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THEORETICAL EVALUATION OF CONSUMER PRODUCTS FROM PROJECT GASBUGGY.
FINAL REPORT, PHASE I: IMPACT OF HYPOTHETICAL RELEASES
OF CONTAMINATED GAS IN THE SAN JUAN BASIN

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ABSTRACT

The first phase of a theoretical evaluation of potential radiation exposures from Project Gasbuggy, dealing with the hypothetical domestic and commercial utilization of contaminated natural gas within the San Juan Basin, has been completed, and the results are reported in detail. Although none of the gas from the Gasbuggy well, the first of a planned series of nuclearly stimulated natural gas wells, has been introduced into the gas gathering and distribution system of the El Paso Natural Gas Company, the analysis was based on this system and on data from the production testing of the Gasbuggy well for maximum realism.

The only long-lived radionuclides found in the Gasbuggy gas were ^{85}Kr , ^3H (tritium), and low concentrations of ^{14}C . The tritium, which will be present in natural gas combustion products as HTO, has the greater radiological impact and is considered in more detail. The concentration of these species in the cavity gas decreased as gas removed from the well was replaced by uncontaminated formation gas.

Various pathways by which individuals living within the San Juan Basin could hypothetically be exposed to radioactivity from contaminated gas are considered, and potential doses are calculated. We conclude that of those pathways considered, the critical exposure pathway would be domestic consumption of gas for cooking, and the critical population group would be composed of housewives in the Blanco camp adjacent to the Blanco process plant. Calculated doses are much lower than dose limits set by national and international authorities.

1. INTRODUCTION

Project Gasbuggy was the first of a planned series of experiments to explore the feasibility of stimulating natural gas production by underground nuclear explosions. A preshot summary report¹ on the project was issued. This project was a joint effort under the U.S. Atomic Energy Commission's Plowshare Program. Participants were the El Paso Natural Gas Company (EPNG), the Bureau of Mines of the U.S. Department of the Interior, and the Atomic Energy Commission, with technical assistance provided by Lawrence Radiation Laboratory. The objectives of the experiment were defined² as:

1. to measure the changes in the deliverability and ultimate recovery of the gas and, insofar as possible, to identify the changes responsible,
2. to measure any radioactivity of the gas, to study the thermodynamics and chemical reactions of the mixture of gaseous products and methane, and to evaluate any necessary control measures,
3. to measure and to evaluate the generation and propagation of seismic energy within the San Juan

Basin as part of a continuing study of ground motion and its effect on structures.

A nominal 26-kiloton nuclear explosive was detonated on December 10, 1967, near Farmington, New Mexico, in the northwest corner of the state, at a depth of 4240 ft. The detonation took place in the Lewis shale about 50 ft below its contact with the Pictured Cliffs gas-bearing formation. Postshot geologic exploration showed that the explosion produced a rubble-filled chimney about 80 ft in radius and 333 ft high. Evidence of significant increases in porosity in the lower interval of the Pictured Cliffs formation was found. This region was intensely fractured to at least 375 ft from the shot, while the Lewis formation was intensely fractured to at least 400 ft. The deformational effects of the experiment were considered to be at least as encouraging for further development of nuclear stimulation as the preshot expectations.²

In the case of nuclear gas-well stimulation, the possibility exists for radiation exposure of people through use of the cavity gas or its by-products. It will be necessary to accurately assess the extent of such potential radiation exposures in order to assure that the consuming public is not unduly exposed.

The Health Physics Division of Oak Ridge National Laboratory has assembled mathematical models for estimating radiation dose into computer codes, both for

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internal and external exposures. This capability led to a request by the Division of Peaceful Nuclear Explosives of the U.S. Atomic Energy Commission that the Division participate in an evaluation of the potential exposures resulting from the use of natural gas or its by-products which contain man-made radionuclides.

This study has been divided into three phases. Phase I, the subject of this report, is a consideration of the radiological impact on people living within the San Juan Basin as a result of *hypothetical* input of gas from the Gasbuggy well into the gas collecting network of the San Juan Division of EPNG. The word *hypothetical* is emphasized because the Gasbuggy well has never been connected to the gas collection system. As an additional precaution, wells in the near vicinity of the Gasbuggy well were disconnected from the collection system. These surrounding wells were recently put back into production, but there is no expectation, at present, that Gasbuggy gas will be introduced into the system. Phase I of the study was divided into various tasks, as indicated by the several divisions of this report. Potential population and employee exposures within the San Juan Basin were selected for initial study, because the possible dilution of Gasbuggy gas would be low in this region and potential radiation exposures would probably be higher than for any other population groups.

The scope of the study is broadened in phase II to include hypothetical utilization of Gasbuggy gas and its by-products by populations outside the San Juan Basin. We assume that the gas would move through the Blanco plant and be diluted with gas produced from the Permian Basin before entering market areas to the southwest or that it would move northward through the Ignacio plant for northwest distribution.

In phase III we will consider the possibility of nuclear stimulation of an entire reservoir. Temporal sequencing of detonations and possible modifications of nuclearly stimulated wells and the collection, processing, and distribution systems will be studied. Consideration will also be given to alternative uses of the initial production of nuclear-cavity gas if it proves necessary to reduce population exposures that might accrue from its use. Some results from these studies, principally phase I results, have been reported in a series of progress reports.³⁻⁷

2. DESCRIPTION OF THE GASBUGGY SOURCE

In this section we consider the data that have been obtained on the chemical and radiochemical composition of gas from the Gasbuggy well as a function of time and gas flow. Since little change in the chemical

and radiochemical quality of the gas occurred after the first month of the initial shut-in period, we have emphasized the effects of gas flow rather than time in our presentation of the data. This information was supplied by the Gas Quality Investigation Program at Lawrence Radiation Laboratory (LRL) and by El Paso Natural Gas Company (EPNG). Analytical data have been reported in a series of LRL reports⁸⁻¹⁰ that also contain gas flow data. These data do not necessarily show representative behavior of future nuclearly stimulated wells; but, until similar data from the Rulison well become available, no comparable information exists.

A postshot cavity gas volume of $1.28 \times 10^8 \text{ ft}^3$ (NTP) was calculated, based on the estimated production of ^{85}Kr (350 Ci) and the measured concentration of ^{85}Kr during the initial 200-day shut-in period ($2.8 \mu\text{Ci}/\text{ft}^3$). This calculation assumed uniform mixing of ^{85}Kr with the cavity gas. The constancy of the measurements during this period gives no cause to doubt the validity of this assumption, and the reported¹¹ measurement of the yield of the nuclear explosion (29 ± 3 kilotons) indicates that the uncertainty in the ^{85}Kr figure is rather small.

Approximate gas flow rates calculated from data in ref. 8 are plotted in Fig. 1 as a function of cumulative gas flow. Also shown at the top of this figure are dates in order to establish the time scale of the experiment and because samples are identified in Appendix A by sampling date. These flow rates represent the average rate between each point on the scale and the preceding point.

Chemical Composition

Data on chemical composition of gas removed from the Gasbuggy cavity were obtained and reported by Smith⁸ and are discussed in greater detail in Appendix A. Analysis of the data indicates that when only hydrocarbon constituents are considered, the fractions of methane and ethane remain relatively constant as chimney gas is replaced by formation gas at values of $86 \pm 2\%$ of the hydrocarbon for methane and $8.5 \pm 0.7\%$ for ethane. However, it appears that the formation gas has a higher propane content than the gas originally in the cavity. The propane in samples taken on or before July 10, 1968, averaged 2.5% of the hydrocarbon content, while those taken after March 5, 1969, have all been in the range 4.5 to 4.6%.

The nonhydrocarbon content of the formation gas prior to the detonation consisted of small concentrations of nitrogen (N_2) and carbon dioxide (CO_2) (Table 1).¹² Immediately after the shot, the concentrations of carbon monoxide (CO) and hydrogen (H_2) were quite

Fig. 1. Gas flow rates and bottom-hole pressure as a function of cumulative gas production from GB-ER.

high, but they decreased and the CO_2 concentration increased until the composition given in Table 1 was attained at the beginning of flaring.

Taylor et al.¹³ hypothesize that the H_2 and CO found in the Gasbuggy chimney came from the oxidation of free carbon in Lewis shale, which contains 0.5 wt % of this element. From the amount of H_2 and CO found in chimney gas, they calculated that 12.2×10^6 moles (about 146 tons) of free carbon was burned. They drew the following tentative conclusions:

1. About 1100 tons of shale per kiloton was heated hot enough so that the free carbon in it reacted with CO_2 and H_2O .
2. About 500 tons of shale per kiloton was heated above 1600°K , hot enough to melt and release all of its CO_2 .
3. About 1500 tons of shale per kiloton was heated above 800°K , but less than 1600°K , which is hot

Table 1. Composition of gas in the Gasbuggy well

Constituent	Composition (%)	
	Preshot formation gas	In cavity at beginning of flaring
CO_2	0.28	36
CO	<0.01	4
H_2	<0.01	17
CH_4	84.9	37
C_2H_6	7.4	3.6
C_3H_8	4.1	1.1
$\text{C}_{>4}\text{H}_x$	2.7	1.0
N_2	0.61	0.65

enough to release CO_2 by the low-temperature decomposition of dolomite.

4. All of the water from at least 2000 tons of shale per kiloton was released.

They also concluded that reactions within the chimney essentially ceased below about 800°K . These conclusions were all based on consideration of the chemical composition of the chimney gas and on the free energy changes as a function of temperature for reactions among C , CO , CO_2 , H_2 , and H_2O .

The rapid increase in CO_2 and the corresponding decrease in CO during the shut-in period were attributed¹⁰ to the water-gas reaction:

The gradual decrease in H_2 concentration was said¹⁰ to be due to the reaction:

Summing these two equations gives:

The slightly increased ethane concentration shown in Table A.1 was said¹⁰ to be possibly due to the reaction:

However, direct reactions of this type as well as reaction (2) are highly unlikely. Taylor et al.¹³ state that they are inclined to believe that most of the CH_4 and C_2H_6 in the chimney came from formation gas

outside the chimney rather than from chemical reactions within the chimney. As flaring proceeded, the concentrations of all nonhydrocarbon species except nitrogen decreased as formation gas replaced the gas originally in the chimney.

Radioactivity

Postshot gas samples have been periodically withdrawn from the Gasbuggy cavity and have been analyzed by Lawrence Radiation Laboratory.⁸⁻¹⁰ It is of interest to note that no ^{131}I was found in the gas and that gamma scans have indicated no gamma emitters other than ^{85}Kr to be present. Traces of ^{37}Ar , ^{39}Ar , and fission product rare gases and low concentrations of ^{14}C (5700-year half-life) were the only radionuclides reported to be found in the gas besides tritium and ^{85}Kr .

A small amount of gas was removed from the well and flared in the early part of 1968, but the major program of production testing and flaring began in late June 1968. Samples at the beginning of production testing showed approximately 707 pCi/cm³ of tritium and 112 pCi/cm³ of ^{85}Kr . The concentrations of tritium and ^{85}Kr in the products removed from the Gasbuggy cavity have been decreasing with time (Fig. 2). The equation of the straight line segments in Fig. 2 is:

$$C_p = C_0 e^{-P/V_0}, \quad (5)$$

where

C_0 = the concentration of the radionuclide in the cavity gas at the time production started, corrected for radioactive decay to the date of the detonation (pCi/cm³),

P = the cumulative production of gas from the wellhead (M²cf) (million cubic feet),

V_0 = the initial volume of gas in the cavity (M²cf), and

C_p = the concentration of the radionuclide in the gas at the wellhead after a cumulative production of P . (C_p is in units of pCi/cm³, corrected for radioactive decay to the day of the detonation.)

When the concentrations are not corrected for radioactive decay, an additional exponential term should be added. The volume of gas in the cavity was assumed to be 128 M²cf (ref. 2), corrected to normal conditions of 1 atm pressure and 65°F. The most notable deviations from the predicted curve occur after the termination of a period of rapid withdrawal of gas from the cavity. During a period of rapid withdrawal, it would be

expected that the formation could not supply gas to the cavity at the rate that it is removed from the wellhead. During such a period, the bottom-hole pressure drops and the concentration of radionuclides in the gas being withdrawn falls at a slow rate. When the cavity is given a chance to recover, the bottom-hole pressure increases and the concentration of radionuclides in the cavity gas drops more rapidly due to mixing with uncontaminated gas from the surrounding formation.

If the concentration history is investigated in more detail, it becomes evident that the concentrations drop below those expected for complete mixing. This suggests that a formation near the top of the cavity is supplying formation gas faster than other strata, thus allowing a blanket of low-activity gas to accumulate at the top of the cavity during shut-ins following periods of rapid production.

As of August 21, 1969, there had been a total of 251 M²cf of gas produced, containing about 2330 Ci of tritium, 360 Ci of ^{85}Kr , and 10 Ci of ^{14}C . The concentrations of these radionuclides had dropped to

Fig. 2. Concentrations of tritium and ^{85}Kr in Gasbuggy gas as a function of the total volume of gas produced. The straight lines represent the predicted concentrations based on complete mixing of 128 M²cf of gas in the chimney up to 210 M²cf production and mixing of 35 M²cf of gas thereafter.

46.1, 8.8, and 0.9 pCi/cm³ respectively. The bottom-hole pressure, which was originally about 64 atm, had dropped to about 18 atm during the final long-term, low-flow-rate testing period. Based on the concentrations of the radionuclides and the bottom-hole pressures, it is estimated that an additional 50 Ci of tritium, 8 Ci of ⁸⁵Kr, and 0.5 Ci of ¹⁴C could be produced from the well.

Upper detection limits for nongaseous radioisotopes. Smith has reported⁹ results of efforts to detect various radioisotopes other than ⁸⁵Kr and ³H that conceivably could be present in Gasbuggy gas. Gas samples taken about one month after the detonation were scanned by use of a 3 × 3 in. NaI crystal, and then the samples were passed through charcoal cartridges presumably fitted with absolute filters. These cartridges were flushed with helium at 100°C for 10 min in order to remove ¹³³Xe and other noble gases prior to gamma scans. None of the radioisotopes sought were found, but the results were used to determine upper detection limits. In Table 2 are given the experimental detection limits plus "probable" limits calculated by assuming that the number of atoms of ¹³¹I present in the gas is equal to or greater than the number of atoms of any of the other nuclides listed.

