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**AN ANALYSIS OF GAS STIMULATION
USING NUCLEAR EXPLOSIVES**

B. Rubin
L. Schwartz
D. Montan
May 15, 1972

Prepared for U.S. Atomic Energy Commission under contract No. W-7405-Eng-48

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Foreword

This report is an updating and expansion of our previous report¹ on nuclear gas stimulation issued in April 1971 and covers the same topics. Where appropriate, the previous text and organization have been used. New topics presented in this report are the gas production results from Rulison, a proposal for large-scale commercial development together with possible plans for delivery of the gas to market, and the calculated radiation exposure to the consuming population from use of the gas associated with these delivery plans. In addition to the production and economic analyses previously presented for a typical nuclear stimulated well in the Green River Basin, we have included a similar analysis for a well representative of the Piceance Basin. Gas sales prices for these examples have been adjusted to 40¢ per thousand cubic feet instead of 30¢ since it appears that this may be consistent with gas prices in the 1975-1980 period.

During the past year the major event of interest to gas stimulation was the successful test in the Miniata Event of the Diamond explosive. An expanded discussion of that explosive is included here.

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AN ANALYSIS OF GAS STIMULATION USING NUCLEAR EXPLOSIVES

Abstract

The United States presently is faced with a developing crisis in its energy resources and specifically in its supply of natural gas. The use of nuclear explosives in the stimulation of low-permeability gas reservoirs has the potential of supplying more than 300 trillion cubic feet of gas, an amount greater than the nation's present proved gas reserves. Two nuclear-explosive gas-stimulation experiments have produced a substantial quantity of gas. We have made an economic projection of commercial production (after the successful completion of a research and development program) for nuclear-explosive stimulation of wells in the Piceance and Green River Basins in Colorado and Wyoming. The internal rate of return on investment varies from $7\frac{1}{2}$ to $28\frac{1}{2}\%$ depending on the properties of the reservoirs and the required number of explosives per well, assuming a wellhead price for gas of 40¢ per thousand cubic feet. We propose a schedule for the commercial development of the Piceance and Green River Basins that could lead

to an annual gas production rate of 3.4 trillion cubic feet by the year 2000. Based on a hypothetical example in which all the gas would be used in California, we calculate that the average whole-body radiation exposure to individuals in the California population would be between less than 0.45 and 0.64 millirem/yr, compared with the 170 millirem/yr average allowable exposure to the population recommended by official guidelines. Compared with other alternatives for increasing U.S. gas production, nuclear stimulation appears to have advantages in terms of required capital investment and gas sales price. A research and development program will be required to achieve this projected capability for nuclear-explosive gas stimulation. The cost of this development program to achieve initial commercial production in about five years is estimated to be \$100-150 million. We recommend that a vigorous government-industry program be conducted to develop this technology to help relieve the shortage in natural gas supply.

Summary

It is becoming increasingly clear that the demand for gas in the U.S. is outstripping supply. In fact, the gap between demand and supply is predicted to be so large in the coming years that, even if all potential new sources of gas are con-

sidered, major deficits will still exist in some geographic areas (see Fig. 1). One potential source is from very low permeability reservoirs that contain large quantities of gas. Recovery of this gas by conventional techniques is not economically

feasible within the life of the wells, but the use of nuclear explosives offers the potential of fracturing the rock and producing, in effect, a very large diameter well capable of substantially increased gas production.

The U.S. Bureau of Mines has estimated that 317 trillion cubic feet ($\text{Tcf} = 10^{12} \text{ ft}^3$) of gas is potentially available using nuclear explosive gas stimulation techniques. This figure should be compared with the proved reserves of 290 Tcf that are currently being produced at the rate of more than 22 Tcf/yr.

To date, two nuclear explosive gas stimulation experiments (Rulison and Gasbuggy) have been successfully fired. Both wells have been reentered and have produced gas for periods totaling $3\frac{1}{2}$ and 12 months, respectively. Each one already has produced many times the quantity of gas produced in several years from nearby conventional wells (Fig. 8).

The key to commercial nuclear explosive gas stimulation lies in obtaining sufficient gas production at a cost that gives a reasonable return on investment. Because drilled holes are expensive, production can be maximized by firing a number of explosives in a vertical array in the same emplacement hole.

It is expected that the gas will be produced by reentering the emplacement hole after the detonations (Fig. 2). The degree of stimulation depends on the size and the character of the fracture zone produced by each nuclear explosion.

