A PRELIMINARY ASSESSMENT OF THE RADIOLOGICAL IMPLICATIONS OF COMMERCIAL UTILIZATION OF NATURAL GAS FROM A NUCLEARLY STIMULATED WELL[a]

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Abstract

Widespread utilization of nuclear explosives, in conjunction with the natural gas industry, can result in radiation exposure of sizable population groups. It is prudent to make realistic assessments of such potential radiation exposures before they occur and, unless the expected exposures are clearly insignificant, to consider these exposures in evaluating the net benefit of this particular use of nuclear energy. All pertinent facts relating to such assessments should be made public and presented in such a way that those who are to assume the risks, if any, can make a reasonable judgment as to whether the risks are acceptable.

Radioactivity in natural gas from the Gasbuggy cavity has been analyzed prior to and during flaring operations. None of this gas has entered the collection and distribution system, but a theoretical analysis has been made of the hypothetical impact on members of the public that would have occurred if the gas had been introduced into the commercial stream. Dose equivalents have been estimated for both workers and consumers. In this analysis, Gasbuggy gas has been traced through a real gas-collection system and processing plant, as represented by the present situation existing in the San Juan Production Division, El Paso Natural Gas Company. In addition, a number of considerations are presented which would apply to radiation exposure in metropolitan areas.

Results of this analysis for the Gasbuggy well indicate hypothetical dose equivalents to various population groups to be well within the annual dose limits suggested by the International Commission on Radiological Protection. Projection to a steady-state situation involving extensive natural gas production from many producing wells also resulted in hypothetical dose equivalents within the annual dose limits.

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Simple extrapolation of the results from this analysis to potential exposures resulting from nuclear stimulation of other gas reservoirs cannot be made on a direct basis, but this method of evaluation should point to the potential exposure situations of greatest concern in any exploitation of this technique.

Introduction

If the peaceful utilization of nuclear explosives becomes widespread, radiation exposures to rather sizable population groups will be unavoidable. It is prudent to make realistic assessments of such potential radiation exposures before they occur and, unless the expected exposures are clearly insignificant, to consider these exposures in evaluating the net benefit of this particular use of nuclear energy. All pertinent facts relating to such assessments should be made public and presented in such a way that those who are to assume the risks, if any, can make a reasonable judgment as to whether the risks are acceptable.

This paper reflects the progress to date of a theoretical study directed to considerations of potential radiation impact on consumer population groups from commercial application of nuclear explosives in the natural gas industry. Potential exposure pathways are evaluated in light of the technology related to production, processing, transmission, and distribution of natural gas.

Federal and state regulatory agencies must become involved in any considerations leading to the actual marketing of natural gas or its by-products which may contain radioactivity resulting from nuclear stimulation of gas reservoirs. These considerations will constitute a "risk versus benefit" judgment.[1,2,3] It must be recognized that the focal point of such a decision will be the potential radiation exposure of a very large number of people and the potential biological risk involved. We hope that studies such as ours will provide the type of realistic information that will allow a reasonable decision to be made. Responsible representatives of federal, state, and local government must make continued efforts to effectively evaluate the potential benefits to be derived against the potential biological risks that may be incurred, but the ultimate decision will lie with the potential consumers.

Recommended Standards for Radiation Exposure

The International Commission on Radiological Protection (ICRP), the National Committee on Radiation Protection and Measurement (NCRP), the Federal Radiation Council (FRC), and other recognized authorities have standards and interpretations that can be applied to Plowshare situations. The basic recommendations are given in terms of maximum permissible radiation doses (MPD's) to organs of the body and maximum permissible body burdens (MPBB's) that will deliver these doses. It is from these basic standards that working limits are derived in the form of maximum permissible intakes (MPI's) and maximum permissible concentrations (MPC's). The ICRP and NCRP recommendations are effectively equivalent.[4,5] These recommendations have been largely adopted by the FRC, reformulated as Radiation Protection Guides,[6] and issued as guidance to federal agencies, such as the Atomic Energy Commission (USAEC) and the Public Health Service (USPHS). The MPD's recommended by the ICRP and NCRP were intended primarily for the protection of occupational workers; that is, individuals directly engaged in radiation work. These workers, by definition, are typical adult males and females in the United States or Europe that are expected to work with radiation and/or radioactive materials and be potentially exposed thereby for a period of 50 years. These basic limits are intended for planning the design and operation of radiation sources subject to close control and for exposure situations that can be carefully monitored.

Radiation exposure situations involving the public differ from occupational exposure situations in a number of ways. First, they may be less subject to control than radiation sources used in the nuclear industry. Second, they may involve contamination of the environment, the assessment of which must be done through procedures of environmental sampling and statistical calculations far more complex than those used in monitoring occupational workers. Third, they involve other considerations because of inhomogeneities in the exposed population groups (for example, age distribution, dietary habits, sources of food and water, etc.).

