conditions, free ion fractions, and carrier particle sizes for attached daughters. Tsivoglou et al. (50) present data showing that these differences could be 20 percent or more depending on the estimation of equilibrium ratios alone. In addition, the choice of parameters to characterize the interaction of radon daughters in various lung models has led to differences in dose conversion factors.

The dose conversion factors tabulated from the literature (table 5) had a range from 12 to 620 rads per year after being normalized for continuous exposure (8,760 hours/year) at one working level.

Barton et al. (19) obtained an average value of 85 rads per year after discarding high and low values of 620 and 12 rads per year, respectively. A literature review by Walsh (51) indicated that continuous exposure to radon daughters at 1 WL for a year should not result in more than 50 to 100 rads to the bronchial epithelium, and possibly less than 50 rads to the basal cells. Lundin (39) concluded that (for uranium miners) an occupational exposure of one WL year (2,040 hours) gave 24 rads averaged over the tracheobronchial epithelium. This becomes 24 x 8,760/2,040 = 103 rads per year for continuous exposure. After review of the literature, Barton (19) selected a conversion factor of 100 rads per year to the bronchial epithelium for continuous exposure at 1 WL. According to Holleman (52), this corresponds to a dose to the total lung mass (1,000 grams) of approximately one-tenth of the dose estimate for the bronchial epithelium.

The dose conversion factors derived for conditions in normal rooms [footnote (d) table 5] are representative of typical dwellings. They may be high by 25 percent on the basis of RaA and free RaA assumptions. In addition, the assumption of continuous exposure may be high by 25 to 40 percent. With these considerations in mind, the dose conversion factor selected for this analysis is 100 rads per year for a radon concentration of 100 pCi/l. Reasonable variations could range from 50 to 125 rads per year at 100 pCi/l. This factor assumes continuous exposure by mouth breathing in a normal home atmosphere with an aerosol concentration of less than 10,000 particles cm^{-3} and a mean aerosol diameter of about 0.1 micrometer. The ratio of radon daughters is assumed to be about 1.0, 0.8, 0.6, 0.4 (for Rn, RaA, RaB, RaC (RaC$'$), respectively).

Quality factor

There is some controversy about the appropriate quality factor (Q) that should be applied to alpha radiation dose from radon daughters to convert from rads to rems (25, 53). The Q is intended to account for differences in linear energy transfer (LET) and depends on type of damage under consideration, dose rate, and specific ionization of the ionizing particles (54). The ICRP (55) recommends a Q of 10 for internal exposure to alpha particles. This Q was therefore selected by Barton et al. (19) for radon dose calculations. On the other hand, Bernhardt (11) concluded that, while Q values ranged from 1 to 20 in the literature, the most predominant value was 3. Gesell[8] also agreed that a Q of 3 more accurately reflected present knowledge of biological effects of alpha radiation. The FRC has also reported that a Q of 3 may be more appropriate than 10 (32-page 1239). Initial dose estimates in this study will use a Q of 10 to be conservative.

Conditions for this analysis

Radon dosimetry is a complex subject with many parameters which cannot be definitely specified at the present state of knowledge. Therefore, this analysis will take the approach of first making a preliminary estimate of dose to an individual for hypothetical exposure conditions. Then this dose and corresponding health effects can be corrected or extrapolated for the general population and for possible variations in exposure conditions.

Postulated exposure conditions

The initial analysis will be based on parameters specified by Barton et al. (19) for dose calculations of radon in natural gas. The primary source of radon from use of natural gas in homes comes from an unvented kitchen range. The Gas Engineers Handbook (15) indicates the average kitchen range uses 0.765m^3 (27 ft^3) of gas per day. When the range is turned on, the radon in the gas combustion products is assumed to be dispersed in a home with a volume of 226.6m^3 (8,000 ft^3) and having an air change rate of once per hour. (This gives a dilution volume of $226.6 \times 24 = 15{,}438\ m^3$.)

Barton et al. (19) concluded from mathematical analyses that the average 24-hour concentration of radionuclides is not affected by the kitchen range-use schedule. That is, it makes no difference whether the gas is used in three 1-hour periods during the day or in 1-hour followed by a 23-hour decay period.

A computer program has been written at ORNL (19) to handle the calculation of radon daughter concentrations in the dynamic situation where radon builds up in the home in proportion to the use of natural gas, and the daughters are removed by radioactive decay and ventilation. This program computes the cumulative average number of atoms of radon and daughters for 1 minute intervals over a 24-hour period for a given radon input and ventilation rate. The average 24-hour values are converted to concentrations for uniform dispersion in the house. These concentrations

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[8]Gesell, op. cit.

are then converted to working levels by use of known decay constants and alpha energies for each daughter. The conversion factor for dose was taken as 100 rads per year for continuous exposure at one WL (100 pCi/1 of radon in secular equilibrium with daughters).

The dose to an individual for these conditions is given in the next section. Barton et al. (19) also give tables of doses for various air change rates and contributions from radon in outside ventilation air.

In the present study, the additional contribution to radon dose from gas used in unvented space heaters was determined on the basis of data compiled by Dr. Thomas Gesell[9] of the University of Texas. He noted that the widespread use of such heaters could add significantly to dose from radon daughters.

The exposure conditions pertinent for both sources of radon in natural gas. i.e., unvented kitchen ranges and space heaters, are tabulated in table 6.

Dose to an individual

For an unvented kitchen range and the exposure conditions specified in the previous section, Barton's (19) computer program calculated an average annual dose equivalent to an individual of 15 millirems to the bronchial epithelium. This assumed there were no radon daughters in the natural gas. Gesell[8] concludes this is the most likely situation, because radon daughters would tend to plate out on pipeline surfaces in distribution systems. Also, Barton et al. (19) noted that radon daughters have not been detected in gas lines at points of use.

For comparison with Barton's (19) computer-estimated dose equivalent to an individual, a sampler calculation may be made by assuming that radon daughters dispersed in the home are at equilibrium with the incoming radon from natural gas. First, the radon concentration in the home is calculated on the basis of dilution into a volume equal to 24 air changes per day. This gives a dilution factor of

$$\frac{226.6 \text{ m}^3 \text{ house x 24 air changes}}{0.765 \text{ m}^3 \text{ gas used per day (in ranges)}} = 7111$$

Dividing the assumed natural gas radon concentration of 20 pCi/1 by the dilution factor gives an average radon concentration in the home of 0.0028 pCi/1 from use of unvented kitchen ranges. At secular equilibrium, this is also the concentration of radon daughters. Dose is then calculated by multiplying this concentration by the dose conversion factor of (100 rads/year)/(100 pCi/1). This gives an absorbed dose of

[9]Gesell, op. cit.