The failure to find ¹³¹I in Gasbuggy gas appears a little surprising in view of the readiness with which alkyl iodides, such as CH₃¹³¹I, are formed in fission product transport experiments and the ready avail-

ability of hydrocarbons in the gas cavity. Estimates based on the published yield of ⁸⁵Kr suggest that there were a few million curies of ¹³¹I present shortly after the detonation. A decay period of 32 days, the approximate time of the search for nongaseous isotopes, would reduce the ¹³¹I activity to a few hundred thousand curies, equivalent to several nanocuries per cubic centimeter of cavity gas. If only 0.1% of the ¹³¹I present at the time of the detonation had been converted to CH₃¹³¹I, the resulting concentration after the 32-day decay period would have been several picocuries per cubic centimeter, which is well above the reported detection limit for this important fission product. One must assume, therefore, that extremely efficient iodine scavenging conditions existed in the cavity in order to account for the absence of a detectable concentration of ¹³¹I. An alternative explanation that merits examination is whether the analytical technique employed in the search for ¹³¹I can be considered reliable. Two assumptions involved in this technique are subject to question: (1) The charcoal used provides an efficient trap for iodine and (2) flushing the charcoal cartridge with helium at 100°C for 10 min does not remove trapped iodine. Both assumptions seem acceptable for iodine in the form of I₂ but seem questionable for CH₃¹³¹I, and we believe that, because of the reactivity of I₂ and its known high rate of deposition in most environments, if fission product iodine existed in the cavity gas 32 days after the detonation, it would most probably be present as an alkyl iodide which is chemically relatively inactive.

The efficiency of CH₃¹³¹I retention under the conditions used in the Lawrence Radiation Laboratory search can only be established by experiment, but it appears that further examination of the problem is appropriate in order to deal with the questions raised in the above discussion. It does not seem likely that ¹³¹I will pose a serious problem even if alkyl iodides are formed, because it will decay to an insignificant concentration during a shut-in period of several months. It could, however, be a significant factor in the determination of the proper sequence of nuclear well stimulation (phase III studies).

Distribution of Radionuclides among Liquid and Gaseous Components in the Products from the Gasbuggy Well

Data on the activity of distillation fractions from the "drip liquid"* taken from the Gasbuggy well on

Table 2. Probable upper limits for nongaseous radionuclide concentrations in femtocuries^a per standard cubic centimeter of chimney gas at *t*₀

Nuclide	Experimental	Probable ^b
¹²⁷ Sb	2000	80
¹³¹ I	40	40
¹²⁵ Sn	2000	30
^{129m} Te	1	1
¹⁰³ Ru	0.08	0.8
^{125m} Te	0.7	0.6
¹²⁷ Te		0.4
¹²³ Sn	20	0.3
¹⁰⁶ Ru	0.1	0.09
¹²⁵ Sb	0.2	0.03
⁹⁰ Sr	1.4	0.03
¹³⁷ Cs	0.01	0.03

^a10³ fCi = 1 pCi.

^bProbable concentration assumes the number of atoms of a given radionuclide is equal to (or less than) the number of ¹³¹I atoms in the chimney gas at any given time.

*Liquids condensing at the wellhead are called drip liquids.

February 25, 1969, are given in Table 3. These samples were examined in an effort to confirm the assumption that the tritium-to-hydrogen ratio was uniform for all hydrocarbons in the cavity.

Activity levels were calculated for normal paraffin hydrocarbons (C_nH_{2n+2}) using the tritium ratio of methane projected to February 25, 1969, and assuming a uniform tritium ratio for all species. There was an increase in the expected activity of the liquid paraffins of only 12% in going from *n*-pentane (bp about 97°F) to tetradecane (bp 488°F). Calculations for selected paraffin isomers, cycloparaffins, and derivatives suggested that they would contain essentially the same activity as the normal paraffins. Only when aromatic hydrocarbons and their derivatives were considered were significant changes noted. The simplest aromatics, benzene and naphthalene, would contain only 63% of the calculated activity of the *n*-paraffin having the same boiling temperature. The difference decreases with the addition of methyl groups to the simple aromatics.

Calculated activity levels are compared with measured values in Table 3. With the exception of sample No. 1, for which this measured value appears low, very good correlation is seen between the measured values and the predicted values. It appears reasonable to assume that the tritium is uniformly distributed among the hydrocarbons in relation to their hydrogen content.

Realizing that the Gasbuggy liquid samples probably contained many compounds, we selected three for gas chromatography measurements. Sample No. 1, collected from 97 to 219°F, was selected because it

appeared to be low in activity. The gas chromatograph results showed 15 separate peaks, 7 over 5% (Table 4). A mixture of aromatic hydrocarbons with paraffins and naphthalenes constitutes a nonideal mixture, and distillation of such a mixture results in concentration of the aromatics in the distillate at temperatures appreciably below their normal boiling point. Hence, we chose peaks likely to correspond to aromatic compounds. If these selections were correct, we would have expected sample No. 1 to contain 85% of the activity of sample No. 8 rather than 67% as measured. Chromatography results from samples No. 8 and No. 16 are also given in Table 4. These show that even for narrow boiling ranges, many compounds exist in a sample. Of perhaps more significance is the fact that the major constituents appear to be normal paraffins.

The specific activity of tritium in the hydrogen gas dropped rapidly during the first month of the shut-in period; this could be accounted for by the reactions of HT with CO to form hydrocarbons or by isotopic exchange with water in the cavity. There is some evidence in favor of the former reaction, but the latter seems more probable. The constancy of the specific activity after June 29, 1968, confirms the belief that there was no significant amount of hydrogen in the formation gas diffusing into the cavity as gas was withdrawn. The effect of this gas on the specific activity of the hydrocarbons is quite pronounced. It is most marked in the case of propane, where there is a larger difference between the propane content of the formation gas and the concentration in the cavity gas, as compared with methane and ethane.

Calculations of the specific activity of ^{14}C in CO_2 , CO, and CH_4 from available data gave values ranging from 4.2 to 7.2 pCi/cm³ for CO_2 with an average value of 5.5; 0.66 to 1.14, average 0.79, pCi/cm³ for CH_4 ; and 6.0 pCi/cm³ for CO. There did not appear to be any trend in the ^{14}C specific activities.

Composition of pigging liquids hypothetically recovered from the Gasbuggy well. Liquids, including hydrocarbons and water, condense at the wellhead and in the gathering lines from the gas stream. Liquids condensing at the wellhead are called drip liquids.⁶ Those liquids condensing in the gathering lines tend to accumulate at low spots in the gathering lines and must be removed periodically so that they do not impede the flow of gas. Removal is accomplished by sending rubber balls (pigs) through the pipelines and removing them and the liquids at pigging stations. These liquids, called pigging liquids, are stored in tanks and sold to local refineries. The primary difference between drip and pigging liquids is that a smaller percentage of water is collected by

Table 3. Tritium activity in liquid hydrocarbons taken from the Gasbuggy well on February 25, 1969^a

Sample	Boiling Range (°F)	Measured tritium concentration (μCi/ml)	<i>n</i> -Paraffin boiling-point range	Calculated tritium concentration (μCi/ml)
1	97-219	0.094	C ₅ -C ₇	0.129
2	219-275	0.14	C ₈	0.134
3	275-325	0.13	C ₉	0.135
4	325-349	0.153	C ₁₀	0.136
8	390-412	0.14	C ₁₁	0.137
13	412-424	0.145	C ₁₂	0.138
14	424-439	0.135		
15	439-451	0.13		
16	451-459	0.145		
22	469-473	0.14	C ₁₃	0.139

^aFractionated samples were supplied by C. R. Bowman, El Paso Natural Gas Company, El Paso, Tex.

Table 4. Chromatographic analyses of drip liquids from the Gasbuggy well on February 25, 1969^a

	Sample No. 1 (97–210° F cut)	Sample No. 8 (390–412° F cut)	Sample No. 10 (469–473° F cut)
Relative percentage ^{b,c}			
Hexane	4		
Benzene (?)	16		
Heptane	10		
Methylcyclohexane (?)	20		
Toluene (?)	15		
1,3-dimethylcyclohexane (?)	7		
Octane	9		
Ethylbenzene	4		
Xylene	6		
Nonane	1.5		
Undecane		4	
Dodecane		26	3
Tridecane		10	28
Tetradecane		5	22
Pentadecane		1	4
Expected activity level of mixture ($\mu\text{Ci/ml}$)	0.120	0.138	0.139

^aFractionated samples were supplied by C. R. Bowman, El Paso Natural Gas Company, El Paso, Tex.

^bQuestion marks in parentheses denote peaks for which identification is not certain.

^cAdditional intermediate peaks were obtained, so that the summation of relative percentages does not equal 100%.

pigging liquids and no hydrocarbons above hexane are present in significant amounts.

Using data reported by Smith and Momyer,¹⁰ we calculate that the tritium activity in the methane fraction 203 days after the detonation was about 2.5×10^{-5} Ci/mole. Assuming that Gasbuggy gas was admitted to the gathering system at this time and that the tritium ratio was uniform for all the hydrocarbons in the gas, we can calculate the activity to be expected in the Gasbuggy pigging liquid fraction using analyses of the pigging liquids from trunk L and loop A supplied by EPNG.

The data used for this calculation are shown in Table 5. Calculations made excluding methane and ethane, the more volatile fractions, resulted in no significant change in the calculated activity per milliliter. The expected activity does not exceed $0.65 \mu\text{Ci/ml}$. This value can be compared with the measured value of $0.14 \mu\text{Ci/ml}$ in drip-liquid samples 542 days after detonation (see Table 3). The calculated concentrations take no account of the exponential decrease in tritium concentration observed with production from the Gasbuggy well (see Fig. 2).

Water production from Gasbuggy. Power and Bowman¹⁴ examined in detail the available information on water from the Gasbuggy reentry well. They state that during gas production testing the Gasbuggy chimney water production increased from the initial rate of

Table 5. Analysis of pigging liquids

	Trunk L ^a	Loop A ^b
Liquid composition ^c (mole %)		
Methane	11.52	12.71
Ethane	8.30	9.22
Propane	11.64	10.73
<i>i</i> -Butane	4.33	4.37
<i>n</i> -Butane	9.16	9.69
<i>i</i> -Pentane	7.55	6.52
<i>n</i> -Pentane	7.80	6.20
Hexane	39.70	40.56
Calculated density	0.601	0.598
Calculated molecular weight	61.58	61.73
Calculated tritium concentration ($\mu\text{Ci/ml}$) ^d	0.65	0.64

^aSample taken Nov. 20, 1968.

^bSample taken Nov. 19, 1968.

^cAnalysis supplied by C. R. Bowman, El Paso Natural Gas Company.

^dBased on uniform T/H for all hydrocarbons.

4 or 5 barrels per 10^6 scf of gas to 40 or 50 barrels. The volume of water in excess of that present as vapor was found to decrease linearly with down-hole pressure and to increase with gas velocity over the threshold value of 40 fps in $2\frac{7}{8}$ -in.-diam tubing.

Table 6. Tritium content of water from the Gasbuggy well^a

Sample date	Tritium concentration ($\mu\text{Ci/ml}$)
July 7, 1968	1.24
July 29, 1968	1.25
Jan. 17, 1969	0.265
Jan. 31, 1969	0.168
Feb. 18, 1969	0.132
Feb. 27, 1969	0.110
Mar. 10, 1969	0.051
Mar. 17, 1969	0.110
Mar. 27, 1969	0.132
Apr. 2, 1969	0.018

^aWater samples were supplied by C. R. Bowman, El Paso Natural Gas Company.

Chemical analysis of water samples demonstrated conclusively that the influx of water was from the Ojo Alamo aquifer. The volume was estimated to be 125,000 ft³.

Samples of water from the Gasbuggy well were counted for tritium (Table 6). The tritium content of the water remained constant at approximately 1.2 $\mu\text{Ci/cm}^3$ until the middle of January 1969, when a sharp decline in the tritium concentration occurred. From February 1969 to October 1969, the tritium concentration varied from 0.2 $\mu\text{Ci/cm}^3$ to about 0.05 $\mu\text{Ci/cm}^3$.

As Smith⁸ pointed out, the concentrations of tritium in water samples obtained from the well are probably not representative of the water in the chimney, and the specific activity of the water obtained at the wellhead would represent a lower limit of that expected for the chimney water. The drop in tritium concentration can be interpreted as indicating an influx of water into the chimney. The low initial tritium content of the water, together with the previously discussed tritium concentration in the gas phase, accounted for only a small fraction of the total amount of tritium that was known to be present in the cavity.

Data obtained during the last gas withdrawal from the well during the period October 28 to November 14, 1969, indicated that leakage into the well had ceased for reasons that are not known at present.

3. DESCRIPTION OF GAS COLLECTION AND PROCESSING IN THE SAN JUAN DIVISION OF EL PASO NATURAL GAS COMPANY

Gas Collection

The gas collection system in the San Juan Basin is quite complex. There are several cross connections

between the trunks so that looping can occur. The rate and direction of flow are dependent on the pressures at the various line junctions, and these pressures depend, in turn, on the production schedule of individual wells and on the distribution of demand. In order to simplify the problem, we will assume that the cross connections can be neglected (or that they could be closed with no impairment in the balancing of production and demand). A simplified diagram of the system is shown in Fig. 3.

In this hypothetical situation the gas from the Gasbuggy well would enter a trunk line heading toward either the Blanco or the Ignacio processing plant. As this gas moves along the system, it would be diluted by uncontaminated gas from other wells in the basin. Ordinarily, gas wells produce hydrocarbons, both in the liquid and vapor state, and some moisture. Most of the water is removed from drip liquids at the wellhead, generally by absorption into glycol or sometimes by absorption on calcium chloride, and is discharged locally into small seepage-evaporation pits. The chemical composition and tritium content of drip liquids from the Gasbuggy well were presented and discussed in Sect. 2. During transmission of the gas, further condensation of water vapor and higher hydrocarbons (pigging liquids) also occurs (see Sect. 2 and Figs. 4 and 5).