Concept of Critical Nuclides, Pathways, and 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, 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 nuclides and pathways. 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 ICRP[7] 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.

The critical group represents 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.[8] 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.

Radioactivity in Gasbuggy Products

The Project Gasbuggy device was detonated on December 10, 1967. Postshot gas samples have been periodically withdrawn from the Gasbuggy cavity and have been analyzed by Lawrence Radiation Laboratory.[9,10,11] 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. Tests for the presence of particulates in the gas stream have indicated that nongaseous fission products are absent.[10] Recent particulate tests on the gas stream have lowered the minimum detection threshold for ^{90}Sr by four orders of magnitude from the previously reported value.[12] Traces of ^{37}A (35-day half-life), ^{131}Xe (8-day half-life), 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. The ^{14}C exists primarily as CO_2 in the cavity gas, although it also exists in the form of CH_4 and CO.

A small amount of gas was removed from the cavity and flared in early 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/cm^3 of tritium and 112 pCi/cm^3 of ^{85}Kr. The concentrations of tritium and ^{85}Kr in the products removed from the Gasbuggy cavity have been decreasing with time. When the concentrations are plotted as a function of the cumulative volume of gas removed from the cavity (Fig. 1), the drop in concentration follows the curve anticipated for the case in which gas removed from the cavity is replenished by uncontaminated gas from the formation with mixing occurring in the cavity. The equation for the straight lines in Fig. 1 is:

$$C_p = C_o e^{-P/V_o} \qquad (1)$$

where

C_o is the concentration of the radionuclide in the cavity gas at one atmosphere of pressure at the time production starts, corrected for radioactive decay to the date of the detonation (pCi/cm^3),

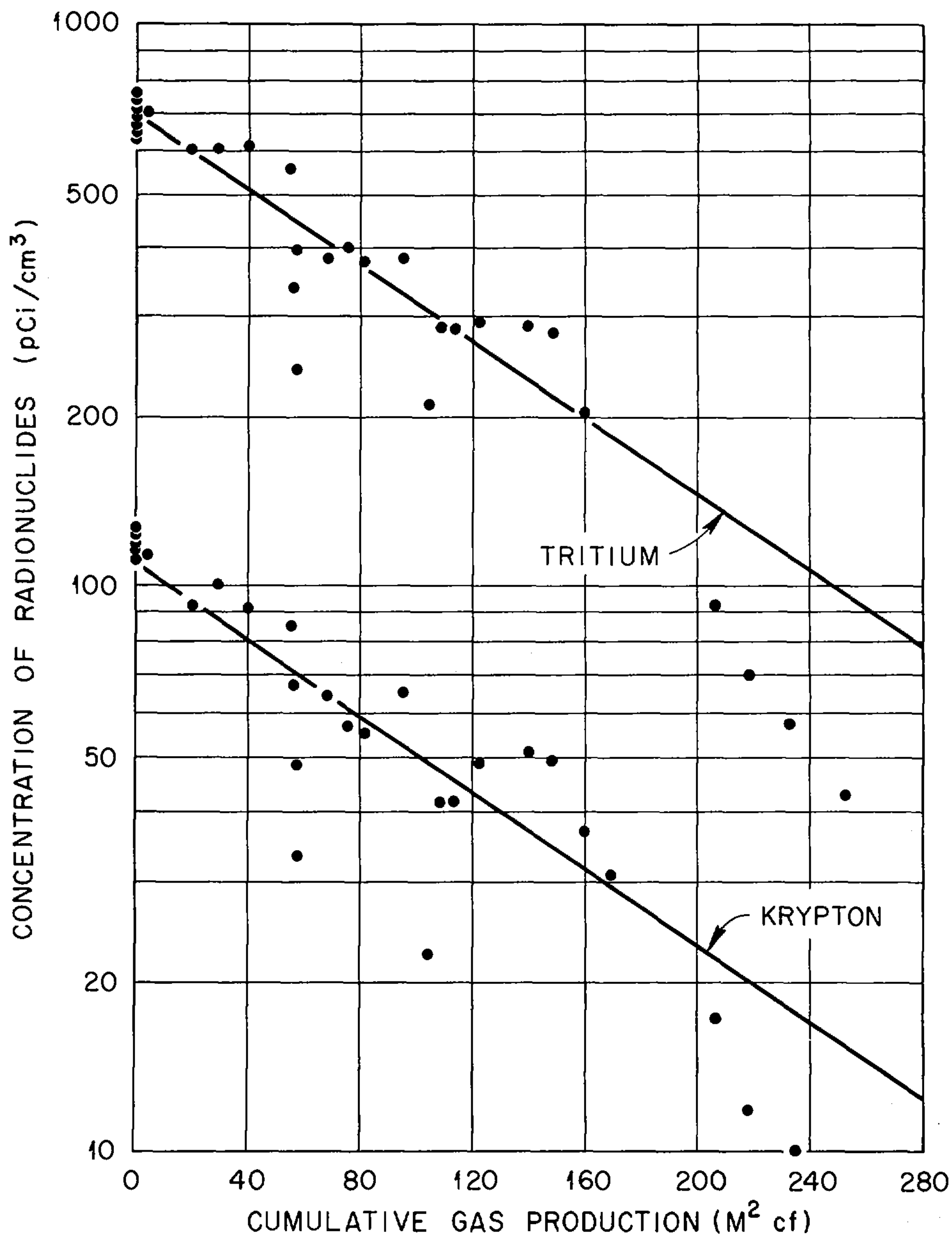
P is the cumulative production of gas from the cavity in millions of cubic feet (M^2cf),