Table 6. Exposure conditions and possible variation in parameters for analyzing dose from radon in natural gas

Parameter	Condition for this analysis[a]	Possible Variation[b]
Radon concentration in gas at point of use	20 pCi/l	10 - 100 pCi/l
Gas appliances	Cooking ranges Space heaters	Could include refrigerators, clothes dryers, etc.
Gas use:		
Ranges	$0.765 m^3$/day	Up to $1.19 m^3$/day
Heaters	$0.354 m^3$/degree-day	$0.28-0.42 m^3$/degree-day
Degree-days	Average for each state	± 25% within states
Appliance venting	Unvented	Ranges could be partly vented
House size	$226.6 m^3$	$142 - 425 m^3$
Air change rate	one per hour	0.25 - 5 per hour
Radon concentration in home		
from ranges	0.0028 pCi/l	0.001-0.05 pCi/l
from heaters[c]	0.01 pCi/l	0.005-0.3 pCi/l
Radon daughters:		
in gas	No daughters	1, 1, 1, 1[d]
in home	1, 0.8, 0.6, 0.4[d]	1, 1, 1, 1 to[d] 1.0, 0.5, 0.25, 0.1
Percent free RaA	8.5 percent	5 - 25 percent
Critical mode of exposure	Inhalation of radon daughters	Radon alone gives < 1% of dose
Critical organ	Bronchial epithelium	Some exposure also to nasopharynx, lung, and whole body
Dose conversion factor[e]	100 rads/year for continuous exposure at 1 WL (100 pCi/l)	50 - 125 rads/year
Quality factor	10	3 - 10

[a]These are intended to be typical average conditions, although some of the less well understood parameters were chosen to give a higher or more conservative dose estimate.

[b]These are reasonable variations which could be encountered for a large fraction of the exposure conditions or population at risk.

[c]See table 7 for average annual degree-days and table 11 for variation with degree-days/day.

[d]Ratio of Rn, RaA, RaB, RaC (RaC').

[e]This factor includes assumptions for daughter equilibria, critical mode of exposure, lung model, and other dosimetry factors.

$$0.0028 \text{ pCi/l} \times \frac{100 \text{ rads per year}}{100 \text{ pCi/l}} = 0.0028 \text{ rads/year}$$

The absorbed dose in rads for alpha radiation to the bronchial epithelium is converted to dose equivalent in rems by use of a quality factor of 10.

$$0.0028 \frac{\text{rads}}{\text{year}} \times 10 = 0.028 \text{ rems/year.}$$

This estimate of dose to an individual is higher than Barton's (19) estimate of 0.015 rem/year, because he calculated lower radon daughter concentrations due to nonequilibrium conditions as a function of air change rate. The latter approach is more realistic, although it does not account for other mechanisms by which radon daughters may be removed from a home atmosphere, such as plating out on walls and surfaces and deposition with dust particles.

The above dose equivalent estimate of 0.028 rem/year corresponds to Barton's computer calculations for radon at equilibrium with its daughters in the incoming natural gas. As noted previously, however, there is probably very little radon daughter activity in the natural gas at points of use.

Dose was not calculated specifically for an individual from use of space heaters, mainly because a typical individual could not be defined, since the use of space heaters depends largely on weather conditions and geographical location. Therefore, annual doses were estimated for average space heater use by each State as shown in the section on population dose. All the assumptions and calculations for estimating dose equivalent from radon released by space heaters were the same as for kitchen ranges except space heaters use different volumes of natural gas.

Radon dose

The radon itself does not contribute significantly to radiation exposure. Since radon is a gas, most of a given amount inhaled is expelled in breathing before it can decay (50). Holleman (52) reported that the absorbed radon produces only about 0.5 percent additional dose to the tracheobronchial tree. Tsivoglou et al. (50) noted that alpha emissions from radon alone contribute about 0.3 percent of the total dose from inhalation of radon together with daughters. Holaday et al. (27) reported that radon dose in the lung is about 1/20 and in the bronchi about 1/260 of the dose from radon daughters.

Beta-gamma dose

Altshuler et al. (25) determined that beta and gamma radiation from radon daughters deliver a negligible dose (less than 5 percent of alpha dose). This is because their greater penetrations distribute their ionizing energy over much more tissue than the alpha radiation.

Average dose equivalent to the United States population

Tracheobronchial (T-B) doses to the United States population are given in table 7. This table was prepared from data compiled by T. F. Gesell[10] from 1970 Census Bureau statistics. The States are ranked according to total T-B dose in person-rem per year from the combined effects of unvented kitchen ranges and space heaters.

The population T-B dose equivalent in person-rems was calculated by extrapolation of Barton's (19) estimate of 15 mrem/year for tracheobronchial dose to an individual as described in the previous section. By this approach, for kitchen ranges the extrapolation factor was:

$$\text{Dwellings} \times \frac{\text{4 occupants}}{\text{dwelling}} \times 0.015 \text{ rems} =$$

$$\text{Dwellings} \times 0.06 = \frac{\text{person-rems}}{\text{year}}$$

The factor 0.06 includes the necessary dimensions for converting from dwellings to person-rems/year. This factor was applied to the number of dwellings with gas ranges in each State. The total population T-B dose from use of gas kitchen ranges was estimated as 1.87 million person-rems per year for the United States.

For space heaters the degree-day[11] parameter was included as follows:

$$\text{Dwellings} \times \frac{\text{degree-days}}{\text{year}} \times \frac{0.354\text{m}^3}{\text{degree-day}} \times \frac{\text{4 occupants}}{\text{dwelling}}$$

$$\times\ 0.015 \text{ rem} \times \frac{1}{0.765\text{m}^3/\text{day}} \times \frac{1}{365 \text{ days/year}} =$$

$$\text{Dwellings} \times \text{degree-days} \times 0.0000761 = \frac{\text{person-rems}}{\text{year}}$$

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[10]Gesell, op. cit.

[11]A degree-day is a term used by the heating industry to specify heating or fuel requirements as a function of outdoor temperature. The number of degree-days on any given day is determined by the difference between a constant indoor temperature of 65° F and the daily mean temperature outdoors. If the outdoor temperature varied from 20° F to 30° F for one day the degree-days would be 65 - (20 + 30)/2 = 40 degree-days. The cumulative degree-days per day for a year give the annual degree-days shown in table 7.