A landowner under lease agreement with El Paso Natural Gas Company (EPNG) may request installation of a "farm tap" on a gas wellhead near his house so that he can obtain gas for domestic use directly from the well. Several farm taps exist in the San Juan Basin, some of which are shown in Fig. 3. These farm taps are isolated from the collection system by means of a one-way valve which prevents backflow of gas from the collection system. Included among these taps into the system are those at the Gobernador camp, which houses families of employees of EPNG, the Gobernador Mission, and the Gobernador School. The community of Dulce also obtains natural gas from the EPNG gathering system. However, the demands of the community are essentially always lower than the production along the spur leading to the town; so it is not likely that gas from the main trunk would flow toward the community.

Gas Processing

Gas entering the system from wells in the vicinity of the Gasbuggy experiment would most probably leave the San Juan Basin through the Blanco processing plant at the southern exit. A second possible but much less likely exit is the Ignacio plant to the north. At the processing plants the gas is dehydrated and processed to

Fig. 3. Simplified schematic of the gas collection system in the San Juan Division of the El Paso Natural Gas Company.

remove propane and higher hydrocarbons from the product gas (Fig. 6). This gas first passes through inlet liquid separators where partial separation of the remaining higher hydrocarbons occurs. More liquids are separated at inlet gas scrubbers. The gas is then compressed from gathering line pressure to slightly above transmission line pressure (Fig. 7). Following this, the gas is cooled and passed through absorbers where the remaining condensables (mostly butane and propane) are sorbed and removed cyclically to collection points (Fig. 8). The processed gas is then dehydrated and discharged into the transmission system.

Power requirements for processing at the processing plant are supplied by utilizing the components of least commercial value, methane and ethane, as fuel. A methane-ethane-enriched fraction for plant fuel results from the separations and treatment process. The higher

hydrocarbons from the Blanco plant, including butanes and propane, amount to about 453,000 gal/day from the reprocessing of 576 M²cf of wet gas per day, based on the 1968 average. The liquids from the Blanco plant are pumped by pipeline to the Wingate plant, where they are mixed with liquids from other sources to give a normal total daily production of about 1.5 million gallons. At the Wingate plant the raw liquids are separated into normal butane, isobutane, propane, and natural gasoline, and these products are distributed nationally. At the Ignacio plant the higher hydrocarbons are separated, and some of the products are marketed locally.

At the Blanco plant the input gas composition is about C₁, 86%; C₂, 7.5%; C₃, 3%; C₄, 1.3%; and C₅₊, 0.6%. (The subscripts refer to the number of carbon atoms in the hydrocarbon chain.) The product gas

Fig. 4. Pigs for removing condensed liquids from gas lines.

Fig. 5. A pigging station for collecting condensed liquids from a gas line.

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Fig. 6. Schematic diagram of the Blanco plant, El Paso Natural Gas Company.

Fig. 7. The compressor plants at Blanco.

Fig. 8. The gasoline process area of the Blanco plant.

entering the transmission line has a chemical composition of about C_1 , 89%; C_2 , 7.1%; C_3 , 2.1%; C_4 , 0.3%; and C_{5+} , 0%. A considerable quantity of C_3 and C_4 is removed, and all of the C_{5+} is removed during processing. The compressors are operated on the output gas to eliminate the possibility of detonation in the cylinder heads which would result if "hotter" gas were used. The electrical power plant is operated by steam-driven generators which are fired by a fuel line having an enriched methane-ethane fraction. Its composition is about C_1 , 56.1%; C_2 , 33.8%; C_3 , 6.8%; C_4 , 1%, and C_{5+} , 0%. The same fuel is used to fire the desiccant dehydrators and the glycol dehydrators. Hydrocarbon residues, including those from the gasoline absorption plant, are flared in a surface pit. These residues have a composition of about C_1 , 2.1%; C_2 , 4.0%; C_3 , 62.8%; C_4 , 26.66%, and C_{5+} , 4.2% and amount to about 1.3 M^2cf per day (Fig. 9). Product gas from the Blanco plant enters pipelines leading to southern California, while that from the Ignacio plant may be transmitted either to the Pacific Northwest or to southern California, depending on demand.

The Aneth and San Juan plants process gas collected from the western part of the basin and do not obtain gas from that part of the field where the Gasbuggy well is located. The Chaco plant cannot process gas from the area of the Gasbuggy well.

Hypothetical Path of Travel of Gasbuggy Gas

Within the San Juan Basin we can describe the most likely path for gas hypothetically produced from the Gasbuggy well, as well as possible alternate routes, with the assumption that average (yearly) flows from other wells remain reasonably constant. Figure 10 shows the gas-gathering system in the Gasbuggy area. The primary routes are shown in detail with feeders from other trunks and loops left out for clarity. Note that the gathering line from the Gasbuggy well is physically cut and welded so that no gas can actually enter the El Paso gathering system from this well.

Natural gas from the Gasbuggy well contains hydrocarbons, both in the liquid and vapor state, and some moisture. The separator collecting the fluids that condense out of the gas at the wellhead due to pressure drop would appear to be the most highly contaminated area. Fortunately, it is probably the most easily controlled both for operating personnel and accidental exposure to others. Based on general gas well operation, as much as 2% of the total tritium activity leaving the well could be collected at this point.

After liquid removal at the wellhead, Gasbuggy gas would hypothetically enter trunk L. Total flow at lateral L-10 in trunk L would be 2.07 M^2cf/day . Lateral L-10 has five gas consumer taps connected which are on

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Fig. 9. The flare pit at Blanco.

Fig. 10. Schematic diagram of the gas gathering system in the Gasbuggy area.

wellheads, separated from the collection system by one-way valves. Under normal conditions, L-10 supplies 1.79 M^2cf/day of gas to trunk L, and no contaminated gas would flow up the lateral. If all the producing wells on lateral L-10 were closed, each thousand feet of line would contain over 10,000 ft^3 of uncontaminated gas available for use before Gasbuggy gas could reach users (calculated for 8-in.-ID line at 30 atm). One can, of course, choose hypothetical circumstances where these users would be supplied gas from the Gasbuggy well, but they appear unlikely.

No alternate paths for the Gasbuggy gas exist until it reaches lateral L-7. Gas added from other connecting laterals would give a total flow in trunk L of 22.2 M^2cf/day .

Normally, 34.3 M^2cf/day enters trunk L from lateral L-7. While it is possible to divert flow at this point into L-7, down L-7 to the junction shown between L-7 and trunk 11S, and north to Ignacio, generally this is not done because of crossover closure. The northern part of

the 11S system is high pressure (450 psi); below the L-7 junction, it is low pressure (250 psi). Gas from the north can never flow south through Chaco. Similarly, gas from the southern low-pressure system can never flow north.

It is very likely that production from lateral L-7 will mix with trunk L production, moving northwest at a total flow rate of 57 M^2cf/day .

If production from trunk L before the trunk 11G crossover to trunk 11S (Fig. 10) is to be processed at Ignacio, it is likely that transfer to trunk 11S will be made here rather than via loop A to the Lajara station and then up trunk 11S. Normal production from wells feeding trunk 11S flows north to Ignacio, and it is part of the Pacific Northwest system. Dilution will occur before reaching Ignacio by trunk 11S regardless of the diversion path; the flow rate at the input to Ignacio is about 174 M^2cf/day .

If Gasbuggy gas were to proceed up trunk L and loop L to trunk A, a total gas flow rate of about 89

M²cf/day will have been achieved at the junction point on trunk A. Further dilution occurs before reaching the Blanco plant.

For our first situation we will assume that all gas produced from the Gasbuggy well will proceed down trunk L to trunk A and by this route to the Blanco plant for processing, the dry gas then entering the main line to Gallup. In the second situation we will assume that 77% of the Gasbuggy gas proceeds by this path to the Blanco plant, with the remaining 23% going to the Ignacio plant; this is the ratio of the average daily amounts of gas processed at these two plants (see Sect. 5).

Gas wells do not flow steadily. They are produced on a pro-rata allowable basis and are switched on and off frequently. We have chosen to use daily flow rates based on yearly average figures. The major uncertainties in these numbers are the feeder or lateral values, since average values of daily gas flow at various points in the system are:

- 2.07 M²cf at lateral L-10,
- 4.8 M²cf after lateral L-10,
- 22 M²cf at lateral L-7,
- 57 M²cf after lateral L-7,
- 89 M²cf at trunk L junction with trunk A,
- 576 M²cf at the input to the Blanco plant,
- 174 M²cf at the input to the Ignacio plant.

Five user taps exist on lateral L-10 and appear to be the only domestic exposure possibilities for Gasbuggy gas with the least degree of dilution, and they are isolated from the gathering system by one-way valves. It is essentially impossible to flow gathering-system gas to these consumers. Trunk M, on which the community of Dulce is located, connects to trunk A as shown in Fig. 3. Sufficient production occurs on trunk M so that Gasbuggy gas would not be transmitted in this direction. Other farm taps are shown in Fig. 3 which could be assumed to be remotely associated with hypothetical gas production from the Gasbuggy well. Most of these taps lie off main gathering trunks on producing laterals; this provides protection in addition to the one-way valves at the wellhead.

The only other disposition of natural gas products from the EPNG system in the San Juan Basin is that used by residents at the Blanco and Ignacio camps.

4. DESCRIPTION OF POPULATION GROUPS IN THE SAN JUAN BASIN

Several different population groups in the San Juan Basin could be exposed by the hypothetical introduction of gas from the Gasbuggy well into the EPNG transmission system. In order to evaluate the impact of hypothetical radiation exposures, it is necessary to consider the numbers and age distribution of these various population groups and to describe the critical pathways leading to their exposure. The population groups of primary interest, because of their location and characteristics, appear to be the employees at the Blanco and Ignacio plants, the families of employees at the Blanco and Ignacio camps, people in the Bloomfield community, and farm families using gas from farm taps. We shall also consider populations downstream from the Bloomfield sewage system and some employees of EPNG who work outside the plants.

The Southwest Radiological Health Laboratory of the U.S. Public Health Service collected information on farm families in the vicinity of the Gasbuggy experiment, including the Gobernador Mission. These data were primarily of interest in evaluating the hazard of escape of activity from the Gasbuggy detonation and are not reproduced here. Information on the populations at the Ignacio and Blanco plants and camps is included in this section.

Population Centers

There are several communities near the San Juan gas production facilities. These include Farmington (population, 23,786), Bloomfield (population, 1292), and Aztec (population, 4137) — all figures from the 1960 census. Of these, Bloomfield, with its northern border only about ½ mile from the Blanco plant, would appear to be of most concern. The largest community, Farmington, is about 11 miles west of Blanco, quite remote as compared with Bloomfield. Aztec is approximately 6 miles north of Blanco. None of these communities use gas supplied by EPNG.

Age distribution data are not readily available for any of these communities, but information on the enrollment in the Bloomfield school district, which includes two grade schools (grades 1 through 6 plus preschool) and one high school (grades 10 through 12), are shown in Table 7. The junior high schoolers (grades 7 through 9) attend a school outside the community. Since the total enrollment in these schools is 1162, not including

junior high students, only 130 less than the 1960 population of Bloomfield, it seems probable that more than half of these students come from the Blanco camp and rural areas.

Company Plants and Camps

There are company-operated camps adjacent to the two processing plants (Blanco and Ignacio) that could process Gasbuggy gas and one camp (Gobernador) that is not near a processing plant but is located approximately 11 miles west of the Gasbuggy site, where gas was flared during testing of the well. Age-distribution data for these three camps, with data on the plants included with those for the adjoining camps, are shown in Table 8.

Inspection of Table 8 shows that the Blanco plant and camp have the largest group of potentially exposed people, and the output of combustion products from this plant is much larger than from Ignacio.

Table 7. Enrollment in Bloomfield municipal schools in March 1969

Grade	Approximate age (years)	Number of students		
		Boys	Girls	Total
Preschool	<5	25	22	47
Prefirst	5	14	8	22
1	6	86	62	148
2	7	72	75	147
3	8	71	67	138
4	9	62	68	130
5	10	45	54	99
6	11	72	65	137
10	15	58	62	120
11	16	52	46	98
12	17	47	34	81

Table 8. Age distribution for El Paso Natural Gas Company camps and plants

Age group (years)	Gobernador camp		Blanco plant and camp		Ignacio plant and camp	
	Male	Female	Male	Female	Male	Female
0-1	2	4	2	2	0	0
1-5	13	10	11	9	0	0
5-10	11	13	29	28	0	1
10-15	3	0	19	13	2	2
15-20	1	4	16	8	1	0
>20	32	28	90 ^a	57	47 ^b	4

^aIncludes 19 employees not living at the camp.

^bIncludes 43 employees not living at the camp.

Farm Families

According to Fig. 3, there are 39 farm taps in the vicinity of the San Juan triangle that lie near the main trunks, including those at the Gobernador camp. Five of these farm families are within 2 to 3 miles of the Blanco plant and might be exposed to contaminated combustion products from the plant. The others are subject only to potential exposure through home use of gas in case of malfunction of the one-way valves through which they are connected to the gas collection system. Because of these one-way valves we have concluded that the probability of exposure of these users would be quite small and they would not constitute a critical population group.

Population and age distribution data for families living on the ranches having farm taps are not available but can be estimated from general population data.

5. DESCRIPTION OF EXPOSURE PATHWAYS AND ESTIMATES OF RADIATION DOSE TO HYPOTHETICALLY EXPOSED POPULATION GROUPS

When radionuclides are introduced into the environment, there may be numerous and complex pathways through which the nuclides may move and ultimately cause radiation exposure to man. Although it is prudent to consider all of the likely pathways of exposure, experience has shown that certain nuclides and certain pathways are much more important than others. These nuclides and pathways have been designated "critical" by the ICRP,¹⁵ although we would be more inclined to consider them as being "important" rather than "critical." After preliminary study indicates which are the important nuclides and pathways, it is recommended that the major effort be devoted to assessing the radiation exposures resulting from these. This does not necessarily mean that other nuclides and pathways can be neglected, only that the major effort should be directed at those that could potentially result in the greatest radiation exposures.

Unlike the group of radiation workers, which constitutes a reasonably homogeneous group of adults, the general public is composed of groups which vary widely in their characteristics, such as habits, location, age, etc. Because of this, certain groups within the population will receive a higher radiation exposure than other groups or individuals in the population. Such groups are termed "critical population groups" by the ICRP¹⁵ and require separate consideration. Of special concern is the possible radiation exposure to children, and it is recommended that specific data for children be used in

cases where the radiation dose to children may be higher than that to other members of an exposed group. Several population groups that might be exposed by the hypothetical use of Gasbuggy gas were described in Sect. 4.

