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AN EVALUATION OF NUCLEAR GAS STIMULATION IN TERMS OF POTENTIAL RADIATION EXPOSURE TO THE PUBLIC[a,b]

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Abstract

Experience gained from Projects Gasbuggy and Rulison and their follow-up studies indicates that natural gas produced from a nuclearly stimulated well field will contain small amounts of man-made radioactivity as it leaves the gas processing plant and enters commercial distribution channels. Individual and population doses have been estimated for hypothetical uses of such gas. For example, it it is estimated that residential use of nuclearly stimulated gas in unvented cook stoves would result in an average whole-body dose to the house occupants of approximately 0.2 millirem/year. Radon concentrations measured in natural gas at various locations in the United States average approximately 20 pCi per liter. Assuming this concentration of radon in the unvented cooking case mentioned, the lung dose is estimated to be 1.5 millirems per year. All of the dose estimates discussed are used to give perspective to the additional radiation exposure of the public which could occur due to use of gas from nuclearly stimulated

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wells. Both somatic risk and genetic risk are considered in the assessment of relative hazard. Comparisons are made with other risks encountered in the normal activities of life in the United States. The studies summarized show that the radiological impact of either domestic or industrial use of the gas can be small.

Introduction

Large areas of several western states, principally Wyoming, Utah, Colorado, and New Mexico, are underlain by gas-containing rock formations from which gas cannot presently be recovered economically because of the low permeability of these formations. It has been estimated that successful use of nuclear explosives to increase gas production from these "tight" rock formations would approximately double the presently known reserves of natural gas (nearly 7.8 trillion m^3). Natural gas is a very clean source of energy and, in addition, provides raw materials for the rapidly growing petrochemical industry. Consequently, United States demand continues to grow at such a rate that domestic production, plus all present and projected imports, is inadequate to meet the country's expanding needs.

The U.S. Atomic Energy Commission's Plowshare Program is almost exclusively devoted at present to the development of the nuclear gas stimulation concept. Two experiments involving detonation of single nuclear explosives in low permeability rock formations, Gasbuggy and Rulison, have been conducted to date. Results of these experiments are considered very encouraging by the AEC and the industrial sponsors. Rio Blanco, the third experiment, involved the use of three nuclear devices in one well hole to stimulate gas production in thicker rock formations than would be possible with only one explosive. The explosives were detonated simultaneously on May 17, 1973.

The Health Physics and Environmental Sciences Divisions of the Oak Ridge National Laboratory have been investigating the radiological impact of potential uses of natural gas from wells stimulated with nuclear explosives. This paper summarizes the more important results of these studies.

Radionuclide Inventory

Radionuclides found in gas produced from the completed experiments, Gasbuggy and Rulison, were ^{3}H, ^{14}C, ^{37}Ar, ^{39}Ar, ^{85}Kr, and ^{203}Hg. The small number of radionuclides found is not surprising when one considers that the explosives were detonated in an atmosphere of water and hydrocarbons where most of the fission and activation products are expected to exist as metals or metal oxides. The principal exceptions are the rare gases, iodine, carbon, and tritium. Most of the radioactive species associated with metals and metal oxides are effectively retained in the glassy material formed as the molten cavity walls solidify and collapse to form the chimney. Since a minimum of 90 days elapses before gas is produced from a stimulated well, radioactive decay eliminates all of the short-lived isotopes. Krypton-85 is the only fission-product rare gas which would not decay to negligible concentrations during the shut-in period.