Table 7. Dose equivalent to U.S. population from radon in natural gas
(All numbers in thousands)

No.	State	(a) Dwellings with unvented heaters	(b) Average Annual Degree-Days	Population T-B dose person-rem/yr	(a) Dwellings with gas ranges	Population T-B dose person-rem/yr	Total Population T-B dose person-rem/yr
1	Calif.	214	2.76	44.7	4,350	261	306
2	N.Y.	58.7	6.27	27.9	4,190	251	279
3	Tex.	942	1.94	139	2,150	129	268
4	Ill.	48.6	5.90	21.8	2,510	150	172
5	Pa.	47.9	5.53	19.8	1,950	117	137
6	Ohio	33.2	5.84	14.7	1,670	100	115
7	N.J.	24.9	4.80	9.1	1,610	96.8	106
8	Mich.	40.4	7.37	22.6	1,260	75.5	98.1
9	La.	373	1.63	46.2	763	45.8	92.0
10	Okla.	204	3.79	58.7	515	30.9	89.6
11	Ga.	280	2.44	51.8	446	26.8	78.6
12	Mass.	21.5	6.52	10.7	914	54.3	65.0
13	Ala.	246	2.37	44.3	296	17.8	62.0
14	Miss.	271	2.19	45.2	233	14.0	59.2
15	Ark.	166	3.02	38.0	320	19.2	57.2
16	Mo.	27.2	4.92	10.2	780	46.8	57.0
17	Ind.	23.1	5.69	10.0	778	46.7	56.7
18	Md.	21.6	4.62	6.6	706	42.3	49.9
19	Wis.	22.1	7.68	13.1	511	30.6	43.7
20	Minn.	19.2	8.89	12.9	442	26.5	39.4
21	W. Va.	61.6	4.84	22.6	280	16.8	39.4
22	Ky.	39.1	4.87	14.5	389	23.3	37.8
23	Va.	40.3	3.78	11.6	424	25.5	37.1
24	Fla.	289	0.74	16.3	323	19.4	35.7
25	N.C.	93	3.28	23.2	136	8.2	31.4
26	Tenn.	68.6	3.49	18.2	211	12.7	30.9
27	Iowa	8.9	6.87	4.7	393	23.6	28.3
28	Kans.	10.8	5.28	4.3	358	21.5	25.8
29	Ariz.	29.3	3.30	7.3	299	17.9	25.2
30	Conn.	10.0	5.92	4.5	327	19.6	24.0
31	Colo.	8.4	6.31	4.0	284	17.0	21.0
32	S.C.	75.9	2.34	13.5	99.7	6.0	19.5
33	Wash.	30.0	5.37	12.2	69.2	4.1	16.3
34	N. Mex.	19.1	4.65	6.7	146	8.8	15.5
35	D.C.	4.6	4.62	1.6	226	13.6	15.2
36	Nebr.	6.0	6.68	3.1	186	11.1	14.2
37	Oreg.	16.5	6.05	7.6	54.3	3.3	10.9
38	R.I.	5.4	5.88	2.4	138	8.3	10.7
39	Utah	4.6	6.11	2.1	83.3	5.0	7.1
40	Mont.	5.5	8.09	3.4	54.4	3.3	6.7
41	Me.	5.4	8.64	3.5	33.7	2.0	5.5
42	S. Dak.	4.9	7.80	2.9	43.1	2.6	5.5
43	Del.	2.5	4.93	0.9	65.6	3.9	4.8
44	Nev.	4.8	6.19	2.3	41.5	2.5	4.8
45	Idaho	8.5	6.13	4.0	12.6	0.7	4.7
46	N. Dak.	3.5	9.31	2.5	27.8	1.7	4.2
47	N. H.	2.7	7.38	1.5	38.8	2.3	3.8
48	Wyo	2.1	7.59	2.5	41.2	1.2	3.7
49	Vt.	3.0	8.27	1.9	14.3	0.9	2.8
50	Hawaii	0.2	----	----	36.5	2.2	2.2
51	Alaska	2.1	8.09	1.3	9.6	0.6	1.9
Total		3,950.7		854	31,234.6	1,874	2,728

(a)Census Bureau data for 1970 compiled by T.F. Gesell, University of Texas. Each dwelling is assumed to have four occupants.

(b)Data compiled by T.F. Gesell from an isodegree-day map of the United States and tabulations of ASHRAE (56), in terms of degree-days per year.

Again, for consistency the necessary dimensions are included with the factor 0.0000761. Thus, the population dose equivalent from use of unvented space heaters was determined by relating the average quantity of gas used in heaters to the quantity of gas used in ranges and the corresponding dose equivalent for ranges. The average quantity of gas used by space heaters was 2.75 m^3 per day (7.77 degree-days at 0.354 m^3 per degree-day). The total population T-B dose equivalent from space heaters was calculated to be 0.854 million person-rems per year.

By assuming four occupants per dwelling, the population at risk for exposure to radon from kitchen ranges is about 125 million or roughly 60 percent of the United States population. For space heaters, the potential population affected is about 15.8 million or 7.5 percent of the population. However, the average individual receives a higher dose from use of space heaters due to the greater quantity of natural gas required for heating. This may be estimated indirectly by dividing the total T-B dose from space heaters by the exposed population, i.e.,

$$854{,}000/15{,}800{,}000 = 0.054 \text{ rem/year}$$

for an average individual. This can be compared with 0.015 rem/year for an individual's exposure from use of kitchen ranges.

The combined population T-B dose equivalent for exposure to radon daughters from use of natural gas in unvented kitchen ranges and space heaters was estimated as 2.73 million person-rems per year for the United States.

POTENTIAL HEALTH EFFECTS

Dose equivalent to health effect conversion factors

The health effects analysis in this study will be based on the absolute somatic and genetic risks from radon daughters as outlined in the report by the National Academy of Science on the biological effects of ionizing radiation (BEIR report) (26). To place the significance of the estimated health effects from radon daughter exposure to the bronchial epithelium in perspective, the corresponding health effects to other parts of the body will also be considered.

The proportional dose to other organs can be estimated by first considering the ratio of bronchial epithelium dose to alveolar dose. This ratio was determined by Albert (57) as 34.3 to 1, respectively; i.e., the alveolar dose is 0.0291 times the bronchial dose. The relationship of alveolar dose to other organs, as caluclated by Pohl and Pohl-Ruling (58), is then applied to complete the extrapolation from bronchial epithelium dose.

Table 8 shows the relative dose to each organ in comparison with dose to the critical tissue, which is the basal cells of the bronchial epithelium. Dose to this tissue is often referred to as the tracheobronchial or T-B dose according to ICRP respiratory tract model (38). The proportional doses to other organis are given as fractions of the T-B dose, for the condition where the body is in equilibrium with the radon containing atmosphere.

