ORNL-4748
UC-41 - Health and Safety
UC-35 - Nuclear Explosions - Peaceful Applications

**THEORETICAL EVALUATION OF CONSUMER
PRODUCTS FROM PROJECT GASBUGGY**

FINAL REPORT

**PHASE II: HYPOTHETICAL POPULATION
EXPOSURES OUTSIDE SAN JUAN BGIN**

D. G. Jacobs C. R. Bowman
C. J. Barton R. Harris
M. J. Kelly F. A. Gifford, Jr.
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National Technical Information Service
U.S. Department of Commerce
5255 Port Royal Road, Springfield, Virginia 22161
Price: Printed Copy \$3.00; Microfilm \$4.00

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HEALTH PHYSICS DIVISION

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FEBRUARY 1972

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THEORETICAL EVALUATION OF CONSUMER PRODUCTS FROM PROJECT GASBUGGY, FINAL REPORT. PHASE II. HYPOTHETICAL POPULATION EXPOSURES OUTSIDE THE SAN JUAN BASIN

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ABSTRACT

Estimates of doses that might be received by individuals living within the San Juan basin in western New Mexico from the hypothetical use of Gasbuggy gas were given in a previous report (ORNL-4646). This report extends those studies to include potential doses to individuals in west coast metropolitan areas. Tritium is the radionuclide of most concern. Calculations show that a maximum annual radiation dose of 2.2 to 2.5 millirems/year might be attained in these areas if gas containing 1 pCi/cm³ of tritium were used in homes having unvented space heaters. The potential average annual dose to members of the public in the same areas is estimated to be about 0.5 millirem/year. These doses, as well as potential doses resulting from use of liquid hydrocarbons separated from gas and from possible use of by-products manufactured with tritium-contaminated gas fractions, were small compared with the Federal Radiation Council's Radiation Protection Guide of 170 millirems/year (whole body) and with background radiation levels in the normal human environment.

INTRODUCTION

A theoretical evaluation of doses that would be anticipated from the hypothetical utilization of natural gas from the Gasbuggy cavity was initiated at ORNL during the latter part of 1968. This study is divided into three parts.³ Phase I was concerned with the impact of the hypothetical injection of Gasbuggy gas into the gas collection network of the San Juan Division of El Paso Natural Gas Company (EPNG). Results of this study, reported initially in project progress reports,⁴⁻⁷ have been collected in a topical report⁸ and described in the open literature.^{9,10} Phase II considers hypothetical exposures from use of Gasbuggy gas or from natural gas by-products by consumers outside the San Juan basin. Phase III, covering the radiological safety assessment of the development of an entire natural gas reservoir by use of nuclear explosives, is being delayed pending the availability of data on probable radioisotope content of natural gas from wells stimulated by nuclear explosives especially designed for the purpose. This work is not presently considered to be part of the Gasbuggy project. The Miniata event, conducted at the Nevada test site on July 8, 1971,

1. El Paso Natural Gas Company, El Paso, Tex.
2. Air Resources Atmospheric Turbulence and Diffusion Laboratory, National Oceanic and Atmospheric Administration, Oak Ridge, Tenn.
3. D. G. Jacobs, E. G. Struxness, and M. J. Kelly, *First Quarterly Progress Report on the Theoretical Safety Evaluation of Consumer Products from Project Gasbuggy*, ORNL-TM-2427 (February 1969).
4. M. J. Kelly et al., *Second Quarterly Progress Report on the Theoretical Evaluation of Consumer Products from Project Gasbuggy*, ORNL-TM-2513 (March 1969).
5. D. G. Jacobs, P. S. Rohwer, and K. E. Cowner, *Third Quarterly Progress Report on the Theoretical Evaluation of Consumer Products from Project Gasbuggy*, ORNL-TM-2657 (July 1969).
6. D. G. Jacobs and M. J. Kelly, *Fourth Quarterly Progress Report on the Theoretical Evaluation of Consumer Products from Project Gasbuggy*, ORNL-TM-2721 (October 1969).
7. D. G. Jacobs and M. J. Kelly, *Fifth Quarterly Progress Report on the Theoretical Evaluation of Consumer Products from Project Gasbuggy*, ORNL-TM-2862 (February 1970).
8. D. G. Jacobs et al., *Theoretical Evaluation of Consumer Products from Project Gasbuggy, Final Report, Phase I. Impact of Hypothetical Releases of Contaminated Gas in the San Juan Basin*, ORNL-4646 (September 1971).
9. D. G. Jacobs, E. G. Struxness, M. J. Kelly, and C. R. Bowman, "Consideration of the Radiological Impact from the Hypothetical Use of Contaminated Gas from Nuclearly Stimulated Reservoirs," *Health Phys.* (in press).
10. C. J. Barton et al., "Radiological Considerations in the Use of Natural Gas from Nuclearly Stimulated Wells," *Nucl. Technol.* 11, 335 (1971).

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was the first test of an explosive designed specifically for underground use. Its success seems to ensure lower tritium concentrations in future gas stimulation tests than were observed in the Rulison and Gasbuggy experiments, but data on actual tritium production of commercially useful explosives are not now available.

A large fraction of the gas produced in the San Juan Division of El Paso Natural Gas Company is consumed in west coast metropolitan areas, principally Los Angeles and San Francisco, and this report considers the hypothetical impact of Gasbuggy gas in these areas. Appendix A describes the computational techniques used to calculate ground-level concentrations of radioisotopes from both ground level and elevated point-source releases, and Appendix B contains the calculations of the tritium concentration in combustion products from a large gas-fired electric generating plant located in Los Angeles. Although the quantities of natural gas components from this area that are converted into gas by-products are not readily available, we have assumed that such products would be manufactured from tritium-containing gas and have calculated doses that could result from exposure to the most important products or manufacturing processes. The ^{85}Kr in the natural gas from nuclearly stimulated wells is believed to be of minor importance in respect to possible doses from gas or gas by-products.

POSSIBLE EXPOSURES TO PETROCHEMICALS AND OTHER NONFUEL PRODUCTS FROM CONTAMINATED NATURAL GAS

A preliminary report was published earlier¹¹ containing doses that might be received from exposure to consumer products made with natural gas containing radioisotopes. A large and rapidly growing quantity of natural gas components is converted to a variety of chemical products usually called petrochemicals, and we will consider in this section the possible impact of radioisotope impurities on consumers.

Data¹² on amounts of the major petrochemicals produced in the period 1965-68 are shown in Table 1. Some of the products listed are marketed without further treatment, but others serve as intermediates in the manufacture of materials such as synthetic rubber, detergents, fibers, resins, plastics, plasticizers, and fertilizers. Many of the materials come from oil rather than natural gas. Figure 1 shows the disposition of natural gas hydrocarbons in 1956.¹³ Spot checks of this disposition from more recent production data¹² indicated that it has not changed drastically in the last 15 years, although there is a definite trend toward increased recovery of ethane and higher natural gas hydrocarbons for nonfuel usage.

11. C. J. Barton, D. G. Jacobs, and M. J. Kelly, *Quarterly Progress Report on Radiological Safety of Peaceful Uses of Nuclear Explosives: Consumer Products from Nuclearly Stimulated Gas Wells*, ORNL-TM-3123 (September 1970).

