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RELATIVE RISKS FROM RADIONUCLIDES FOUND
IN NUCLEARLY STIMULATED NATURAL GAS*

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INTRODUCTION

There are numerous pathways through which the nuclides present in gas from nuclearly stimulated wells can cause radiation exposure to man. Certain nuclides and pathways have been designated as critical by the International Commission on Radiological Protection (ICRP) [1] although "important" may be a more appropriate adjective than "critical."

In this paper the risks from man-made radionuclides possibly present in nuclearly stimulated natural gas are considered in three steps: (1) radionuclides are ranked on the basis of their estimated radiation dose potentials; (2) projected doses expected to result from gas usage are compared with estimated doses from other radiation sources; and (3) risk projections for the estimated doses are compared with other risks encountered in the normal activities of life in technologically developed nations.

It is prudent to assess the radiological impact of nuclear gas stimulation technology, because the results of this development could affect millions of people. Caution should be exercised in establishing acceptable concentrations of man-made radioactivity in natural gas for industrial and domestic consumption.

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MASTER

EXPECTED RADIONUCLIDE CONCENTRATIONS IN WELLHEAD GAS

Table I shows radionuclide concentrations observed in the cavity gas initially present in the Gasbuggy and Rulison experiments with estimates of the concentrations expected in the forthcoming Rio Blanco and Wagon Wheel experiments. The right-hand column is an estimate of the average tritium and ^{85}Kr concentrations for a proposed Piceance Basin well producing 4.25×10^9 standard cubic feet (SCF) during the first year of production. It is estimated that Piceance Basin wells will require three 100-kiloton explosives fired sequentially.

The small number of radionuclides found a number of months after detonation is not surprising when one considers that the explosives are fired in an atmosphere of water and hydrocarbons where most of the fission and activation products exist as metals or metal oxides. The principal exceptions are the rare gases, iodine, and tritium.

Most of the radioactive species associated with metals and metal oxides are effectively retained in the glassy masses formed as the molten cavity walls solidify and collapse to form the chimney. Smith [2] attempted to detect in early Gasbuggy samples the radionuclides shown in Table II and concluded they could not have existed in the cavity gas at concentrations higher than those shown. Of the radionuclides not detected, the rare earths (^{147}Pm , ^{155}Eu , ^{144}Ce , ^{141}Ce , ^{156}Eu , ^{143}Pr , and ^{147}Nd) may be excluded because of the low vapor pressure of their oxides. Three isotopes (^{89}Sr , ^{90}Sr , and ^{91}Y) have rare gas precursors and, in the elemental or oxide form, exhibit higher boiling points than ^{137}Cs , which also has a rare gas precursor. Thus, the strontium and yttrium isotopes would be present at a lower concentration than the upper limit shown for cesium, and our estimated concentrations for ^{90}Sr and ^{89}Sr used in this paper are not based on the experimental ^{90}Sr detection limit (1.4×10^{-3} pCi/cm³) reported by Smith [2].

Zirconium isotopes and ^{111}Ag would not be expected in the gas because of the low volatility of zirconium oxide and metallic silver, the most likely chemical forms of these elements in post-detonation cavities. Cadmium-115m cannot be excluded as a possible contaminant, but its low yield and 45-day half-life indicate that it should not be a significant problem. All of the other solid fission radionuclides can be excluded

TABLE I

RADIONUCLIDE CONCENTRATIONS MEASURED OR ESTIMATED
FOR CAVITY GAS IN NUCLEAR STIMULATION PROJECTS

Radionuclide	Concentration [pCi/cc (STP)]				
	Gasbuggy (measured) ^a	Rulison (measured) ^a	Rio Blanco (estimate) ^{b, c}	Wagon Wheel (estimate) ^{d, c}	Piceance Basin First-Year Average (estimated) ^e
⁸⁵ Kr	123	150	205	140	60
³ H	707	176 (107 1st yr)	<123 ^f	<70 ^f	<8
³⁷ Ar	4720	6500	<1600	<150	--
³⁹ Ar	0.085	1.4	<2	<2	--
¹⁴ C	0.6 ^h	0.41 ^h	<2.3 ^g	<3 ^g	--
²⁰³ Hg	--	4.5 x 10 ⁻⁸ (est)	--	<<1	--

^aAt detonation [2-5].