The T-B dose effect or risk of concern from radon daughter exposure is lung carcinoma. Since lung cancer has such a high mortality rate, it is assumed that morbidity for this dose effect is equivalent to mortality. Morbidity does not equal mortality for the corresponding dose to other organs. However, the relative doses to other organs are so small that their contribution to either morbidity or mortality is insignificant when added to the risk from T-B dose.

The dose equivalent to health effects conversion factors for each organ are also shown in table 8. These factors are in terms of absolute risk, which means excess risk or mortality from the source of radiation in this study (radon daughters).

The absolute risk from T-B dose was calculated from the BEIR report, table 3-2 (26), by multiplying the sum of the fractional risks by age times the expected plateau region. In this case, the plateau region, or time beyond the latent period during which the risk remains elevated, was taken as 30 years. The calculation for risk in terms of lung cancer deaths was based on the following analysis, where the adult risk for cancer of the lung from T-B dose is 1.3 deaths/10^6 persons at risk/year/rem.

Age group	Percent of population	Proportion of adult risk	Fractional risk deaths/10^6 persons/year/rem
10+	80	1	1.3 x 1 x 0.8 = 1.04
0-9	20	0.2	1.3 x 0.2 x 0.2 = 0.05
In Utero[12]	1.3	5	1.3 x 5 x 0.013 = 0.08
			1.17

Annual risk = 1.17 deaths/10^6 persons/year/rem

This annual risk is then multiplied by 30 to estimate excess deaths for a plateau region of 30 years to give the absolute risk as

$$1.17 \times 30 \simeq 35 \text{ excess deaths}/10^6 \text{ persons/year/rem}$$

[12]Exposed through placental transfer of radioactivity in maternal blood.

Table 8. Organ dose ratios and absolute risk

Organ	Organ to T-B dose ratio[a]	Absolute risk[b] deaths/10^6 persons/year/rem (26)
Somatic effects		
Bronchial epithelium	1.000	35
Alveoli	0.0291	--[c]
Liver	0.0013	--
Gonads	0.0009	--
Bone	0.0005	3
Bone marrow	0.0011	26
Kidneys	0.0066	--
Blood	0.0026	--
Muscle (soft tissue)	0.0007	67

Total - 35.077 deaths/10^6 persons/year/rem for T-B dose

Organ	Organ to T-B dose ratio[a]	Absolute risk[b]
Genetic effects		
Gonads	0.0007	200 effects/10^6 persons/year/rem

Total - 0.14 effects/10^6 persons/year/rem for T-B dose

(a)Ratio of organ dose to T-B dose for conditions where the body is in equilibrium with the radon containing atmosphere.
(b)For organ at risk.
(c)No risk factor data available.

This number represents a combined population at risk estimate, weighted for age group distribution and proportional risk for continuous exposure to radon daughters.

The absolute risks for the other organs were derived in the same manner as described above for risk from T-B dose. Risk factor data were not available for some organs. However, the relative contribution of the organs to excess deaths for a given T-B dose is very small (0.077 deaths/10^6 persons/year/rem for organs where data was available in table 8). Thus, it is concluded that the combined effects from all the organs would not significantly increase the absolute risk for T-B dose. This study will therefore use the absolute risk estimate of

35 excess deaths/10^6 persons/year/rem

as a dose to health effects conversion factor for continuous exposure to radon daughters.

It should be noted, however, that very little data are available on carcinogenic alpha dose to the lung (25). Furthermore, the above health risk estimate was derived by extrapolation from effects observed at high doses and dose rates to those for low doses. Information is still vitally needed to establish whether lung cancer production has a threshold dose (42). If the relevent damage to man is indeed a nonthreshold effect, as assumed in this study, then the question of permissible limits on concentrations of radon and daughters requires a complex answer which relates economics, benefits, and risks.

Health effects estimate

The total dose equivalent for continuous exposure to radon daughters from use of natural gas in unvented kitchen ranges and space heaters in the United States is estimated to be 2.728 x 10^6 person-rems per year. This dose may be converted to potential health effects by the factor 35 deaths per 10^6 persons/year/rem. This conversion gives an estimate of 95 excess deaths per year.

However, the significance of this estimate of potential mortalities should only be interpreted by comparison with other reference guides and by consideration for the uncertainties in this analysis. Such comparisons are made in the Discussion Section to provide the basis or proper perspective for interpreting estimates of mortality.

The estimate of potential health effects will vary for different exposure conditions. The nature of corrections to be applied to the estimate of 95 excess deaths per year for other exposure conditions are illustrated in table 9. Each of these corrections will not be applied

Table 9. Corrections to adjust estimated health effects for different exposure conditions

Parameter	Correction multiplier
Air changes per hour (19)	
0.25	6.01
1.0	1.0
2.0	0.339
Radon activity	Linear[a]
Quantity of gas used	linear
House size	linear
Daughter equilibria (50)	
Ratio 1, 1, 1, 1	1.9
1, 0.9, 0.8, 0.7	1.3
1, 0.8, 0.6, 0.4	1.0
1, 0.75, 0.5, 0.3	0.84
1, 0.5, 0.25, 0.1	0.39
Percent unattached RaA[b]	
3	0.75
8.5	1.0
10	1.3
25	2
Dose conversion factor	linear
Quality factor	linear
Health effects conversion factor	linear

[a] A linear correction means the correction is proportional to the variation in the parameter

[b] Estimated from Jacobi (33, 34), Altshuler et al. (25).

here specifically; however, the influence of variations in exposure conditions will be included in the discussion of uncertainties.

DISCUSSION

Review of uncertainties

The fundamental problem in an analysis of potential health effects as derived in this study is the necessity of extrapolating from a few measurements or reported values to average conditions for large populations. Because of inadequate information, values often have to be estimated or assumptions made to represent typical exposure conditions or population at risk. Assumed values are normally selected so the calculated dose or health effects will be overestimated, i.e., conservative. However, without more supporting data some of the estimates used in this analysis may not represent average conditions, and other values may be overly conservative. Both aspects of this analysis will be considered as far as possible for two purposes: (1) to place the estimate of health effects in reasonable perspective, and (2) to indicate where better values might be obtained from field measurements or studies of exposure conditions which would significantly enhance the estimate of potential health effects from radon in natural gas.

The possible variations which could be encountered for reasonable exposure conditions were summarized previously in table 6. The corrections to adjust estimated health effects for these possible differences in exposure conditions were also given in table 9. It should be emphasized that this analysis considers only those variations which could be typical for exposure of a large part of the population. Extreme conditions for small parts of the population, such as users of 'farm taps', cannot be evaluated from present information.