V_o is the initial volume of gas at one atmosphere of pressure in the cavity (M^2cf), and

C_p is the concentration of the radionuclide in the gas at the wellhead at one atmosphere of pressure after a cumulative production of P. (C_p is in units of pCi/cm^3, corrected for radioactive decay to the date of the detonation.)

The initial volume of gas in the cavity was assumed to be 128 M^2cf, corrected to normal conditions of one atmosphere of pressure and 65°F. It should be recognized that a close fit of the data to the assumed exponentially declining curve would be obtained only if the influx of gas into the cavity from the formation occurs as rapidly as removal of gas at the wellhead. This is not always the case since the bottom-hole pressure decreases during periods of rapid gas withdrawal and changes in flow rate are evidenced by departures from the curve.

Based on radiochemical analyses and flow-rate data,[11] it is estimated that 1860 curies of tritium and 290 curies of ^{85}Kr were produced through February 3, 1969, in the first 161 M^2cf of gas. Estimates of the total quantity of tritium and ^{85}Kr that will be produced during the lifetime of the well are approximately 2500 and 350 curies, respectively, from Eq. (1). The krypton value agrees closely with the predicted quantity that was estimated to have been produced.[9] The projected value for tritium assumes that no appreciable



Concentrations of Tritium and Krypton-85 in Gasbuggy Gas as a Function of the Total Volume of Gas Produced (the Straight Line Represents the Predicted Concentrations Based on Complete Mixing of 128 M^2 cf of Gas in the Chimney).

Fig. 1. Concentrations of Tritium and Krypton-85 in Gasbuggy Gas as a Function of the Total Volume of Gas Produced.

exchange of tritium from water to methane will occur, since approximately 40,000 curies of tritium were estimated to be present initially.

Samples of liquid hydrocarbons taken from the Gasbuggy well on February 25, 1969, were fractionated by distillation. Total tritium and chromatographic analyses on these fractions were performed by the Analytical Chemistry Division of the Oak Ridge National Laboratory. Except for the low boiling fraction (97 to 219°F), there was very good correlation between the measured activity levels (about 0.14 μCi/ml) and the activity levels for the mixtures of hydrocarbons in the various fractions predicted assuming a constant tritium to hydrogen ratio. It appears reasonable to assume that tritium is uniformly distributed over all the hydrocarbons in relation to their hydrogen content, although there is a suggestion from this, and other available data, that the tritium concentration of propane through heptane is somewhat lower than one would estimate on the basis of a constant tritium ratio for all hydrogen-containing species.

Collection and Processing of Natural Gas

The gas-collection system in the San Juan Basin is internally quite complex, but only two principal outlets exist through Blanco plant or Ignacio plant (Fig. 2). Discussion of this collection and processing system is useful in developing an understanding of potential exposure pathways that would result from real disposition of natural gas and by-products from a nuclearly stimulated well. In this hypothetical situation the gas from the Gasbuggy well would enter a trunk line heading toward either the Blanco or Ignacio processing plants. As the gas moves along the system, it is mixed with uncontaminated gas being produced from other wells in the basin.

A landowner under lease agreement with El Paso Natural Gas Company 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. 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. Several farm taps exist in the San Juan Basin. The potential dilution of gas introduced into the system from the Gasbuggy well would be least at these farm taps if the one-way valve should fail. The location of farm taps lying closest to the main collection trunks are shown in Fig. 2.

Ordinarily, gas wells produce liquid hydrocarbons and water as well as gaseous products. Some of these liquids, called "drip liquids," condense at the wellhead and are collected in tanks for sale to local refineries in the Farmington-Aztec-Bloomfield area where they are fractionated and further refined. Most of the water is removed from these drip liquids at the wellhead, generally by adsorption into glycol, and disposed by evaporation.