^bAt 90 days after detonation.

^cEnvironmental Statements [7,8].

^dAt 180 days after detonation.

^eReference 6.

^fWater not removed.

^gHydrocarbons and carbon dioxide.

^hHydrocarbons only.

TABLE II

DETECTION LIMITS FOR RADIONUCLIDES IN CAVITY GAS
(GASBUGGY EXPERIMENT)^a

Radionuclide	Half-life (days)	Detection Limit ($\mu\text{Ci/cc}$)
^{127}Sb	3.9	2.3
^{131}I	8.05	0.04
^{125}Sn	9.04	4.5
$^{129\text{m}}\text{Te}$	33	1×10^{-3}
^{103}Ru	41	8×10^{-5}
$^{125\text{m}}\text{Te}$	58	0.23
^{123}Sn	131	2×10^{-2}
^{106}Ru	367	1×10^{-4}
^{125}Sb	985	2×10^{-4}
^{137}Cs	10^4	2×10^{-5}

^aReference 2.

on the basis of yield or half-life since a minimum of 90 days will occur before gas would be produced from a stimulated well.

Except for ^{85}Kr , the fission product rare gases, whose total production should be released to the chimney, have sufficiently short half-lives (^{133}Xe at 5.27 is the most significant) that they would decay to negligible concentrations.

RANKING OF RADIONUCLIDES ACCORDING TO THEIR BIOLOGICAL SIGNIFICANCE

Consideration of the available information on probable radionuclide concentrations in cavity gas and the maximum permissible concentration in air [(MPC)_a] values in Appendix B, Table II of 10 CFR 20 [9], leads to the implied ranking of these radionuclides in terms of potential dose to man listed in Table III.

The only activation radionuclides that have been observed in cavity gas are tritium, ^{203}Hg , ^{37}Ar , ^{39}Ar , and ^{14}C . Mercury-203 was observed early in the Rulison testing program [5] but only at a level of 1.27×10^{-5} pCi/cc of cavity gas. Activation production of tritium, also a fission product, depends on constituents of the formation. It appears unlikely that any other activation radionuclide will be significant, but each geological formation of interest as well as components of the explosive device must be analyzed with respect to this possibility.

Most of the radionuclides listed in Table III were not detected in experimental measurements, but none of these could be classed as a significant contributor to radiation exposure even at the upper limit of its estimated concentration in the gas. The remainder of this discussion is limited to those radioisotopes which have been found in nuclearly stimulated gas. Of these, ^{85}Kr and ^3H deserve detailed consideration, because their combined dose potential is over 95% of the total estimated dose.

Using fission yields for ^{85}Kr of 0.0031 from ^{235}U and 0.001446 from ^{239}Pu [10] together with the value of 1.46×10^{23} fissions per kiloton [11], we calculate nominal yields as 25.0 Ci/kiloton for ^{235}U fission and 11.7 Ci/kiloton for ^{239}Pu fission. Using fission yield estimates for ^3H at 1 MeV neutron energy of 1.2×10^{-4} for ^{235}U and 2.5×10^{-4} for ^{239}Pu

TABLE III

DOSE POTENTIAL OF SELECTED RADIONUCLIDES ON THE BASIS OF THEIR MAXIMUM PERMISSIBLE CONCENTRATION IN AIR
(MPC)_a AND ESTIMATED MAXIMUM CONCENTRATION IN CAVITY GAS