To test and verify this principle, two additional experiments have been proposed by industry that will employ multiple explosives. In the Rio Blanco experiment, three 30-kt explosives will be simultane-

ously detonated at a depth near 6000 ft in the Piceance Basin in Colorado (Fig. 3). The Wagon Wheel experiment is planned for sequential detonation of five 100-kt explosives at a depth of 11,000 ft in the Green River Basin in Wyoming (Fig. 5).

For the present study we obtained the fracture radius for production calculations by matching the early production from Rulison; the Rulison chimney consists of a high permeability zone extending out to 2.75 times the initial cavity radius (Fig. 10). This is consistent with the extent of fracturing measured in Gasbuggy.

We calculated gas productivity for typical nuclear stimulated wells in the Piceance and Green River Basins. As examples, three 100-kt explosives were assumed to stimulate a 2000-ft vertical interval in the Piceance Basin containing 100 billion cubic feet ($\text{Bcf} = 10^9 \text{ ft}^3$) of gas per section, and four 100-kt explosives were assumed for a 2400-ft vertical interval in the Green River Basin containing 170 Bcf per section. Permeabilities of 10-40 microdarcies (μd) and 5-10 μd , respectively, were assumed for the two regions. The corresponding 20-yr gas production from single wells in the two basins is 14-31 and 21-35 Bcf, respectively (Figs. 11 and 12).

Based on these typical gas production rates, a plan has been postulated for commercial development of the two basins. We assume that upon completion of a 5-yr government-industry research and pilot development program industrial development teams could begin commercial field development in 1977. Three such operations in parallel might reach a continuous nuclear stimulated well construction rate of 100 wells per year by

1981 (Table 5). Using gas productivities corresponding to permeabilities of 40 and 10 μ d in the Piceance and Green River Basins, respectively, and making the conservative assumption that the wells would produce for only 20 yr, we find that gas production would start in 1977 and rise to a steady state production rate of 3.4 Tcf/yr by the year 2000 (Fig. 13).

We also make an economic evaluation of the production from single wells in the two basins. In this analysis we consider the federal royalty, severance, and ad valorem taxes, administrative costs, and lease operating expenses in calculating the future net revenue from one well year by year, as well as the present worth of 20 years' future production. The projected nuclear development costs are estimated at about \$2.41 million per well in the Piceance Basin and \$3.34 million per well in the Green River Basin (Table 7). Using this cost and a price of 40¢ per thousand cubic feet (Mcf), the internal rate of return on invested capital varies from 7.5 to 28.5%, depending on the permeabilities encountered (Figs. 14 and 15). If depletion allowance, depreciation, and corporate federal income tax are included and one assumes that the loss in the development years can be written off against other corporate profits, the internal return on investment is slightly increased.

A comparison of nuclear stimulation with the several alternative ways of increasing gas availability shows that the cost of research and development, the required capital investment, and the time needed to achieve a new production capability of 1 Tcf/yr are less than or competitive with conventional exploration,

coal gasification, or import of liquefied natural gas (Table 10). Gas sales prices from nuclear stimulation should be lower than from any other source except conventional exploration.

The total gas production rate resulting from the commercial development program proposed here could furnish a large portion of the needed supply in selected major market areas; for example, 80% of the demand of the state of California could be supplied in the year 2000 (Fig. 17).

To evaluate the radiation exposure to the population resulting from low levels of radioactivity in the gas, we considered two methods of distribution of this gas in California. If all the gas were uniformly mixed with other out-of-state gas supplied to California and consumed in general use, the average year-2000 individual exposure would be 0.45 millirem (mrem) per year. The maximum individual exposure would be 0.7 mrem/yr, and the population dose would be less than 14,000 man-rem/yr.

Alternatively, the 0.47 Tcf of more highly contaminated gas occurring during the first year of new well production might be collected into a separate pipeline and consumed in power plants; the gas produced in later years and representing the major portion would be essentially contamination-free. In this case, the average individual exposure would be less than 0.11 mrem/yr and the maximum exposure would be less than 2.1 mrem/yr. The population dose would be lowered to less than 2000 man-rem per year.