12. F. G. Sawyer, "Petrochemicals: Near Great in '59," *Hydrocarbon Proc.* 47(4), 187 (April 1968).

13. V. B. Guthrie, ed., *Petroleum Products Handbook*, pp. 12-15, McGraw-Hill, New York, 1960.

14. C. F. Smith, Jr., *Gas Analysis Results for Project Rulison Calibration Flaring Samples*, UCRL-50986 (January 1971).

Table 1. Major petrochemicals - capacity and production^a

	Capacity estimated		Production				Percent petrochemical
	1967	1968	Actual		Estimated		
			1965	1966	1967	1968	
Hydrocarbon intermediates							
Aliphatic							
Ethylene	14,000	15,000	9,570	11,240	12,200	13,000	100
Propylene and mixtures	6,000	6,500	3,740	4,680	5,300	6,000	100
Butylene and mixtures	3,300	4,000	2,100	3,320	3,650	4,000	100
Butadiene	3,050	3,110	2,690	2,920	2,670	3,000	100
Acetylene	1,550	1,700	1,150	1,400	1,550	1,700	50

Table 1 (continued)

	Capacity estimated		Production				Percent petrochemical
	1967	1968	Actual		Estimated		
			1965	1966	1967	1968	
Aromatic							
Benzene	8,000	9,200	6,060	6,980	7,030	7,500	90
Cyclohexane	2,700	2,800	1,700	1,900	1,670	1,800	100
Cyclopropane	200	200	130	120	110	100	90
Cumene	1,420	1,750	660	890	1,100	1,400	95
Ethylbenzene	4,000	4,200	3,020	3,250	3,450	3,700	90
Naphthalene	900	900	810	800	880	900	42
Styrene	3,210	4,000	2,760	3,190	3,280	3,400	90
Toluene	4,700	4,700	3,980	4,230	4,330	4,500	97
Xylene	4,000	4,200	2,490	3,150	3,470	3,700	99
Polymers							
Polyethylene	4,500	4,700	3,050	3,560	3,710	4,150	100
Polypropylene	650	800	370	550	650	800	100
Polyvinyl chloride and copolymers	2,780	2,900	1,840	2,160	2,080	2,450	90
Styrene polymers	2,330	2,500	2,030	2,380	2,370	2,750	90
Synthetic rubber	3,900	4,000	3,590	3,930	3,700	4,150	90
Aromatic chemicals							
Chlorobenzene	650	650	550	580	490	490	60
Nitrobenzene	380	380	280	330	360	400	60
Phenol	1,650	1,800	1,250	1,350	1,240	1,300	96
Phthalic anhydride	800	1,000	610	680	720	730	60
Aliphatic chemicals							
Acetaldehyde	1,660	1,800	1,230	1,300	1,400	1,500	80
Acetic acid	2,030	2,030	1,350	1,410	1,500	1,600	90
Acetic anhydride	1,660	1,800	1,530	1,600	1,550	1,650	99
Acetone	1,400	1,500	1,120	1,330	1,210	1,300	85
Acrylonitrile	1,030	1,030	770	720	670	700	100
Butanols	900	900	830	490 ^b	520 ^b	520 ^b	85
Carbon disulfide	900	900	760	750	570	570	85
Carbon tetrachloride	740	740	590	540	710	750	95
Ethanol	2,800	2,800	2,530	2,200	2,130	2,150	95
Ethyl chloride	800	750	690	680	690	680	100
Ethylene dichloride	2,900	3,200	2,460	3,620	3,600	4,000	100
Ethylene glycol	2,430	2,430	1,800	2,080	2,150	2,200	95
Ethylene oxide	3,000	3,400	2,190	2,330	2,260	2,400	99
Fluorocarbons	725	725	460	460	500	550	100
Formaldehyde (100%)	1,700	1,800	1,150	1,370	1,360	1,500	98
Glycerol	430	430	350	350	360	370	58
Isopropanol	1,760	2,310	1,540	1,710	1,850	2,000	100
Maleic anhydride	200	210	130	170	170	180	30
Methanol	4,000	4,300	2,870	3,270	3,450	3,600	99
Methyl chloride	375	450	190	240	260	280	90
Methylene chloride	335	350	210	270	240	250	100
Oxo chemicals	850	850	500	570	570	600	100
Perchloroethylene	535	600	430	460	530	600	80
Propylene glycol	310	330	210	260	280	300	100
Propylene oxide	870	1,020	600	710	800	930	100
Trichloroethylene	645	645	430	480	490	500	50
Urea	5,000	6,000	2,570	3,430	4,200	4,500	99
Vinyl acetate	780	800	510	610	610	640	75
Vinyl chloride	3,300	3,500	2,000	2,500	2,430	2,600	90
Ammonia	30,400	36,000	17,200	21,320	25,000	30,000	99

^aAll figures in millions of pounds.^bn-Butyl and isobutyl only.

Fig. 1. Disposition of natural gas hydrocarbons in 1956.

Source Term

In our calculations of potential exposures to nonfuel products, we have essentially ignored the Gasbuggy analytical data¹⁵ and adopted the value 1 pCi/cm³ for the total tritium concentration in the gas at the processing plant, that is, just before the tritium-containing components used to make petrochemicals are separated from the raw gas. There are several reasons for this decision. One is that the tritium content of Gasbuggy gas is almost certainly much higher than will be observed in future nuclearly stimulated wells, as indicated by analytical data on gas from the Rulison well¹⁴ and by the published statement¹⁶ that non-weapon-type nuclear explosives will produce less tritium than was found in the Gasbuggy and Rulison tests. It should be noted that production testing of the Gasbuggy¹⁵ and Rulison¹⁷ wells ceased after approximately two cavity volumes of gas had been removed. Many cavity volumes of gas would be produced during the lifetime of a commercial well, generally assumed to be at least 20 years. For the Rulison case, the average tritium concentration during the production life of the well was calculated to be 6 to 8 pCi/cm³. We believe it is reasonable to assume that the average tritium concentration will be 1 pCi/cm³ or less for large-scale development of a reservoir through nuclear stimulation with improved nuclear explosives, where newly stimulated wells will be brought into production as the quantity of gas from other wells declines. Another, less important, consideration is that analytical data are generally

15. C. F. Smith, Jr., *Project Gasbuggy Gas Quality Analysis and Evaluation Program Tabulation of Radiochemical and Chemical Analytical Results*, UCRL-50635, rev. 1 (November 1969).

16. G. C. Werth et al., *An Analysis of Nuclear Explosive Gas Stimulation and the Program Required for Its Development*, UCRL-50966 (April 1971).

17. R. L. Gotchy, *Project Rulison Interim Radioactivity Reports* (January, February, May 1971).

reported in picocuries per cubic centimeter and that doses calculated on the basis of the value of 1 pCi/cm^3 can be adjusted easily by use of appropriate concentration values.

In spite of the above assumption, it is interesting to examine data on changes of concentration with the volume of gas removed from the cavity.

