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RADIATION DOSES FROM HYPOTHETICAL EXPOSURES TO RULISON GAS

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ABSTRACT

Production testing of the Rulison well, the second natural gas well developed by use of nuclear explosives, was completed in April 1971. This study examined the hypothetical situation that would have resulted if the dry, carbon dioxide-free gas originally present in the well had been withdrawn at a rate of 1 million ft³/day and distributed by two gas companies to small communities in the area near the well.

Tritium and ⁸⁵Kr are the principal radionuclides present in the gas from the Rulison well. The average whole body dose from inhalation and skin absorption of tritium to members of the exposed public served by one of the gas transmission companies was estimated to be 0.6 mrem for the first year of gas use. The principal source of this hypothetical dose was exposure in the home to tritiated water vapor from cooking with unvented gas ranges. Use of unvented home heaters was not considered creditable. Whole body doses from exposure to tritiated water vapor dispersed in the atmosphere of the same communities averaged 0.1 millirem for the first year. Continuing use of gas at the same rate would reduce the average dose to 0.06 millirem in the second year and to 0.01 millirem in the third year as contaminated gas in the well is removed and the remaining gas is diluted with uncontaminated gas from the surrounding formation. Whole body doses from ⁸⁵Kr were estimated to be about 2% of the tritium whole body doses.

INTRODUCTION

Several publications¹⁻⁴ have estimated radiation doses that people could receive from hypothetical uses of Gasbuggy gas. This paper reports estimates of doses resulting from hypothetical use of gas from the Rulison well, the second natural gas well developed by underground use of a nuclear explosive. Data on chemical and radiochemical analyses of samples obtained during production testing of the well are available,^{5,6} and most of the data were compiled by Gotchy.⁷ The results have been evaluated by Smith⁸ and Reynolds.⁹ Public acceptance of natural gas containing small amounts of tritium and ⁸⁵Kr (radionuclides that result from use of nuclear explosives) may govern the success of this potentially important technique for increasing the supply of natural gas, which is an environmentally acceptable energy source. The Gasbuggy dose studies¹⁻⁴ demonstrated that tritium is the principal contributor to whole body doses where the tritium is present as tritiated water vapor (HTO) in gas combustion products. It was also shown that inhalation and skin absorption of tritiated moisture from unvented heaters or appliances in homes is the critical exposure pathway.

GAS DISTRIBUTION SYSTEMS

Two gas companies [Rocky Mountain Natural Gas Company, Inc. (RMNGC) and Western Slope Gas Company, Rifle Division (WSGC)] supply communities sufficiently close to the Rulison well to be considered potential distributors of the gas from this well if it were deemed marketable (See Fig. 1).

Fig. 1. Location of the Rulison Well, Rocky Mountain Natural Gas Co., and Western Slope Gas Company - Rifle Division.

Rocky Mountain Natural Gas Company

A sketch of the RMNGC gas system, including points of entry for gas supplies, is shown in Fig. 2. Data on the various communities including population, area, gas consumption, and annual volume of Rulison gas assumed to be used over a three-year period are included in Table I. These data are derived by assuming that the 1970 total gas consumption of each community is constant over the three-year period, that a constant volume of 365 million ft³ of Rulison gas is supplied each year, and that other sources of gas vary in accordance with projected production patterns.

Western Slope Gas Company, Rifle Division

The general location of the WSGC system is shown in Fig. 1 and its gas flow pattern is outlined in Fig. 3. Only two communities, Rifle and Grand Valley, are assumed to receive Rulison gas full-time because the flow pattern would prevent other communities, except possibly Debeque, from getting gas from this source. (Debeque was not considered in this study because data were not available on the amount of Rulison gas this community might receive.) Data on population, area, and 1970 gas consumption are given in Table II for Rifle and Grand Valley.

ATMOSPHERIC DISPERSION OF GAS COMBUSTION PRODUCTS

The communities served by the RMNGC and WSGC systems are in the mountainous area of Western Colorado. The topography exerts a strong influence on the local winds, stabilities, and diffusion. According

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Fig. 2. System Map of Rocky Mountain Natural Gas Company System.

**Table I. Hypothetical Consumption of Rulison Gas in the Rocky Mountain
Natural Gas Company System Over a Three-Year Period (Case 1)^a**

Community	Gas Consumption (Million ft ³ /year)				Fraction of Gas From Rulison.			1970 Population	Area (Sq. Miles) ^b
	Total 1970	Rulison 1972	Rulison 1973	Rulison 1974	1972	1973	1974		
Aspen	1021	103	155	165	0.10	0.15	0.16	2404	1.2
Basalt	55	6	8	9	0.11	0.15	0.16	419	0.2
Carbondale	155	16	23	25	0.10	0.15	0.16	726	0.3
Cedaredge	56	5	1	0	0.09	0.02	0	581	0.6
Collbran	63	0	0	0	0	0	0	225	0.2
Delta	1277	118	19	0	0.09	0.02	0	3694	1.3
Eagle	72	7	11	11	0.10	0.16	0.16	207	0.5
Eckert	38	4	1	0	0.11	0.03	0	c	0.8
Glenwood Springs	602	69	103	110	0.11	0.15	0.16	4106	1.8
Gypsum	24	2	4	4	0.08	0.17	0.17	420	0.8
Hotchkiss	48	4	1	0	0.08	0.02	0	507	0.3
Montrose	603	0	0	0	0	0	0	6496	2.0
Olathe	51	0	0	0	0	0	0	756	0.9
Paonia	35	4	1	0	0.11	0.03	0	1161	0.3
Snowmass	220	22	33	36	0.10	0.15	0.16	c	0.6 ^d

^aAssumes that 360 million ft³ Rulison gas is used per year and that total gas consumption remains at 1970 values

^bAll gas attributed to a community is assumed to be consumed within the area shown although it is probable that some customers live outside the community boundaries.