Of the radionuclides found, ^{3}H, ^{14}C, and ^{85}Kr have been studied in greatest detail because they contribute over 99% of the potential dose equivalent* at the radionuclide concentrations observed, and at those projected for future wells (see Table 1). It appears unlikely that other radionuclides will become significant, but each geological formation and each device component must be analyzed with respect to that possibility. The tritium concentration used in this paper, 1 pCi/cm^{3}, is the value projected for the average concentration during the lifetime production of future wells.[1] The concentrations for ^{14}C and ^{85}Kr are scaled to the tritium value on the basis of literature values or fission and activation yield.[2-5] Comparable projections by Rubin et al.[6] are in good agreement with those presented here for tritium; however, their ^{85}Kr concentration is approximately a factor of 2 larger. At the estimated gas production rate (assume ~10% of total lifetime volume produced during the first year), more than 99% of the radioactivity initially present in a nuclearly stimulated well is removed during the first year of production. In subsequent years such a well will produce essentially uncontaminated gas. Therefore first-year average concentrations for a new well may be ten times the average lifetime concentration projections used here. It has been shown that sizable amounts of nuclearly stimulated gas, including first-year gas from new wells, could be distributed through existing facilities to supplement present production as it declines, without elevating the projected average tritium concentration of 1 pCi/cm^{3}.[7]

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*Dose-Equivalent (rem) = Absorbed Dose (rads) x modifying factors. For the sake of convenience, "dose" will be used hereafter instead of "dose equivalent."

Table 1. Relative Percentage of Total Estimated Dose from Man-made Radionuclides in Nuclearly Stimulated Natural Gas

Radionuclide	Projected Average First Year Concentration (pCi/cm^3)	Projected Average Lifetime Concentration (pCi/cm^3)	Percentage of Estimated Total Somatic Dose[a]	Percentage of Estimated Total Genetic Dose[b]
^{3}H	<20	1.0	60	93
^{14}C	<1	0.02	0.3	0.3
^{85}Kr	65	3.3	39	6
All others			<<1	<<1

[a] Dose to total body.

[b] Dose to gonads.

The tritium inventory is distributed in the H_2O-H_2-hydrocarbon system with less than 25% of the total production in the form of hydrocarbons or hydrogen.[6] The remaining 75% appears as tritiated water (HTO) which would normally be removed at the wellhead. Carbon dioxide is also normally removed from natural gas before it enters commercial distribution channels. According to analysis of Gasbuggy gas,[8] the carbon dioxide released from formation rock by the nuclear explosion accounts for at least two-thirds of the ^{14}C inventory. The tritium and ^{14}C present as hydrocarbons will be released as HTO and $^{14}CO_2$, respectively, when the gas is burned.

Estimation of Dose to Man

There are numerous pathways through which radionuclides present in gas from nuclearly stimulated wells may cause radiation exposure to man. Our studies have indicated that ^3H and ^{85}Kr are the critical radionuclides and that exposure to combustion products from unvented home usage of natural gas containing radionuclides is the critical exposure pathway. Although the two critical radionuclides have similar $(MPC)_a$ values (0.2 pCi/cm^3 for ^3H and 0.3 pCi/cm^3 for ^{85}Kr),[9] equal concentrations of the two nuclides in air do not produce radiation doses of equal biological significance to the exposed individual. Tritium is a source of internal exposure with no significant external exposure potential. Tritiated water is rapidly absorbed by the body and distributed throughout the body water pool, resulting in essentially uniform irradiation of the total body. Continuous exposure to HTO at a concentration of 1 pCi/cm^3 results in estimated total-body or gonad doses of 1000 mrem per year of exposure. In contrast to HTO, krypton is only slightly absorbed by the body and its internal exposure contribution is negligible. The limiting dose for ^{85}Kr exposure is that to the skin; approximately 2000 mrem/year is received at the skin surface from continuous exposure at a concentration of 1 pCi/cm^3. The ^{85}Kr dose to the shallowest layer of live skin is 50 to 70% of the dose at the skin surface. Both the total-body and gonadal dose estimates for ^{85}Kr are approximately 1% of the skin surface dose. If one accepts cancer induction as the radiological response and death as the end point, analysis of these dose estimates on a risk basis shows that, at equal concentrations, the somatic risk from ^{85}Kr is approximately one-tenth of that from ^{3}H.[7] The genetic risk from ^{85}Kr is one-fiftieth of that from ^{3}H at equal concentrations, based on the respective gonadal dose estimates.