By combining data reported by Smith¹⁵ on the chemical composition with the radioisotope content of Gasbuggy samples, specific activities (pCi/cm^3) of gas components can be calculated. The data are rather scanty for propane (11 samples) but are sufficient to show the effect of gas withdrawal. The results of these calculations are plotted in Fig. 2 (see ref. 8, p. 30, for a discussion of V_0). The effect of the diffusion of formation gas into the cavity, as gas was withdrawn, on the specific activity of the hydrocarbons is quite evident. It is most marked in the case of propane because there was a larger difference between the propane content of the formation gas and the concentration in the cavity gas, as compared with methane and ethane.

The significance of the data in Fig. 2 in regard to calculation of potential doses from gas products is that the tritium content of the various gas components may not change at the same rate when gas is removed from a nuclearly stimulated well. Sufficient data on the specific activity of butane and higher hydrocarbons are not available at present to define trends for these gas components.

Fig. 2. Specific activity of tritium species in Gasbuggy gas.

An average concentration of 1 pCi/cm³ for total tritium seems reasonable, as was discussed earlier in this section. The comparable figure for ⁸⁵Kr may be somewhat higher, but this is not important because of the relatively small biological impact of this isotope.

Carbon Black

In 1966, the total production of carbon black from natural gas and liquid hydrocarbons was 2.57×10^9 lb.¹⁸ It is obvious that the only radioisotope that will be found in carbon black is ¹⁴C. From the reported ¹⁴C concentration of 0.5 pCi/cm³ in Gasbuggy gas,¹⁵ we calculate a value of approximately 10³ pCi/g in carbon black produced from *undiluted* Gasbuggy gas. Statistics¹⁸ on sales of carbon black for 1964 and 1965 show that about 0.4 to 0.5% of this product was used as a chemical or in food production. It seems unlikely that the concentration of carbon black in food products would exceed a few tenths of a percent, but at 1% the ¹⁴C content of the food material would be 10 pCi/g.

If we assume a daily intake of 500 g of carbon-containing food, the ¹⁴C ingested would amount to 5×10^{-3} μ Ci/day. Considering bone as the critical organ and using the bone dose factor 1 μ Ci of ¹⁴C = 2.6 millirems, this intake rate corresponds to a daily dose of 0.013 millirem or 4.8 millirems per year. This is a conservative upper limit for possible exposure through this pathway.

We must also consider the potential radiological impact from exposure to radioisotopes in the combustion products evolved in manufacturing carbon black. It is likely that a number of years will be required to develop widespread exploitation of nuclear stimulation of natural gas reservoirs. Therefore, a projection of future gas use is needed to evaluate the impact of certain aspects of contaminated gas usage including carbon black. The 1969 edition of *Gas Facts*¹⁹ has such a projection to 1990. We selected the 1980 total sales figure of 271 billion therms, equivalent to 25.2 trillion cubic feet of gas, for these calculations. Assuming that the distribution shown in Fig. 1 applies to 1980 gas production, the yearly consumption of natural gas for carbon-black production (assuming that only gas is used) could be 4.5×10^{11} ft³, which would contain 1.3×10^6 Ci of tritium or ⁸⁵Kr. This is equivalent to 35 Ci/day of tritium or ⁸⁵Kr. If we further assume no change in the number of United States carbon-black plants in the interval 1966–80 and that all 34 plants existing in 1966 are equal in size, each plant would emit 1 Ci/day of tritium and of ⁸⁵Kr. The annual tritium production rate of 1.3×10^6 Ci from carbon-black production is much lower than the natural production rate of 4 to 8×10^6 Ci/year. These plant emission rates are quite low, and the radioisotopes would be diluted and dispersed in the atmosphere through plant stacks. (Difficulties that these plants are experiencing in meeting environmental quality requirements could reduce their number to zero before the advent of large-scale gas stimulation.)

Ammonia Fertilizer

Ammonia is produced by the reaction of hydrogen from natural gas with nitrogen. Hydrogen production from all sources was recently reported²⁰ to be 2.5×10^{12} ft³. The same publication showed that hydrogen was being produced from methane at a cost of \$0.21/M ft³ compared with \$4/M ft³ by electrolysis. (In the natural gas industry $M = 10^3$, $M^2 = 10^6$.) It seems safe to assume, therefore, that all synthetic NH₃ used in fertilizers comes from natural gas. It was also reported that 35% of the hydrogen (8.75×10^{11} ft³/year) was used to make ammonia.²⁰ Since two volumes of hydrogen are produced from

18. U.S. Bureau of Mines, *Minerals Yearbook* – 1967, vols. I and II, pp. 263–72, Washington, D.C., 1968.

19. American Gas Association, Inc., 1969 *Gas Facts*, New York, 1969.

20. J. H. Finneran and J. P. Mazur, "Plant Size and Feed, Key to Lower Hydrogen Costs," *Oil Gas J.* 67(29) (July 21, 1969).

each volume of methane, assuming 100% conversion, 4.4×10^{11} ft³/year of CH₄ would be required to produce this amount of hydrogen. This is equivalent to 5.8×10^{11} ft³ of NH₃ or 2.8×10^{10} lb NH₃ per year.

If we assume that the tritium concentration in natural gas is 1 pCi/cm³ and that all the tritium is present as CH₃T, the resulting tritium concentration in NH₃ would be 4.3×10^{-7} Ci/lb, or 0.43 μCi/lb. For the calculation of tritium absorption in fertilized food materials, we assumed an ammonia application rate of 100 lb/acre-year, annual rainfall of 40 in. (4000 m³/acre), uniform dilution of tritium, grain production of 100 bu/acre at 60 lb/bu, and that the grain contained 20% moisture as well as the water involved in synthesis of carbohydrates. The concentration of tritium in ground water would be

$$\left(\frac{100 \text{ lb NH}_3}{\text{acre}}\right) \left(\frac{0.43 \times 10^6 \text{ pCi } ^3\text{H}}{\text{lb NH}_3}\right) \left(\frac{4 \times 10^9 \text{ cm}^3}{\text{acre}}\right) = 0.01 \frac{\text{pCi}}{\text{cm}^3}.$$

If we assume that the rain has the recently reported²¹ average concentration of tritium, 500 pCi/liter, we find that 98% of the total tritium present is contributed by rainfall.

The permissible body tissue burden of tritium, 100 μCi, is equivalent to the tritium in 1×10^{10} cm³ of ground water (considering only tritium from the ammonia).²² Since the fraction of water molecules in carbohydrates is about 0.6, the concentration in grain would be approximately

$$0.8 (0.006) + 0.2 (0.01) = 0.0068 \text{ pCi/g} = 3 \times 10^{-6} \text{ } \mu\text{Ci/lb}.$$

Therefore, if a person ingested 2 liters of ground water and 1 lb of grain per day, the daily rate of tritium intake contributed through use of tritiated NH₃ would be 2.3×10^{-5} μCi, most of which would be from the water. This would result in a dose of 0.001 millirem/year. It appears from these calculations that it would not be possible to get a tritium body burden approaching the permissible level with a tritium concentration several orders of magnitude greater than the assumed value and that doses through this pathway are likely to be negligibly small.