^cData not available.

^dEstimated value.

Fig. 3. System Map of Western Slope Gas Company - Rifle Division.

Table II. Population, Area, and Gas Consumption of Communities Served by the Western Slope Gas Company - Rifle Division^a

Community	1970 Population	Area (sq. miles)	1970 Gas Consumption (million ft ³)			Fraction of Rulison Gas
			Res'l & Com'l	Ind'l	Total	
Rifle	2150	0.8	191	753	944	0.368
Grand Valley	270	0.3	18.7	---	18.7	0.686

^aIncludes only the communities for which hypothetical use of Rulison gas could be estimated.

to the state climatologist, Joseph Berry,¹⁰ the classical mountain wind system develops in all the valleys occupied by the communities we are considering. Wind directions are along the valley axis, with upslope motions at speeds of about 5 m/sec during the day and downslope motions of about 2 m/sec during the night. Stagnation often occurs over this area with very little wind movement in the valleys for periods of several days.¹⁰ Atmospheric dispersion of natural gas combustion products would be at a minimum during these periods but it does not seem likely that such stagnation would significantly affect the average potential radiation doses.

The only published meteorological data from this area are from Grand Junction, Colorado, where the winds are also largely controlled by topography. A study of air pollution potential by Holzworth¹¹ showed that the average wind speed in this community is 5 m/sec. The frequency of calms (stagnation periods) is 5% in winter and 1% in summer. The mean maximum mixing depth at Grand Junction was estimated to be 400 m in winter and 2400 m in summer.¹¹ In this report we assume that the average atmospheric mixing depth is 100 m during the night and 1000 m during the day for each town. Most of the towns considered in this report are in narrower valleys than the valley occupied by Grand Junction.

Three types of diffusion calculations have been made for these communities:

1. Surface concentrations in the towns due to ground-level release in the town area.
2. Surface concentrations due to industrial point-source emissions.
3. Concentrations due to all emissions, assuming a valley box model.

Area Source Calculations

A formula suggested by Hanna¹² is used for these calculations.

The surface concentration x_{AS} is proportional to the local area source strength Q_0 divided by the wind speed U . The proportionality factor C is a weak function of atmospheric stability. The formulas applying at different times for the communities considered are:

$$\text{afternoon, } x_{AS} = 30 Q_0 \text{ (} U = 5 \text{ m/sec and } C = 150 \text{)}$$

$$\text{night, } x_{AS} = 220 Q_0 \text{ (} U = 2 \text{ m/sec and } C = 440 \text{)}$$

$$\text{yearly avg, } x_{AS} = 100 Q_0$$

where Q_0 in all cases is expressed as $\text{cm}^3/\text{m}^2/\text{sec}$ and is calculated from the data in Table I for communities served by RMNGC and in Table II for the two communities served by WSGC. The results are combined with gas flow data in Table I to calculate hypothetical concentrations of Rulison gas (shown in Table III in terms of cm^3 of gas per m^3 of air). Since radionuclide concentrations in the gas are expressed in terms of pCi/cm^3 , this value multiplied by the concentration figures in Table III gives pCi/m^3 .

Point Source Calculations

The point sources (industrial plants having stacks) considered in this study are summarized in Table IV. Plume rise is accounted for in the effective height. Montrose is not included in Table IV because, as shown in Table I, it would not be expected to receive Rulison gas.

The surface concentrations beneath the axis of the plume from these sources were calculated as suggested by Slade¹³ for afternoon upvalley winds (B stability, speed 5 m/sec) and night downvalley winds (E stability,

Table III. Average Ground-Level Source Data for Communities Served by RMNGC

Community	Average Total Conc. (cm ³ /m ³) ^a	1972		1973		1974	
		Fraction of Rulison Gas	Av. Conc. Rulison Gas (cm ³ /m ³) ^a	Fraction of Rulison Gas	Av. Conc. Rulison Gas (cm ³ /m ³) ^a	Fraction of Rulison Gas	Av. Conc. Rulison (cm ³ /m ³) ^a
Aspen	29	0.10	2.9	0.15	4.3	0.16	4.7
Basalt	9.4	0.11	1.0	0.15	1.4	0.16	1.5
Carbondale	18	0.10	1.8	0.15	2.7	0.16	2.9
Cedaredge	3.3	0.09	0.3	0.02	0.1	0	0
Collbran	11	0	0	0	0	0	0
Delta	9.4	0.09	0.9	0.02	0.2	0	0
Eagle	3.9	0.10	0.4	0.16	0.6	0.16	0.6
Eckert	1.6	0.11	0.2	0.03	0.05	0	0
Glenwood Springs	12	0.11	1.3	0.15	1.8	0.16	1.9
Gypsum	1.0	0.08	0.1	0.17	0.2	0.17	0.2
Hotchkiss	5.6	0.08	0.4	0.02	0.1	0	0
Montrose	10	0	0	0	0	0	0
Olathe	1.9	0	0	0	0	0	0
Paonia	3.9	0.11	0.4	0.03	0.1	0	0
Snowmass	13	0.10	1.3	0.15	2.0	0.16	2.1

^aConcentrations are expressed in terms of cubic centimeters of gas (1atm, 60°F) burned and uniformly dispersed in one cubic meter of air.