Considering the model for analysis of health effects depicted in figure 1, the first parameter of concern is radon-222 concentration in the natural gas at the point of use. A level of 20 pCi/l was chosen as an average for the United States, however, Barton et al. (19) noted that a level of 10 pCi/l may be more representative. On the other hand, large segments of the population may use natural gas with an average of 50 pCi/l of radon-222. Ideally, therefore, the estimate for the United States should be based on regional concentrations in natural gas, as well as regional gas use and populations.

Another parameter of special concern to Barton et al. (19) was the influence of home ventilation or air change rates. An average air change rate of one per hour was assumed in this study. This is considered typical for air infiltration in normal home with windows closed and doors opened only for entry or exit at an outside wind velocity of 7.5 mph. A typical home is also assumed to have no makeup air for heating or air conditioning. In contrast, apartments may have 25 percent makeup air from central heating and air conditioning systems. Barton's calculations indicate that an air change rate of 0.25 per hour could increase the dose a factor of 6 over that at one change per hour. However, a United Nations study (21) indicates that better ventilated dwellings more commonly have air changes of five or more per hour which could reduce the dose by a factor of four or more. Again, one air change per hour is considered conservative by architects, but information is not available for better estimates for average dwellings. Resolution of this factor would require an evaluation of air infiltration by house type, and a regional distribution according to use of heating or air conditioning for closed houses or the proportion of houses with open windows for summer cooling. Such a study could also provide information on the distribution of house sizes for calculating dilution volumes.

The third parameter for consideration is reflected by the dose conversion factor and has to do with radon daughter product equilibria. The ratio of daughters to radon is of concern for dose calculation from all sources of radon. Most studies have determined this ratio for uranium mine conditions where secular equilibrium is prevented by air circulation which removes daughters as they are formed. Normal air change in a house also prevents daughter product secular equilibrium with radon. Barton's (19) calculations show that the dose at one air change per hour for non equilibrium conditions (15 mrem/year) is only 53 percent of the dose for secular equilibrium (28.1 mrem/year). The nonequilibrium condition was based only on air change rate; therefore the dose would be even less if loss of daughter products by plating out or deposition on surfaces was considered. When Barton's data are compared with Tsivoglou et al. (50), it was determined that 53 percent of the equilibrium dose corresponds to a radon-daughter ratio of about 1, 0.8, 0.6, 0.4. This ratio agrees well with studies by Altshuler et al. (25). Table 9 indicates that the dose could vary by ± 16 to 30 percent for small variations from the above ratio which would be expected to include normal variations in equilibrium conditions for typical dwellings in the United States.

Another parameter which affects the dose conversion factor is the percentage of free ions of RaA. The dose conversion factor from this study (100 rads/WL for continuous exposure) was based on 8.5 percent of free RaA ions (25, 39). This percentage of free ions is determined largely by the presence of dust particles or condensation nuclei for attachment of daughter products. Therefore, dusty air (more than 10,000 particles cm^{-3}) has a lower free ion fraction of about 3 percent. Relatively clean air of normal dwellings could have from 8.5 to 25 percent free ions. The latter condition would result in about twice the dose at

8.5 percent. This is because free ions are essentially 100 percent deposited in the respiratory system (38, 59). In contrast, only about 10 percent of the daughters attached to dust particles are retained in the tracheobronchial region.

The two parameters, daughter equilibria and free ion fraction, largely determine the dose conversion factor. Also, these two parameters may be more easily quantified than other variables included in the dose conversion factor. The overall analysis of health effects could be improved by better definition of these parameters. Since neither of them depends on the source of radon, a review of studies on radon from uranium mill tailings or construction materials may provide better information. Otherwise a special study could be directed at determining daughter product ratios and percent free ions from natural radon for a few typical dwellings.

The uncertainty in the dose to health effects conversion factor in terms of absolute risk is rather hard to determine. This risk estimate is based on extrapolation from observed incidences of lung carcinomas in uranium miners receiving relatively high exposures from radon daughters. However, no health effects have been reported for exposures to less than 4 working level months (WLM) or 1/3 of a WL for a year (39). Therefore, the potential health effects estimated in this study for exposures to radon levels of 0.01 pCi/l (0.0001 WL) or less are statistical projections for evaluation of large populations, based on the assumption of a linear nonthreshold dose response to alpha radiation from radon daughters.

Interpretation of estimated health effects

The previous review of uncertainties has indicated a few of the possible variations in parameters which determine the significance of the overall estimate of health effects. To further place the potential for health effects from radon in natural gas in perspective, parameters in this analysis will be related to current guides and recommendations, natural background radon in the ambient environment, and normal respiratory cancer mortality.

Current guides and recommendations

The guides for control of radon have been primarily oriented towards health protection of uranium miners. These guides have undergone several changes over the years as the potential for lung carcinomas from radon daughters became better understood. This development of guides is shown in table 10. Of particular interest here are those guides for continuous exposure (168 hour week) for the general public. These vary from 0.33 to 4 pCi/l. The lowest recommendation of 0.33 pCi/l is derived from ICRP No. 2, 1960, (60). This was derived as 1/30 of the radon-222 guide for continuous occupational exposure.

Table 10. Guides for radon-222 concentrations in air above natural background[a]

Rn-222 concentrations for occupational exposure (pCi/l) 40 hour week	168 hour week	Source, date and reference
10	none	U.S. X-ray and radium Protection Committee, 1941, (61)
30	10	NCRP, 1953, (62)
300	100	ICRP, 1955, (63)
300	100	NCRP, 1955, (64)
100[b]	none	PHS, 1957, (27)
30	10	NCRP, 1959, (65)
30	0.33[c]	ICRP, 1960, (60)
100[b]	none	ASA, 1960, (66)
100[b]	none	Governors Conference, 1961, (67)
30[b]	none	Secretary of Labor, 1967, (32)
100	4[c]	10 CFR 20, 1970, (68)
30[b]	none	FRC, 1971, (31)

[a] Review by David E. Janes, EPA, Office of Radiation Programs.
[b] Values originally expressed in working levels.
[c] General public or unrestricted areas.

For comparison, the concentration of radon-222 released in an average home ($226.6m^3$ and one air change an hour) from the use of $0.765m^3$ a day of natural gas containing 20 pCi/l of radon) in an unvented kitchen range is 0.0028 pCi/l. This represents about 0.85 percent of the ICRP No. 2 guide.

If the same home had an unvented space heater, the radon concentrations shown in table 11 could be expected for various heating requirements. These concentrations were estimated for the exposure conditions postulated previously in table 6. For these conditions, even with an extreme heating requirement of 100 degree-days/day (corresponds to outdoor temperature of 35° F below zero), the indoor radon concentration is less than 40 percent of the ICRP guide. It is not likely this guide would be exceeded, therefore, for normal conditions, unless the radon concentration in the gas was much higher than 20 pCi/l. For example, at a heating requirement of 50 degree-days/day, the guide would not be exceeded unless the gas contained over 100 pCi/l of radon.