We can calculate the dose to an individual resulting from combustion of gas in unvented home appliances and heaters based on the projected radionuclide concentrations given in Table 1. For a residence (93 m^2 floor space, 227 m^3 volume) of normal construction with one air change per hour ventilation rate, we estimate the following potential total-body doses (mrem/year) for various unvented domestic uses: cooking, 0.16; water heater, 0.38; refrigerator, 0.20; and heating (5000-degree days), 2.8. The maximum doses estimated for an individual at the projected radionuclide concentrations and assumed exposure conditions with no venting of appliances or heaters is less than 20 mrem/year to the total body. Most cities and states in the United States now require venting of all heaters and appliances except those used for cooking. The advent of large-scale nuclear stimulation of natural gas production may require that this practice be made mandatory (except for ranges) in order to keep the population exposure as low as practicable. If this suggestion is implemented, the estimated average dose to an individual in the exposed population would be slightly less than 0.2 mrem/year for gas containing the average lifetime radionuclide concentrations listed in Table 1. This estimated dose includes a contribution from unvented cooking (0.76 m^3 of gas per day, United States average) plus an average atmospheric contribution from all gas used in the area. This contribution was shown in a study of the Los Angeles Basin to be less than 10% of the calculated individual dose from unvented cooking.[10] Even this small calculated average individual dose (0.2 mrem/year) would deliver a potential 200 man-rems per year to each million people exposed. The man-rem dose estimate is obtained by summation of all individual doses within the exposed population.

Use of nuclearly stimulated natural gas in power stations has been suggested as an alternative to residential use. Study of the hypothetical use of Gasbuggy gas in the Los Angeles Basin has shown that the average population exposure is at least a factor of 10 less for power station gas use than when the gas is distributed for household use.[10] Power station use of nuclearly stimulated gas was given further consideration in the Rulison study[11,12] by assuming that the Cherokee electricity generating plant located in the Denver, Colorado, metropolitan area burned 2.66×10^6 m^3 of gas per day (9.72×10^8 m^3 per year) contaminated with the projected average lifetime radionuclide concentrations listed in Table 1. The estimated dose to the population (1,500,000) in the Denver area due to power station use of that quantity of gas is 0.32 man-rem. The maximum individual dose estimate for the entire area is 0.006 millirem/year.

A rather unusual meteorological condition that prevails in the Denver area, the frequent and regular reversal of wind direction, results in increased doses from combustion products which are blown back over the populated area after initially being blown out of the area. The resulting increase in maximum individual dose is less important than the increase in total population dose (nearly a factor of 2 in this case). The dose estimates for the Denver area include contributions due to blowback. The 9.72 x 10^8 m^3 of gas will supply 174,000 households for 1 year under the following assumptions: unvented cooking (0.76 m^3/day), vented water heater (1.8 m^3/day), and vented heating for 5000-degree days per year (13.4 m^3/day). If each household is assumed to have 3.5 residents, the total number of persons exposed is 610,000, approximately one-third of the total population in the Denver metropolitan area. Then the comparable estimated population dose due to residential gas use is 110 man-rems for 9.72 x 10^8 m^3 of gas having the projected lifetime radionuclide concentrations. Thus, under the conditions specified, the population dose estimate for household use of the nuclearly stimualted gas is nearly 350 times that for power station use.

Assessment of the Estimated Dose to Man

Assessment of the ~~dose~~ estimate projected for use of gas from nuclearly stimulated fields can vary in form and complexity. We believe that the assessment should begin with the recognition that natural gas contains natural radioactivity and that one result of nuclear stimulation is an incremental change in the total radioactivity concentration to which gas users are exposed.

It has been known for nearly 70 years that natural gas contains a radioactive species, radon, but little effort has been devoted to estimation of doses that gas users receive from this source of natural radioactivity. This was due, in part, to lack of reliable data on the radon content of natural gas at points of use. Samples supplied by gas transmission companies were analyzed in 1972 and 1973 by scientists in four institutions to provide data on radon concentration in gas being supplied to several metropolitan areas in the United States.[13] The average value (20 pCi/liter) for all sample locations is used in our dose estimations; but, if results from one sample location where the average concentration is 95 pCi/liter are disregarded, the average drops to about 10 pCi/liter.