These dose levels should be compared with the 170 mrem/yr average allowable exposure to individuals in the population at large as recommended by the former Federal Radiation Council

(now a part of the Environmental Protection Agency). The California population exposures should be compared with doses from natural sources of $2.3-3.5 \times 10^6$ man-rem/yr or doses from medical sources of $2-5 \times 10^6$ man-rem/yr (Table 13).

As in all considerations of radioactivity, the exposure should be made as low as possible and the risk must be evaluated against benefit. The benefit in this case is the availability of substantial quantities of a clean (low sulfur content), inexpensive, convenient fuel. The radioactivity levels appear to be small compared with established recommended guidelines and with natural background. However, an official regulatory framework for distribution and consumption of the gas does not exist at present and the acceptability of these projected levels of radioactivity has yet to be established.

The principal local environmental effects resulting from nuclear stimulation would be those associated with construction of the gas well, access roads, electric power lines, and gas pipelines. Also, there would be the seismic effects resulting from detonation of the explosives on a few selected days during the year. Based on experience from Rulison, from the Salmon experiment in Mississippi, and from many experiments at the Nevada Test Site, the expected damage to structures would be low in the remote locations where nuclear stimulation would be conducted. Such damage as does occur should be limited to architectural effects such as cracking of plaster or fallen bricks. Estimates of the total value of such damage claims to be paid are in the \$100,000 to \$200,000

per year range in each of the two basins.

Minimal amounts of radioactivity would be released in the local environment that could enter the biosphere. Flaring of gas should not be necessary except for production testing of wells in new and untested areas. As exemplified by the proposed Rio Blanco releases, such flaring would release only minor amounts of radioactivity. It is expected that tritiated water produced with the gas would be disposed of without environmental release, possibly by reinjection underground.

The economic projections and estimates of radiation exposure presented here are based on what might be achieved after a successful research and development program. One feature of such a program is the design and testing of a small-diameter, low-tritium, inexpensive nuclear explosive for sequential firing. Lawrence Livermore Laboratory successfully tested a prototype explosive (characterized by the name Diamond) in the Miniata Event at the Nevada Test Site on July 8, 1971. In a typical gas field environment this 80-kt explosive is projected to leave less than 2000 curies of tritium. Further development on hardening this explosive to withstand sequential firing is yet to be accomplished.

Other development tasks also remain to be done. Ways must be found to create connected fracture regions from which gas can be most economically produced. Operational systems must be developed that are safe and efficient. Lastly, data are needed on which administrative decisions regarding commercial use would be based. Each of these areas requires

a specific research and development effort.

Several policy actions must be taken by government and by industry for the commercial development program envisioned here. In addition to funding a major share of the development program, the government must adopt legislation that permits commercial use of nuclear explosives and must announce how much is to be charged for these explosives. Also, pricing policies for the sale of the gas and regulation guidelines for the distribution to consumers must be established. In addition, information on explosive characteristics such as diameter and amount of residual tritium must be declassified so that industry can make reliable design and economic studies.

Industry must be willing to assume its share of the development program cost. A small number of companies so far have borne the burden of supporting the technical development of gas stimulation. Industry should find ways by which the additional necessary development funds

can be provided, perhaps by support of nonprofit research organizations.

Ultimately, public acceptance of nuclear gas stimulation will depend on public awareness of the fuel shortage, on a realization that the radioactivity associated with the gas is extremely low, and on an awareness of the direct financial benefits from use of this resource. As examples of these financial benefits, by 1991 the nuclear stimulation industry would have a product sales value of about \$1 billion per year (Table 15). Government revenues in the form of local and state taxes plus federal royalties would amount to \$180 million in that year. If instead of producing this gas the equivalent quantity of energy were to be obtained through import of petroleum, the effect on balance of trade would represent an outflow of \$1.3 billion.

In addition to these direct monetary benefits, there would be the economic stimulus to local and state commerce of this new industry and, overall, the benefit to society of providing a large source of clean, inexpensive energy.