Table IV. Characteristics of Industrial Sources

Town	Source Strength (m ³ /sec)	Stack Height (m)	Effective Height (m)
Delta	0.83	25	50
Rifle	0.68	25	50

speed 2 m/sec). These concentrations are plotted as a function of downwind distance in Fig. 4 for Rifle where the maxima were $7 \text{ cm}^3/\text{m}^3$ at 0.6 km from the stack during the day and $12.7 \text{ cm}^3/\text{m}^3$ at 2.3 km at night. It is important to realize that these concentrations (which are expressed in terms of cubic centimeters of burned gas dispersed in one cubic meter of air) apply only to a narrow band 50-100 m wide beneath the plume axis. Because of shifting wind direction, maximum concentrations from point sources would be expected to prevail for only a small fraction of the time.

Valley Box Model

In this calculation we assume that all pollution is completely mixed in a valley of width W (expressed in meters). The mixing depth D (in meters), represents the height above the ground of the top of the polluted air. Concentrations are given by the formula

$$F = \frac{Q \text{ total}}{U W D}$$

where

night downvalley $U = 2 \text{ m/sec}$, $D = 100 \text{ m}$

day upvalley $U = 5 \text{ m/sec}$, $D = 1000 \text{ m}$.

Valley widths W were estimated from topographic maps and the resulting concentrations are summarized in Table V.

CONCENTRATION OF RADIOACTIVE SPECIES IN RULISON GAS

Project Rulison is an experiment that was performed to confirm the technical feasibility of stimulating the Mesaverde formation in the Rulison field with nuclear explosives.⁹ Testing of the experimental

Fig. 1 Surface Center Line Concentration Beneath Industrial Plume at Rifle.

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Table V. Average Concentrations Calculated from Valley Box Model

Town	Major Upvalley Direction	Side Creek Upvalley Direction	Valley Width (km)	Source (m ³ /sec)	Concentration (cm ³ /m ³) ^b		
					Upvalley Day	Downvalley Night	24 Hour
Aspen	SE		3	0.91	0.06	1.5	0.78
Basalt	SE	E	1	0.049	0.01	0.25	0.13
Carbondale	SE	S	3	0.20	0.013	0.40	0.21
Cedaredge	N		10	0.050	0.001	0.025	0.013
Collbran	NE		3	0.056	0.004	0.10	0.05
Delta	E		10	1.15	0.023	0.57	0.30
Eagle	E	SE	1	0.066	0.013	0.33	0.17
Eckert	N		10	0.033	0.0006	0.015	0.008
Glenwood Springs	E	SSE	1	0.54	0.11	2.8	1.45
Gypsum	E	S	1	0.022	0.004	0.11	0.06
Grand Valley ^a	NE		3	0.015	0.001	0.025	0.013
Hotchkiss	E		10	0.042	0.001	0.025	0.013
Montrose	SSE		10	0.54	0.011	0.26	0.14
Olathe	S		10	0.045	0.001	0.025	0.013
Paonia	NE	E	3	0.031	0.002	0.050	0.026
Rifle ^a	E	N	3	0.85	0.05	1.4	0.73
Snowmass	E		1	0.195	0.04	1.0	0.52

^aWestern Slope Gas Company - Rifle System; all other towns are served by Rocky Mountain Natural Gas Company.

^bSee footnote, Table III.

well to determine post-shot production characteristics was carried out during the period October 1970 - April 1971, and the tests resulted in removal of 455 million ft^3 of gas and a large fraction of the gasborne radionuclides that were present in the well at the beginning of the tests.⁶⁻⁹

We examine in this paper two hypothetical situations involving exposures to the radionuclides in Rulison gas. In Case 1 we estimate doses that could have resulted from using the gas from the well rather than burning it at the well site. This case has some practical importance, because it would not be desirable to burn large volumes of gas from actual production wells at the well site unless this procedure was necessitated by a requirement to reduce population exposures during the early stages of well production when the concentration of radionuclides in the gas is at its maximum value.

In Case 2 we make the simple assumption that all the radionuclide content of the gas now present in the Rulison well is distributed by the previously described gas transmission companies under the same gas flow conditions used in Case 1.

Average annual concentrations of radionuclides in the gas entering the gas transmission systems are needed in our dose calculations. The data used in calculating these values and the derivation of the equation used in the calculations are discussed below.

Annual Average Concentration for Case 1

Data reported by Smith^{5,6} show that tritium and ^{85}Kr are the principal radioactive species in Rulison gas.¹⁴ The initial ratio of

total activity to ^{85}Kr activity was found to be 1.17 and this ratio seems to have prevailed during the production testing program, within the limit of experimental error. Consequently, we do not consider the ^{85}Kr concentration in detail but focus our attention on tritium which is more important from the radiological hazard standpoint.

Production testing data^{7,9} show that a large quantity of tritiated water was produced along with the gas. The average tritium concentration during the production tests was 4.0×10^5 pCi/cm³ of water.⁵ Commercial processing of natural gas includes water removal before the gas is introduced into pipelines. In our study we assumed that H₂O is almost completely removed. The allowable moisture content of 5 lb in 10⁶ ft³ is equivalent to 0.032 pCi H₂O/cm³ of gas, which can be neglected in Case 1 calculations but not in Case 2. Rulison gas was also found^{5,6} to contain 48% carbon dioxide (CO₂) before the beginning of production testing. This gas would be an inert diluent of the combustible hydrocarbons, and we have assumed that it would be removed during processing. Therefore, the initial tritium concentration in gas supplied to the gas distributors is calculated to be 339 pCi/cm³ for Case 1. The CO₂ concentration in the gas did not decrease in direct relation to the quantity of gas removed from the Rulison well, and we took this into account in our calculations.