The critical group should represent a small, rather homogeneous group receiving, or potentially receiving, the highest dose in a given situation. When the critical group has been identified, a representative sample from the group should be considered for more detailed assessment of actual or potential radiation exposure. In assessing such a sample the ICRP's *annual dose limits* for members of the public should be applied.¹⁶ In some cases, when the potential dose to the population will undoubtedly be very small, it may not be necessary to clearly identify the critical group. In this situation it may suffice to postulate a hypothetical group of extreme characteristics that would obtain an upper limit to the dose that any real critical group could possibly receive.

Important Radionuclides

Tritium and ^{85}Kr are the radionuclides of major concern in the Gasbuggy gas. Although there is some ^{14}C present in the gas, it has primarily existed as CO_2 . The CO_2 would have to be removed before the gas could be marketed, and this would result in a reduction of the ^{14}C content in product gas by about a factor of 2 to 3. Krypton is not retained to any significant extent by the body, and the primary mode of exposure is from immersion in ^{85}Kr -contaminated air.¹⁷ The dose to the whole body or to the gonads from immersion in a cloud of ^{85}Kr -contaminated air is estimated to be only about 1% of the dose.^{18,19} Note that the skin dose is also lower than the whole-body dose calculated at the skin surface.

When tritium enters the body in the form of HTO, the body-water pool is assumed to be the critical organ with respect to somatic doses. The method used to estimate the dose to the body-water pool resulting from inhalation of HTO has been discussed previously.²⁰ Age-dependent variation of the dose commitment to the body-water pool per day of intake resulting from inhalation of air containing 1 pCi of HTO per cubic centimeter is shown in Fig. 11. It should be pointed out that during the inhalation exposure, HTO would also be entering the body at about half this rate due to absorption through the skin.²¹ Vennart²² has estimated that the contribution to the whole-body dose from those components having biological half-lives in excess of the normal 12-day half-life of body water

Fig. 11. Age-dependent variation of dose commitment to the body water per day of intake resulting from inhalation of air containing 1 pCi of HTO per cubic centimeter.

would amount to about 8%. He also cites evidence that suggests a lowering of the quality factor from 1.7 to 1.0. These factors were used in our estimates of the potential whole-body dose from hypothetical exposure to tritium.

Important Exposure Pathways

Human exposure to methane would be quite limited, and it is presumed that tritiated methane would behave much like tritiated hydrogen gas and would not be retained to any significant extent by body water. Thus the most important radiation exposures from use of natural gas produced from nuclearly stimulated wells are likely to occur after combustion of gas to form carbon dioxide and water vapor. This mode of exposure is especially important for members of the public, since more than 98% of the total production of natural gas and its associated liquid hydrocarbons is consumed as fuel. The most direct modes of exposure are immersion,

inhalation, and absorption through the skin. Only these modes of exposure have been considered in this preliminary analysis. Experimental results obtained by the U.S. Public Health Service indicate that tritium intake from ingestion of food and water that have been exposed to the combustion products in homes where natural gas is used as a source of fuel would amount to 2 to 7% of the total intake.^{2,3}

Flaring. During production testing of the Gasbuggy well, the products from the well were released to the atmosphere by flaring. During the flaring operations the Southwestern Radiological Health Laboratory of the U.S. Public Health Service conducted an environmental surveillance program within a 10-mile radius of the well.²⁴ The highest concentration of tritium in the environmental samples coincided with the highest daily release rates of tritium, which occurred during the initial stages of the flaring operation in November 1968. After the middle of 1969 only occasional samples showed positive evidence of tritium above background levels. Several samples had ¹⁴C concentrations up to three times background, and ⁸⁵Kr was found in two air samples. No evidence was found of radioactivity from the Gasbuggy well beyond the immediate environs of the test area. The highest concentration of tritium in the air, at a distance of 0.3 mile, was less than 1% of the maximum permissible concentration in air for members of the public (2×10^{-7} $\mu\text{Ci}/\text{cm}^3$) in Table II of 10 CFR 20, *Standards for Protection Against Radiation*, USAEC Rules and Regulations. If one conservatively assumes that the same dilution factor would hold for the flaring of all the cavity gas, continuous occupancy at the point of the peak measured air concentration would result in a lifetime dose of the order of 5 millirems. This is an academic exercise, however, as there are no permanent residents living within 5 miles of the Gasbuggy site.

Operational personnel at the site routinely submitted samples for urinalysis. Such a personnel surveillance program would be required for any similar flaring operations in subsequent utilization of nuclear explosives for gas reservoir stimulation.

Inhalation of gas during repair of pipeline breaks and from leaks. The number of individuals likely to be exposed during repair of pipeline breaks or to gas escaping from leaky valves or flanges is undoubtedly quite small. It is necessary, however, to consider the possibility that operating personnel might be exposed to releases of this type, because the potential radiation dose rate is likely to be much greater than that from other exposure pathways. These workers, however, would be considered as radiation workers, and per-

sonnel monitoring and surveillance programs such as periodic urinalysis would be provided.

It appears to be common practice to repair breaks in gas-pressurized pipelines by igniting the escaping gas and welding through the flame. This means that the welder could be exposed to the combustion products of Gasbuggy gas. In order to estimate the extent of his potential exposure, it is necessary to use assumed values for several variables that cannot be calculated or predicted with any degree of accuracy. These include the rate of gas escape through the pipeline break (here assumed to be 10 cfm) and the dilution of the gas combustion products before being inhaled by the welder. We have assumed, very conservatively, that, in addition to a dilution factor of 20 required for complete combustion of gas, there is an additional atmospheric dilution factor of 3. A minimum dilution factor of 60 seems reasonable. For the purpose of this calculation we will use the initial concentration of tritium in Gasbuggy gas of 20 $\mu\text{Ci}/\text{ft}^3$. The hypothetical release rate of tritium would then be 200 $\mu\text{Ci}/\text{min}$; and, on the basis of a dilution factor of 60, the air breathed by the welder would have a concentration of 0.33 $\mu\text{Ci}/\text{ft}^3$ or 12 pCi/cm³. During a welding operation lasting an hour, a welder could conceivably breathe in as much as 15 μCi of tritiated water and absorb through the skin half this amount. This could lead to a whole-body dose commitment of about 3 millirems. It seems highly unlikely that the number of pipeline breaks would be large enough to require this type of exposure more than a few hours per week. The above figure, therefore, appears to be a very conservative upper limit for the maximum single 8-hr exposure to this type of release at or near the wellhead of the Gasbuggy well. Most of the welding operations would be expected to occur at other places in the collection system where there are no Gasbuggy radionuclides or where the concentrations have been greatly reduced by dilution with gas from other wells. Also, the concentrations of radionuclides have decreased with continued production of gas from the cavity.

In case of direct exposure to gas leaking from a pipeline, the gas would not be burned, and the dose commitment would be from exposure to tritium in the gas as it exists in the pipeline (in the form of methane and other hydrocarbons) after atmospheric dilution. Again, it is difficult to predict leak rates, but, as will be seen from the following discussion, this is probably not important. In an enclosed space, such as a gas processing building, the hazard of reaching the lower explosive limit with a leak of large magnitude seems to be greater than the potential tritium exposure, and it

seems unlikely that such a leak would go undetected for long. The explosive hazard does not exist when the leak is in an unenclosed space, and it is quite conceivable that a relatively large leak in such a location would not be detected except by odor. The extent of this hazard is determined by the sensitivity of the human nose for untreated natural gas. The hydrogen, methane, ethane, and carbon dioxide that make up a large fraction of the Gasbuggy gas are odorless, but the higher hydrocarbons have a pungent odor. A number of states require consumer gas to be odorized so that it can be detected at a concentration of 1% (one-fifth of the lower explosive limit). We will assume that raw natural gas can be detected at this concentration. If the gas is assumed to contain $20 \mu\text{Ci}/\text{ft}^3$ initially, then the diluted gas would contain a maximum of $0.2 \mu\text{Ci}/\text{ft}^3$ at the detection limit or approximately $7 \text{ pCi}/\text{cm}^3$. At this concentration an adult's daily intake from inhalation would be about $70 \mu\text{Ci}$ during an 8-hr working day. It is assumed that the tritium in this case would be mainly in the form of CH_3T and $\text{C}_2\text{H}_5\text{T}$. Exposure limits for tritium in hydrocarbons have not been established, but retention rates for these relatively inert compounds should certainly be no greater than that of HT or T_2 . The ICRP recommendations for the maximum permissible concentration of T_2 in air are at least a factor of 100 greater than for HTO .¹⁷ Therefore, if our assumption concerning the sensitivity of the human nose for untreated natural gas is correct, the dose commitment from breathing tritium-contaminated gas leaking from a pipeline should be much less than that of repairing leaks, on an equal time basis. Using the assumptions described for these two hypothetical exposure conditions, the potential radiation dose from breathing tritium-contaminated gas leaking from a pipeline should be no more than 10% of that from inhalation and skin absorption of tritium oxide from burning of the gas during welding operations on an equal time basis.

It seems improbable that a home would be close enough to an exposed pipeline for gas leaks to be of concern; so it is reasonable to assume that this pathway of exposure would be experienced only by gas company workers on the job.

Exposure from hypothetical home consumption of Gasbuggy gas. One of the major uses of natural gas is domestic consumption for heating and for appliance operation. In this hypothetical study, Gasbuggy gas was assumed to be introduced into the EPNG collecting and transmission system. Gasbuggy gas contains radionuclides as shown in Table A.3, and it is necessary to consider all factors which could influence the potential exposures of domestic users. These factors include:

1. Concentration of radionuclides at the wellhead. In this regard it is seen in Sect. 2 that the concentrations of radioactivity in Gasbuggy gas have been decreasing with time.
2. Pipeline dilution. As Gasbuggy gas, hypothetically introduced, moved through the collection system it would be diluted with gas from other wells as described in Sect. 3. For purposes of this report we have used average daily gas flows. In this hypothetical situation, involving only the Gasbuggy well, the dilution factors would be quite large. However, if a substantial number of wells in a single production field were nuclearly stimulated, the dilution factor would be much smaller.
3. Quantity of gas consumed. The quantity of gas consumed depends on the requirements for heating and on the amounts required by other home appliances. The amounts required for heating depend on climatic factors and on the quality of home construction.
4. Fraction of combustion products vented inside the home. The fraction of combustion products that are vented inside the home depends largely on the relative amounts of gas used in nonvented and vented appliances and upon the efficiency of the venting system. When well-vented appliances and heating systems are used, the fraction of combustion products released inside the home may approach zero. At the other extreme, when there is no venting, the fraction may approach 1. Because of the possible combination of nonvented and vented appliances, or of cases where the venting is less than perfect, there will undoubtedly be a variable range of combustion products released within the home.
5. Home dilution factor. An approach to estimation of household dilution of combustion products is described in Appendix B. A limited number of cases are described which may, or may not, represent typical dilutions.
6. Home occupancy factor. The home occupancy factor can range up to a value of 1. An occupancy factor of 1 implies that someone is present in the home continuously during the time gas is being consumed. This is not too realistic, but occupancy factors of 1 may be approached. On the other hand, it is unlikely that the occupancy factor would approach zero. An estimate of this factor is discussed in Appendix C.

These factors are multiplicative, and the product gives the collective influence upon the quantity of the radionuclide available for intake.

The first potential domestic use of Gasbuggy natural gas could be at a farm tap near trunk L between its junctions with lateral L-7 and trunk A (see Fig. 3). In this region, the average daily flow of gas is between 57 and 89 M² cf. As mentioned previously, these farm taps are isolated from the system by a one-way valve, so that the flow of gas from the trunk to the user at this point would only occur if the valve failed. Thus this postulated exposure is nearly impossible for any extended period of time. Estimates of potential radiation doses for Gasbuggy gas use at this point, where the average daily flow of gas is 60 M² cf, are given in Table 9. From these estimates it is seen that maximum doses would occur from the use of nonvented heaters. However, considering the climate in the San Juan Basin, it appears that exposures from the use of nonvented ranges and refrigerators might be an important source of exposure; it also seems likely that venting of combustion products from ranges would be less efficient than from normal heating systems.

The 50-year dose commitments and the external gamma dose potentials were also calculated for the nongaseous radionuclides, based on the detection limits in Table 2 and hypothetical use of Gasbuggy gas in a house of normal construction (type B residence) at a point where the average daily flow of gas is 60 M² cf. The results of these calculations are tabulated in Table 10. It is important to note that the doses listed in Table 10 are based on the detection limits (i.e., they represent the highest concentration of the radionuclide that could have escaped detection) and that the true doses, based

on actual or probable concentrations of these radionuclides, would probably be well below these limits. It is assumed that the concentration of these radionuclides will also decrease exponentially as a function of cumulative gas production as did the concentrations of ³H and ⁸⁵Kr shown in Fig. 2. Of the radionuclides listed in Table 10, ⁹⁰Sr might contribute a significant dose commitment (after a shut-in period of a few months) if it were initially present in a concentration approaching its present detection limit. However, the dose from ⁹⁰Sr based on the probable upper-limit concentration in Table 2 is only 0.1 millirem.

The more probable first hypothetical use of Gasbuggy gas would be by residents of the Blanco camp who use gas processed through the Blanco plant. At this point the products from the Gasbuggy well would have been mixed with an average of 576 M²cf/day of non-contaminated products from conventional wells. Thus the dose estimates would be about one-tenth of those tabulated in Tables 9 and 10 for equivalent exposure conditions. If a proportionate share of the Gasbuggy gas were processed through the Ignacio plant the radiation doses would be even lower due to additional dilution.