Radionuclide	Half-life (days)	(MPC) _a ($\mu\text{Ci/cc}$) ^a	Estimated Maximum Concentration 90 Days Post-Shot ($\mu\text{C/cc}$)	Fraction of (MPC) _a (%)	Fraction of Total Dose (%)	Numerical Rank of Potential Dose
⁸⁵ Kr ^b	3.75×10^3	3×10^{-7}	2.0×10^{-4}	670.00	54.59	1
³ H ^b	4.51×10^3	2×10^{-7}	1.0×10^{-4}	500.00	40.74	2
¹⁴ C ^b	2.00×10^{14}	1.0×10^{-7}	3.0×10^{-6}	30.00	2.44	3
³⁷ Ar ^{b,c}	3.41×10	1.0×10^{-4}	1.0×10^{-3}	10.00	7.81	4
¹²⁵ Te ^d	5.80×10	1.0×10^{-8}	8×10^{-8}	8.00	0.65	5
³⁹ Ar ^b	9.56×10^4	$<3 \times 10^{-7}$	2.0×10^{-6}	6.66	0.54	6
¹²⁵ Sn ^d	9.4×1	4.0×10^{-9}	5×10^{-9}	1.25	0.10	7
²⁰³ Hg ^b	4.58×10	2.0×10^{-9}	1.5×10^{-9}	0.75	0.06	8
⁹⁰ Sr ^e	1.02×10^4	3.0×10^{-11}	1.0×10^{-11}	0.33	0.03	9
¹³¹ I ^d	8.05×1	1.0×10^{-10}	2.0×10^{-11}	0.20	0.02	10
^{129m} Te ^d	3.30×10	3.0×10^{-9}	4×10^{-10}	0.13	0.01	11
¹³⁷ Cs ^d	9.70×10^3	2.0×10^{-11}	2.0×10^{-11}	0.01	--	
⁸⁹ Sr ^e	5.40×10	3.0×10^{-10}	1.0×10^{-11}	0.03	--	
¹²⁵ Sb ^d	9.85×10^2	2.0×10^{-8}	2×10^{-10}	0.01	--	
¹⁰⁶ Ru ^d	3.67×10^2	3.0×10^{-9}	1×10^{-10}	0.03	--	
¹²³ Sn ^d	1.31×10^2	1.0×10^{-8}	2×10^{-10}	0.02	--	
¹⁰³ Ru ^d	4.10×10	2.0×10^{-8}	4×10^{-11}	negligible	--	

^aFrom Table II, Appendix B, Reference 9.

^bDetected in nuclear stimulated gas.

^c(MPC)_a for ⁸⁵Kr was used.

^dMaximum possible concentration based on detection limit, not observed in sample analysis.

^eEstimates based on ¹³⁷Cs detection limit, precursors, and chemistry.

[12], we calculate nominal tritium yields as 0.84 Ci/kiloton for ^{235}U and 1.75 Ci/kiloton for ^{239}Pu . Tritium is, however, also produced by neutron reactions in the surrounding rock, the largest production resulting from neutron capture by ^6Li . Green and Lessler [13] estimate that for 10 ppm ^6Li in the surrounding rock, 500 Ci of ^3H will be produced by 1 mole of neutrons. If a value of 2.5 neutrons per fission is used, this would yield 300 Ci/kiloton. A 10-cm polyethylene shield (25 mole % boron) could reduce this figure by an order of magnitude [13], but it appears unlikely that production of tritium by activation can be eliminated. Tritium is distributed in the H_2O - H_2 -hydrocarbon system with not more than 25% of the total production in the form of hydrocarbons or hydrogen. The remaining 75% appears as HTO which would normally be removed at the wellhead and must have a means for disposal.

Using these estimated tritium and ^{85}Kr production figures and the gas production figures of Rubin et al. [6], we calculate an expected 30 to 65 pCi/cc (STP) of ^3H as the average radionuclide concentrations in first-year production of 4.25×10^9 SCF of gas from a Piceance Basin well. These values are consistent with the production of 60 pCi/cc of ^{85}Kr and less than 8 pCi/cc of ^3H given by Rubin et al. At the estimated production rate, more than 99% of the activity initially present in a nucleary stimulated well is removed during the first year of production. In subsequent years, such a well produces essentially uncontaminated gas.

The ranking of potential dose contribution based on $(\text{MPC})_a$ (Table III) does not provide a true measure of the relative risk of exposures to tritium and ^{85}Kr . It is often erroneously assumed that the $(\text{MPC})_a$ value for each radionuclide produces an equivalent radiation dose to the individual. This is not true for tritium and ^{85}Kr . Tritium is a source of internal exposure with no significant external exposure potential. Tritium as HTO (the form usually present) is rapidly absorbed by the body and distributed throughout the body water pool, resulting in essentially uniform irradiation of the whole body. In contrast, krypton is only slightly absorbed by the body and the internal exposure contribution is negligible. The skin dose (primarily due to beta components) is the overall limiting factor for ^{85}Kr , with the whole body dose (primarily due to gamma rays and bremsstrahlung) being approximately 1% of the skin dose.