For the average annual heating requirement of 7.77 degree-days/day plus use of a gas range, the indoor radon concentration would be 0.0129 pCi/l or 3.87 percent of the guide. At these average conditions, the natural gas could contain up to 516 pCi/l before the ICRP guide would be exceeded for continuous exposure to the general public.

Natural background radon

Natural radon in the ambient environment goes through a daily cycle of concentrations from 0.03 to 3.50 pCi/l of air (21, 69). The average atmospheric content of radon from one to four meters above the ground is about 0.3 pCi/l (69). It is interesting to note here that the ICRP guide of 0.33 pCi/l is about the level of natural background radon. Of course, the ICRP guide applies to controllable radon concentrations above background levels.

Indoors the radon levels are typically from 3 to 4 times the outdoor levels due to emanation of radon from building materials. The indoor radon concentration is also influenced by infiltration from outside air. Thus, radon levels inside homes might be 0.6 to 1.2 pCi/l for ventilation rates below four air changes an hour, and from 0.1 to 0.3 pCi/l for over six air changes an hour (21).

In this analysis the air change rate was conservatively assumed to be one per hour. Therefore, the average radon concentration from use of natural gas in kitchen ranges (0.0028 pCi/l) represents from 0.23 to 0.47 percent of ambient indoor radon levels for less than four air changes an hour. The average combination of radon from kitchen ranges and space heaters (0.0129 pCi/l) would still be only about 1.1 to 2.2 percent of expected indoor radon concentrations from natural background. The higher

Table 11. Comparison of indoor radon concentrations from natural gas with the ICRP No. 2 guide of 0.33 pCi/1

Degree-days[a] day	Radon-222 concentration[b] Space heaters	Heaters + ranges[c]	Percent of ICRP guide
0	0.0	0.003	0.85
10	0.013	0.016	4.8
20	0.026	0.029	8.7
30	0.039	0.042	12.6
40	0.052	0.055	16.5
50	0.065	0.068	20.4
60	0.078	0.081	24.3
70	0.091	0.094	28.2
80	0.104	0.107	32.1
90	0.117	0.120	36.0
100	0.130	0.133	39.9

(a) Heaters use about 0.354 m^3 of natural gas per degree-day.
(b) For radon in natural gas at 20 pCi/1.
(c) Gas use in ranges produces an indoor radon concentration of about 0.003 pCi/1.

percentages of expected indoor radon concentrations which would result from increased use of space heaters may be derived from the data in table 11. For example, at 100 degree-days/day the resulting radon concentration would represent about 11 to 22 percent of normal indoor radon levels for ventilation rates below four air changes an hour.

It is pertinent at this point to also consider how the total usage of natural gas may affect ambient levels of radon. Barton et al. (70) evaluated total gas usage in the metropolitan areas of Los Angeles and San Francisco to determine atmospheric concentrations of tritium which might occur from use of gas from nuclearly stimulated wells. Computer modeling was used to determine dilution parameters resulting from domestic and industrial gas use as ground level sources of pollutant, as well as from gas use in electric generating plants having tall stacks for release of combustion products. Applying these same dilution parameters to the total use of natural gas (containing 20 pCi/l of radon-222) gave the atmospheric concentrations shown in table 12. It is apparent that even the highest expected concentration of 0.002 pCi/l is still only about 0.6 percent of the natural atmospheric content of radon. These data also indicate that the radon concentrations indoors from household use of natural gas significantly exceed concentrations in the atmosphere from all uses of natural gas.

Normal excess mortality from respiratory cancer

Using data provided in Patterns of Cancer Mortality in the United States: 1950-1967 (71) and population statistics for the United States: 1972 (72), a reasonable estimate of respiratory cancer mortality would be 40,000 to 45,000 deaths per year in the United States. This estimate is probably high since it classifies tumors of the bronchus, lung, and pleura with pulmonary tumors as one group. Of these deaths, about 20,000 are due to primary tumors, i.e., those originating in the respiratory system. The other 20,000 to 25,000 are not specified as to point of origin.

In this study, a conservative estimate is made that radon from natural gas could lead to a potential of 95 excess deaths from lung cancer per year. This would represent about 0.2 to 0.5 percent of the normal lung cancer mortality of 20,000 to 45,000 per year. Even if the normal mortality estimate was reduced to 10,000 lung cancer deaths per year to account for the population at risk from radon in natural gas, and the fact that 50-75 percent of the normal lung cancers may not originate in the tracheobronchial region, the comparative risk from radon in natural gas is still less than one percent.

Table 12. Atmospheric radon-222 concentrations from all uses of natural gas in metropolitan areas

	Radon concentration-pCi/l	
	Maximum[a]	Population Weighted Average[b]
Los Angeles Basin	0.002	0.00026
San Francisco Bay Area	0.00026	0.000074

[a]At point of peak concentration.
[b]Mean concentration for entire area.

Conservatism in health effects estimate

Further insight may be had as to the significance of this study's initial estimate of 95 excess deaths a year from radon in natural gas by applying the same dose and health effects conversion factors to natural background radon. Barton et al. (19), using the same exposure conditions and dose model as for the earlier dose estimates, calculated that a background concentration of 0.13 pCi/l of radon-222 in secular equilibrium with its daughters would result in 1,300 mrem/year for T-B dose to an individual. This would lead to 273 x 10^6 person-rems for a United States population of 210 x 10^6. The corresponding estimate of potential effects, at 35 excess deaths/10^6 persons/year/rem, gives 9,555 excess lung cancer mortalities or about 20 to 50 percent of normal respitatory cancer mortality. If the average background radon is actually 0.3 pCi/l or more, then the corresponding estimate of excess lung cancer deaths would exceed 22,000 deaths per year or 50 to 110 percent of the normal annual mortalities.

The above calculation for potential health effects from natural background radon indicates that most or all of the normal lung cancer mortality could be attributed to radon-222. This is not a likely conclusion, because this ignores all the other known carcinogenic factors influencing lung cancer, such as smoking, smog, and other naturally occurring isotopes in the atmosphere. What can be concluded from this calculation is that the dose and health effects conversion factors used in this study are very conservative in terms of overestimating potential health effects.

The philosophy in the health physics profession is to estimate high for calculating health effects in order to develop conservative criteria for protection of public health and safety. However, in this study the initial choice of parameters from available data in the literature for estimating health effects from radon appear to be more conservative than necessary as noted above. The conservatism in many of the parameters used in this overall health assessment has been discussed in the previous section on review of uncertainties. However, the most important factors will be listed here again with an indication of the extent of overconservatism.