Exposures from combustion of liquid hydrocarbons. Drip liquids from the San Juan Basin are sold to local refineries, where they end up primarily as fuels. Drip liquids collected from the Gasbuggy well would be diluted with uncontaminated liquid hydrocarbons from other wells in the basin, and the tritium concentration of combustion products from these fuels would be the same as from the combustion of natural gas having the

Table 9. Estimates of whole-body doses from the hypothetical use of Gasbuggy gas at a point where the average daily gas flow is 60 M² cf

Hypothetical exposure conditions	Estimated whole-body doses (millirems)		
	³ H	⁸⁵ Kr ^a	¹⁴ C
One day of exposure with 1 M²cf/day of Gasbuggy gas at concentrations of 700 pCi/cm³ (³H) and 112 pCi/cm³ (⁸⁵Kr) hypothetically introduced to the system and an occupancy factor of 1			
80 degree-days of nonvented heating and average use of nonvented appliances in type B residence	0.14	0.001	0.002
Vented heating but average use of nonvented appliances for type B residence ^b	0.02	0.0002	0.0003
Total exposure for entire production of radioactivity from the Gasbuggy well with an occupancy factor of 0.7^c			
6000 degree-days annually of nonvented heating and average use of nonvented appliances in type B residence	4.5	0.04	0.08
Vented heating but average use of nonvented appliances for type B residence	1.9	0.02	0.03

^aThe whole-body dose from ⁸⁵Kr is estimated to be 0.024 times the dose calculated at the skin surface.¹⁹

^bThe home dilution factors for typical dwellings during extreme weather in the San Juan Basin are listed in Table B.2, Appendix B.

^cThe fraction of time a home is occupied by members of a family (see Appendix C).

Table 10. Limits of detection of radionuclides in gas from the Gasbuggy well and their impact on potential doses

The contributions of the daughters are considered in the total. Gas production is assumed to begin immediately following the detonation. Pipeline dilution factor = 50.

Radionuclide	Detection limit in undiluted gas at the time of analysis extrapolated to the time of detonation ^a (pCi/cm ³)	Radioactive half-life (days)	Critical organ	Upper limit of internal dose commitment (50 years) (millirems)	Upper limit of potential external gamma dose (millirems)
⁹⁰ Sr	1.4×10^{-3}	1.0×10^4	Bone	5	
¹²⁵ Sn	2.0	9.5	GI (LLI) ^b	0.9	2×10^{-3}
¹³¹ I	0.04	8.05	Thyroid	0.4	1×10^{-4}
¹⁴ C ^c	0.05	2×10^{14}	Fat	0.02	
¹²⁷ Sb	2.0	3.9			5×10^{-3}
^{129m} Te	0.001	3.3	Kidneys	2×10^{-3}	5×10^{-6}
^{125m} Te	7×10^{-4}	58	GI (LLI)	6×10^{-4}	2×10^{-6}
¹³⁷ Cs	1×10^{-5}	1.1×10^4	Liver	1×10^{-4}	1×10^{-6}
¹²⁵ Sb	2×10^{-4}	877	Bone	8×10^{-5}	1×10^{-6}
¹⁰⁶ Ru	1×10^{-4}	365	GI (LLI)	7×10^{-5}	3×10^{-7}
¹⁰³ Ru	8×10^{-5}	41	GI (LLI)	3×10^{-5}	6×10^{-8}

^aData from ref. 9 except for ¹⁴C and ⁹⁰Sr; the latter was furnished by private communication from C. F. Smith, LRL.

^bGastrointestinal tract (lower large intestine).

^cData on the detection limit of ¹⁴C were supplied by C. R. Bowman, El Paso Natural Gas Company.

same tritium-to-hydrogen ratio. Thus, if the production of liquid hydrocarbons is assumed to be uniform throughout the basin, though this is known not to be the case, the liquid fuels produced from the drip liquids would give rise to the same concentration of tritium in their combustion products as would the natural gas processed through the Blanco and Ignacio plants. However, the primary use of liquid fuels is for internal combustion engines, and the combustion products are ordinarily discharged directly into the atmosphere rather than being vented into a closed space, such as a house, and the exposures and resultant radiation dose would be very much lower.

Exposures from releases of radioactivity at processing plants. Gas produced in the vicinity of the Gasbuggy well in the San Juan Division of EPNG is normally processed at the Blanco plant. Nearly 95% of the input gas stream leaves the plant as dry product gas. Approximately 2.4% of the input stream is used or released at the plant site, and about 2.6% is separated as liquid hydrocarbon product. The average input of gas to the Blanco plant is about 576 M²cf/day. About 4.3 M²cf/day is used as fuel for compressors, approximately 5.2 M²cf/day is used as fuel for boilers and as other fuel, and roughly 1.3 M²cf/day of nonmarketable material is flared in an open pit (Fig. 12). In each of these cases, combustion products are released to the environment. In addition to these releases, about 0.2 M²cf/day is released in desiccant dehydration and 0.01 M²cf/day in glycol dehydration.

Fig. 12. Product disposal diagram for the daily operation of the Blanco plant.

There are two compressor plants at Blanco, designated A and B. The A plant is equipped with 14 units. Each unit exhausts 7500 cfm at 750°F with a velocity of 7000 fpm through 14-in.-diam pipes 26 ft high. The tops of the exhaust pipes are 6½ ft below the roof top. The compressors in the B plant are more diverse. Five have an exhaust flow of 16,200 cfm (11,600 fpm), three exhaust 12,080 cfm (8650 fpm), two put out 13,140 cfm (9400 fpm). All these have 16-in.-diam

pipes 29 ft high (4 $\frac{1}{4}$ ft below the roof top), while one compressor with a 22-in.-diam pipe exhausts 21,600 cfm (8190 fpm) at a height of 42 ft, 9 ft above the roof top. The nominal exhaust gas temperature is 750°F for all units. Less detailed data are available for the boiler plant, but the tops of its stacks are about 5 or 10 ft above the roof tops, and, on the basis of the volume of gas consumed, the total output of combustion products is greater than from the two compressor plants combined.

The combustion product output from desiccant dehydration (0.2 M²cf/day) is small compared with the total output from the compressors and the boiler plant and will not be considered in detail. The liquid water removed from the dehydration beds (2460 gal/day) is released to a seepage pond and eventually is released to the San Juan River through the Bloomfield sewage system. The various releases from the plants are not uniform in composition. Thus the hypothetical amount of tritium released is not directly proportional to the amount of gas released. The hypothetical quantities of tritiated hydrocarbons entering the plant were estimated on the basis of the chemical and radiochemical quality of Gasbuggy gas during production testing. The various tritiated hydrocarbons were assumed to be diluted with equivalent species from other wells. Krypton was assumed to follow the gaseous releases, but not to go into the liquids. With these assumptions, the estimated dispositions at the Blanco plant of tritium, krypton, and ¹⁴C for the processing of all the Gasbuggy gas during the lifetime of the well are indicated in Table 11. The probable behavior of these releases to the environment was estimated by W. M. Culkowski and G. A. Briggs of the Air Resources Atmospheric Turbulence and Diffusion Laboratory, National Oceanic and Atmospheric Administration, Oak Ridge, Tennessee²⁶ (see Appendix D). Their estimates of average annual dilution factors were based on the assumption that wind data from Farmington, New Mexico, could be applied to the Blanco plant site.

Releases from the flare pit. Winds blow toward the residential area of the Blanco camp about 12% of the time. During the time when wind speeds in this direction exceed 10 mph, the plume from the flare pit would not rise but would travel along the ground. Wind vectors meeting both these direction and speed conditions occur about 5% of the time. When wind speeds are lower than 10 mph, the heat of the plume would permit a sufficient rise to carry it above the plant and residential areas.

Using these conditions, Culkowski and Briggs²⁶ suggest that typical annual average dilution of the com-

Table 11. Disposition of radionuclides during the hypothetical processing of all Gasbuggy gas at the Blanco plant during the lifetime of the well

Disposition	Estimated hypothetical quantity of activity released (Ci) ^a		
	³ H	⁸⁵ Kr	¹⁴ C
Flare pit	9	1	0.01
Boiler fuel	28	3	0.04
Compressor fuel	19	2.5	0.03
Dehydration	1	0.1	
Liquid product (to Wingate)	126		0.2
Dry gas product	2180	360.	3.6
Liquid water from dehydration	2.5		
Not accounted for	12	2.5	0.02

^aIt is assumed that the ¹⁴C in the form of CO₂ and CO would be removed from the gas stream during processing, leaving only that associated with the hydrocarbons.

bustion products for both the residential and plant areas would be about 5 × 10⁵ cfs. The potential radiation doses from continuous exposure at this dilution, assuming processing of all Gasbuggy gas during the lifetime of the well at the Blanco plant, would be due primarily to tritium and would amount to about 0.014 millirem to the whole body.

Releases from compressor and boiler fuel use. The exhaust stacks of the compressor facilities and the boiler plant are low, allowing a great deal of the effluent to reach the ground within the first few hundred meters. Downwash from the exhausts of the compressor facilities begins at wind speeds of 3 to 6 mph, and at about 10 to 15 mph these exhausts are not effective in dispersing the combustion product effluents. Boiler plant stacks might become ineffective at wind speeds higher than about 25 mph.

Culkowski and Briggs²⁶ estimate the average dilution factor for all emissions from the plant, except for the flare pit, would be about 10⁶ cfs. The concentrations would be higher in the plant area, especially near the compressor facilities. In this area the annual average concentration of the combustion products may be as high as $x = Q(3 \times 10^{-5})$ Ci/ft³, where Q is the total emission of all of the compressor facilities in curies per second.

For the residential area the potential radiation to the whole body from the processing of all Gasbuggy gas would be about 0.06 millirem. Near the compressor facilities the potential radiation dose to the whole body for exposure during a 40-hr week would be about 0.09 millirem.

Waste disposal. Water is removed from the gas being processed through the Blanco plant at a rate of about 2460 gal/day (Fig. 12). There are, at present, no reliable data on the HTO content of the water in Gasbuggy gas. However, as a first approximation, we can assume that the water content of gas hypothetically reaching the Blanco plant from the Gasbuggy well has the same moisture content as gas normally processed through the plant. Using this approximation and the analysis of the tritium content of water produced from the Gasbuggy well tabulated in Table 6, we estimate that a total of about 2.5 Ci of tritiated water would be released to the disposal pond during the lifetime of the well. This water flows through the Bloomfield sewage disposal system into the San Juan River, which has an average annual flow rate of 958 cfs at Farmington, a few miles downstream from Bloomfield. If this stream has a tritium ratio of 100, the average quantity of fallout and naturally produced tritium passing this point would be about 0.75 Ci/day or 275 Ci/year. The tritium added by processing of Gasbuggy gas would not be distinguishable in the stream; people obtaining drinking water from the San Juan River at this point could receive an estimated whole-body dose of about 0.13 microrem from the added tritium.

All of the releases at the Blanco plant would be reduced if a proportionate share (23%) of the Gasbuggy gas were hypothetically processed at the Ignacio plant. The additional dilution would result in lower radiation doses to individuals, but the number of people exposed would be increased.

6. SUMMARY AND CONCLUSIONS

Preliminary estimates have been made of the potential radiation doses that might result from the hypothetical

domestic and commercial utilization of Gasbuggy gas within the San Juan Basin. Although none of the Gasbuggy gas has been introduced into the gathering and distribution system of the El Paso Natural Gas Company, the analysis was based on historical data from production testing of the well. Such an analysis is useful since it makes possible the consideration of a real system with regard to collection, processing, and distribution.

On the basis of this study, we feel that the major radionuclide of importance in Gasbuggy gas is tritium, the critical exposure pathway is domestic use, and the critical population group among the general public would be housewives and children at the Blanco camp who are exposed to the combustion products of natural gas used for cooking. The critical radionuclide is not likely to change, even if improvements are made in the design of the nuclear explosive device and in emplacement techniques.

The hypothetical radiation doses to various population groups from the direct modes of exposure were very much lower than the annual dose limits prescribed by the ICRP and other authorities, when the single well was considered.^{17,27,28} At these low levels of radiation dose, we consider the somatic risk to be of minor importance. In the gas use situation providing the least dilution (home heating without venting of the combustion products), an individual would take into the body only about 0.5% of the tritium released during combustion. Assuming an average family size of four persons, domestic use of all Gasbuggy gas with unvented heating would result in a total of about 4 man-rems whole-body dose.

Appendix A

DETAILED CHEMICAL AND RADIOCHEMICAL DATA ON GASBUGGY CAVITY
GAS AND DISCUSSION OF THE DATA

C. J. Barton, Sr.

Data on the chemical and radiochemical composition of Gasbuggy gas are presented here and analyzed in greater detail than in Sect. 3. These data were supplied by the Gas Quality Investigation Program at Lawrence Radiation Laboratory (LRL) and by the El Paso Natural Gas Company (EPNG).

Chemical Composition

Data⁸ on the chemical composition of Gasbuggy gas covering the period from one day after the explosion through August 1969 are shown in Table A.1. Most of the gas samples were contaminated with air to varying degrees, and the results in the table have been corrected for air contamination based on the oxygen content. The one-day samples were badly contaminated with air, and the uncertainties in the values are consequently larger than for other samples in the table; but it is fortunate that these samples were obtained, because the largest changes in composition occurred during the first month.

It has been suggested that a formation near the top of the cavity supplied uncontaminated gas faster than other strata, allowing a blanket of low-activity gas to accumulate at the top of the cavity during shut-in following periods of rapid production. This theory accounts for most of the concentration history of products removed from the well but not the composition of the June 28 sample, which was removed at the beginning of a withdrawal period rather than at the end.

The measured carbon dioxide and hydrogen concentrations are plotted in Fig. A.1 as a function of cumulative gas flow. Also shown in this graph is a line representing the theoretical concentrations, assuming an initial cavity gas volume of 128 M²cf and perfect mixing. Most of the data fall above the theoretical line, which could be interpreted as indicating a larger initial volume of gas than that calculated from the krypton data. It is interesting to compare this graph with Fig. 2. The peaks and troughs in the concentration data can be correlated with changes in gas flow rate, although the correlation is not perfect. Rather surprisingly, the concentrations at 58.5 M²cf flow at the end of a shut-in period of more than two months were significantly lower than those obtained after resumption of gas flow. One would expect uniform mixing to occur during this long shut-in period, but the persistent stratification in

the top of the cavity mentioned above seems to be the most likely explanation for the low observed concentrations.

A straight line can be drawn from the initial concentration of CO₂ or H₂ through or near the three peaks in the curve, although its significance is not completely clear. In the case of the H₂ data, this line is an extension of the "best line" through the data obtained during the initial high-flow test period. The carbon dioxide concentration for this period shows a smaller rate of decrease than hydrogen, possibly because of its lower diffusion rate. The apparent initial volume of cavity gas calculated from the slope of these lines through the peaks is 200 M²cf for hydrogen and 240 M²cf for carbon dioxide. There is a remarkably close correspondence between the H₂ and CO₂ data in Fig. A.1. This indicates a high degree of reliability for the data and shows that the two gases behaved quite similarly throughout the duration of the flow test period.