During transmission of the gas, further condensation of water vapor and higher hydrocarbons also occurs. The quantity varies seasonally due to temperature changes. These liquids 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 lines to facilitate removal of the liquids at pigging stations along the lines. These pigged liquids are stored in tanks and sold to the local refineries.

At the processing plants the gas stream is further dehydrated and liquid hydrocarbons (propane and higher) are removed from the product gas. Liquid hydrocarbons from Blanco plant are piped to Wingate plant near Gallup, New Mexico, where they are fractionated and distributed by rail and truck. At

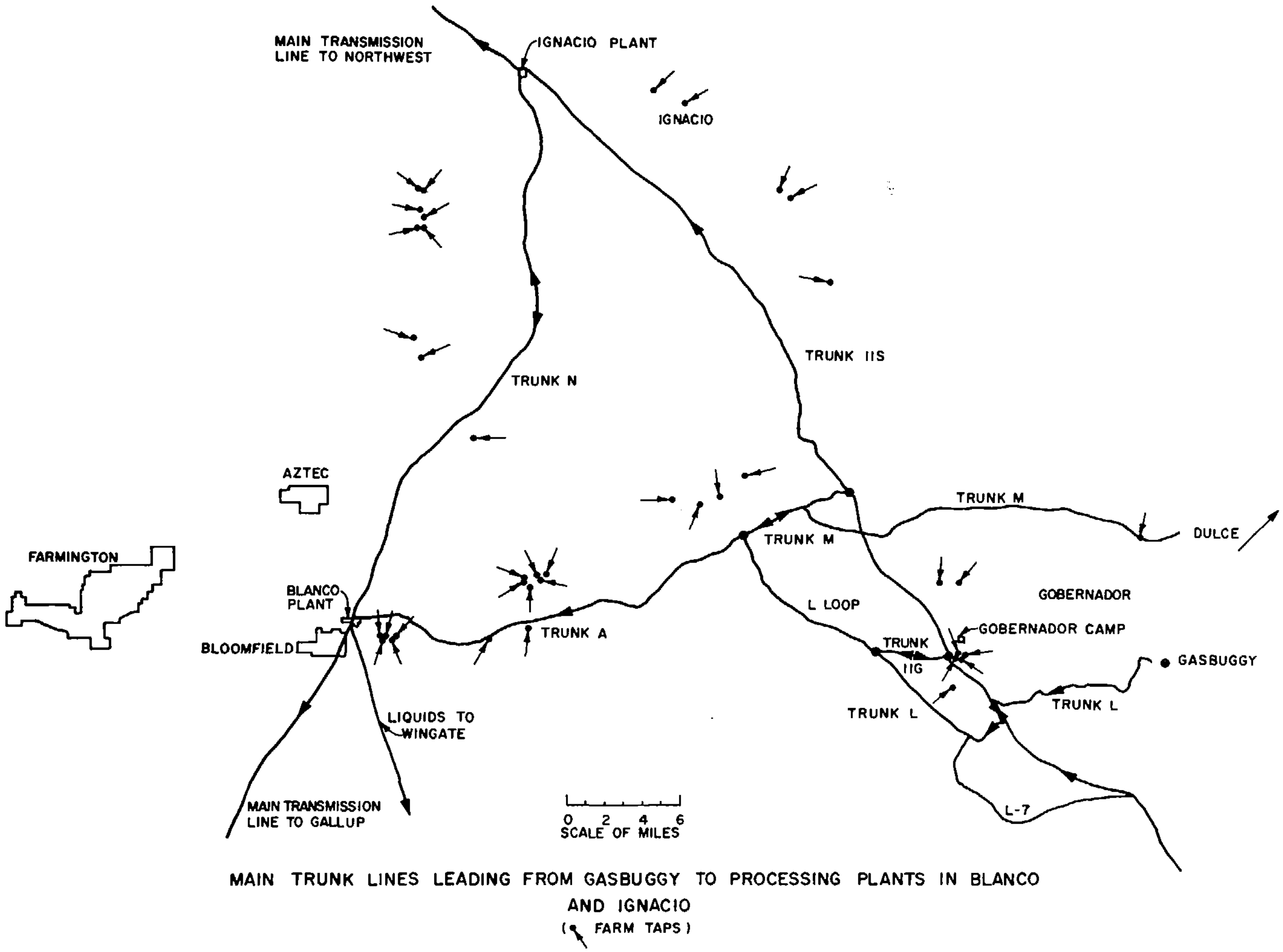


Fig. 2. Main Trunk Lines Leading from Gasbuggy to Processing Plants in Blanco and Ignacio.