Hydrogenated Fats and Oils

One exposure pathway that must be considered in the use of natural gas contaminated from tritium is the use of hydrogen gas in the hydrogenation of foodstuff. The statement is made²³ that 10⁹ ft³ of H₂ was used in the hydrogenation of fats and oils in 1967. If we assume that the natural gas from which the hydrogen was produced had a tritium concentration of 1 pCi/cm³ and that oleic acid with a molecular weight of 282 is typical of unsaturated fats and oils, we can calculate the tritium content of the hydrogenated products. Since 2 moles of H₂ are produced from 1 mole of CH₄, the principal constituent of natural gas, the concentration of tritium in the hydrogen would be about 0.5 pCi/cm³, or 1.4×10^4 pCi/ft³. It follows, then, that 1 g of H₂ = 141 g of oleic acid, 3.22 g of H₂ = 454 g of oleic acid = 1 lb = 1.28 ft³ of H₂, and 10⁹ ft³ of H₂ would contain 14 Ci of ³H and this would be contained in 7.8×10^6 lb of oleic acid; thus 1 lb of oleic acid would contain 0.018 μCi.

21. N. W. Golchert and J. Sedlet, "Airborne Tritium Monitoring near a Heavy Water Nuclear Reactor," paper presented at the Tritium Symposium, Las Vegas, Nev., Aug. 30–Sept. 2, 1971.

22. National Committee on Radiation Protection, *Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and Water for Occupational Exposure*, National Bureau of Standards Handbook 69 (June 1959).

23. *Chem. Eng. News*, 45(20) (Nov. 27, 1967).

Therefore it would be necessary to retain all the tritium from 5500 lb of hydrogenated product to obtain one body burden. A person consuming $\frac{1}{4}$ lb/day of this product would get 0.0045 μCi of tritium, which would give a dose of 0.00061 millirem. One year's consumption at this rate would result in a total dose of 0.2 millirem. These calculations, of course, do not require knowledge of total hydrogen consumption, but they do require hydrogenation of one double bond per oil or fat molecule. Variations in molecular weight of the hydrogenated product will produce only minor changes in the calculated dose.

Ethyl Alcohol

Although a large fraction of the ethyl alcohol produced from natural gas is undoubtedly used to manufacture other products, such as synthetic rubber, we must consider the possibility that tritiated ethanol might be ingested by human beings. We have assumed that the contaminated natural gas has the chemical composition of Gasbuggy gas in June 1969 (ref. 15), with an ethane concentration of 6.95%, and that 16% of the total tritium (1 pCi/cm^3) is $\text{C}_2\text{H}_5\text{T}$. Then the specific activity of ethane = $4.5 \times 10^{-3} / 0.0695 = 0.065 \mu\text{Ci/ft}^3$, 1 ft³ of ethane weighs 37.9 g, and thus 1 g of ethanol would contain $1 \times 10^{-3} \mu\text{Ci}$ of ^3H . A concentration of 0.15% of alcohol in the blood is a generally accepted definition of intoxication level. For an average-sized individual containing 5.2 liters of blood, this corresponds to 7.8 cm³ of alcohol. If we assume that all body water has this concentration of alcohol, retention of approximately 90 cm³ of alcohol would be required to intoxicate a 150-lb adult. In other words, a person drinking tritiated alcohol would pass out long before reaching the 0.1 μCi level. In fact, it would not be possible for many people to accumulate the 100 kg of ethanol required to attain a body burden of 100 μCi , even if all of their body fluid were replaced with pure alcohol. Consumption of 150 cm³/day of liquor containing 50% alcohol (100 proof) would result in a dose commitment of 3.7 millirems for one year. This indicates that tritium in tritiated alcohol at the level considered here would not be likely to constitute a significant health hazard.

Other Products

Quantities of petrochemicals produced in recent years are listed in Table 1, and some of the more important end uses of these chemicals are mentioned in the discussion of the table. Although some of the compounds in Table 1, in addition to those previously considered, may find use in foods or beverages, it seems unlikely that the potential radiation dose from human consumption of such products will be significantly greater than that of tritiated fats or of beverage alcohol. Other products, such as plastics, resins, and synthetic rubber, would present only the possibility of external radiation. Since tritium emits only beta particles with a maximum energy of 18 keV, it appears probable that the potential dose from all noningested tritium-contaminated products would be negligibly small. Their combustion products could be absorbed by the body, but this is not an ordinary disposition of most materials manufactured from petrochemicals.

DISPOSITION OF LIQUIDS HYPOTHETICALLY RECOVERED FROM GASBUGGY GAS

Pigging Liquids

This term includes the hydrocarbons and water condensing in the gathering lines from the gas stream. 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

Table 2. Analysis of pigging liquids

	Liquid composition ^a (mole %)		Tritium activity ^d (Ci/mole)
	Trunk L ^b	A loop ^c	
			$\times 10^{-5}$
Methane	11.52	12.71	2.50
Ethane	8.30	9.22	3.75
Propane	11.64	10.73	5.00
<i>i</i> -Butane	4.33	4.37	6.25
<i>n</i> -Butane	9.16	9.69	6.25
<i>i</i> -Pentane	7.55	6.52	7.50
<i>n</i> -Pentane	7.80	6.20	7.50
Hexane	39.70	40.56	8.75
Calculated density	0.601	0.598	
Calculated mole weight	61.58	61.73	

^aAnalysis supplied by El Paso Natural Gas Company.

^bSample taken Nov. 20, 1968.

^cSample taken Nov. 29, 1968.

^dBased on fractionation and measured methane activity 203 days post shot.

the pipelines and removing them and the liquids at pigging stations. These pigging liquids are stored in tanks and sold to local refineries.

Pigging liquids may be considered to be related to drip liquids, since they represent the condensable fraction of the natural gas not removed at the wellhead. The primary differences between drip and pigging liquids are that a smaller percentage of water is collected with pigging liquids and no hydrocarbons above hexane are present in significant amounts.

Using data reported by Smith and Monyer,²⁴ we can calculate that at 203 days after the Gasbuggy detonation, the tritium activity in the methane fraction was about 2.5×10^{-5} Ci/mole. Assuming that Gasbuggy gas was admitted to the gathering system at this time at a nominal production rate of $1 \text{ M}^2 \text{ ft}^3/\text{day}$ and that tritium fractionation was uniform over 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 A loop supplied by El Paso Natural Gas Company.

The data used for this calculation are shown in Table 2. Calculations were also made excluding methane and ethane, the more volatile fractions, but these gave no significant change in the calculated activity per milliliter.

The expected activity does not exceed 6.4×10^{-7} Ci/ml. This value can be compared with the measured value of 1.4×10^{-7} Ci/ml in drip liquid samples collected 542 days after detonation.⁶ The first collection point for this pigging liquid is where trunk L enters trunk A (see Fig. 2, ref. 4 or 8). The tritium concentration in Gasbuggy liquid at this point, assuming all wells on the gathering system produce the same amount of liquid per unit of gas, would be 8.2×10^{-9} Ci/ml. If the pigging liquid were not collected until it reached the Blanco plant through trunk A, then the calculated tritium activity would be 3.6×10^{-9} Ci/ml.