The value of 1200 Ci of tritium that we adopted as the initial (HT + C_xH_{2x+1}T) content of the dry gas in the Rulison well was calculated by adjusting the earlier figure of 1120 Ci, based on the quantity of ^{85}Kr expected from the nominal 40-kt yield of the nuclear explosive and the observed ratio of ^{85}Kr to tritium in the gas, to the revised yield value of 43 kt.¹⁵

Figure 5 is a plot of tritium concentration in dry Rulison gas and in dry gas from which CO_2 is assumed to have been removed versus the total dry gas produced. By averaging the tritium concentration over the total gas withdrawal of 455 million ft^3 , we calculated that 1255 Ci of tritium was removed from the well. This value exceeds the calculated initial quantity but the discrepancy is not large (about 5%) and the total agrees fairly well with the 1300 Ci value reported by Smith.⁵

Figure 6 is a plot of tritium concentration versus total dry gas produced from the well for Case 1 where a flow rate of 1 million ft^3/day of dry CO_2 -free gas was assumed. For the first year, it was also assumed that the gas flowing into the chimney from the adjacent rock formation completely replaced the gas withdrawn. The applicable equation under these conditions is

$$K_{\text{CHIM}} = K_0 e^{-V_{\text{REM}}/V_0}$$

where

K_{CHIM} = tritium concentration, picocuries per cubic centimeter

K_0 = initial tritium concentration, picocuries per cubic centimeter

V_{REM} = volume of dry gas produced, cubic feet

V_0 = initial volume of gas in the chimney, cubic feet

$K_0 = R_0/V_0$ where R_0 is the total amount of tritium present at the beginning of the first year.

Based on the value of 1200 Ci for R_0 , a total of 1040 Ci of tritium would have been removed from the well during the first year of withdrawal of 365 million ft^3 of dry CO_2 -free gas. The average tritium concentration

Fig. 8. Tritium Concentration in Rulison Gases as a Function of Volume that was Produced.

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Fig. 6 Tritium Concentration During Hypothetical Withdrawal of Dry, CO₂-Free Rulison Gas at a Rate of 1 M² ft³/Day.
million

in dry, CO_2 -free gas during the first year was calculated to be 107 pCi/cm³.

Replacement of withdrawn gas was assumed to be 80% for the second year and 70% for the third year. The applicable equation for the second and third years is derived as:

$$K_{\text{CHIM}} = R_{\text{CHIM}}/V_{\text{CHIM}}$$

where R_{CHIM} and V_{CHIM} are curies of tritium in the gas in the chimney and the volume of gas in the chimney, respectively. Therefore,

$$K_{\text{CHIM}} = R_0 - R_{\text{REM}}/V_0 - k V_{\text{REM}}$$

where

R_{REM} = curies tritium removed from the well,

R_0 = number of curies of tritium in the chimney at the beginning of the year,

V_0 = volume of gas in chimney at the beginning of the year, cubic feet,

k = 1 - fraction of gas replaced.

Since $dR_{\text{REM}} = K_{\text{CHIM}} dV_{\text{REM}}$, $dR_{\text{REM}}/R_0 - R_{\text{REM}} = dV_{\text{REM}}/V_0 - kV_{\text{REM}}$. Integrating the last equation results in the following equation:

$$K_{\text{CHIM}} = \frac{R_0 \left(\frac{V_0 - k V_{\text{REM}}}{V_0} \right)^{1/k}}{V_0 - k V_{\text{REM}}}$$

The results of these calculations are summarized in Table VI.

Table VI. Tritium Concentration in Dry, CO₂-Free Rulison Gas Hypothetically Removed at a Rate of One Million Cubic Feet Per Day (Case 1).

Period	Tritium Removed (Ci)	Average Concentration (pCi/cm ³ ,STP)
1st year	1040	107
2nd year	143.4	14
3rd year	16.6	1.7

At the end of the third year, only 0.02 Ci of tritium would remain in the gas in the well. The total volume of dry gas produced would be 1460 million ft^3 .

Annual Average Concentration for Case 2

In addition to calculating radiation doses that might be received during the hypothetical use of Rulison gas, starting with the initial (preflaring) concentration of tritium, it is also of interest to calculate possible doses assuming that the gas presently in the Rulison cavity is introduced into either of the gas distribution systems after removal of water and CO_2 .

The pressure in the cavity has been building up steadily since gas flow from the well stopped on April 23, 1971. The total tritium concentration in the dry gas at that time was 3.3 pCi/cm^3 (STP), the total pressure in the cavity was 242 psi, and the temperature was 380°F . Steam pressure in the cavity at 380°F was 196 psi; therefore, the actual dry gas pressure was only 46 psi. From this information and the calculated cavity volume ($5.7 \times 10^{10} \text{ cm}^3$), we calculate a value of 0.35 Ci of tritium in the dry gas. By May 1972 the cavity temperature had dropped to 278°F and the cavity pressure had risen to 1162 psi. The steam pressure at 278°F was 48 psi, leaving a dry gas pressure of 1114 psi. The tritium concentration in the dry gas calculated from these data was 0.12 pCi/cm^3 .