Ignacio plant some butane and propane is separated and may be marketed locally. Mercaptan is added to the product gas (primarily methane), and it enters pipelines leading to California to the southwest from the Blanco plant or to the Pacific Northwest from the Ignacio plant. Fuel for the operation of compressors, electric power plants, and dehydrators is removed from the product stream and is combusted at the plant site. Wet fuel (containing hydrocarbons above propane) is used for the operation of gasoline absorbers. Excess wet fuel and residue from the absorption plant which cannot be economically recovered is flared in a surface pit.

The Approach to Assessment

In order to facilitate the assessment of the radiological impact from the commercial use of gas from nuclearly stimulated well, the study is divided into three phases. Phase I is a consideration of the potential population and employee exposures within the San Juan Basin from the hypothetical utilization of gas from the Gasbuggy well. It seems likely that in this region the possible dilution of the radioactivity from this single source would be the lowest and the potential exposures, the highest.

In Phase II the considerations are extended to include the hypothetical utilization of natural gas and other contaminated by-products from the Gasbuggy well by population groups outside the San Juan Basin. In this phase we take into account the dilution of gas from the San Juan Basin with gas produced in other fields, such as the Permian Basin.

The final extension of the problem, Phase III, will consider the potential nuclear stimulation of an entire reservoir in which temporal sequencing of detonations combined with decreasing concentrations of radioactivity in the individual wells would lead to a steady-state condition in which the concentration of radioactivity in consumed gas would remain relatively constant. Before we begin this phase of the study, we hope to have more representative information available on the likely radionuclide content of cavity gas from wells stimulated using nuclear explosives and emplacement configurations designed to produce lower quantities of residual tritium in the gas.

This paper reflects our progress to date, but it should be emphasized that our analysis is not yet complete. We anticipate making similar assessments for product disposition from Rulison before beginning Phase III.

In assessing each of these phases, we attempt to make conservative, but realistic, assumptions regarding the disposition and use of natural gas and its by-products. Using such information, the more important exposure pathways are delineated. Potential radiation exposure situations and estimates of the associated dose equivalents using existing computer programs are made. These programs include the flexibility to consider external beta and gamma radiation from submersion and from contaminated surfaces, as well as internal exposures following ingestion, skin absorption, and inhalation. Furthermore, information is built into the computer programs to allow consideration of age-dependent factors in the dose rate that would be obtained from tritium.

Hypothetical Population Exposures

Tritium and ^{85}Kr are the radionuclides of major concern in the gas removed from the Gasbuggy cavity. Although there is some ^{14}C present in the gas, it exists primarily 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 3 to 5. Krypton is not retained to any significant extent by the body, and the primary mode of exposure is from submersion in contaminated air.[4] In the case of tritium, retention by the body is about two orders of magnitude greater for the oxide than for the gas. 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 significant radiation exposures from use of natural gas 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 since more than 98% of the total production of natural gas and its associated liquid hydrocarbons is consumed as fuel. Tritiated water vapor enters the body from the air in approximately equal amounts by inhalation and absorption through the skin.[4]

Numerous exposure pathways can be postulated. The most direct modes of exposure are submersion, inhalation, and absorption through the skin. Only these modes of exposure have been considered in this preliminary analysis, though we are awaiting with interest the experimental results being obtained by the U. S. Public Health Service so that we can consider intake by 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.[14]

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

There are a number of factors which affect the concentration of radionuclides available for the exposure of domestic consumers. These factors include:

1. Concentration of radionuclide at the wellhead.
2. Production rate.
3. Pipeline dilution.
4. Quantity of gas consumed.
5. Fraction of combustion products vented inside the home.
6. Home dilution.
7. Home occupancy.

Home Heating and Other Domestic Uses[15]

Open flame burning of natural gas in a dwelling results in the production of heat, carbon dioxide, and moisture within a confined space. Nonventilated heating is not representative; however, it represents a "worst" case for this preliminary assessment. In warm weather ventilation will be at a maximum to remove undesirable heat and dilution of combustion products from nonheating appliances would be at a maximum. In the winter the opposite occurs and minimum dilution of these combustion products and those from heating would be achieved. Hence, use of natural gas from a nuclearly stimulated well would probably give rise to maximum radiation exposures during the heating season.

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 a normal inside temperature (70°F). Exchange of outside air with that inside the dwelling unit must also be evaluated so that we may determine the average dilution of combustion products within the living space. Several types of dwellings have been considered, and the estimated dilution factors during one 80-degree day of nonvented heating are shown, along with the characteristics of the dwellings, in Table 1. All of the tritium is assumed to be present as HTO following combustion of the gas.