At Blanco the liquids from trunk A, A loop, and L loop, which would contain the hypothetical pigging liquids from Gasbuggy, are dumped into a 2000-bbl tank. They are then blended with liquids from trunks H

24. C. F. Smith, Jr., and F. F. Monyer, *Gas Quality Investigation Program Status Report for Project Gasbuggy*, UCRL-71314 (September 1968).

and O and transferred to the Blanco tank battery, from which they are transmitted to a local refinery through a connecting pipeline. Calculations indicate that the Gasbuggy drip liquid would not amount to more than 16 gpd; therefore the average activity in these liquids at Blanco should not exceed 1.3×10^{-9} Ci/ml.

It is of interest to note that if this liquid were burned and the water vapor formed collected as liquid water, its activity would not exceed 4×10^{-10} Ci/ml. This is about 0.1 of the maximum allowable concentration of tritium in drinking water.²²

Normally these liquids are processed with other petroleum fractions into gasoline that could be marketed outside the San Juan basin. The product is used as fuel for internal combustion engines, mostly in mobile equipment outdoors, where dilution and atmospheric dispersion of the combustion products are so great that a significant radiation dose from exposure to the products of combustion of tritium-contaminated liquids would appear to be improbable.

Plant Liquids

The liquids that are separated from natural gas during plant processing have a greater radiation dose potential than drip or pigging liquids, because the volume of these liquids is much greater and, consequently, the total quantity of tritium can be larger. Here, we will consider only liquids from the Blanco plant, which processes about $576 \text{ M}^2 \text{ ft}^3$ of gas per day. We assume that no Gasbuggy gas is sent to the Ignacio plant.

In the Blanco plant, essentially all the higher hydrocarbons (C_5 and higher) and part of the propane and butane are removed from the gas. Based on the volume from the processed gas⁸ and on the radiochemical analysis of the Gasbuggy components,¹⁵ we calculated that these components could contain up to 2.6% of the hypothetical tritium activity due to Gasbuggy production entering the plant. These liquids are produced at a rate of 453 M gpd and are pumped to the Wingate plant, where they are diluted with similar liquids from other plants of the EPNG system to a volume of approximately $1.5 \text{ M}^2 \text{ gpd}$. At Wingate these liquids are separated into propane, normal butane, isobutane, and natural gasoline fractions.

To provide an estimate of the hypothetical dose potential of tritium in these liquids, we will assume that all the tritium calculated to be present in the Gasbuggy cavity gas at the beginning of the flaring program (2400 Ci) is processed through the Blanco plant during a period of one year. The total quantity of tritium in the liquids would then be $2400 \times 0.026 = 62.4 \text{ Ci}$. Thus the concentration of tritium in the liquids after dilution in the Wingate plant would be

$$\frac{62.4 \times 10^6}{1.5 \times 10^6 \times 365} = 0.114 \mu\text{Ci/gal} = 14.6 \text{ pCi/cm}^3.$$

If we further assume that the liquid composition can be represented by the formula C_4H_{10} and that the liquid density is 0.6 g/cm^3 , we can calculate the daily tritium intake from breathing the combustion products of this liquid. Oxidation of 1 cm^3 will produce 1.82 g of CO_2 . The industrial limit for CO_2 is 5000 ppm, or 9 mg/liter. Therefore, 1.82 g of CO_2 is equivalent to 2.0×10^2 liters of air at the maximum breathing level. Since "standard man" (a typical or average adult) breathes $20 \times 10^6 \text{ cm}^3/\text{day}$,²⁵ the daily tritium intake would be

25. International Commission on Radiological Protection, *Recommendations of the International Commission on Radiological Protection* (Report of Committee 2), ICRP Publication 2, Pergamon, London, 1959.

$$\frac{2 \times 10^6}{2 \times 10^2} \times 14.6 = 1.46 \times 10^3 \text{ pCi of HTO.}$$

Continuous exposure at this concentration level for one year could result in a gonadal dose from inhalation and skin absorption of approximately 0.13 millirem. Since it is very unlikely that anyone could or would tolerate continuous breathing of such an undesirable atmosphere, this obviously represents an upper limit situation. Even if the Blanco liquids were burned without the dilution that we assume occurs at Wingate, the corresponding total continuous one-year radiation dose would be only 0.43 millirem.

HYPOTHETICAL POPULATION EXPOSURE IN THE METROPOLITAN AREAS

Gas from the Gasbuggy area can be processed either in the Blanco plant for transmittal to the southern California market or in the Ignacio plant for use in the northwest market. Only the first route will be considered, because, in this report, we assume that only Blanco receives Gasbuggy gas.

As shown in Fig. 3, the output of the Blanco plant, approximately $600 \text{ M}^2 \text{ ft}^3/\text{day}$, is mixed with an equal volume of gas from other parts of the San Juan basin to give a total daily flow rate of $1200 \text{ M}^2 \text{ ft}^3/\text{day}$. This gas is then mixed at Gallup with $700 \text{ M}^2 \text{ ft}^3/\text{day}$ of gas from the Permian basin to give a total of $1900 \text{ M}^2 \text{ ft}^3/\text{day}$. Part of this gas is consumed enroute to California, so that approximately $1680 \text{ M}^2 \text{ ft}^3/\text{day}$ arrives at Topock. Here the gas is divided, with $1140 \text{ M}^2 \text{ ft}^3/\text{day}$ going to Pacific Gas and Electric Company and $540 \text{ M}^2 \text{ ft}^3/\text{day}$ being received by Pacific Lighting Service Company for use in the southwestern part of Los Angeles after being mixed with $375 \text{ M}^2 \text{ ft}^3/\text{day}$ from Transwestern Pipeline Company. A small fraction ($90 \text{ M}^2 \text{ ft}^3/\text{day}$) of the gas that goes to Pacific Gas and Electric Company

Fig. 3. El Paso Natural Gas Company transmission system and marketing area of customer companies.

Table 3. Potential dose equivalents to various population groups from the hypothetical domestic use of Gasbuggy gas containing all the tritium initially present in dry gas

City	Heating requirements (degree-days/year)	Further dilution factor for Blanco gas	Dose equivalent from tritium (millirems)
San Francisco	2950	6.0	0.15
Peninsula cities	2700	6.0	0.14
San Jose	2450	6.0	0.14
Bakersfield	2100	3.2	0.25
Fresno	2490	3.2	0.27
Salinas	2700	3.2	0.28
Lake Arrowhead	5400	5.4	0.23
San Fernando Valley	1700	16	0.05
Southeastern Los Angeles basin	1700	5.4	0.14

arrives in Los Angeles from the north after being mixed with $350 \text{ M}^2 \text{ ft}^3/\text{day}$ of California gas. The dilution factor for Blanco gas arriving by this route is $440/90 \times 1900/600 = 16$. The corresponding factor for Blanco gas consumed in southeastern Los Angeles is $915/540 \times 1900/600 = 5.4$. Part of the latter gas ($33 \text{ M}^2 \text{ ft}^3/\text{day}$) is used in the resort town of Lake Arrowhead, which is much colder than Los Angeles and other nearby communities.