The Need for Gas

Recently there has been a growing awareness in the U. S. that there is an urgent need for increasing the country's supplies of natural gas. In addition to warnings over the past several years by leaders of the gas industry that proved reserves were being consumed at a rate greatly in excess of new reserve additions,² the symptoms of an impending shortage have begun to appear. As examples, in January 1971 the East Ohio Gas Company invoked its right to limit

gas supplied to its "interruptible" customers in Cleveland and reduced the supply to a number of industries by 75%, thereby causing them to close down for 8 days and forcing 30,000 employees to forego working.³ Several cases are pending before the Federal Power Commission in which gas transmission companies are attempting to reduce the supply to distribution companies.⁴

That these are not isolated examples is indicated by the directive issued in

April 1971 by the FPC to all U.S. gas transmission companies to prepare plans for the order in which they will cut back supplies to their interruptible customers when necessary.⁵ Several gas transmission companies already have notified their customers that no further increase in gas services can be provided because of the limited supply situation.⁶

The past record of U.S. gas consumption and its projection to 1995 (if unconstrained by supply limitations), as given recently by the gas industry's Future Requirements Committee, is shown in Fig. 1.⁷ Also shown are the expected supplies of gas from domestic production, synthesized gas, pipeline imports, and liquefied natural gas (LNG) imports as projected by the National Petroleum Council.⁸ The notable feature of this graph is the gap between supply and projected demand that appears in 1971 and rapidly increases with time.

The Administration is fully aware of the impending shortage. In a recent address, the Secretary of Interior predicted that the outlook for natural gas supply, based on present U.S. reserves "is that supply will reach its limit by the middle of this decade and, at that point, will have to adjust consumption to the available supply. I intend to exercise the following options to increase our supply of natural gas. I will encourage domestic exploration and production, explore the expansion of imports, and foster the development of new techniques in gas recovery and synthetic fuels. . . . For the near-term solutions, I am hopeful that the regular sales of United States Outer Continental Shelf and state offshore exploration and drainage leases will

Fig. 1. U.S. natural gas demand and supply.⁷

precipitate discovery of major gas areas. But I will not allow this program to mushroom willy-nilly into an environmental disaster."⁹

Table 1 lists some of the ways by which additional gas may be supplied. In addition to the comments listed there relative to the total quantities potentially available, it is important to note that the rates at which these potential supplies can be developed and delivered to U.S. consumers are quite limited, as indicated in Fig. 1. Factors likely to affect these rates of development may be (1) limited availability of investment capital needed to construct facilities such as exploratory gas wells, coal gasification plants with their associated coal mines, or refrigerated

Table 1. Possible alternatives for increasing U.S. natural gas supplies.

Method	Potential quantities ^a (Tcf)		Comments
	Proved	Potential	
<u>Conventional exploration</u>			
Onshore	225	613	Exploration now directed much deeper onshore, into deeper water offshore, and into remote areas.
Offshore	39	238	
Alaska	26	327	
	290	1178	
Imports from Canada	—	?	Canadian proved reserves (53 Tcf) not available to U.S. Potential discoveries could be large; availability for export to U.S. will depend on Canadian policy.
<u>Liquefied natural gas imports</u>			
South America	50		1967 proved reserves—not all available for export. Europe and Japan compete with the U.S. for these supplies.
North Africa	135		
Nigeria	4		
Middle East	350		
<u>Synthetic gas</u>			
Naphtha and heavy-oil gasification		Some	Availability of imported naphtha and heavy oil for this purpose is uncertain. Gasification of naphtha and oil are primarily for meeting peak loads. Sales price will be high, and imported liquids may be subject to import control.
Coal gasification		1750	Based on conversion of all the U.S. strippable coal (140 billion tons) to gas at 50% efficiency.
<u>Nuclear stimulation</u>		317	There is a large uncertainty in this value.

^aThe U.S. 1970 consumption was 22 Tcf.

LNG tankers and liquefaction and re-gasification plants and (2) possible environmental constraints on the development of facilities such as new coal strip mines for coal gasification, Arctic gas transmission pipelines, or LNG marine unloading and on-shore storage facilities.

Therefore, in view of the imminent shortage of natural gas and the apparent

magnitude of that shortage in the coming years, it would appear that all possible sources of gas will be needed; projected development rates of all supply methods will still fall short of meeting total potential demand. Gas provided by nuclear explosive stimulation of low-permeability reservoirs can supply an important fraction of the new supply needed.

Concept of Commercial Gas Stimulation

DESCRIPTION OF THE CONCEPT

Large quantities of gas are known to exist in low-permeability (or "tight") reservoirs. The gas is present in the pores in the rock, but the pores are very poorly connected. Gas may flow through minute fractures and connections between the pores to the well, but not fast enough to amortize the investment in conventional wells.