We have, as in Case 1, assumed a rate of .1 million ft^3/day of dry CO_2 -free gas, or $3.65 \times 10^8 \text{ ft}^3/\text{yr}$. The total quantity of tritium assumed to be removed from the well is 0.35 Ci or 100% of the calculated

initial quantity, and the average tritium concentration in completely dry gas for the year is 0.036 pCi/cm^3 . This is 0.034% of the Case 1 first-year production average (107 pCi/cm^3). If the gas is assumed to contain 5 lb of water in 10^6 ft^3 of gas, with $4.0 \times 10^5 \text{ pCi HTO/cm}^3$ of water, the average total tritium concentration is 0.07 pCi/cm^3 .

Because we assume complete removal of all tritium in the cavity during a one-year period, continuing increase in cavity gas pressure will not affect the assumed annual average concentration.

DOSE CALCULATIONS FOR CASE 1

Exposure from Release of Tritiated Water Vapor to the Atmosphere

Atmospheric dispersion data in Tables III and IV combined with gas system dilution factors and annual average tritium concentrations calculated for Case 1, assuming an initial concentration of 175 pCi/cm^3 , permit dose calculations to be made for this hypothetical gas-use situation. Potential doses from ground-level sources of Rulison gas combustion products are given in Table VII. In earlier calculations of these doses¹⁶ we used the factor given by Cowser¹⁷ for inhalation and skin absorption of tritium during a 168-hr week exposure:

$$\mu\text{Ci}^3\text{H/cm}^3 \times 3.6 \times 10^4 = \text{rems/week.}$$

This factor estimates dose to "standard man", a typical or average adult.¹⁸ It was calculated using 1.7 as the quality factor (QF) for tritium and 12 days for the biological half-life of HTO in man.

The ICRP has recommended¹⁹ that QF be taken as 1 for radiation of this type and that 10 days be used for the biological half-life.²⁰

Table VII. Case 1 Yearly Doses from Ground-Level Release of Rulison Gas Combustion Products^a

Community	Calculated Doses (mrem/year)		
	1972	1973	1974
Aspen	0.29	0.06	0.01
Basalt	0.10	0.02	<0.01
Carbondale	0.18	0.04	<0.01
Cedaredge	0.03	<0.01	0
Collbran	0	0	0
Delta	0.09	<0.01	0
Eagle	0.04	0.01	<0.01
Eckert	0.02	<0.01	0
Glenwood Springs	0.13	0.03	<0.01
Gypsum	0.01	<0.01	<0.01
Grand Valley	0.13		
Hotchkiss	0.04	<0.01	0
Montrose	0	0	0
Olathe	0	0	0
Paonia	0.04	<0.01	0
Rifle	0.33		
Snowmass	0.13	0.03	<0.01

^aAssumes 1 million ft³/day of dry, CO₂-free Rulison gas containing initially 339 pCi/cm³ total tritium concentration completely mixed with inflowing gas as shown in Figs. 2 and 3.

Also Osborne²¹ has shown that skin intake of HTO is only five-sevenths of that received by inhalation instead of 100% as assumed by the ICRP. Osborne concluded²² that the concentration of HTO in air required to give 170 mrem/year is twice that calculated with the ICRP-2 assumptions.¹⁷ We believe that Osborne's conclusion is correct, and the estimated tritium doses reported here are calculated on the basis of the newer ICRP recommendations and Osborne's skin absorption data.

For the first year of production, the average concentration was calculated to be 107 pCi/cm³ or 1.07×10^{-4} μ Ci/cm³. The factor for yearly whole body dose in millirems was calculated as:

$$\frac{\text{cm}^3 \text{ Rulison gas}}{\text{cubic meter}} \times 0.10 = \text{mrem/year.}$$

Similarly, the dose factor for the second year is:

$$\frac{\text{cm}^3 \text{ Rulison gas}}{\text{cubic meter}} \times 0.013 = \text{mrem/yr}$$

and for the third year:

$$\frac{\text{cm}^3 \text{ Rulison gas}}{\text{cubic meter}} \times 0.0016 = \text{mrem/year.}$$

As shown in Table VII the potential whole body tritium doses from ground-level sources in all these communities are very small, even for the Case 1 first year.

Age Dependent and Man - Rem Tritium Doses

Rohwer and Kaye²³ calculated the inhalation dose for various age groups resulting from exposures to 1 pCi of HTO per cubic centimeter of air. Their values, together with age-distribution data, were used

to calculate doses from tritium dispersed in the atmosphere at Aspen, Colorado (Table VIII). The annual inhalation dose for each age group, multiplied by the number in the group, gave a total town dose of 0.39 man-rem. The average inhalation dose of 0.16 mrem, with the addition of 0.11 mrem to take skin absorption into account, gives a total annual dose of 0.27 mrem per person. This value compares well with the value of 0.29 mrem for the "standard man" calculations shown in Table VII. This agreement indicates that use of the "standard man" assumptions for dose calculations in this paper does not introduce a significant error in the calculation of total population exposure (man-rem) to airborne HTO.

The total man-rem values for all the communities potentially receiving Rulison gas through the RMNGC system (total population about 22,000) ranged from 2.1 for Case 1, first year, to 0.0015 for Case 2.