If we choose a concentration for each of these radionuclides in air of 1 pCi/cc, we find a range of published doses in millirems per year as tabulated in Table IV. Radiation dose limits recommended by the ICRP [1] for various reference organs allow six times as much skin dose as whole body dose. If this radiosensitivity differential is applied to the dose estimated for the shallowest layer of the live skin, the somatic risk from ^{85}Kr is less than one-tenth of the somatic risk from tritium oxide. In addition, the significance of the skin dose is reduced by another factor of 10 because more than nine out of ten skin cancers are curable [19]. Because ^{85}Kr has low beta energy, clothing also provides protection to an extent that has not yet been evaluated. Even with these reductions, the somatic risk from the ^{85}Kr skin dose will probably remain as large as that from its whole body dose.

It would appear that the somatic risk from ^{85}Kr is less than one-tenth of the somatic risk from tritium at equal radionuclide concentrations, but experimental data to substantiate this conclusion are not available. For calculating the effective ^{85}Kr dose, we shall use 10% of the estimated dose at the skin surface. The genetic risk from ^{85}Kr is only about one-eightieth of that from tritium at equal radionuclide concentrations, and the long-term genetic effects are, we believe, more important than the somatic effects at the dose levels we are considering. If it is assumed that there would be three times as much ^{85}Kr as tritium oxide in the gas combustion products, less than 25% of the estimated total somatic dose and less than 4% of the estimated total genetic dose from these radionuclides would come from ^{85}Kr .

Device design can reduce the amount of tritium formed, but it is considered unlikely that total tritium in cavity gas will be reduced to a point where the somatic dose from ^{85}Kr will become the controlling factor. However, the dose from ^{85}Kr may represent an appreciable fraction of the man-rem dose.

Argon-39 may be combined with ^{85}Kr in considering the total effect of the radionuclides in natural gas, because it is a pure beta emitter whose energy is slightly less than that of ^{85}Kr . Argon-37 with a 34.1-day half-life will decay to a negligible activity level early in the production period.

TABLE IV
ESTIMATED DOSE FOR ^{85}Kr AND HTO IN AIR AT
A CONCENTRATION OF 1 pCi/cc (STP)

Exposure	Dose (millirems per year)	Reference
<u>^{85}Kr at 1 pCi/cc</u>		
Surface of skin or clothing	2093	Kirk [10]
	1690	Hendrickson [14]
	2080	Dunster and Warner [15]
	1664	Whitton [16]
Shallowest layer of live skin	1000	Hendrickson
Whole body	14.2	Kirk
	23.3	Hendrickson
	14.1	Dunster and Warner
Gonads	16.7	Kirk
	23.3	Hendrickson
	17.3	Dunster and Warner
<u>^3H (HTO) at 1 pCi/cc</u>		
Surface of skin or clothing	~0	Turner, Kaye, and Rohwer [17]
Whole body	1825	Rohwer and Kaye [18]
Gonads	1825	Rohwer and Kaye

The only remaining isotope of potential dose significance in Table III is ^{14}C . Production of this radionuclide depends on the chemical composition of the stimulated formation but should be less than 2% of the ^{85}Kr yield. According to analyses of Gasbuggy gas [2], at least two-thirds of ^{14}C activity is in the carbon dioxide released from formation rock by the nuclear explosion. Carbon dioxide is normally removed from natural gas before it enters commercial distribution channels. The remaining carbon activity is bound chemically in the hydrocarbons and will be released as $^{14}\text{CO}_2$ when the gas is burned.

In terms of the somatic effect of radionuclides in nuclearly stimulated gas, tritium would, therefore, be the major contributor to the total estimated dose (Table V). The percentages shown are arbitrary and are subject to change as more experimental information becomes available.

RADIONUCLIDE CONCENTRATION IN GAS COMBUSTION PRODUCTS

The fact that tritium and ^{85}Kr will exist in the initial wellhead gas at concentrations many times their $(\text{MPC})_a$ is cause for concern and must be considered. There are several ways of calculating minimum dilutions: (1) Natural gas (principally CH_4) when burned in air becomes diluted by a factor of 11, based on the stoichiometric amount of oxygen required. (2) The lower explosive limit is 5% gas in air which gives an effective dilution of 20. (3) At 80°F only 2.50% moisture exists in saturated air. Since two molecules of water vapor are formed from each methane molecule burned, a minimum eighty-fold dilution of tritium occurs under these conditions. Any further addition of combustion-produced moisture will condense. (4) The industrial limit of carbon dioxide in air, 0.5%, gives an effective dilution of 200.