Therefore, we have calculated the potential dose for the small number of residents of this community. Table 3 summarizes data on dilution factors applying to the tritium concentration in Blanco gas in various California market areas, the degree-days of heating required in each, and the potential dose equivalents estimated to result from the hypothetical domestic use of the Gasbuggy gas flowing at an assumed rate of $1 \text{ M}^2 \text{ ft}^3/\text{day}$ for the lifetime of the well (20 years) by individuals living full time in 1000-ft^2 houses of normal construction. (Average lifetime tritium concentration = 11.7 pCi/cm^3 entering the Blanco plant.) In considering the doses listed in the last column of Table 3, it should be recognized that it is assumed that the Gasbuggy gas is diluted by a factor of 576 (rounded off to 600 above) at Blanco ($1 \text{ M}^2 \text{ ft}^3 \text{ gas/day}$ from Gasbuggy) and that the total dilution factor at points of consumption ranges from 1843 to 9216. Such high dilution factors would not prevail if an entire field were developed by nuclear stimulation and the gas was used to supply the southern California market. However, the total demand of this market is so large and it is growing so rapidly that it seems very unlikely that a single nuclearly stimulated field would supply a large fraction of the total requirements of this market. Also, as was discussed earlier in this report, nuclear explosives that will be used in large-scale application of this technique will almost certainly produce much less tritium than the Gasbuggy and Rulison explosives. Until more quantitative data from future nuclear stimulation tests become available, there seems to be no reason to change our earlier decision to use 1 pCi/cm^3 for the tritium concentration in natural gas at the point of consumption.

Natural gas is used in metropolitan areas for fueling steam plants to generate electricity and for a wide variety of industrial and commercial applications, as well as for domestic consumption. Combustion products released from steam plants through tall stacks represent elevated point sources, while releases from most of the industrial and domestic uses can be considered to be spread uniformly over a sizable area of ground surface. Models have been developed²⁶⁻²⁸ to describe the dispersion of pollutants from

26. S. R. Hanna and F. A. Gifford, Air Resources Atmospheric Turbulence and Diffusion Laboratory, National Oceanic and Atmospheric Administration, Oak Ridge, Tenn., private communication with D. G. Jacobs, October 1969.

27. F. A. Gifford, "Atmospheric Diffusion in an Urban Area," *Proceedings of the Second International Congress of the International Radiation Protection Society*, Brighton, England, May 3-8, 1970.

28. F. A. Gifford, Jr., and S. R. Hanna, "Urban Air Pollution Modeling," paper presented at the 1970 International Air Pollution Conference of the International Union of Air Pollution Prevention Association.

Fig. 4. Gas consumption in the Los Angeles basin.

ground-level area sources in metropolitan areas. Data are introduced into the computer program in a grid format as described in Appendix A. This program can be used to compute the ground-level atmospheric concentration of any type of pollutant, including radioactivity, for ground-level area sources. On this the concentrations of pollutant released from elevated point sources are superimposed. The computer code for both types of release uses local meteorological conditions for determining the ground-level air concentration of pollutants. The results of calculations for the Los Angeles basin were compared with the results of similar calculations based on a model developed by Lamb,²⁹ and it was concluded that the Atmospheric Turbulence Diffusion Laboratory (ATDL) model gave area-source concentration values higher than Lamb's by a factor of 2, which is considered reasonably good agreement for this type of calculation. No conclusion as to which model gives the best values could be drawn. Ground-level air concentrations for the combustion products from natural gas in the Los Angeles basin and in the San Francisco Bay area given in this report are based on average daily usage of gas in these areas and on annual average wind frequencies and wind speed. They are expressed in terms of cubic centimeters of natural gas per cubic meter of air.

29. R. Lamb, "An Air Pollution Model of Los Angeles," Master's thesis, University of California at Los Angeles, 1968.

Fig. 5. Concentration in air at ground level of combustion products from natural gas consumed in residences. The concentration is expressed as the equivalent content of the combustion products from the gas in cubic centimeters per cubic meter of air.

Figure 4 shows gas usage data for Los Angeles, including the location of gas-fired electric generating plants. Figure 5 shows values for residential sources in the Los Angeles area, and Fig. 6 shows the corresponding data for industrial sources. These two area sources of release were combined with the releases from stacks to provide the data in Fig. 7. Since less detailed data on gas usage were available for the San Francisco area, only total ground-level gas usage and elevated source values are shown in Fig. 8; Fig. 9 shows the combined effect of both types of release.

In the Los Angeles basin there are three grids that have quite high concentrations of combustion products in the air at ground level due to large releases from tall stacks. The peak concentration of combustion products in the air at ground level was estimated to be equivalent to the amount produced from combustion of 100 cm^3 of natural gas per cubic meter of air; thus, if the gas being consumed has a concentration of 1 pCi/cm^3 , the ground-level concentration in this grid would be 100 pCi/m^3 . It is estimated that the population-weighted mean concentration would be $13 \text{ cm}^3/\text{m}^3$ in the Los Angeles basin. In the San Francisco Bay area the peak concentration is due primarily to ground-level sources and is estimated to be $13 \text{ cm}^3/\text{m}^3$. The population-weighted mean concentration is estimated to be $3.7 \text{ cm}^3/\text{m}^3$.

The potential dose equivalents that could be attained from the use of natural gas having a concentration of 1 pCi/cm^3 of tritium in these two major metropolitan areas are given in Table 4. From these respective estimates it is seen that the major exposure would be due to domestic consumption of gas in houses equipped with unvented space heaters.

In considering the dose equivalents in Table 4, we must remember that, although these hypothetical radiation doses are very much less than 170 millirems/year, the use of natural gas from nuclearly stimulated wells represents only one potential source of population radiation exposure. Also, in this preliminary analysis only direct modes of exposure through inhalation, immersion, and absorption through the skin

ORNL-DWG 70-5376R

Fig. 6. Concentration in air at ground level of combustion products from natural gas consumed in industrial plants.

ORNL-DWG 70-5376R

Fig. 7. Concentration in air at ground level of combustion products from natural gas consumed by all users in the Los Angeles area. The concentration is expressed as the equivalent content of the combustion products from the gas in cubic centimeters per cubic meter of air.

Fig. 8. Gas consumption in the San Francisco Bay area.

have been considered. The recommendations of the ICRP and other authorities require that radiation exposures from all sources, other than natural background and medical sources, be considered in any radiological safety evaluation.^{22,25,30} Furthermore, these potential doses 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.

30. Federal Radiation Council, *Background Material for the Development of Radiation Protection Standards*, Federal Radiation Council Report No. 5 (July 1964).

CONCENTRATION OF COMBUSTION PRODUCTS FROM NATURAL GAS IN AIR AT THE GROUND SURFACE. THE CONCENTRATION IS EXPRESSED AS THE EQUIVALENT CONTENT OF THE COMBUSTION PRODUCTS FROM THE GAS IN cm^3 PER CUBIC METER OF AIR.

San Francisco Bay Region.

Fig. 9. Concentration in air at ground level of combustion products from natural gas consumed by all San Francisco Bay area users. The concentration is expressed as the equivalent content of the combustion products from the gas in cubic centimeters per cubic meter of air.