Krypton-85 Doses

We did not consider ^{85}Kr doses in detail, but these can be calculated from the tritium doses. Hendrickson²⁴ has reported data indicating that immersion in air containing $1 \mu\text{Ci}/\text{cm}^3$ of ^{85}Kr produces a whole body dose of 467 rads/week, while data from Dunster and Warner²⁵ gives a value of 267 rads/week. If these values are averaged, we obtain a value of 367 rads/week compared with 1.8×10^4 rads/week for immersion and skin absorption in air containing $1 \mu\text{Ci}/\text{cm}^3$ of HTO. If the concentration of ^{85}Kr in Rulison gas is 86% of the tritium concentration, we obtain a factor of $\frac{0.86 \times 367}{1.8 \times 10^4} = 1.75 \times 10^{-2}$. This means that one can obtain approximate values for the ^{85}Kr whole body dose by dividing the values

**Table VIII. Age-Dependent Annual Dose Calculated
for Tritium Dispersed in the Atmosphere at Ground
Level in Aspen, Colorado**

Age Group	Inhalation Dose (mrem)	Number in Group	Dose x Number
<u>Female</u>			
<5	0.14	92	12.9
5-9	0.14	102	14.3
10-14	0.15	104	15.6
15-19	0.13	94	12.2
>19	0.11	786	125.8
<u>Male</u>			
<5	0.14	101	14.1
5-9	0.14	115	16.1
9-14	0.14	104	14.6
15-19	0.15	101	15.2
>19	0.18	805	144.9
Total		2404	385.7

in Table VII by 60. The maximum whole body dose (in Aspen) due to ^{85}Kr would be about 0.006 mrem or 6 microrems/year.

Maximum Doses from Industrial Sources

Maximum doses for hypothetical industrial (point) sources can be calculated from the maximum ground-level concentrations under the plumes (see Fig. 4) together with the appropriate dilution factors for the communities involved. The results (Table IX) show that the potential maximum doses from these sources are smaller than from ground level sources. These maximum doses to individuals are actually conservative values because variations in the location of the narrow plume due to changes in wind direction would undoubtedly reduce the actual exposure of the town inhabitants to these sources.

Average Doses in Valleys

Potential doses to people living within the bounds of the valleys in which the various communities are located are given in Table X. These doses were calculated from the data in Table V which are based on the valley-box model previously described. These doses are orders of magnitude lower than the doses from ground-level sources in the towns because the tritium from gas burned in the towns is assumed to be uniformly dispersed in a much larger area. The resulting doses are so small that they are best expressed in microrems (10^{-6} rems) as they are in Table X.

Table IX. Case 1 First-Year Maximum Whole Body Doses from Industrial Sources of Rulison Gas Combustion Products

Community	Maximum Day Concentration (cm³/m³)^a	Maximum Day Dose (mrem/year)	Maximum Night Concentration (cm³/m³)^a	Maximum Night Dose (mrem/year)	Average Maximum Yearly Dose (mrem)
Rifle	6.9	0.12	12.7 ^b	0.22 ^b	0.12
Delta	10	0.04	14	0.06	0.05

^aSee Tables I and II for system dilutions factors and footnote, Table III.

^bPlant stack is located at southwest corner of Rifle. The night wind direction is away from the town so the maximum night exposure to plant combustion products will be experienced by ranchers or other suburbanites living west of the town.

**Table X. First-Year Case 1 Average Dose from Tritium
Dispersed in the Atmosphere of Valleys**

Community	24-hr Conc. (cm^3/m^3) ^a	Fraction of Rulison Gas	One-Year Dose (microrems)
Aspen	0.78	0.10	8
Basalt	0.13	0.11	2
Carbondale	0.21	0.10	2
Cedaredge	0.013	0.09	<1
Collbran	0.05	0	0
Delta	0.30	0.09	3
Eagle	0.17	0.10	2
Eckert	0.008	0.11	<1
Glenwood Springs	1.45	0.11	16
Gypsum	0.06	0.08	<1
Grand Valley	0.013	0.686	1
Hotchkiss	0.013	0.08	<1
Montrose	0.14	0	0
Olathe	0.013	0	0
Paonia	0.026	0.11	<1
Rifle	0.73	0.368	27
Snowmass	0.52	0.10	10

^aSee footnote, Table III.

Home Exposure Doses

In the Gasbuggy studies,¹⁻⁴ it was known that some houses were heated with unvented heaters, and we concluded that inhabitants of such homes constituted the critical population group (the group potentially receiving the highest radiation exposure). In the relatively mild climate of Los Angeles and San Francisco, the two metropolitan areas considered,¹⁻⁴ there was the possibility that a significant number of people could be exposed to radionuclides in natural gas combustion products in this manner, although it is estimated that less than 10% of homes are likely to be heated in this way.

In Colorado, the climate is much colder (>6000 degree-days of heating per year as compared with 1700 for Los Angeles and 2950 for San Francisco) so the use of unvented heaters in Colorado would produce larger quantities of undesirable gas combustion products. More importantly, however, the use of unvented space heaters is illegal in Colorado and the gas companies will not provide service to a home until their inspection shows that the home heating system meets the legal requirements. Therefore, it would be unrealistic to assume unvented heating for homes hypothetically receiving Rulison gas. We also consider it very unlikely that gas hot-water heaters or gas clothes dryers would be unvented. Gas ranges and gas refrigerators may be assumed to be unvented, but the latter appliance is not commonly used.

The home occupancy factor, the fraction of the time a home is occupied, must be considered in estimating doses to occupants of a home having unvented natural-gas appliances used continuously. The person-hours of home occupancy shown in Table XI were based on 1968 census figures²⁶ and the following assumptions:

Table XI. Average Person-Hours per Day Spent in the Home

Family Member	Average Number Per Family	Assumed Hours Per Day	Average Person-Hours Per Day
Preschool children (<5 years)	0.37	21	7.8
School children (5 to 17 years)	1.03	15	15.5
Retired people (>65 years)	0.38	21	8.0
Housewives	0.53	21	11.1
Working adults	1.35	14	18.9
Total	3.66		61.3

Average time at home for housewives, preschool children, and retired men: 21 hr/day.