Dilution factors during periods when heating is required are based on heat conduction through typical construction materials and infiltration of air into dwelling units around doors and windows. Heat requirements are based on the thermal input required to warm infiltrating air and to balance conductive losses. The quality of construction is reflected in the rate of heat loss from the dwelling. As an example, a dilution factor of 190 is obtained during heating at an inside-outside temperature differential of 80°F for a 1000 ft^2 house of normal construction. During periods when the heating requirements are lower, gas consumption is also lower and the effective dilution factor is greater. Heat losses are related to the surface area exposed to the outside air; therefore, larger dwellings require less heat per unit volume to maintain a given temperature and the dilution factor increases with an increasing size of house.

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 Indiana indicates an average total consumption of about 150 ft^3/day for this combination of appliances.[16] This can be compared to 12.5 ft^3 of gas required per degree day of heating for a normally constructed house with 1000 ft^2 of floor area. 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. To be conservative, we can assume that the infiltration rate of air remains constant throughout the year. This would then give a dilution factor of 1270 for the combustion products of the gas under nonheating conditions for the Type B residence.

In addition to these considerations, appropriate corrections in the calculated dose equivalents for exposure situations from domestic consumption of gas should be made for the fraction of combustion products vented outside the home and home occupancy.

Potential Radiation Exposure from Domestic Use at Farm Taps

As mentioned previously, several farm taps exist in the San Juan Basin and those lying closest to the main transmission lines are shown in Fig. 2. Potential dilution of Gasbuggy gas introduced into the collection system would be minimal in laterals and trunks near the well. The nearest farm tap is located near a point in the collection system having an average daily gas flow over 50 M^2cf. Failure of the one-way isolation valve could result in potential domestic consumption of gas having the highest concentration of radioactivity. Dose equivalents have been estimated for the occupants of the hypothetical normal house of 1000 sq ft of floor area (Type B) for average

Table 1. Dilution Factors for Typical Dwellings During Heating at an Inside-Outside Temperature Differential of $80^{\circ}F$

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

nonheating usage and for heating corresponding to about 6000-degree days per year.[17] Measured values for the production of gas and for the concentration of tritium, ^{85}Kr, and ^{14}C during production testing of the Gasbuggy well were used (Fig. 1). The values listed in Table 2 are potential annual dose equivalents for an occupant of such a house, assuming continuous occupancy. The dose from all forms of ^{14}C is shown in the table. Although CO_2 would undoubtedly be removed from the gas to render the gas of sufficient quality for commercial uses, such removal would probably occur at the processing plants.

Exposures from Releases of Activity at Processing Plants

As mentioned previously, gas produced in the vicinity of the Gasbuggy well in the San Juan Division of El Paso Natural Gas Company is processed at either Blanco plant or Ignacio plant. Since Blanco plant has the larger capacity, our initial consideration is limited to that plant. Nearly 95% of the input gas stream leaves the plant as dry product gas. Approximately 2.4% of the material is used or released at the plant site, and about 2.6% of the input stream is separated as liquid hydrocarbons which are pumped to Wingate plant for further distribution. The average input of gas to Blanco plant is about 576 M^2cf/day. About 4.3 M^2cf/day is used as fuel for compressors; approximately 5.2 M^2cf/day is used as fuel for boilers and as other fuel; and roughly 1.3 M^2cf/day of nonmarketable material is flared in an open pit. In each of these cases, combustion products are released to the environment. In addition to these releases, about 0.2 M^2cf/day is released in desiccant dehydration and 0.01 M^2cf/day in glycol dehydration.

The various releases from the plant 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 pumped to the Wingate plant. With these assumptions, the estimated dispositions of tritium and krypton are indicated in Table 3.

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, Environmental Science Services Administration, Oak Ridge, Tennessee.[18] Their estimates were based on the assumption that wind data from Farmington, New Mexico, is representative of the 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 miles per hour, 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 miles per hour, the heat of the plume would permit a sufficient rise to carry it above the plant and residential areas.

Using these conditions, Culkowski and Briggs[18] suggest that typical annual average dilution of the combustion products for both the residential and plant areas would be about 5×10^5 ft^3/sec. During the hypothetical production of the first 161 M^2cf of Gasbuggy gas, the average ground level atmospheric concentrations would be about 1.3×10^{-11} μCi/cm^3 for ^{3}H and 2×10^{-12} μCi/cm^3 for ^{85}Kr.[19] The dose equivalents from 168 hr per week exposure to these concentrations would be primarily due to tritium and would amount to about 0.025 mrem to the total body for an annual exposure.

Table 2. Annual Dose Equivalents from the Hypothetical Use of Gas from the Gasbuggy Well at a Point in the San Juan Basin Where the Average Daily Flow in the Pipeline is 50 M^2cf

	Annual Hypothetical Dose Equivalents (mrem)		
Production Year	^{3}H (Total Body)	^{85}Kr (Skin Dose from Submersion)	^{14}C (Total Body)
1968	4.1	0.25	0.04
1969	2.8	0.17	0.08
1970[a]	0.29	0.017	0.01
1971[a]	0.24	0.014	0.01
1972[a]	0.20	0.012	0.01

[a]Projected on the basis of 0.2 M^2cf/day gas production with a decreasing concentration of tritium and krypton-85. The concentration of carbon-14 has remained relatively constant during the first 161 M^2cf of gas production.