Of the two real limits (mass in saturated air and the lower explosive limit), we shall use the dilution factor of 20, based on the lower explosive limit to set a maximum allowable concentration in natural gas. This factor applied to the present $(\text{MPC})_a$ of 0.2 pCi/cc for tritium oxide yields a maximum ^3H concentration in gas of 4 pCi/cc (STP).

If one were to consider Piceance Basin development and a pipeline delivering first-year gas to Farmington, New Mexico, where it could be

TABLE V

RELATIVE PERCENTAGE OF TOTAL ESTIMATED SOMATIC DOSE
FROM RADIONUCLIDES IN NUCLEARLY STIMULATED GAS

Radionuclide	Estimated Concentration (pCi/cc)	Percentage of Total Estimated Dose	Average Concentration First-Year Production (pCi/cc)	Percentage of (MPC) _a
^3H	4	69	<20	<100
^{85}Kr	13	26	65	217
^{14}C	0.20	<5	<1	<10
All others		<<1	--	--

blended with uncontaminated natural gas (6×10^8 SCF/day or 2.19×10^{11} SCF/year) before transmission to the west coast, one could produce gas from ten nuclearly stimulated wells per year (4.25×10^{10} SCF) without exceeding 4 pCi/cc at the point of use. The total amount of gas used in the Pacific Southwest in 1970 (about 2×10^{12} SCF) was ten times the volume of gas in the Farmington pipeline [6]. In principle, 100 new wells per year could be added to serve this region without exceeding the above limit, although achievement of uniform mixing could be a limiting consideration. It can be seen that large amounts of nuclearly stimulated gas could be distributed through existing facilities supplemental to present production as it declines. It has been shown that the average population exposure is at least a factor of 10 less for power station gas use than when gas is distributed for household use [20]. Therefore, if estimated total population doses (man-rems) prove to be undesirably large for extensive use of nuclearly stimulated natural gas in homes, power-station use is a possible alternative.

ESTIMATED WHOLE BODY DOSES

Based on 4 pCi/cc (STP) for ^3H , 13 pCi/cc (STP) for ^{85}Kr , and 0.20 pCi/cc (STP) for ^{14}C , we can calculate the maximum dose to an individual resulting from combustion of gas in unvented home appliances or heaters based on air saturated with moisture from combustion products at 80°F . This condition can be realized only when unvented heaters or appliances are used under weather conditions where ventilation air contains little or no moisture and should be considered calculable, but not credible. Our conversions are based on data from Table IV for $20 \text{ m}^3/\text{day}$ air intake [21] and a 50-year whole body dose commitment from ^{14}C of 0.424 millirem/ μCi inhaled. The dose conversion factor used for tritium is 0.126 millirem/ μCi inhaled. This dose factor for tritium is based on a quality factor of 1.0 as recommended by ICRP [22], a biological half-time of 10 days for HTO in man [23], and the assumption that HTO vapor intake by skin absorption is equal to 70% of that by inhalation [24]. The calculated values are shown in Table VI. The dose limit for individual members of the general public (500 millirems/year) [21] would not be exceeded even for these conditions.

TABLE VI

UPPER LIMIT DOSE ESTIMATES FOR USE OF NUCLEARLY STIMULATED GAS
UNDER SPECIFIED CONDITIONS^a

Radionuclide	Estimated Concentration (pCi/cc)	Dose Limit (millirems/year)	
		Whole Body	Skin
^3H	4	<45	----
^{85}Kr	13	3.8	341 (surface) 163 (top live layer)
^{14}C	0.20	<8	----

^aThe conditions assumed in making these calculations are illegal in many states and are considered very unlikely to occur.

We realize, of course, that one should not allow one source of exposure (in this case, the combustion of nuclearly stimulated gas in unvented home appliances) to take up a disproportionate share of the 500-millirem annual dose.

An extensive theoretical study of the impact of the use of nuclearly stimulated gas in the Pacific Southwest has been completed [25]. For a 1000-ft² residence of normal construction with one air change per hour we can calculate the potential dose equivalents for various domestic uses (Table VII). These calculated values are believed to be conservative.