Average time at home for working wives and husbands: 14 hr/day.

Average time at home for school children: 15 hr/day.

The home occupancy factor is:

$$\frac{61.3 \text{ person-hr/day}}{24 \text{ hr/day} \times 3.66 \text{ persons/family}} = 0.70$$

There appears to be no way to verify the assumed hours per day spent at home by the various family members. These estimates are probably higher than the true annual average values for most parts of the country, so calculations based on this home occupancy factor may over estimate the potential dose.

The kitchen range is used intermittently during the day. The equation

$$C = \frac{R(1-e^{-kt})}{k} + C_0 e^{-kt}$$

is used to calculate the tritium content of the home, during periods when the range is in use and when it is not in use. Analysis shows that the tritium content increases during the period that the range is in use and then decreases at an exponential rate.

The average tritium content of the home during each period is calculated from the equation

$$C(\text{average pCi/cm}^3) = \frac{\int_0^t \left(\frac{R(1-e^{-kt})}{k} + C_0 e^{-kt} \right) dt}{t}$$

where

C_0 = initial quantity of tritium in home (picocuries)

C = tritium in home at time t (picocuries)

R = rate at which tritium is released into the home through the kitchen range (picocuries/sec)

k = ventilation constant (1/sec)

t = time from beginning of period (sec)

The average tritium content can be converted to concentration by use of the home volume. The average concentration calculated with the above equation is lower than the value calculated in earlier estimates¹⁶ of doses.

Data on nonheating use of natural gas in the United States²⁷ show an average daily consumption of 27 ft³ for ranges. We assume that the range is in use in a 1000-ft² house with an 8-ft ceiling. If there is one air change per hour, $k = 2.778 \times 10^{-4}$ (1/sec). Some modern well constructed homes are reported²⁸ to have air change rates as low as 0.5/hr; but, according to the ASHRAE Handbook,²⁹ the average rate is probably near or higher than the rate we have assumed. If the Case 1 first-year tritium concentration and a gas system dilution factor of 10 (RMNGC) are used, the gas burned in the range will contain 10.7 pCi/cm³ of tritium.

It can be demonstrated from the above integral equation that, for air change rates at least as low as 0.5/hr, the average tritium content in a home over a 24-hr period is independent of the operating schedule of the kitchen range. The average tritium content depends only on the quantity of tritium emitted by the range during the day and on the air change rate. Individual doses depend only on the average tritium

concentration and the home occupancy factor. The average tritium content of the home during the entire 24-hr period is 3.20×10^5 pCi. The volume of the house is 2.26×10^8 cm³, so the average tritium concentration is 1.42×10^{-3} pCi/cm³. This concentration, when multiplied by 940, a factor derived from recent ICRP assumptions previously discussed in this paper, results in a potential annual whole body dose of 1.3 mrem from inhalation and skin absorption of tritium in the combustion products from a kitchen range. A home occupancy factor of 1.0 is used in calculating doses resulting from the use of the range, because we assume that all of the family is present at meal times when most of this type of exposure would be received.

The gas consumption of gas refrigerators in the few homes that have this appliance is presumably uniform throughout the day, averaging 37.24 ft³/day.²⁷ The tritium content in a home from this source builds up to 4.4×10^5 pCi under the conditions assumed in the range calculations above if we let $t \rightarrow \infty$, in which case $C \rightarrow R/k$ as a limiting value. The steady state tritium concentration in the home is, therefore,

$$4.4 \times 10^5 / 2.26 \times 10^8 = 1.95 \times 10^{-3} \text{ pCi/cm}^3.$$

Multiplying by the factor 940 and by the home occupancy factor 0.7 results in a potential annual whole body dose from inhalation and skin absorption of 1.3 mrem from a gas refrigerator. Thus, the most highly exposed population group in communities served by RMNG, occupants of homes having unvented gas refrigerators and ranges (estimated to represent less than 2% of the total population) would receive an estimated annual whole body dose of 2.6 mrem.

Potential annual whole body doses from gas refrigerators in Grand Valley and Rifle, calculated as shown above, are 9 and 4.5 mrem, respectively. The corresponding range doses are 9 and 5 mrem/year, giving a total potential dose of 18 mrem/year in Grand Valley and, 9.5 mrem/year in Rifle.

— The Case 1 first-year tritium concentration we have considered here is much higher than may be expected in future nuclearly stimulated gas wells using explosives specially designed for gas stimulation. The second-year Case 1 doses would be lower than those in the first year by a factor of 0.13. The third-year doses would be lower by a factor of 0.016. Furthermore, the people constituting the most highly exposed population group that we have considered in this study, inhabitants of Grand Valley (population, 270) homes having both unvented gas ranges and unvented gas refrigerators, are estimated to include fewer than five people.

Although we have eliminated general household heating from consideration, it seems worthwhile to consider the possible consequences of occasional use of unvented heaters to provide supplemental heat in a single room as, for example, a basement workroom. If we assume that a 6000 BTU/h heater is used in a small room ($8 \text{ ft} \times 10 \text{ ft} \times 8 \text{ ft} = 640 \text{ ft}^3$), the gas input at heater capacity would be about $6 \text{ ft}^3/\text{h}$. The hypothetical average 1972 dilution factor for Rulison gas in the RMNGC system is 10, and we will use the 1972 average tritium concentration of $1.07 \times 10^{-4} \text{ } \mu\text{Ci}/\text{cm}^3$. The input rate of Rulison gas would be $0.6 \text{ ft}^3/\text{h}$. We assume one air change per hour and that the heater is turned on at the start of a 1-h occupancy period. The potential annual dose for 100% occupancy is calculated to be 33 mrem, based on an average tritium

concentration of 0.035 pCi/cm^3 for the assumed 1-h occupancy period and no exposure to tritium from the heater except this room. If we assume that a person spends 2% of his time per year in the heated workroom, which is equivalent to about 1 h/day for half the year, the potential annual exposure is 0.7 mrem. Potential doses by this exposure mode could be somewhat higher in Grand Valley and Rifle (4.5 and 2.5 mrem/year, respectively) where the system dilution factor for Rulison gas is assumed to be lower than in communities served by RMNGC.