One exposure situation that we consider for radon daughters produced by decay of radon in natural gas is the same as that assumed in the previously described studies.[11] An unvented kitchen range using 0.76 m^3 of gas per day was assumed to be located in a house having a volume of 227 m^3. Lacking data on the average air change rate in homes having unvented kitchen ranges, we calculated the concentration of radon daughters in the home for air change rates varying from 0.25 to 2.0 changes per hour. We then estimated doses to the bronchial epithelium from radon daughters resulting from decay of radon introduced with the natural gas and compared these doses with those from an assumed concentration of 0.13 pCi/liter of radon (the average concentration from a number of radon measurements in the United States) and each of its daughters in ventilation air. The estimated dose rate to the bronchial epithelium due to radon and its daughters in the ventilation air was 1300 to 1400 millirem per year. Additional estimated dose to the bronchial epithelium due to the radon (20 pCi/liter) present in natural gas ranges from 90 mrem/year, for 0.25 air change per hour, to 5 mrem/year, for two air changes per hour. At most, the estimated dose increase due to radon present in natural gas is less than 7%, considering only the two sources of radon. The relative importance of this natural activity in the gas is reduced still further if one considers the daughter activity due to the decay of radon and thoron emanating from home building materials which in some situations exceeds our assumed concentration in ventilation air by a factor of 10. It appears likely, therefore, that the dose which can be attributed to the radon in natural gas is small (less than 1%) compared to the total dose received in the home from all sources of airborne radioactivity. These localized radon-radon daughter dose estimates are for a limited tissue volume: the basal cells of the bronchial epithelium, which are assumed to be the critical tissue. It has been estimated that the corresponding dose to the total lung mass (1000g) is an order of magnitude lower.[14] The dose to the total lung due to radon in the gas (1.5 millirem/year, assuming one air change per hour) is more suitable for comparison with the total-body estimates obtained for the man-made radioactivity in nuclearly stimulated gas. The comparison indicates that the projected concentrations of man-made radioactivity will contribute a dose which is approximately 12% of the dose due to radon in the gas. Local conditions may, however, alter this percentage significantly.

Another possible assessment, and one which will be required, is comparison of the dose estimate with applicable radiation safety standards. At this time, however, there are no standards which are specific to the use of nuclearly stimulated gas. Since millions of people could potentially be users of gas produced with this technology, caution must be exercised in establishing acceptable concentrations of man-made radioactivity in natural gas for industrial and domestic consumption. The Federal Radiation Council (FRC) has established 170 millirem/year as the upper limit for the average total-body dose to a suitable sample of an exposed population group for radiation from all sources exclusive of natural background and medical exposures.[15] However, this single source of exposure must not be permitted to take up a disproportionate share of the 170 millirem/year total. The estimated average total-body dose for the population group expected to be exposed via home use of nuclearly stimulated gas is a small fraction (0.1%) of the dose limit of 170 millirem/year.

Our estimate of dose to the whole body from nuclearly stimulated gas (0.2 millirem/year) may also be put in perspective by comparing it with dose estimates (millirem/year) to the whole body for other sources of radiation received by members of the public: natural background radiation, 130; medical diagnostic X-rays, 110; nuclear weapons fallout, 2; consumer devices, 2; industrial uses of radiation, less than 1; and power reactors, less than 1.[6] Note that the individual dose estimates for fallout and for consumer devices are approximately ten times the average dose estimated for members of the population hypothetically using the gas.