Many cities and 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 for all gas appliances in order to keep the population dose as low as practicable. If this suggestion is implemented, the average dose to an individual in the exposed population would be less than 0.70 millirem/year since the average atmospheric contribution from all gas used in the Los Angeles Basin has been shown to be less than 10% of the calculated dose from unvented cooking [20]. Even this small calculated individual dose would deliver a potential 700 man-rem per year to each million people exposed.

It should be kept in mind, in considering this population exposure value, that a conservative assumption in regard to the tritium concentration in nuclearly stimulated gas was made in arriving at the average dose to individuals in the population group. The value used in this report (4 pCi/cc) can be compared with the figure of approximately 1 pCi/cc projected for the average concentration during the lifetime production of future wells [26]. However, it should also be recognized that home use of gas containing radioactivity in unvented appliances probably involves smaller variations in estimated dose to individuals in the home than the orders of magnitude variation that occurs among individuals exposed to radioactivity dispersed in the atmosphere and in streams. In fact, transporting long-lived radioactivity into homes where the activity released from unvented appliances receives limited dilution is a situation that has not been previously encountered in actual population exposure situations from man-made radioactivity, and, accordingly, the risks must

TABLE VII

EXPECTED AVERAGE WHOLE BODY DOSE EQUIVALENTS FROM HYPOTHETICAL DOMESTIC USES
OF NUCLEARLY STIMULATED GAS

Radionuclide	Estimated Concentration (pCi/cc)	Whole Body Dose (millirems/year)			
		Unvented Cooking	Unvented Water Heater ^a	Unvented Refrigerator ^b	Unvented Heating ^{a, c}
³ H	4	0.51	1.21	0.64	4.50
⁸⁵ Kr	13	0.04	0.09	0.05	0.37
¹⁴ C	0.20	0.09	0.21	0.11	0.76
Total		0.64	1.51	0.80	5.63

^aIllegal in many states.

^bBased on estimates made in Colorado and sales of gas refrigerators, it is estimated that less than 2% of United States homes have gas refrigerators.

^c2500-degree days.

be carefully examined and evaluated before large population groups are exposed in this manner. Fortunately, the concentration of radioactivity in gas transmitted in pipelines can be monitored continuously and absolute control can be exercised on the concentration permitted in homes. In addition, if the concentration cannot be reduced to acceptable levels by dilution before reaching the homes, it could be diverted to electric generating plants where the overall man rems expected to be delivered to the population would be considerably less (and, hopefully, acceptable).

ASSESSMENT OF THE ESTIMATED AVERAGE WHOLE BODY DOSE

Assessment of the dose estimate projected for use of gas from nuclearly stimulated fields can vary in form and complexity, reflecting the perspective of the person performing the analysis and the reason for the assessment. Our first assessment is a comparison of the dose estimate with applicable radiation safety standards.

At this time, there are no standards which are specific to the use of nuclearly stimulated gas. The Federal Radiation Council (FRC) established 500 millirems/year as the upper limit for whole body dose to individual members of the population and 170 millirems/year as the upper limit for the average whole body dose to a suitable sample of an exposed population group for radiation from all sources exclusive of natural background and medical exposure [27]. The FRC further recommends that every reasonable effort be made to keep exposures as far below these levels as practicable. Some apportionment of these dose limits among the many potential sources of exposure has been suggested. Brodsky [28] provides a framework for balancing and controlling the allotment of radiation exposure from consumer items on the basis of a benefit-risk assessment, but he gives no specific values applicable to our case. Morgan [29] suggests apportionment of the specified 170-millirem limit as: nuclear power operations, 67 millirems; other industrial operations, 45 millirems; medical, 50 millirems; occupational, 4 millirems; weapons fallout, 2 millirems; and miscellaneous, 2 millirems. Regardless of the allocation method used, the estimated average whole body dose for the population group expected to be exposed via home use of nuclearly stimulated gas is a small fraction (0.4%) of the dose limit of 170 millirems/year.