DOSE CALCULATIONS FOR CASE 2

Earlier in this paper we gave an average value of 0.07 pCi/cm^3 for the estimated total concentration of tritium in post-flaring Rulison gas, assuming that all tritium presently in the cavity had been removed by a gas flow of 1 million ft^3/day of dry, CO_2 -free gas for one year with a normal water content of "dry" gas of $5 \text{ lb}/10^6 \text{ ft}^3$. Since this value is 0.07% of the hypothetical first-year production average concentration, we can convert the Case 1 first-year dose values reported in the previous section to post-flaring doses by multiplying by 0.0007. Applying this factor to the average whole body dose to members of the most highly exposed population group (18 mrem/year for home exposure in Grand Valley), we calculate a post-flaring dose of about 0.013 mrem/year. This dose, which represents the highest average value for a population group (less than five people) that might be expected if gas presently in the Rulison well were fed into the RMNGC or WSGC distribution systems over a period of one year, is so small that it does not seem worthwhile to apply the factor to all the other potential doses calculated in the previous section. For the RMNGC system, the corresponding dose

is 0.002 mrem/year for home exposure alone. Adding the highest ground-level dose from Table VII (0.0002 mrem) gives a total dose of 0.0002 mrem/year.

AVERAGE DOSE

Average doses to people potentially exposed to radionuclides from the Rulison well can be estimated, based on the above calculations and the fraction of homes having unvented appliances. The value for gas ranges is estimated to be 40% for RMNGC and 28% for WSGC. The average total dose for people supplied by RMNGC and living in one of the communities listed in Table I, excluding those that could not receive Rulison gas, is 1.3×0.4 (range) + 1.3×0.02 (refrigerator) + 0.09×1.0 (ground-level sources) = 0.6 mrem/year for the first year, Case 1, situation. This corresponds to a total population dose of 14 man-rem to RMNGC customers. In communities having gas-consuming plants, the average industrial source dose, which we have not estimated, must be added. The corresponding Case 2 average total dose would be 0.0004 mrem/year or 0.4 microrem/year. It appears that most of the average dose is contributed by the kitchen range.

These dose levels can be placed in perspective by comparison with variations in cosmic ray doses with altitude. People living at an altitude of 10,000 ft throughout the year would receive a dose of about 100 millirads from this source compared with about 35 millirads at sea level.³⁰ This means that 1 millirad (which is approximately equal to 1 mrem for whole body doses) corresponds to a 150-ft change in altitude and 1 microrad to 0.15 ft or about 2 in.

It was shown earlier that the total dose to the RMNGC population (22,000) was 14 man-rem. If the same gas were supplied to a large number of homes, the resulting population dose would be 640 man-rem per million people.

The average concentration of tritium in the gas assumed in making the above estimate of total population dose is 10.7 pCi/cm^3 . This compares with 11 (Green River) or $<8 \text{ pCi/cm}^3$ (Piceance Basin) postulated by Rubin et al.³¹ for the average tritium concentration in the gas from future nuclearly stimulated well fields. Therefore, doses estimated in our hypothetical Case 1, first year RMNGC situation, are as high or higher than may be expected for large-scale well field developments using nuclear explosives, assuming that no uncontaminated gas is available from other fields for dilution purposes.

It seems unlikely that any large city would receive its entire gas supply from wells created by use of nuclear explosives; but, if this should be the case, there are several ways of reducing population doses that seem worthy of consideration. One way is to provide venting for all gas appliances or, if this should prove impractical, to require that they be replaced by electrical appliances. Another possibility would be to use gas from nuclearly stimulated gas fields exclusively in plants, such as gas-fired electricity generating plants, having tall stacks for discharge of gas combustion products.

We recognize that no standards for use of gas containing radio-nuclides, including allowable man-rem of population exposure, have been established. A cost-benefit analysis may favor use of the gas from nuclearly stimulated wells in homes in spite of the population dose.

CONCLUSIONS

Studies of doses received from hypothetical uses of Rulison⁹ have confirmed the finding of the Gasbuggy investigations that unvented home usage of natural gas containing radionuclides is the critical exposure pathway. The kitchen range is the principal source of unvented gas combustion products in Western Colorado homes, and the critical population group would be occupants of the small number of homes having both gas ranges and gas refrigerators. The calculation for this hypothetical situation in Grand Valley, the community which could receive the highest fraction of Rulison gas, gave an estimated annual tritium whole body dose equivalent to 11% of the Federal Radiation Council's Protection Guide of 170 mrem/year to the small population group (<5 people) potentially exposed in this manner. An average value of 0.6 mrem/year is estimated for gas usage by the larger population group served by RMNGC. Whole body doses from ⁸⁵Kr in Rulison gas are estimated to be only about 2% of the tritium whole body doses.

The studies reported here have principally considered tritium doses from inhalation and skin absorption. There is no evidence at present that other exposure modes would provide doses in excess of those received through direct exposure, but the possibility cannot be excluded until all possible modes have been examined.

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