A hypothetical assessment of the projected dose may be obtained by estimating the risks which the exposure represents in terms of additional deaths, additional death equivalents due to radiation-induced life span shortening, and additional genetic deaths. A total risk estimate was obtained by summing all three types in spite of the recognized inherent difficulties in combining somatic and genetic insults whose manifestations may differ so greatly. The factors used to convert estimates of radiation dose into estimates of risk are those suggested by the ICRP.[16,17] Those factors are based on the conservative assumption that there is a linear relationship between dose and effect. The estimates of additional deaths calculated here are believed to be upper limits of risk for the low dose levels considered. The actual risk in fact may be zero, for at such low doses, there is no practical method to reliably determine the actual risk involved. The risk estimated for the projected gas usage is compared in Table 2 with similar estimates of risk for other sources of radiation exposure of the public. These estimated risks (theoretical deaths) may also be compared with known death rates (number of deaths per million population) among the United States population due to other causes[18]: all causes, 9650; heart disease, 3730; cancer, 1590; stroke, 1060; accidents, 560; pneumonia, 330; diabetes mellitus, 190; arteriosclerosis, 170; and other causes, 2020.

The population dose (man-rem) estimates for the hypothesized gas uses may also be assessed, but to a lesser extent, as there have been no official numerical limits established with which the population dose estimates can be compared. We have shown that the man-rem dose to the local population is sensitive to the manner of gas usage. The population dose in the Denver area due to background radiation (approximately 200 mrem per person) is nearly 3.0×10^5 man-rems per year, while that estimated for residential gas use (110 man-rems) is 0.037% of the background dose. Dose to the global population is another point to be considered for comparison. Based on dose conversion factors presented in a recent report of the United Nations Committee on the Effects of Atomic Radiation (UNSCEAR),[19] the estimated infinite dose (integrated over infinite time) to the population of the northern hemisphere due to the release of the man-made radioactivity in that volume of gas is approximately 840 man-rems. Nearly all (99%) of that infinite dose is contributed by ^{14}C due to its long radioactive half-life (5730 years). This estimated dose must be added to the estimated local population dose in assessing the total population dose incurred as a result of the release.

Table 2. Comparison of Estimated Deaths Due to Man-Made Radioactivity in Nuclearly Stimulated Natural Gas with Similar Estimates for Other Sources of Radiation Exposure of the Public in the United States

Sources of Exposure	Estimated Deaths per Million Individuals Exposed[a]
Natural background radiation[b]	17
Radioactivity in natural gas[c]	
Natural (radon + daughters)	0.3
Man-made	0.03
Other man-made sources of radiation	
Medical diagnostic x-rays	20
Fallout from nuclear weapons	0.4
Consumer devices	0.4
Industrial uses of radiation	<0.2
Power reactors	<0.2

[a] Obtained by summing estimated somatic and genetic effects; therefore, some of these estimated deaths will occur among the exposed individuals or the first generation of their offspring, but a large majority (over 80%) will occur in succeeding generations.

[b] 0.1 rem per year.

[c] Based on projected radionuclide concentrations used in this study.

V. SUMMARY AND CONCLUSIONS

The radiological impacts of hypothetical uses of nuclearly stimulated gas for domestic and industrial purposes were studied. Average radionuclide concentrations in the gas were projected for lifetime production of future wells. The critical exposure pathway were determined to be the release of combustion products from unvented appliances in the home. The estimated average whole-body dose from man-made radioactivity for that pathway is 0.2 millirem per year of gas use. The estimated lung dose due to natural radioactivity (radon) in the gas is 1.5 millirem per year. The critical man-made radionuclides are ^{3}H, ^{14}C, and ^{85}Kr. The largest fraction of the local population dose received via the critical pathway is due to ^{3}H, followed by ^{85}Kr. Carbon-14 is of importance as the major contributor to the infinite population dose estimated for the northern hemisphere, with the total dose to the local population being very dependent on the manner of gas use. The radiological impact of the hypothesized gas use was assessed in terms of dose and in terms of risk, in the interest of incorporating radiological impact of gas use as an integral part of the cost-benefit analysis for the development of nuclear gas stimulation technology. The results of the assessment indicate that the radiological impact would be very small. Although the dose and risk estimates obtained in this study are small, the possible exposures still must be scrutinized to achieve the lowest practicable local and global doses.

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