TABLE VIII
ESTIMATED AVERAGE ANNUAL DOSE TO AN INDIVIDUAL IN THE UNITED STATES
FROM NATURAL AND MAN-MADE RADIATION SOURCES

Source of Radiation	Estimated Dose (millirems/year)	References
<u>Natural Sources:</u>		
Terrestrial radiation ^a	70	27, 30, 31
Cosmic radiation ^b	30	
<u>Man-Made Sources</u>		
Medical diagnostic x-rays ^c	110	27, 30, 32
Fallout from nuclear weapons ^d	2	33, 34
Consumer devices ^e		27, 30
Industrial uses of radiation	<1	35
Power reactors ^f	<1	32, 36

^aExternal exposure contributes about 50 millirems and internal exposure about 20 millirems.

^bExternal exposure at sea level.

^cBased on an assumed genetically significant dose of 36 millirems per year, with the further assumption that the effective somatic dose is approximately three times the genetically significant dose.

^dInternal exposure per year averaged over the lifetime of an individual.

^eExternal exposure from television sets, luminous dial watches, etc.

^fEstimated annual dose to sizable population groups from radioactivity released in effluents from all light water-cooled nuclear power reactors on all sites in the United States through the year 2000.

TABLE IX

THEORETICAL RISK ESTIMATES FOR RADIATION INSULTS
AT LOW DOSE RATES

Type of Risk	Calculated Mortality Probability
<u>Somatic Insult</u>	
All types of cancer	10^{-4} /person/rem
Nonspecific life shortening	5×10^{-5} /person/rem
<u>Genetic Insult</u>	
First-generation genetic deaths	2×10^{-5} /person/rem
Total genetic deaths	7×10^{-4} /person/rem

Another approach for putting this estimated dose (0.70 millirem/year) in perspective is to compare it with dose estimates for other exposures received by members of the United States public (see Table VIII). The values presented in this table are averages for the entire United States population, but the major portion of the dose estimated from nuclearly stimulated gas (for unvented cooking) would be received only by that segment of the population utilizing the gas in this manner. The dose attributed to natural sources varies considerably with geographic location; the terrestrial component is estimated to range from 30 to 200 millirads/year, the cosmic component from 30 to 100 millirads/year. The annual whole body dose projected for home users of natural gas from nuclearly stimulated gas fields is approximately 0.5% of the average dose of 130 millirems/year received by members of the United States population from natural background radiation reported in a recent survey [37]. In comparison with man-made radiation sources, the estimated whole body dose due to medical diagnostic x-rays in 1970 approximately equals the background radiation dose shown in Table VIII and thus is 160 times larger than the projected dose to the average natural gas user (as developed in this report). In contrast, the individual dose estimates for fallout and for consumer device radiation are approximately three times the average dose estimated for members of the hypothetical gas-using population.

A more complex, although largely hypothetical, assessment of the projected dose from use of nuclearly stimulated gas is obtained by estimating the risk which the exposure represents in terms of additional theoretical deaths, additional theoretical death equivalents due to radiation-induced life span shortening (For this calculation, 70 years of life shortening equals one death.), and additional theoretical genetic deaths. The risks (theoretical deaths) may then be compared with known death rates among the United States population from other causes. The term "theoretical death" is used because the calculation results in what is believed to be an upper limit of risk for the low average dose level (0.70 millirem/year) calculated in this paper. The factors used to convert estimates of radiation dose into estimates of risk (see Table IX) are those suggested by the ICRP [38, 40]. It is important to note that these factors are based on the conservative assumption that there is a linear relationship between dose and effect. The actual risk in fact ~~may~~

may be zero. However, at such low doses, there is no practical method to reliably determine the actual risk involved. In defining its basic concepts, the ICRP has stated "that the permissible doses for occupational workers* can 'be expected to produce effects which could be detected only by statistical methods applied to large groups.' This circumstance would by itself create great difficulty in evaluating, by direct observation, the risks attendant on these levels of exposure; in practice the problem is made considerably more difficult because the same types of injury arise frequently from other and unidentified causes. The only practical approach is an indirect one, namely, to assume that the response per unit dose at very low doses is the same as that observed at the considerably higher levels of exposure for which reasonably quantitative observation is possible. This procedure, as the United Nations Scientific Committee on the Effects of Atomic Radiation has recently concluded, is likely in the majority of cases to indicate an upper limit of risk because 'it is unlikely that the risk per unit dose at very low doses will be any greater than at high doses and likely to be much less.' A further source of uncertainty is that in the assessment of genetic risks it is necessary to depend almost entirely on observations made on organisms other than man" [40].