Fig. A.1. Carbon dioxide and hydrogen concentrations in chimney gas as a function of cumulative gas flow.

Table A.1. Chemical composition of LRL Project Gasbuggy samples in volume percent
as determined by mass spectrometric analysis⁸

Sample No.	Date	Total gas flow (10 ⁶ ft ³)	N ₂	CO ₂	CO	H ₂	CH ₄	C ₂ H ₆	C ₃ H ₈	Other
2 ^a	12-11-67	0		9.87	21.7	23.1	42.6	1.73		0.96
3 ^a	12-11-67	0		9.92	21.7	22.6	43.5	1.75		0.47
5	1-13-68	0	0.64	36.2	3.9	16.7	36.4	3.61	1.21	1.15
6	1-13-68	0	0.99	36.1	3.7	16.9	36.5	3.63	1.15	1.09
7	1-13-68	0	0.22	35.0	4.1	17.4	36.5	3.52	1.25	1.97
8	1-17-68	0.3	0.90	34.6	4.0	18.0	37.2	3.42	1.01	0.77
9	1-17-68	0.3		35.8	4.5	16.8	37.5	3.63	1.14	0.79
10	1-17-68	0.3	0.53	36.0	3.9	16.7	37.2	3.68	1.27	0.79
11	1-17-68	0.3	0.61	35.6	3.9	17.0	37.7	3.56	0.97	0.63
12	2-27-68	0.3	0.71	34.8	3.1	14.4	40.0	4.10	1.13	1.78
13	2-27-68	0.3		35.6	3.3	14.8	40.4	4.10	1.23	0.67
14	2-27-68	0.34	0.62	35.7	2.6	14.8	39.9	4.12	1.21	0.98
16	2-27-68	0.34	0.45	35.6	2.6	15.0	40.2	4.12	1.17	0.84
17	4-22-68	0.35		35.4	2.2	13.1	43.2	4.57	1.05	0.53
18	4-22-68	0.35		35.1	2.2	13.3	43.3	4.50	0.98	0.61
19	6-28-68	0.36	0.31	4.39		0.27	82.5	7.31	2.71	1.87
20	6-29-68	5.4	1.32	36.2		12.0	44.2	4.70	0.97	0.61
21	6-30-68	10.4		34.0	1.5	12.2	45.9	4.73	1.09	0.74
23	7-02-68	20.4	1.13	33.5		11.1	46.8	4.78	1.18	0.74
25	7-04-68	30.4	1.05	33.1		10.8	47.8	4.92	1.31	1.01
26	7-07-68	40.4	1.10	32.2		10.5	48.9	4.97	1.37	0.93
27	7-08-68									
28	7-09-68									
29	7-10-68	55.4	1.01	30.9		9.9	49.8	5.06	1.58	1.08
30	7-11-68	56.1	0.13	14.9		5.5	67.7	5.96	2.47	1.37
31	7-12-68	56.9		18.9	0.7	6.80	64.0	5.80	2.38	1.38
32	7-13-68									
33	7-14-68	58.4	0.79	21.7		6.72	60.9	5.77	2.38	1.77
34 ^b	7-22-68		0.49	0.70		0.20	83.4	7.94	4.42	2.83
35	7-22-68									
36	9-18-68	58.5	0.42	13.0		5.8	69.8	6.07	2.98	1.96
37	9-18-68									
38	11-07-68									
39	11-08-68	68.7	0.43	22.0		7.92	59.7	5.66	2.52	1.72
40	11-15-68									
41	11-22-68	75.9	0.49	23.1		8.11	58.6	5.50	2.24	1.88
42	11-29-68									
43	12-06-68									
44	12-07-68	81.4	0.42	22.7		8.10	59.9	5.50	2.18	1.21
45	12-10-68	95.6	1.16	22.5		7.70	59.2	5.62	2.40	1.44
46	12-13-68	104.5	0.33	14.1		4.62	70.0	6.24	3.02	1.67
47	12-12-68		0.4	26.6		9.25	74.8	6.94	3.19	2.75
48	12-19-68									
49	12-26-68	114.1	2.85	16.7		5.81	64.5	5.94	2.89	1.26
50	1-02-69									
51	1-11-69	122.5	0.60	18.8		6.37	64.2	5.96	2.73	1.38
52	1-14-69	140	0.29	20.1		6.72	63.0	5.86	2.60	1.39
53	1-17-69	~149	0.40	19.0		6.20	63.9	6.00	2.80	1.64
54	1-27-69									
55	2-03-69	~161	0.40	14.2		4.67	69.8	6.31	3.09	1.50
56	2-10-69									
57	2-18-69	~170	0.46	13.0		4.33	71.1	6.51	3.05	1.50
58	2-25-69	~186	0.50	16.1		5.02	66.9	6.44	3.14	1.91
59	3-05-69	~204	0.39	14.6		4.25	68.3	6.67	3.35	2.44
60	4-11-69	~218		9.90		2.60	73.9	7.10	3.90	2.72
61	4-18-69	~222	0.56	9.42		2.54	73.7	7.01	3.97	2.81

Table A.1. (continued)

Sample No.	Date	Total gas flow (10 ⁶ ft ³)	N ₂	CO ₂	CO	H ₂	CH ₄	C ₂ H ₆	C ₃ H ₈	Other
62	4-25-69	~224	0.42	9.44		2.55	74.3	6.96	3.91	2.45
63	5-09-69	~228	2.15	9.29		2.46	73.2	6.90	3.98	2.04
64	5-16-69	~232	0.72	8.60		2.28	74.7	6.94	3.94	2.86
65	6-06-69	~237		7.92		2.06	76.0	7.07	4.09	2.82
66	6-12-69	~238	0.81	7.97		2.15	75.4	6.95	3.98	2.74
67	6-27-69	~241	0.40	8.10		2.10	75.0	7.0	4.0	3.4
68	7-04-69	~243	0.40	7.73		1.96	76.1	7.08	4.07	2.67
69	7-11-69	~244	0.77	7.55		1.98	75.9	6.97	4.07	2.76
70	7-18-69	~245	0.34	7.72		1.96	76.1	7.05	4.12	2.70
71	8-01-69	~247	0.3	7.56		2.01	76.2	7.02	4.11	2.80
72	8-08-69	~248	0.40	7.48		1.98	76.2	7.03	4.13	2.73
73	8-15-69	~250	0.40	7.4		1.97	76.3	7.02	4.14	2.77
74	8-21-69	~251	0.45	7.23		1.90	76.4	7.06	4.18	2.76
75	8-29-69	~252	0.4	7.1		1.86	76.4	7.05	4.18	3.0

^aCable leak to sealed wellhead annulus.

^bGB-2RS sample (reentry of 2B-2 preshot investigation hole). All other samples except 2 and 3 from GB-ER (reentry of emplacement hole).

Mass spectrographic analysis data on samples covering the first period of rapid withdrawal of gas, June 28, 1968, to July 14, 1968, obtained by EPNG, are shown in Table A.2. These data appear to be in essential agreement with the LRL data in Table A.1, but none of the EPNG samples on June 28 resembles the LRL sample taken on that date. The most striking variation shown by the EPNG results occurred on July 10, 1968, at the end of a period of rapid withdrawal of gas. In an interval of 3¼ hr between the first and second samples on that date, there was a decrease in the CO₂ content of the gas of nearly 12% and a corresponding increase in the hydrocarbon concentrations. The LRL sample on this date apparently was taken before the sudden influx of uncontaminated formation gas occurred, but their July 12, 1968, sample did show the change. The hydrocarbon content of the gas reached a maximum on July 11, 1968, and then started decreasing slowly as the CO₂ concentration increased when mixing of the formation gas and cavity gas began.

Radioactivity

Data on the long-half-life activities found in Gasbuggy gas samples are contained in Table A.3, as reported by Lawrence Radiation Laboratory.⁸ By combining data in Tables A.1 and A.3, specific activities (pCi/cm³) can be calculated for the various components of the Gasbuggy samples. The data are rather scanty for propane (11 samples), but there are sufficient data to show the effect of gas withdrawal. The results of these calculations

Table A.2. Mass spectrographic analysis in volume percent of Gasbuggy samples by El Paso Natural Gas Company
June 28, 1968, to July 14, 1968

Date	H ₂ S	CO ₂	CO	N ₂	CH ₄	C ₂ H ₆	C ₃ H ₈	C ₄₊
June 28	0.10	34.40	0.80	0.53	45.58	4.86	0.94	0.53
June 28	0.11	35.20	0.60	0.53	45.07	4.86	0.95	0.59
June 28	0.11	35.00	0.60	0.51	45.45	4.83	0.95	0.52
June 29	0.12	34.60	0.60	0.48	46.46	4.83	0.98	0.64
June 30	0.11	33.60	0.60	0.50	46.96	4.92	1.07	0.73
July 1	0.11	33.20	0.60	0.51	46.17	5.00	1.14	0.76
July 2	0.11	32.80		0.50	48.22	5.05	1.18	0.72
July 3	0.10	32.00		0.47	49.36	5.02	1.20	0.72
July 4	0.10	32.00		0.47	49.10	5.04	1.24	0.72
July 5	0.04	13.20		0.43	69.00	5.95	2.60	1.59
July 6	0.09	31.40		0.48	49.38	5.11	1.29	0.75
July 7	0.09	31.00		0.48	50.13	5.12	1.35	0.81
July 8	0.08	30.40		0.51	50.36	5.21	1.42	0.82
July 9	0.08	30.00		0.46	51.12	5.15	1.46	0.91
July 10	0.09	29.60		0.48	51.43	5.24	1.52	0.92
July 10	0.06	17.80		0.43	63.43	5.81	2.37	1.50
July 10	0.06	18.20		0.43	65.20	5.88	2.47	1.43
July 11	0.06	17.60		0.48	67.98	5.94	2.57	1.48
July 11	0.05	17.60		0.48	67.22	5.96	2.49	1.52
July 12	0.05	19.20		0.77	64.26	5.87	2.39	1.39
July 13	0.06	20.20		0.71	64.04	5.81	2.31	1.38
July 14	0.06	20.60		0.70	62.84	5.75	2.23	1.37

tions are given in Table A.4 and are plotted in Fig. A.2. The HT specific activities were omitted from the figure because of scatter in the data. The rapid drop in specific activity of tritium in the hydrogen gas during the first month of the shut-in period shown in Table A.4 could

Table A.3. Radionuclide concentrations for Gasbuggy gas samples in picocuries per standard cubic centimeter of chimney gas^{a, b}

Sample No.	Date	⁸⁵ Kr	HT	CH ₃ T	C ₂ H ₅ T	C ₃ H ₇ T	¹⁴ CO ₂	¹⁴ CH ₄	¹⁴ CO	Gross beta ^c
1	12-10-67									
2	12-11-67	110.0 (1.0)	3690.0 (1.7)	319.0 (1.7)	17.2 (0.5)					
3	12-11-67	118.0 (0.4)	3360.0 (0.7)	346.0 (1.3)	17.8 (0.7)					
4	12-10-67									
5	1-13-68	124.0 (0.4)	225.0 (1.6)	457.5 (2.6)	79.6 (1.0)				0.343 (4.0)	
6	1-13-68	125.0 (1.0)	124.0 (1.0)	430.0 (4.2)	76.3 (1.8)				0.201 (9.4)	
7	1-13-68	119.0 (0.5)	189.0 (1.3)	454.0 (0.7)	79.8 (0.6)	34.0 (1.8)	2.11 (0.4)	0.256 (1.2)	0.216 (2.3)	
8	1-17-68									
9	1-17-68									
10	1-17-68	124.0 (0.7)	125.0 (0.5)	458.0 (1.2)	80.6 (1.5)				0.310 (6.8)	
11	1-17-68	123.0 (0.3)	175.0 (1.0)	450.0 (0.9)	77.8 (2.2)		1.34 (0.4)		0.218 (1.0)	
12	2-27-68									
13	2-27-68									
14	2-27-68	124.0 (0.3)	97.1 (0.8)	461.0 (2.0)	83.4 (1.1)			0.370 (4.1)	0.129 (1.8)	
15	2-27-68									
16	2-27-68	115.0 (1.7)	128.0 (0.3)	470.0 (0.4)	81.6 (1.0)	15.2 (1.7)	2.48 (1.4)	0.290 (1.6)	0.125 (1.1)	
17	4-22-68	111.0 (1.2)								
18	4-22-68	115.0 (0.5)	90.3 (1.4)	523.0 (1.9)	90.4 (0.7)	13.8 (2.5)	1.77 (1.2)	0.493 (7.4)	0.107 (4.5)	
19	6-28-68	10.8 (0.7)		45.2 (4.0)	9.40 (0.6)					
20	6-29-68	112.0 (1.1)	63.0 (0.7)	537.0 (0.4)	92.8 (1.1)	13.9 (1.0)	2.15 (1.9)			
21	6-30-68									
22	7-1-68									
23	7-2-68	92.0 (1.0)	42.5 (0.4)	472.0 (0.9)	86.8 (3.2)					
24	7-3-68									
25	7-4-68	99.2 (2.4)	44.9 (0.4)	468.0 (1.7)	87.1 (1.1)					
26	7-7-68	90.4 (1.0)	54.1 (0.7)	483.0 (0.4)	76.9 (2.3)					
27	7-8-68									
28	7-9-68									
29	7-10-68	84.1 (1.4)	41.3 (0.8)	436.0 (0.4)	79.8 (1.5)					
30	7-11-68	41.3 (4.2)		212.0 (4.1)	31.4 (1.0)					
31	7-12-68	66.4 (1.1)	32.0 (2.7)	262.0 (0.8)	42.3 (4.2)		0.91 (1.0)			
32	7-13-68									
33	7-14-68	48.4 (0.7)	29.9 (0.4)	309.0 (1.0)	55.1 (1.2)					
34	7-22-68	3.98 (0.7)	0.11 (12)	14.6 (0.9)						
35	7-22-68									
36	9-18-68	33.0 (1.4)	15.1 (0.8)	191.0 (0.6)	29.3 (0.9)	6.78 (5.6)	0.80 (4.7)	0.54 (1.3)		
37	9-18-68									
38	11-7-68									
39	11-8-68	63.6 (1.2)	41.2 (0.6)	292.0 (0.9)	49.6 (3.2)		1.15 (2.9)	0.36 (1.8)		406 (4.4)
40	11-15-68									
41	11-22-68	56.5 (0.4)	32.2 (10.9)	309.0 (3.5)	55.8 (0.8)		1.35 (1.8)			504 (1.4)
42	11-29-68									