Table 3. Disposition of Tritium and Krypton During the Hypothetical Processing of Gasbuggy Gas at the Blanco Plant During the First 160 M^2cf Production

	Estimated Hypothetical Quantity of Activity Released (curies)	
Disposition	^{3}H	^{85}Kr
Flare pit	6	1
Boiler fuel	20	2.5
Compressor fuel	13	2
Dehydration	1	0.1
Liquid product (to Wingate)	90	---
Dry gas product	1720	290
Not accounted for	10	2

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 Briggs[18] estimate the average dilution factor for all emissions from the plant, except for the flare pit, to be about 10^6 ft^3/sec. In the plant area the concentrations would be higher, especially near the compressor facilities. In this area the annual average concentration of the combustion products may be as high as $x = Q(3 \times 10^{-5})$ parts/ft^3 where Q is the total emission of each of the compressor facilities.

For the residential area the average ground level atmospheric concentration of tritium and ^{85}Kr from emissions other than the flare pit is estimated to be 5×10^{-11} $\mu Ci/cm^3$ and 7×10^{-12} $\mu Ci/cm^3$, respectively. The dose equivalents to the whole body from an annual exposure to these air concentrations would be about 0.09 mrem.

Near the compressor facilities the average concentrations of ^3H and ^{85}Kr are estimated to be about 2×10^{-10} $\mu Ci/cm^3$ and 3×10^{-11} $\mu Ci/cm^3$, respectively, during the production of the hypothetical 161 M^2cf of Gasbuggy gas. Dose equivalents to the whole body from an annual exposure at these concentrations for 40 hr per week would be about 0.14 mrem.

Considering the sum of these hypothetical exposures, the dose equivalents to the whole body for a nonworking resident of the Blanco camp is estimated to be a maximum of 0.12 mrem during the first year of production testing; and, for a Blanco plant employee residing at the camp, the maximum is estimated to be 0.23 mrem. An additional 0.5 mrem would potentially have been received during this period if we assume normal gas consumption for appliances and home heating by nonvented heaters for 6000-degree days of heating in a normally constructed house. Hypothetical exposures in subsequent years would be considerably lower, because the concentrations of radioactivity in the gas being removed from the Gasbuggy well are more than an order of magnitude lower than the original levels.

Hypothetical Population Exposures in Metropolitan Areas

Gas leaving the San Juan Basin is mixed with gas from other basins during its transmission to eventual consumer areas. While an analysis of a specific area using real input data has not been made, we have made some preliminary estimates of exposure situations that might be encountered in a metropolitan area.

Natural gas is used in metropolitan areas for operation of steam plants to generate electricity and for a wide variety of industrial and commercial applications, as well as for domestic consumption. Releases of combustion products from steam plants are through tall stacks, and they represent elevated point sources, while the releases from most of the industrial and domestic uses can be considered to be spread uniformly over a sizable area of ground surface.

S. R. Hanna and F. A. Gifford of the Air Resources Atmospheric Turbulence and Diffusion Laboratory, ESSA, are in the process of developing models to describe the dispersion of pollutants from ground level area sources in metropolitan areas.[19] Data is introduced into their computer program in a grid format. This program can be used to describe the ground level atmospheric concentration of any type of pollutant, including radioactivity, for a ground level area source. Some of their preliminary trials indicate that the ground level air concentration of a pollutant will be on the order of 10^{-5} ppm for the daily generation of a unit concentration of the pollutant per square mile. In considering the total atmospheric concentration of radioactivity over metropolitan areas from the hypothetical use of natural gas from nuclear stimulated wells, the concentrations estimated for the ground level area sources need to be added to the concentrations estimated for releases from elevated point sources, which can be estimated using local meteorological conditions with available mathematical models. In addition to these potential contributions to the radiation exposure from general atmospheric levels of radioactivity in a metropolitan area, it will also be necessary to consider the potential contributions from radiation exposure inside dwellings from domestic consumption of gas.

We can describe a hypothetical exposure situation based on these types of releases. Table 4 shows dose equivalents calculated for a hypothetical situation for the center of a metropolitan area where the average daily use of gas is 2 M^2cf/day per square mile, where heating for 1700-degree days for a 1000-sq-ft house is accomplished with nonvented heaters, and where nonvented appliances are assumed to be used. In most localities, the use of gas would be lower than the rate we have assumed, as would the resultant atmospheric concentration.