The theoretical nonspecific life shortening accounts for increased mortality following radiation exposure of populations, mortality which is not specifically associated with any disease but would appear as an accelerated aging process. It should be understood that the expression of genetic insult in terms of numbers of theoretical deaths is not the same as the calculated somatic death. A genetic death may be defined as the eventual loss of a gene lineage (e.g., reduced fertility, sterility of a person carrying the gene, stillbirth, abortion, and prereproductive death). The basic assumption is that each genetic mutation eventually results in a calculable "death." Some "deaths" will occur in the first generation, but a large majority will occur in succeeding generations.

Risk estimates calculated for the projected use of natural gas from nuclearly stimulated wells are presented in Table X. The estimates for

*The authors of this report point out that the dose limits for members of the public are one-tenth the permissible doses for occupational workers.

TABLE X

UPPER LIMIT ESTIMATES OF ADDITIONAL DEATHS EXPECTED TO RESULT FROM
THE RADIATION DOSE (0.70 MILLIREMS PER YEAR) RECEIVED FROM THE
HYPOTHETICAL HOME USE OF NUCLEARLY STIMULATED NATURAL GAS

Type of Radiation Damage	Theoretical "Deaths" per Year per Million Gas Users
a. Cancer	0.07
b. Nonspecific life shortening	0.03
c. Genetic (first generation)	0.01
d. Genetic (future generations) ^a	0.5

Total "deaths" per year (a+b+c)	0.1
Total "deaths" introduced into population each year ^a (a+b+d)	0.6

^aUpper limit of estimate of risk from recessive mutations.

TABLE XI

COMPARISON OF ESTIMATED DEATHS IN THE UNITED STATES POPULATION
DUE TO NATURAL BACKGROUND AND MAN-MADE RADIATION WITH DEATHS
DUE TO OTHER CAUSES

Causes. of Death	Number of Deaths	Rate ^a
All causes	1,930,082	9660
Heart disease	744,658	3730
Cancer	318,547	1590
Stroke	211,390	1060
Accidents	114,864	570
Pneumonia	66,430	330
Diabetes mellitus	38,352	190
Arteriosclerosis	33,568	170
Natural background radiation ^b	3,400	17
Man-made sources of radiation		
Medical diagnostic x-rays	4,000	20
Fallout from nuclear weapons	80	0.4
Consumer devices	80	0.4
Nuclearly stimulated natural gas ^c		0.1
Industrial uses of radiation	<40	<0.2
Power reactors	<40	<0.2

^aDeaths per million population, known or calculated (for all types of radiation).

^b0.1 rem per year.

^cBased on this study.

specific types of radiation damage presented in the upper portion of the table are added to obtain the total estimates given in the lower portion. We recognized the inherent difficulties in combining somatic and genetic insults whose manifestations may differ so greatly, in making these estimates. Otway et al [42] suggested that calculation of radiation-induced mutation frequency (genetic death frequency as calculated here) is meaningful only in comparison with the natural rate of mutation. They indicate that the natural genetic death rate, based on normal mutation rates and genetic equilibrium, may be estimated as 0.2 per person per generation [42]. If 30 years is assumed to be the mean age for child bearing, the estimated genetic insult from continuous radiation exposure via use of natural gas containing low levels of radioactivity during that 30-year period is approximately 0.01% of the above-cited estimate for the natural genetic death rate.

The risk estimated for the projected gas usage is compared in Table XI with similar estimates of risk for other sources of radiation exposure of the public. Death rates associated with other risks encountered in the normal activities of life in the United States are provided for comparison [43]. The intent is to give perspective and not to minimize the significance of the possible risk to man from the use of nuclearly stimulated natural gas, although the radiation dose and the associated risk may be small in comparison with some other risks. The use of nuclearly stimulated gas assumed in this hypothetical analysis is reasonable, and the results of the dose assessments indicate that the impact is acceptably small. All radiation exposure should be scrutinized in the interest of keeping the dose "as low as practicable." There is a responsibility to assess the impact of the estimated radiation exposure, to place the assessment in perspective, and to present it in a form which can be understood by all interested parties. The radiation risk associated with the use of nuclearly stimulated gas needs to be studied as an integral part of the cost-benefit analysis in development of nuclear gas stimulation technology.

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