Table A.3. (continued)

Sample No.	Date	^{85}Kr	HT	CH_3T	$\text{C}_2\text{H}_5\text{T}$	$\text{C}_3\text{H}_7\text{T}$	$^{14}\text{CO}_2$	$^{14}\text{CH}_4$	^{14}CO	Gross beta ^c
43	12-6-68									
44	12-7-68	54.6 (0.5)	31.0 (1.2)	311.0 (0.4)	35.0 (2.1)		1.08 (9.4)			488 (2.4)
45	12-10-68	64.2 (0.3)	30.0 (1.0)	299.0 (1.5)	51.2 (0.4)		1.31 (0.3)			
46	12-13-68	36.8 (0.7)	33.2 (1.0)	178.0 (1.5)	31.8 (2.3)		0.70 (0.5)			310 (5.7)
47	12-12-68	54.8 (1.3)	27.4 (0.9)	276.0 (1.7)		7.85 (0.4)	1.11 (3.0)			
48	12-19-68									
49	12-26-68	41.4 (0.8)	22.5 (4.1)	242.0 (8.0)	42.1 (3.9)		1.30 (0.8)			352 (5.7)
50	1-2-69									
51	1-11-69	48.9 (1.9)	19.9 (4.6)	254.0 (6.3)	37.5 (3.7)		0.92 (0.7)			369 (3.0)
52	1-14-69	50.8 (0.5)	18.5 (15)	244.0 (0.7)	44.8 (0.4)		0.88 (0.9)			403 (0.8)
53	1-17-69	49.0 (0.6)	41.0 (4.1)	236.0 (1.7)	44.5 (6.0)		1.28 (1.2)			374 (1.9)
54	1-27-69									
55	2-3-69	36.7 (0.5)	19.0 (1.3)	171.0 (0.8)	30.1 (0.9)		0.62 (0.6)			285 (6.4)
56	2-10-69									
57	2-18-69	32.2 (0.8)	18.6 (14)	137.0 (1.6)	26.1 (0.4)		0.73 (0.6)			232 (0.6)
58	2-25-69	37.6 (2.2)	19.6 (4.0)	168.0 (1.0)	32.7 (0.4)	3.18 (0.4)	0.74 (36)	0.45 (5.3)*		294 (8.0)
59	3-5-69	[35.3 (6.0)]								234 (0.4)
60	4-11-69	17.7 (0.4)	18.5 (4.0)	73.0 (6.4)	13.9 (1.6)	2.91 (6.2)	0.49 (5.1)	0.49 (7.1)		127 (3.4)
61	4-18-69	[16.6 (0.7)]								116 (0.6)
62	4-25-69	17.0 (1.0)	16.3 (4.0)	63.8 (1.1)	9.83 (3.3)		0.68 (3.1)			112 (0.6)
63	5-9-69	[15.3 (3.7)]								103 (1.5)
64	5-16-69	14.0 (2.0)	6.90 (4.0)	54.6 (1.8)	11.7 (2.0)					96.1 (0.4)
65	6-6-69	[12.1 (1.7)]								82.4 (0.4)
66	6-12-69	12.0 (1.3)		46.4 (2.0)	11.2 (6.6)	2.09 (2.1)		0.673 (9.1)		78.2 (0.4)
67	6-27-69	[11.5 (1.1)]								80.7 (0.7)
68	7-4-69	13.1 (0.9)	6.52 (6.9)	43.1 (0.4)	9.29 (0.8)	1.77 (1.3)	0.56 (5.5)			71.7 (0.4)
69	7-11-69	[10.7 (3.2)]								73.2 (0.7)
70	7-18-69	8.83 (1.7)		39.5 (2.8)	9.53 (1.0)	2.34 (2.5)				70.9 (0.1)
71	8-1-69	[10.1 (2.0)]								71.9 (1.5)
72	8-8-69	8.69 (3.4)		37.0 (0.4)	8.86 (1.3)		0.33 (4.7)			68.2 (0.4)
73	8-15-69	[9.10 (1.9)]								66.1 (1.1)
74	8-21-69	8.76 (0.5)	4.50 (24)	34.5 (0.4)	7.09 (5.1)			0.614 (12)		62.1 (0.2)
75	8-29-69	[8.56 (2.2)]								63.2 (5.4)

^aValues stated in parentheses indicate the precision of the measurement in percent standard deviation.

^bValues enclosed in brackets are determined by direct counting without pretreatment.

^cValues given for gross beta are determined by direct counting without pretreatment.

Table A.4. Specific activity of tritium in Gasbuggy gas components

Sample date	Specific activity (pCi/cm ³)			
	HT	CH ₃ T	C ₂ H ₅ T	C ₃ H ₇ T
Dec. 11, 1967	16,000	750	1000	
Dec. 11, 1967	14,900	795	1020	
Jan. 13, 1968	1,350	1180	2200	
Jan. 13, 1968	735	1180	2100	
Jan. 13, 1968	1,085	1245	2270	2720
Jan. 17, 1968	750	1230	2190	
Jan. 17, 1968	1,030	1195	2185	
Feb. 27, 1968	660	1150	1980	
Feb. 27, 1968	855	1170	1980	1440
Apr. 22, 1968	680	1210	2010	1410
June 28, 1968		55	128	
June 29, 1968	525	1215	1975	1435
July 2, 1968	390	990	1815	
July 4, 1968	415	980	1770	
July 7, 1968	515	990	1545	
July 10, 1968	415	865	1560	
July 11, 1968		313	527	
July 12, 1968	470	410	730	
July 14, 1968	445	505	955	
Sept. 18, 1968	260	275	485	230
Nov. 8, 1968	520	490	875	
Nov. 22, 1968	395	525	1015	
Dec. 7, 1968	385	520	635	
Dec. 10, 1968	390	505	910	
Dec. 12, 1968	296	369		246
Dec. 13, 1968	720	254	510	
Dec. 26, 1968	387	375	710	
Jan. 11, 1969	313	395	630	
Jan. 14, 1969	275	387	764	
Jan. 17, 1969	661	370	740	
Feb. 3, 1969	406	245	475	
Feb. 18, 1969	430	192	400	
Feb. 25, 1969	390	252	508	101
Apr. 11, 1969	712	99	196	75
Apr. 25, 1969	640	86	141	
May 16, 1969	303	73	168	
June 12, 1969		62	161	52
July 4, 1969	332	57	131	43
July 18, 1969		52	135	57
Aug. 8, 1969		49	126	
Aug. 21, 1969	236	45	100	
Average	432 ^a	423 ^a	760 ^a	280

^aExcluding initial shut-in period and August 1969 figures (averages are for the first year of production, including June 28–30, 1968).

be accounted for by the reactions of HT with CO to form hydrocarbons or by isotopic exchange with water in the cavity. There is some evidence in favor of the former reaction, but the latter seems more probable. There is a significant difference between the average specific activity of HT during the initial shut-in period

Fig. A.2. Specific activity of Gasbuggy gas components as a function of cumulative gas flow.

(893 pCi/cm³) and that following the initiation of gas flow (432 pCi/cm³). The reason for this variation in specific activity of the hydrogen is not clear, but the constancy of this value after June 29, 1968, confirms the belief that there was no significant amount of hydrogen in the formation gas flowing into the cavity as gas was withdrawn. The effect of the incoming formation gas on the specific activity of the hydrocarbons in gas removed at the wellhead is quite evident. It is most marked in the case of propane, where there is a larger difference between the propane content of the formation gas and the concentration in the cavity gas, as compared with methane and ethane.

Lines connecting the initial concentrations of CH₃T and C₂H₅T with the several peaks gave values for the initial cavity volume of 120 M²cf for CH₃T activity and 140 M²cf for C₂H₅T. The average of these two values is very close to the predicted value based on the ⁸⁵Kr concentration. This may be only an interesting coincidence, since the actual significance of the peaks in the concentration curves is not clear. A similar treatment of the ⁸⁵Kr data (Fig. 2) gave a value of 180 M²cf for the initial cavity volume, and this determination is apparently the most reliable of the radioactivity measurements made on the Gasbuggy samples.

The specific activity of both CH₃T and C₂H₅T fell at a constant rate during the long-term production test.

The effective initial volume indicated by the slope of the lines is about 40 M²cf. This compares with values of 38 M²cf from the total tritium data (Fig. 2) and 51 M²cf from the ⁸⁵Kr data. These low values for the initial volume apparently can be correlated with the drop in down-hole pressure from its initial (zero flow) value of about 64 atm to 18 atm at the beginning of the long-term production test.

Data on the specific activity of CH₃T and C₂H₅T (Table A.4) were used with data on CO₂ and H₂

concentrations in Table A.1 to calculate the ratios CH₃T/CO₂, CH₃T/H₂, C₂H₅T/CO₂, and C₂H₅T/H₂. The resulting data are plotted in Figs. A.3 and A.4. It is clear that the tritium activities have been dropping off more rapidly than the CO₂ or the H₂ concentration. We have no explanation for the difference in behavior of the methane and ethane ratios during the long-term production test.

Calculations of the specific activity of ¹⁴C in CO₂, CO, and CH₄ from the data in Tables A.1 and A.3 gave values ranging from 4.2 to 7.2 pCi/cm³ for CO₂ with an average value of 5.5; 0.66 to 1.14, average 0.7, pCi/cm³ for CH₄; and 0.6 pCi/cm³ for CO. There did not appear to be any trend in the ¹⁴C specific activities.

Fig. A.3. Ratio of activity of CH₃T to concentration of CO₂ or H₂ as a function of cumulative gas flow.

Fig. A.4. Ratio of activity of C₂H₅T to concentration of CO₂ or H₂ as a function of cumulative gas flow.

Appendix B

ESTIMATES OF DILUTION FACTORS FOR NONVENTED NATURAL GAS
COMBUSTION PRODUCTS IN HOMES

M. J. Kelly

For natural gas containing radionuclides, maximum radiation exposure will probably occur during the heating season. To assess the probable magnitude of this exposure, it is necessary to establish appropriate concentrations of the natural gas reaction products within a variety of inhabited dwelling units.

Home Heating

A consistent approach to the problem is to consider heat requirements as the independent variable and gas usage dependent on the heat required to maintain normal inside temperatures (70°F). Exchange of outside air with that within the dwelling unit must also be evaluated so that we may determine the average dilution of the combustion products within the living space. To accomplish this, we need a basic framework relating heat transfer, infiltration of air into dwelling units, thermal conductivity, and construction practice.

A useful number for the film coefficient for convective heat transfer is:²⁹

$$h = 0.8 + 0.3V,$$

where V is the wind velocity in miles per hour and h is the convective heat transfer film coefficient in British thermal units per hour per square foot per degree Fahrenheit. Using this as a general formula, the possible heat removal rate from a dwelling surface is:

$$Q/A = (0.8 + 0.3V) \Delta t \text{ Btu hr}^{-1} \text{ ft}^{-2} \text{ }^{\circ}\text{F}^{-1},$$

where Δt is the temperature difference in degrees Fahrenheit, Q is the heat removal rate in British thermal units per hour, and A is the area of external surfaces in square feet.

Heat removal is dependent on the rate at which it is supplied by conductivity through the walls, windows, doors, and roof. Table B.1 gives the thermal conductivities³⁰ in British thermal units per hour per square foot per degree Fahrenheit per inch of thickness for several building materials.

Infiltration of air into dwellings is not so definitive as previous numbers, but the *Handbook of Building Construction*³¹ gives values of 9 ft³ of air per hour per mile of wind velocity per foot of crack around windows

Table B.1. Thermal conductivity of typical construction materials

Material	Thermal conductivity (Btu ft ⁻² hr ⁻¹ (°F/in.) ⁻¹)
Rock wool	0.24
Glass wool	0.29
Wood	1.0
Brick	3-6
Cinder block	2-3
Glass	5-6

and doors. *Warm Air Heating and Winter Air Conditioning*³² gives values as shown below in cubic feet per hour per foot of crack, neglecting velocity.

Wooden window, average fit, not weather-stripped	37
Wooden window, poor fit, not weather-stripped	104
Well-fitted door, not weather-stripped	104
Poorly fitted door, not weather-stripped	208

These values, in conjunction with the minimum recommended design value of at least one total air change per hour, will be used as required in further calculations.

We are now able to consider what could realistically be the worst hypothetical exposure case. Consider a wooden hunting shack, 10 ft by 10 ft by 8 ft high, with one door and two 3- by 4-ft windows, with an outside temperature of -10°F with a 10-mph wind and an inside temperature of 70°F. Consider all outside surfaces at -10°F. The wall thickness is assumed to be 1 in., and the total external surface area is 520 ft², of which 24 ft² is window. The convective heat loss from the windows would be:

$$(0.8 + 0.3 \times 10) \times 24 \times 80 = 7300 \text{ Btu/hr.}$$

The conductive loss from the walls, ceiling, floor, and door would be:

$$1.0 \times 496 \times 80 = 39,700 \text{ Btu/hr.}$$

This gives a total heat loss of 47,000 Btu/hr. Poor construction is implied, and air infiltration, using references cited, varies from 4200 to 6700 ft³/hr, considering only doors and windows. Air weighs about 8×10^{-2} lb/ft³ and has a heat capacity of 0.24 Btu lb⁻¹ °F⁻¹, resulting in an infiltration loss of from 6500 to 10,300 Btu/hr. Using the average value of 8400 Btu/hr, the total heat requirement would be 55,500 Btu/hr.

The nominal heating value for natural gas is assumed to be 1100 Btu/ft³; and, to maintain the inside temperature, 50 ft³ of gas per hour must be burned. The average value for infiltrated air is 5450 ft³/hr, giving a dilution factor of 110. Weather-stripping of windows and doors will improve the infiltration by a factor of 2 without changing the heating requirements appreciably, and the dilution factor would be reduced to 58.