Table 4. Potential dose equivalents from the hypothetical use of natural gas containing 1 pCi/cm^3 of tritium in the Los Angeles basin and in the San Francisco Bay area

Source of exposure	Dose equivalents (millirems/year)	
	Los Angeles basin	San Francisco Bay area
Atmosphere		
At point of peak concentration	0.19	0.024
Population weighted average	0.024	0.007
Domestic use		
Nonvented heating and appliances ^a	2.0	2.5
All appliances vented except range	0.27	0.27
Weighted average ^b	0.45	0.49
Total		
Maximum dose equivalents	2.2	2.5
Weighted average dose equivalents ^b	0.47	0.50

^aAssumes 1700 deg-days of heating for Los Angeles and 2950 for San Francisco and a 1000-ft² residence of normal construction (see ref. 8, Appendix B), having one air change per hour. Although recent data (R. H. Elkins and C. E. Wenman, "Natural Ventilation of Modern Tightly Constructed Homes," paper presented at the American Gas Association - Institute of Gas Technology Conference on Natural Gas Research and Technology, Chicago, Ill., Feb. 28-Mar. 3, 1971) indicate that tight homes can have rates as low as 0.5/hr, homes of this type would almost certainly have vented space heating systems.

^bAssumes nonvented heating for 10% of the population.

HYPOTHETICAL USE OF NUCLEARLY STIMULATED GAS IN A LARGE ELECTRIC PLANT IN LOS ANGELES

Modern electric generating stations depend on large capacity for economic performance. A typical plant has a supercritical steam cycle with an overall station efficiency of about 40%, delivering approximately 1000 MW of electric power. This corresponds to 2500 MW of input thermal energy. If natural gas at 1100 Btu/ft³ is used as the fuel, the daily requirement for such a plant is 185 M² ft³. We will assume, for simplicity, that the gas delivered to the plant contains 1.0 pCi total tritium and 1.0 pCi of ⁸⁵Kr per cubic centimeter (0.028 μCi/ft³) respectively. At this concentration the daily release rate is comparable with the reported average release rate from 1000-MW(e) pressurized-water nuclear power plants of 10 to 20 Ci/day, primarily to surface waters.

The assumed tritium to ⁸⁵Kr ratio of 1:1 is close to the actual ratio of these impurities in Rulison gas of 1.17:1 reported by Smith¹⁴ for preflaring gas samples.

Meteorological analysis for a given location and stack height is required in order to estimate the exposure from the hypothetical use of nuclearly stimulated gas in a steam plant. Dilution factors have been estimated for a plant located in Los Angeles, using 185 M² ft³ of gas daily.³¹ The stack height of 450 ft (137 m) assumed in these calculations is typical of the large electric plants in Los Angeles that use natural gas as fuel. Details of the calculations are given in Appendix B.

The daily output of radioactivity of 5.3 Ci each of tritium and ⁸⁵Kr is equivalent to 6.1×10^{-5} Ci/sec.

The calculations show that for Pasquill's "C" type of turbulence,³²⁻³⁴ with slightly unstable weather conditions, the maximum concentration of tritium or ⁸⁵Kr at a distance of 7000 m from the plant would be 3×10^{-6} μCi/m³. At this tritium concentration, an average adult might receive a gonadal dose of 0.005 millirem/year from inhalation and absorption through the skin. The equivalent gonadal dose from ⁸⁵Kr would be about 10⁻⁵ millirem.

For the "worst possible" meteorological situation in the Los Angeles terrain, a stable plume meandering through an occupied pass at its final level under heavy inversion conditions (Pasquill's "F" category), the calculations show that at 10,000 m from the plant the maximum concentration of tritium or ⁸⁵Kr would be 7.5×10^{-4} μCi/m³. Even if exposure under these unusual conditions continued for a period of one year, the resulting gonadal dose from tritium would be only 1.3 millirems. The skin dose from ⁸⁵Kr would be 1.5 millirems, which is equivalent to a gonadal dose of about 0.017 millirem.

Appendix A

THE ATDL AREA-SOURCE MODEL²⁸

F. A. Gifford, Jr. S. R. Hanna

A simple model of urban air pollution, based on reasonable first principles and incorporating some attempt at rigor, is presented below. The result, a simple, easily applied area-source concentration formula, has been compared with several of the previous formulas, and the conclusion is that it performs well.

First, we assume that the problem of urban air pollution can be simplified by considering separately the isolated point sources such as tall stacks and lumping the contribution of the multitude of lesser sources of

31. W. M. Culkowski, Air Resources Atmospheric Turbulence and Diffusion Laboratory, communication with C. J. Barton, ORNL, May 1970.

32. D. Slade, ed., *Meteorology and Atomic Energy*, 1968, TID-24190 (1968).

33. G. A. Briggs, *Plume Rise*, AEC Critical Review Series Report, TID-25075 (November 1969).

34. F. Pasquill, *Atmospheric Diffusion*, Van Nostrand, Princeton, N.J., 1962.

all types into a spatially variable area-source concentration X_A . This is assumed to obey the steady-state diffusion equation in two independent variables,

$$u(z) \frac{\partial X_A}{\partial x} = \frac{\partial}{\partial z} K(z) \frac{\partial X_A}{\partial z}, \quad (1)$$

where the mean wind $u(z)$ blows in the x direction. Neglect of the y component of the diffusion is equivalent to the observation that point-source plumes in the atmosphere tend to be long and narrow, and so the concentration at a point can be influenced only by sources in a narrow, plume-shaped upwind section (see ref. 31). If u and eddy-diffusivity K are assumed to obey the usual power laws,

$$u(z) = u_1 \left(\frac{z}{z_1} \right)^m, \quad (2)$$

$$K(z) = K_1 \left(\frac{z}{z_1} \right)^n, \quad (3)$$

the "partial" solution to Eq. (1) for the ground-level concentration distribution X_{AO} due to an area source has been shown by Gifford³⁵ to be

$$X_{AO} = \frac{z_1^m}{c_1 u_1 B (1-s)} \left(\frac{\Delta x}{2} \right)^{1-s} \left\{ Q_0 + \sum_{i=1}^N Q_i [(2i+1)^{1-s} - (2i-1)^{1-s}] \right\}, \quad (4)$$

where $s = (m+1)/(2+m-n)$ and the distance x from the receptor point to the upwind edge of the city is given by $x = (N + \frac{1}{2}) \Delta x$, where N is the number of upwind grid squares in the source inventory and Δx is the grid size as given by the usual "checkerboard" source-inventory pattern. Source strength Q is constant for each square. The receptor point is assumed to be located at the center of a source square. There is no particular difficulty involved in adapting the model to other geometries, including irregular area-source patterns.