There is a lower limit to the average annual tritium concentration due to tritium from natural sources and weapons testing. If we assume that air is 1% water vapor by volume (8 ml of liquid water per cubic meter of air) and that the tritium ratio of atmospheric water vapor is 100, the lower limit of tritium concentration in air is about 2.6 pCi/m^3, which would give rise to an annual whole body dose of 0.0048 mrem.

The estimated radiation exposure from domestic consumption could be largely eliminated by using proper venting. The radiation exposure from nonheating use of natural gas would be about the same, regardless of geographic location, but the exposure from heating would be directly related to the degree days of heating required. In the United States the number of degree days ranges from less than 100 for Key West, Florida, to 10,000 in some areas of the Rocky Mountains. The population is distributed rather normally with respect to the required degree days of heating with average requirements of about 5100 ± 1600.

Looking ahead to the possible wide-scale application of nuclear devices for stimulation of natural gas reservoirs, we anticipate that a steady-state concentration of radioactivity in the gaseous products would result from dilution of gas from newly stimulated wells with gas from other basins or from stimulated wells in which the radioactivity had been depleted. Although one cannot predict, at this time, what this steady-state concentration would be, if the original concentrations of tritium in the Gasbuggy well were representative and each well could produce 1 M^2cf/day for 25 years, the steady-state concentration of tritium would be about 0.3 μCi/ft^3 or 10 pCi/cm^3. These levels of tritium are not representative of those expected in future applications of nuclear stimulation where explosive design and emplacement techniques will be used to reduce the quantity of residual tritium. We are looking forward to the analysis of gas samples from the Rulison cavity. In order for nuclear stimulation of gas reservoirs to be economically attractive, the rate of production associated with each detonation will need to be on the order of 5 to 10 M^2cf/day.[20] Furthermore, it is unlikely that all future supplies of natural gas will be produced from nuclearly stimulated wells; so there would be further dilution afforded by mixing of the contaminated gas with uncontaminated gas from other basins. Each of these factors would contribute to lowering the steady-state concentration of tritium at the point of natural gas consumption.

Table 4. Annual Potential Dose Equivalents from Hypothetical Exposure of Populations in Metropolitan Areas

	Maximum Potential Dose from Tritium (mrem/year)		
	From Atmospheric Exposure for Ground Level Release of 2 M^2 cf/mi^2-day	From Domestic Consumption in Type B Residence	
Tritium Concentration in Gas at the Point of Use (pCi/cm^3)		Heating for 1700-degree days[a]	Nonheating[b]
10 (~ 0.3 μCi/ft^3)	0.38	5.8	15
5	0.19	2.9	7.4
2	0.08	1.2	2.9
1	0.042	0.58	1.5
0.5	0.024	0.29	0.74
0.2	0.012	0.12	0.29
0.1	0.0086	0.06	0.15
0.05	0.0067	0.03	0.07
0.0	0.0048[c]	0.00	0.00

[a]Assumes no venting and gas consumption of 12.5 ft^3/degree-day of heating.

[b]Assumes no venting and 150 ft^3/day gas consumption.

[c]Whole body dose from tritium due to its presence from natural sources and from fallout from weapons testing.

In considering the dose values presented in Table 4, we must remember that, although these hypothetical radiation exposures would give rise to potential doses of less than 170 mrem per year, the use of natural gas from nuclearly stimulated wells represents only one potential source of exposure. Also, in this preliminary analysis, only direct modes of exposure through inhalation, submersion, and absorption through the skin have been considered. The recommendations of the ICRP and other authorities specifically require that radiation exposures from all sources, other than natural background, be considered in any radiological safety evaluation.[4-6] Furthermore, these potential exposures could involve many millions of people; so extreme caution should be used in establishing "permissible" concentrations of man-made radioactivity in natural gas that would be considered acceptable for industrial and domestic consumption.

Summary and Conclusions

Preliminary estimates have been made of the potential radiation exposures that might result from the domestic and commercial utilization of natural gas from a nuclearly stimulated well. Although none of the gas from the Gasbuggy well 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.

The hypothetical dose equivalents to various population groups were well within the annual dose limits prescribed by the ICRP and other authorities when the single well was considered.[4-6] Projection to a steady-state situation also yielded dose equivalents that are within these limits, even though we have considered the very conservative condition of domestic consumption with no provision for venting of combustion products. In spite of the fact that the prescribed limits seem attainable, because of anticipated improvements in device, design, and emplacement techniques, we feel that extreme caution should be used in establishing "permissible" concentrations of man-made radioactivity in natural gas for industrial and domestic consumption. We base our caution on the fact that nuclear stimulation of natural gas reservoirs represents only one of many potential sources of radiation exposure and that an extremely large population is involved. We subscribe to the philosophy that any amount of radiation exposure involves some risk and that every practicable effort should be made to keep the dose levels to members of the public as low as possible.

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