We must now consider what would happen to the dilution factor if infiltration is further reduced. From the stoichiometry of combustion:

two volumes of water vapor are produced from each volume of burned gas. At 70°F only 2.5% water vapor can exist in equilibrium with air; condensation to liquid occurs above this point. Thus a positive dilution factor of 80 for inhalation exists, assuming equilibrium at 70°F. Local temperature gradients within the shack (higher temperatures would exist near the stove) will decrease this somewhat, but a conservative dilution factor for inhalation is over 60 even without air infiltration. Continued combustion without infiltration will lead to oxygen depletion, carbon monoxide formation, and eventual asphyxiation. The minimum dilution of 60 is dependent only on temperature and on the combustion process and may be considered a fundamental limit. It is not dependent on the size of the dwelling.

For a more typical residential unit, we assume one house (one room) volume of air infiltration per hour. Dwellings of first-class construction are designed with this value as a minimum, and in poorer construction it is probably always higher. An arbitrary assignment of 15% of the outside surface to windows and doors will be made. Insulation (4 in.) will be assumed. As shown in Fig. B.1 the surface-to-volume ratio decreases rapidly with increasing floor space and approaches a limit. Since the heat required is a function of surface area, smaller dwellings require more heat per unit volume. The walls and ceiling are considered to be exposed to outside temperature.

A unit of 100 ft², the same size as the hunting "shack," would have 63 ft² of doors and windows and 357 ft² of walls and ceiling. The windows are assumed to be curtained, and the heat loss at -10°F with a 10-mph wind with 70°F inside temperature would be:

$$1 \times 63 \times 80 = 5050 \text{ Btu/hr.}$$

The wall and ceiling losses would be:

$$0.24 \times 357 \times 80/4 = 1700 \text{ Btu/hr.}$$

Air infiltration requires:

$$800 \times 8 \times 10^{-2} \times 0.24 \times 80 = 1250 \text{ Btu/hr.}$$

This gives a total heat loss of 8000 Btu/hr and requires 7.27 ft³ of gas per hour. The apparent dilution is 110. A similar consumption in a 1000-ft² unit containing 8000 ft³ with 312 ft² of doors and windows and 1768 ft² of walls and ceiling (from Fig. B.1) totals:

	Btu/hr
Doors and windows, $1 \times 312 \times 80$	25,000
Walls and ceiling, $0.24 \times 1768 \times 80/4$	8,500
Infiltration air, $8000 \times 8 \times 10^{-2} \times 0.24 \times 80$	12,500
	<hr/> 46,000

and would require 41.8 ft³/hr of gas and would give a dilution of 191. For a 3000-ft² house the dilution would be 213.

Fig. B.1. Surface-to-volume ratios of rooms as a function of floor area. Assumes 8-ft ceilings and no weather access to under floor except for shacks.

Inspection of the calculations indicates that heat loss through the door and window units constitutes the primary loss factor. The addition of storm doors and windows, together with a reduction in surface area, tends to improve this situation. The dilution factor is also directly dependent on the assumed infiltration air value, since, if net losses occur and only entrant air is considered, the dilution factor cannot exceed 710 for the assumed temperature conditions.

For extremely well-designed and well-built construction, an overall value of 14,000 Btu/hr loss for a 1000-ft² house is approached, plus 12,500 Btu/hr for heating infiltration air, leading to a net dilution of 334. The characteristics and dilution factors for the various types of dwelling are given in Table B.2.

These calculations put on a rational basis the dilution which would be observed for open-flame burning of natural gas under extreme weather conditions for various types of dwelling units. They cannot be considered exact, but they supply information for judgment values on the dose commitment involved if the natural gas burned contains radioactive contaminants of known concentration. It should be borne in mind that open-flame heating is not a general practice, but these considerations are equally applicable to common unvented open-flame home items, such as cookstoves, bathroom heaters, and refrigerators. The dilution of about 60 as a minimum is considered conservative. For "normal" dwelling units, a dilution of about 200 appears reasonable with an upper dilution limit for best construction approaching 335.

Table B.2. Dilution factors for typical dwellings during heating at an inside-outside temperature differential of 80°F

Residence identity	Description	Dilution factor
A	10 × 10 × 8 ft shack; walls made of 1-in. wood; one door; two windows, 3 × 4 ft	110
B	Normally constructed dwelling unit of 1000 ft ² of floor area; 4 in. of rock-wool insulation; doors and windows constituting 15% of the outside surface; windows curtained	190
C	Same as residence B but with 3000 ft ² of floor area	215
D	Extremely well-designed and well-built house with storm doors and windows; 1000 ft ² of floor area	335

Our calculation can easily be extended to cover any outside temperature below 70°F, and these data appear in Fig. B.2. If temperature data for a given area and hypothetical contamination levels of natural gas are available, dose commitment calculations can be made for extended time periods.

Nonheating Domestic Gas Usage

When heating is not required, residential gas consumption is restricted to ranges, water heaters, refrigerators, clothes dryers, and other nonheating appliances. A study of nonheating gas usage in Indiana³³ on 30,417 meters gave an average usage of 6870 Btu/hr, of 6.2 ft³/hr of natural gas, with a range from 4.0 to 8.6 ft³/hr. This may be compared with the one-day average usage by:

	ft ³ /day	ft ³ /hr
Kitchen range	27	1.13
Refrigerator	34	1.42
Water heater	64	2.67
		5.22

Other appliances, such as clothes dryers, account for the remaining usage shown in the Indiana study. This consumption of natural gas does not vary widely with season, and it is much more difficult to establish dilution factors of the combustion products within the dwelling. Water heaters and clothes dryers are invariably vented. To be conservative, we can assume that venting is ineffective and that the infiltration rate of air remains constant throughout the year. This would then give a

Fig. B.2. Calculated dilution of natural gas combustion products when used for open-flame heating of various types of dwelling units. Note: the theoretical condensation limit at 70°F is 0.0125.

dilution factor of 1270 for the combustion products of the gas under nonheating conditions for the type B residence — and an annual average dilution factor of 535 for the 6000 degree-days of heating required in the San Juan Basin.

As a cross check, we can consider the kitchen only, assuming a volume of 800 ft³, with the stove and refrigerator using 2.55 ft³/hr of natural gas. This would give a dilution factor of 314. This would appear the worst credible case under nonheating conditions.

Appendix C

ESTIMATE OF HOME OCCUPANCY

C. J. Barton, Sr.

The fraction of time that a home hypothetically heated with contaminated natural gas is occupied by members of the family is an important factor in the assessment of population exposure through this exposure pathway. A preliminary estimate of the home occupancy factor for an average-size family of 3.67 (1960 census figures) during the heating season has been made using a number of assumptions as follows:

Average time at home for housewives, preschool children, and retired men	Estd 21 hr/day
Average time at home for working wives and husbands	Estd 14 hr/day
Average time at home for school children	Estd 15 hr/day
Fraction of wives working	0.25 (1960 census)
Fraction of preschool children	0.28 (1960 census)
Fraction of men retired	0.084 (1960 census)

For women	$(0.75 \times 21) + (0.25 \times 14)$ = 19.3 hr/day, av
For men	$(0.916 \times 14) + (0.084 \times 21)$ = 14.6 hr/day, av
For children	$(0.28 \times 21) + (0.72 \times 15)$ = 16.7 hr/day, av
Total person-hours	$19.3 + 14.6 + (1.67 \times 16.7)$ = 61.8 hr
Home occupancy factor	$\frac{61.8}{3.67 \times 24} = 0.70$

Data from the 1960 census have been used in this estimate because the 1970 information was not available at the time this calculation was made. The new data will probably not affect the occupancy factor very much. There is no way to check the assumptions as to the hours per day spent at home by the various members of the family, but these estimates are considered to be conservative.

Appendix D

METEOROLOGICAL BEHAVIOR OF COMBUSTION PRODUCTS RELEASED AT THE BLANCO PLANT

W. M. Culkowski G. A. Briggs

The probable behavior of combustion products released at the Blanco plant has been estimated on the assumption that wind data from Farmington, New Mexico,³⁴ are representative of the area. There are several sources of release at the plant, and these are considered separately.

The Flare Pit

The behavior of combustion products released from the flare pit is of concern when the wind blows toward the Blanco camp, just north of the plant, or toward the

plant area. The residential area will be affected by winds from the south-southwest through the southeast directions, which occur roughly 12% of the time (see Table D.1). When wind speeds are less than 10 mph, it is estimated that the plume will have risen more than 20 ft at a point 100 ft downwind due to the buoyancy induced by the heat of the plume. At wind speeds over 10 to 15 mph the plume will hug the ground. Winds from SSW to SE exceeding 10 mph occur about 5% of the time.

The plant area would be affected by winds from the northeast through east-northeast with speeds over 10

Table D.1. Frequency of occurrence of surface winds at Farmington, New Mexico, by direction and speed group (from ref. 34)

Direction	Frequency of speed group					
	1-3 mph	4-12 mph	13-24 mph	25-31 mph	32-46 mph	>47 mph
N	0.0032	0.0334	0.0030	0.0003	0.0000 ₅	
NNE	0.0033	0.0309	0.0018	0.0001	0.0000 ₅	
NE	0.0056	0.0788	0.0047	0.0001		
ENE	0.0078	0.1401	0.0090	0.0001		
E	0.0053	0.0921	0.0051	0.0000 ₂		
ESE	0.0030	0.0679	0.0080	0.0001		
SE	0.0022	0.0231	0.0036	0.0001	0.0000 ₂	
SSE	0.0012	0.0201	0.0084	0.0006	0.0001	
S	0.0016	0.0226	0.0099	0.0010	0.0004	
SSW	0.0013	0.0240	0.0122	0.0011	0.0001	0.0000 ₂
SW	0.0021	0.0398	0.0123	0.0006	0.0001	
WSW	0.0021	0.0624	0.0253	0.0009	0.0001	
W	0.0022	0.0519	0.0325	0.0023	0.0003	
WNW	0.0025	0.0361	0.0372	0.0049	0.0007	
NW	0.0011	0.0154	0.0078	0.0012	0.0004	
NNW	0.0014	0.0149	0.0038	0.0004	0.0001	

mph. Winds meeting these conditions also occur about 5% of the time.

Assuming type C stability conditions, it is estimated that typical dilutions of the combustion products at ground level from this source would be about 5×10^5 cfs as an annual average for both the residential and the plant area.³⁶

The Compressor Plants

The stacks of the compressor plants are slightly shorter than the tallest section of the roof, and this produces a complex wind regime. The behavior of the plumes from these stacks will appear "normal" when the winds are light or when the winds are directly north or south. Moderate to strong winds will force the plumes into the lee side of the building, and the center line of the plume will undulate from ground to rooftop. It is estimated that downwash would begin at about 3 to 6 mph. At about 10 mph for plant A and 15 mph for plant B the backwash is total, and the stacks serve no real purpose.

It is generally sufficient to employ a simple model to estimate downwind concentrations from buildings which create downwash effects. The equation is

$$X = \frac{Q}{CA\bar{u} + \sigma_y \sigma_z \bar{u}},$$

where

X = concentration,

Q = amount of activity emitted per unit time, curies per second,

C = empirical constant ≤ 1.0 , describing fraction of time plume is downwashed sufficiently to act as if its source were the entire or a substantial part of the building,

A = area of side(s) of building where downwash is occurring,

$\bar{u}$ = average wind speed,

$\sigma_y \sigma_z$ = diffusion constants (ref. 36).

Winds from the southwest through northwest would create downwash problems to the entire Blanco plant area. At times, the concentration of material immediately adjacent to these buildings may reach $X = Q \times 3.10^{-5}$ Ci/ft³, where Q is the entire output of the plant in curies per second assuming a 6-mph wind. Winds of this nature occur about 10% of the time.

As a general statement, one might say the stacks of the Blanco A and B plants are not high enough to prevent a great deal of the effluent from reaching the ground within the first few hundred meters.

The Boiler Plant

A similar situation occurs at the boiler plant, but the five stacks are slightly above roof level. In this case it is

estimated that downwash will commence at about 6 mph and will be total at about 25 mph. Total downwash into the plant area from the boiler plant stacks would be expected to occur less than 1% of the time.

Summary

It is estimated that the average annual ground-level concentration of combustion products in the residential area would be given by:

$$X = Q_f \times 2 \times 10^{-6} + Q_p \times 10^{-6} \text{ Ci/ft}^3,$$

where Q_f is the release of activity in combustion products from the flare pit in curies per second and Q_p is the release of activity in combustion products from the compressor plant and boiler plant in curies per second.

The average annual concentration of combustion products in the plant area would be higher. The contribution to the plant area from the flare pit would be about the same as that to the residential area, but the contributions from the boiler plant and compressors would be greater. Personnel in the buildings immediately to the east of these sites may be exposed to an annual average concentration of combustion products three times that of the residential area.

Appendix E

PUBLICATIONS AND ORAL PRESENTATIONS

1. D. G. Jacobs, E. G. Struxness, and C. R. Bowman, "A Preliminary Assessment of the Radiological Implications of Commercial Utilization of Natural Gas from a Nuclearly Stimulated Well," presented by D. G. Jacobs at the Symposium on Engineering With Nuclear Explosives, Las Vegas, Nevada, January 14-16, 1970. Published in the proceedings of the symposium, CONF-700101 (vol. 1) pp. 831-49.

2. D. G. Jacobs, E. G. Struxness, M. J. Kelly, and C. R. Bowman, "Consideration of the Radiological Impact from the Hypothetical Use of Contaminated Natural Gas from Nuclearly Stimulated Reservoirs," presented by D. G. Jacobs at the Second International Radiological Protection Association Congress, Brighton, England, May 5, 1971. To be published in *Health Physics*.

3. C. J. Barton, D. G. Jacobs, M. J. Kelly, and E. G. Struxness, "Radiological Considerations in the Use of Natural Gas from Nuclearly Stimulated Wells," presented by C. J. Barton at the Atomic Industrial Forum 1970 Annual Conference, Washington, D.C., November 16-19. Published in *Nuclear Technology*, July 1971.

4. C. J. Barton, "Radiological Considerations in the Use of Natural Gas from Nuclearly Stimulated Wells," presented by C. J. Barton in the institute on "Environmental Aspects of Radiation Sciences," conducted by the Special Training Division of Oak Ridge Associated Universities. Published as ORNL-CF-71-1-12.

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