The parameter B depends on the vertical concentration distribution. The total concentration distribution X_A is related to the ground-level value X_{AO} by

$$X_A = X_{AO}(x) f\left(\frac{z}{Z}\right). \quad (5)$$

Here the reference height Z essentially represents the "top" of the polluted air and increases with distance from the upwind edge according to the formula

$$Z = c_1 x^{1/(2+m-n)}. \quad (6)$$

This assures that a "variables separable" solution of the type of Eq. (5) will satisfy Eq. (1). Then, with $\xi = z/Z$, the value of B follows from the continuity condition

$$\int_0^\infty u(z) X_A(x, z) dz = \int_0^\infty Q(x) dx. \quad (7)$$

35. F. Gifford, "Computation of Pollution from Several Sources," *Int. J. Air Pollut.* 2, 109 (1959).

From this and Eq. (5),

$$B = \int_0^\infty \xi f(\xi) d\xi. \quad (8)$$

The constant c_1 is determined from the relation $c_1 = 3d^{1/(m+1)}$, where a is defined by the usual power-law formula for the standard deviation of the vertical concentration distribution

$$\sigma_z = ax^b, \quad (9)$$

and $Z \cong 3\sigma_z$. Values of a and b based on extensive observational data have been summarized by, for instance, Slade³² and Smith.³⁶

Table A.1.

Meteorological conditions	a	b	$(1 - b)$	$a(1 - b)$
Very unstable	0.40	0.91	0.09	0.036
Unstable	0.33	0.86	0.14	0.046
Neutral	0.22	0.80	0.20	0.044
Estimated Pasquill "D"	0.15	0.75	0.25	0.037
Stable	0.06	0.71	0.29	0.017

Table A.1 is based on the values given by Smith³⁶ and includes our estimate of the value corresponding to Pasquill's "D" (slightly stable) condition. We believe that this value is more appropriate to urban conditions than Smith's "stable" value. Unfortunately, few data are as yet available on diffusion over cities. For a Gaussian vertical distribution, with the above assumptions,

$$B = \frac{1}{3} \left(\frac{\pi}{2} \right)^{1/2};$$

for a linear decrease in concentration, $B \cong 0.4$. In general, it is unlikely that B will differ much from these values.

Equation (4) can be generalized in the usual ways, by introducing wind direction and speed frequency class intervals and varying the meteorological parameter s . The only real problem that arises in the extension of Eq. (4) to the case of annual average concentrations is that of adapting the basic rectilinear source configuration to radial wind directions other than the cardinal ones. Our arbitrary but simple scheme for doing this is illustrated in Fig. A.1.

36. M. E. Smith, ed., *Recommended Guide for the Prediction of the Dispersion of Airborne Effluents*, 1st ed., American Society of Mechanical Engineers, New York, May 1968.

Fig. A.1. Scheme for combining rectilinear source-grid squares with radial wind directions.

Appendix B

ATMOSPHERIC DISPERSION OF GAS COMBUSTION PRODUCTS FROM A 1000-MW(e) ELECTRIC GENERATING PLANT IN LOS ANGELES³¹

W. M. Culkowski

Plume rise is assumed to be described by equations in *Meteorology and Atomic Energy*,³² namely,

$\Delta h = 400F u^{-3}$ (neutral conditions, atmosphere well mixed because of vigorous, turbulent mixing. Temperature decrease of adiabatic lapse rate of $5.4^\circ/1000$ ft).

$\Delta h = 2.6(F/u)^{1/3} S^{-1/3}$ (stable conditions, temperature lapse of the atmosphere less than the adiabatic lapse rate. Air lifted adiabatically tends to sink back).

$\Delta h = 2.0F^{1/3} u^{-1} x^{2/3}$ [transitional conditions — plume rise is affected only by the mean wind and the properties of the plume itself (see ref. 32)].

In the above

Δh = plume rise (m),

x = distance from stack (m),

$F = 3.8 \times 10^{-5} Q_h$,

Q_h = calories per second of heat output of the stack = 3.6×10^7 ,

$$F = 1.4 \times 10^3 \text{ m}^4/\text{sec}^3,$$

u = wind velocity (m/sec),

S = stability parameter g/T ($13^\circ\text{C}/\text{km}$)
 $= 4 \times 10^{-4}$ (typical stable) sec^{-2} .

For neutral conditions with $\bar{u} = 10$ m/sec,

$$\Delta h = (400)(1400)(10^{-3}) = 560 \text{ m}.$$

A later model³³ for neutral conditions suggests the formula

$$\Delta h = 1.6F^{1/3} u^{-1} (3x^*)^{2/3},$$

where

$$x^* = 2.16F^{2/5} h_s^{3/5} = 750 \text{ m. This gives } \Delta h = 307 \text{ m.}$$

For stable conditions with $u = 2$ m/sec,

$$\Delta h = (2.6)(1.8 \times 10^6)^{1/3} = 320 \text{ m}.$$

For transitional conditions, assuming $\bar{u} = 10$ m/sec,

$$\Delta h = (2.0)(1.4 \times 10^3)^{1/3} (10^{-1}) x^{2/3} = 2x^{2/3},$$

and

$$H = \Delta h + h_s,$$

where H is total height of the plume center line and h_s = height of stack above ground, at $x = 1000$ m, $\Delta h = 200$ and $H = 337$ m. Thus

$$X_{\max} = \frac{Q}{\pi \sigma_y H \bar{u}} = \frac{Q}{\pi \sigma_y \sigma_x u}.$$

and

$$H = 1.4 \sigma_z,$$

where Q is tritium source strength (Ci/sec), $X_{\max}$ is maximum tritium concentration (Ci/m^3), and σ_z is vertical dispersion parameter. Using the neutral $\Delta h = 307$,

$$H = 307 + 137 = 444 \text{ m},$$

and

$$\sigma_z = \frac{444}{1.4} = 316 \text{ m}.$$

For Pasquill's "C" type of turbulence,³²⁻³⁴ with slightly unstable weather conditions, $\sigma_z = 316$ m at $x = 7000$ m and $\sigma_y = 600$ m,

$$X_{\max} = \frac{6.1 \times 10^{-5}}{\pi (316)(600)(10)} = 3 \times 10^{-12} \text{ Ci/m}^3.$$

At this tritium concentration, an average adult will breathe in $3 \times 10^{-12} \times 20 = 6 \times 10^{-11}$ Ci of tritium per day.

The maximum body burden of tritium for continuous exposure at this level would be about 2×10^{-3} μ Ci for inhalation and absorption through the skin and would result in an annual whole-body or gonadal dose of only 5 microrems. The gonadal dose from ^{85}Kr in this gas would be much less than for tritium.

The Los Angeles terrain ranges from hilly to mountainous. A possibility exists, therefore, that a stable plume meandering at its final level could move through a pass and result in an exposure level higher than that indicated above. For a meandering plume during a heavy inversion condition (Pasquill's "F" category),³²⁻³⁴ $H = 400$ m, $\bar{u} = 1$ m/sec and $X = Q/2\pi\sigma_y\sigma_z = 7.5 \times 10^{-10}$ Ci/m³ at 10^4 m, or 5×10^{-11} Ci/m³ at 10^5 m.

It seems quite unlikely that such an unusual condition would prevail for a large fraction of the time or for many people at any time. We can calculate, however, that for continuous exposure under these conditions, the maximum tritium intake through inhalation and absorption through the skin will be 0.03 μ Ci/day, corresponding to a body burden of 0.5 μ Ci. This body burden would give an annual whole-body or gonadal dose of 1.3 millirems if maintained continuously.