(1) Daughter product ratios: no account was taken for loss of daughter products by plating out or deposition on surfaces. Possible adjustment multiplier - 0.75 (50).

(2) Ventilation rate: the ventilation rate could readily be 2 to 3 times the one air change per hour assumed in this study (21). Adjustment multiplier - 0.34 (19).

(3) Mouth breathing was assumed in this study but nose breathing would reduce the inhalation of daughters due

to deposition in the nasopharynx areas. Adjustment multiplier - 0.5 (25).

(4) Exposure time: a continuous residence time in dwellings is not very likely for the average population. An average time spent in the home of about 70 percent would be more representative. Adjustment multiplier - 0.7.

In addition, it should be noted that about 30 percent of the total population dose was estimated from use of unvented space heaters. However, use of such heaters is illegal in most states, and many states are becoming more strict in limiting these heaters. Furthermore, many houses with gas kitchen ranges also have outside vents or recirculating charcoal filters to remove cooking odors. The use of these vents or filters would reduce the amount of radon and daughters dispersed within the home. Other adjustment factors could also be enumerated, but application of those above leads to a considerable reduction in the initial estimate of potential health effects, as indicated in table 13. This table also shows the conclusions which this study determined as to the probability of various estimates of excess deaths. This analysis indicates that radon in natural gas could possibly lead to 15 excess deaths per year due to tracheobronchial cancer. This estimate is only 0.03 to 0.08 percent of the normal respiratory cancer mortality. As such, the increase in mortality can be projected on a theoretical basis, as done in this assessment, but the actual increase in mortality could not be detected due to normal variations in respiratory cancer mortality.

Table 13. Conclusions on estimates of excess mortality from radon-222 in natural gas used in unvented kitchen ranges and space heaters

Conclusion	Estimated excess mortality deaths/year	Percent of normal respiratory mortality
Impossible	95	0.2 to 0.5
Improbable	30	0.07 to 0.15
Possible	15	0.03 to 0.08
Likely	5	0.01 to 0.02

The overall conclusion of this assessment of potential health effects from radon in natural gas is that in the United States from 5 to 15 excess deaths from T-B dose may be postulated on the basis of available data. However, a review of uncertainties in this analysis indicates that many of the dosimetry parameters and conversion factors may be overly conservative. Also, it should be noted that this analysis is based on the assumption of a linear-nonthreshold dose response for low concentrations of radon. But, very little data is available relating lung carcinogensis to dose from radon daughters (25) and no lung carcinomas have been confirmed for radon levels expected in homes resulting from use of natural gas (39).

ALTERNATIVE METHODS FOR REDUCING HEALTH EFFECTS

Potential health effects arising from use of natural gas containing radon-222 may be reduced in several ways. These include controls on radon concentrations or on the use of natural gas, as follows:

Production - Control production of wells with highest radon contents or levels above a given concentration.

Processing - Route gas with higher radon levels to special processing for LPG separation and inherent radon removal. This should be followed by LPG storage to reduce the radon concentration in LPG. The natural gas could also be routed through special processing just for radon removal, i.e., by methods in use at nuclear reactors for removing other noble gases (krypton, xenon) from off-gas streams.

Distribution - Route gas with higher radon content, (a) to more distant points of use to allow maximum decay during transport, (b) to industrial or commercial users, and (c) to storage for one or more half-lives to allow radon to decay.

Gas Use - Regulate use of gas by 'farm taps', e.g., perhaps by requiring some storage delay before use. Regulate venting requirements for cooking ranges and space heaters. Require installation permits and inspections.

Analysis of cost for control of radon in natural gas

The simplest approach for control of radon in natural gas would be to limit production from gas wells with high radon levels. However, with increasing demands for natural gas, production from every available well may be required, and therefore the costs for radon removal should be considered.

At the present time the most feasible method for removing radon from natural gas would be to store the gas and take advantage of the relatively short half-life of radon-222 (3.83 days). For example, a storage period of two weeks between production at the well head and the use of natural gas would reduce radon levels by radioactive decay to less than 10 percent of the original content. Storage is also a first consideration for radon control, because this is already an integral part of the gas industry. As noted previously, storage is used to provide the necessary balance between a constant production rate and seasonal demands for natural gas. Most storage operations are now carried out by using underground reservoirs, mainly depleted gas and oil wells. Such reservoirs presently have sufficient capacity to store about 30 percent of the annual net marketed production of natural gas. Since the average storage time is probably between 2 and 6 months, then much more than 30 percent of the annual production could be routed through storage.

Ideally, storage reservoirs should be located near distribution centers for meeting peak demands. At present, most of the readily accessible underground reservoirs in the desired locations have already been developed. Therefore, additional storage for meeting seasonal demands or for radon control would require development of other storage methods such as cryogenic storage of liquified natural gas (LNG) or pressurized tank storage. The gas industry is rapidly increasing the number of LNG facilities, in particular, in order to provide cost effective storage where it is most needed.

It should also be noted that the use of underground gas storage may not result in a reduction in radon concentrations. Gas stored in depleted wells may accumulate additional radon in the same manner that radon builds up in regular production wells. This potential for radon buildup would not be a problem for LNG storage. In addition, LNG storage for radon control has the advantage that LNG facilities could be located wherever necessary in conjunction with the wellfield needing radon control. The same factors apply to use of pressurized tank storage.

The following cost analysis for LNG and pressurized tank storage is intended to provide order-of-magnitude estimates for comparison with the reduction in potential health effects which might be expected with a reduction of radon levels in natural gas. The actual costs for these storage methods can vary widely as functions of facility size, processing rates, compression and pumping costs, and distribution logistics.

For this analysis, costs will be estimated for a two week storage of ten percent of the presently net marketed gas volume, which is 19.5 x 10^{12} ft^3 per year. This should allow sufficient reduction for most anticipated radon levels at well heads. The storage requirement for two weeks would then be

$$19.5 \times 10^{12} \frac{ft^3}{year} \times \frac{14}{365} \times 0.1 = 7.5 \times 10^{10} \ ft^3$$

The costs for storing 7.5 x 10^{10} cubic feet of natural gas will be estimated by the present worth method for annualized costs. This method estimates the yearly capital cost by multiplying the total capital cost by an annual fixed charge rate, i.e.,

capital cost x fixed charge rate = annual capital cost

The fixed charge rate includes interest, taxes, insurance, and depreciation for a 30 year plant life (73). The fixed charge rate used in this analysis was 16.6 percent per year (74). The sum of the annual capital costs and annual operating cost gives the annualized costs which can be compared with the potential reduction in yearly health effects due to reduction in radon levels in natural gas.

Using the cost data from table 14, the annualized costs for storage of natural gas were estimated according to the present worth method as tabulated in table 15.

The total annualized costs for storage of natural gas to allow radon to decay would be from about 0.89 to 8 billion dollars depending on the storage method as shown in table 15. These cost estimates also indicate that liquified natural gas would be less expensive than storage in pressurized tanks. This is partly because a liquified natural gas facility would be designed for a daily liquifaction rate with subsequent storage of the liquified gas which has been reduced in volume by a factor of 650. In contrast, a pressurized tank facility would be designed to accommodate two weeks of production without the great volume reduction inherent to LNG. A LNG facility would also be designed for regasification to return the liquified gas to the normal gaseous state for distribution to customers. After regasification, the gas would typically be stored further to coincide with market demands.

It should be noted also that pressurized gas storage would be less favorable than LNG for reasons other than cost. Namely, pressurized storage of gas has a greater hazard potential for explosion and the huge tanks required would be aesthetically unfavorable.

Table 14. Cost summary for natural gas storage (1972 basis)

	Capital costs	Operating cost
Pressurized tank storage (15)		
Low pressure (1 atmosphere)	\$500/MCF[a]	\$25/MCF
High pressure (50-100 psi)	\$500/MCF	\$25/MCF
Liquified natural gas (LNG) (75)		
Liquification	\$350-450/MCF/Day	
Plant total	\$340-450/MCF/Day	\$75-125/MCF/Day
Storage	\$30-40/MDF/Day	
Regasification		
Depot total	\$150-250/MCF/Day	\$10-17/MCF/Day
Storage	\$20-30/MCF/Day	

[a] MCF = Gas industry notation for 1,000 cubic feet.

Table 15. Annualized cost estimate for storage of natural gas[a]

Storage method	Total annualized cost	Annualized unit costs dollars per thousand cubic feet
Low pressure tanks	\$8 x 10^9	\$4.10
High pressure tanks	\$6.5 x 10^9	\$3.85
Liquified natural gas	\$0.89 x 10^9 to \$1.35 x 10^9	\$0.46 to \$0.69

[a] Storage of 10 percent of the annual marketed production, i.e., 1.95 x 10^{12} cubic feet.

The annual unit costs for storage are also shown in table 15. These costs may be compared with the value of natural gas which varies from $0.20 to $0.30 per thousand cubic feet at the well head to $1.50 to $2.00 per thousand cubic feet at the point of consumer use. The annual unit cost for LNG ($0.46 to $0.69) represents about twice the cost which gas transmission companies would normally pay for natural gas at the well head. Therefore, the customer price would have to be raised accordingly.

The American Gas Association noted that a LNG facility would not be practicable for storage control of radon at an individual well. However, a LNG facility might be constructed for a small group of wells where radon control would be desirable. Such facilities are commonly designed in multiples of a daily processing rate of 250 million cubic feet. A typical well produces about 2 million cubic feet a day. Therefore, the normal facility would handle production from 125 wells. A smaller facility might be designed, but the cost could not be scaled proportionately. Therefore, the unit cost for a smaller facility would make the market value of the gas even less favorable. For example, the unit cost for a small LNG facility could be $2.00 per thousand cubic feet or higher. A facility to handle 25 wells with a combined daily production of 50 million cubic feet would then have an annualized cost of $36.5 million. The value of this gas to transmission companies would be only about $5.5 million a year.

There are no cost data available for evaluating alternative methods other than storage for reducing radon exposures from use of natural gas. Some of the methods used in nuclear reactors for removing noble gases might be applicable to individual or small groups of wells. However, none of these methods have been tested for removing radon from natural gas.

Comparison of radon control costs to reduction in potential health effects

The cost estimates for control of radon in natural gas by storage in pressurized tanks or as liquified gas would be a billion dollars or more a year for 10 percent of normal annual production. For this storage to be effective in reducing radon levels, it would have to be oriented towards the well fields with the highest radon levels. Even then, the overall average radon level for the country may not be reduced by even a factor of 2. Such a reduction would correspondingly reduce the estimated possible health effects (15 excess deaths a year) by less than a factor of 2 by such storage endeavors.

Thus, for a reduction of 8 to 10 hypothetical excess deaths from radon in natural gas, an expenditure of about $1 billion would be required. This corresponds to an investment of $100 million or more for each reduction of one potential excess death. Therefore, this approach for radon control at the national level is clearly not cost effective in terms of the possible reduction in health effects.

It should be noted, however, that local or regional conditions could exist where individuals might receive doses from radon daughters which are much higher than the national average. For example, natural gas users with 'farm taps' close to wells or well fields with high radon content could possibly receive higher radon exposure. Similar circumstances could also occur for small closed gas systems where there is little or no storage and short transmission lines from processing plants to consumers.

For such conditions, it is possible that storage provisions for a small group of wells could be more cost effective than radon control at the national level. However, special studies would be required to determine which wells had the highest radon contents. Then the use of gas from each well would have to be evaluated to determine whether a significant population T-B dose could potentially result. For example, if most of the gas from a given well with high radon content is used industrially and combustion products are vented to the atmosphere, then very little T-B dose is likely. In contrast, the same well may supply only nearby residential customers using unvented appliances. In this case, storage controls may be justified, but such cases would have to be identified first. At the present time, there is no information by which to determine the extent or significance of these local conditions.

CONCLUSIONS

The conclusions that can be drawn from this evaluation of potential radiological health effects from radon in natural gas are as follows:

(a) The use of natural gas containing radon-222 for average exposure conditions does not contribute significantly to lung cancer deaths in the United States.

(b) Controls for reducing radon concentrations in natural gas by storage methods would cost over $100 million for each reduction in one potential excess death. Therefore, it would not be cost effective to require controls on radon in natural gas by storage on a national basis.

(c) No information is available to evaluate local conditions where individuals may receive exposures from radon daughters much higher than the national average. There is also no information on control methods or costs applicable to such local conditions even if they could be identified.

(d) For average exposure conditions the radon from natural gas produces indoor radon concentrations about 3.9 percent of the guide of 0.33 pCi/l derived from ICRP No. 2, 1.1 to 1.2 percent of the average indoor radon concentrations from natural background, and 0.03 to 0.08 percent of normal lung cancer mortality.

(e) Continuous exposure to the bronchial epithelium by alpha radiation from radon daughters could potentially result in 35 excess deaths from lung cancer for each million person-rems.

(f) The average population tracheobronchial dose equivalent resulting from use of unvented kitchen ranges and space heaters in the United States is 2.73 million person-rems per year.

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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-

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