Many of these gas-bearing formations in the basin of the Rocky Mountain area are located at relatively great depths. On the average, total drilling and completion costs for conventional wells to depths of about 5000 ft are approximately proportional to depth. For deeper wells they increase very rapidly; at depths of 15,000 ft the cost per foot of total depth is four times as much as for shallow wells. The relatively large investment together with the low rate of gas production from these tight formations makes conventional wells unattractive, even though the total reserves ultimately produceable are very large.

Some low-permeability reservoirs have been made economically productive by the use of chemical explosives or by hydraulic fracturing; however, this method has not been successful in deep, tight gas reservoirs whose permeabilities are measured in microdarcies. Of course, should the price of gas increase substantially, some marginal-permeability fields would become economically feasible and increase the gas supply.

The nuclear explosive gives a new dimension to the possibilities of stimu-

lating tight gas reservoirs because tremendous energy can be packaged in a very small volume and emplaced through a drilled hole. The explosion produces a region of broken rock called a chimney and a fracture system that surrounds and is connected to the chimney; as a result, instead of producing gas from a well 6 in. in diameter, the nuclear-stimulated well produces gas from an effective diameter of several hundred feet.

Many calculations have been made of the expected performance of such a well.¹⁰⁻¹² The results of gas production calculations will vary according to the particular model and flow parameters chosen to represent the stimulated underground formations. However, with reasonable assumptions there is general agreement that over an investment return period like 20 yr such a well may produce 10 to 30% of the gas in place. A noteworthy point is that if the return on investment during the initial 20 yr is sufficiently attractive to justify the project, there is the additional attraction that the well may continue to produce for another 20 to 30 yr at only a slightly diminished rate. Although the financial present worth of such long-term future production is relatively small, there would be a strong benefit to the nation in terms of stable proved reserves.

Other factors being equal, the increase in well diameter alone might not lead to sufficiently increased production to justify the additional cost of the nuclear stimulation method. However, it is believed that concomitant factors may act

to further enhance production. One such factor is the greatly increased number of separate gas-bearing lenses and strata that are expected to be intersected by the nuclear chimney and fracture zone as compared with the number intersected by a single 6-in. hole. In addition, the drilled well-bore surface, which in conventional wells is sometimes suspected of being sealed off by drilling fluids, will disappear over the entire height of the chimney and the producing cavity will communicate directly with the gas-bearing formations.

Figure 2 shows the concept of commercial nuclear-explosive gas stimulation. A number of explosives would be emplaced one above another in the same hole to stimulate the greatest possible thickness of gas-bearing rock and thus achieve maximum production. This concept envisages that the emplacement hole would be reentered after the detonation and used to produce the gas. This requires that the yields and depths of the nuclear explosives be so planned that the chimneys are connected by means of intersecting fractures or, alternatively, that a method be devised to keep the emplacement hole open between chimneys.

The larger the explosive yield, the larger the fracture radius and the more gas economically produced. While the horizontal fracture radius is important, the amount of gas produced depends much more strongly, given the same permeability, on the total thickness of the formation fractures. The limitation of explosive yield depends on the remoteness of the site relative to surrounding towns. Some seismic damage to structures may

be tolerated, but adverse public reaction and damage compensation will seriously hamper the project. Therefore, it is anticipated that the explosives would be fired sequentially, with perhaps 5 min delays between detonations. In this way, each explosive can have several times the yield that it otherwise would have if simultaneous detonations were used. To minimize inconvenience to the surrounding population and for efficiency in the field operation, it is envisioned that in a development of a gas field a number of wells could be stimulated in one day, followed by a period of no firing.

To construct a well in this manner, it will be necessary to develop a special nuclear explosive that can survive the shock of the earlier detonations and still function properly with high reliability. An alternative method of operation that would eliminate the need for such a hardened explosive could be that of emplacing each explosive after the previous one had been detonated. This method still would have the advantage of maximum net pay thickness stimulated; however, it would require the development of a reliable downhole stemming procedure that could survive the previous detonation and still permit safe emplacement of the next explosive above. Both of these operational methods will require detailed study to determine which one appears to offer the best tradeoffs in technical feasibility, cost, reliability, and safety.

Reentry after the detonations could be delayed for a number of months, if necessary, to permit the decay of short-lived radioisotopes. In a proved gas field, gas need not be released to

Fig. 2. Nuclear gas-reservoir stimulation. The reservoir is modeled after the Green River Basin in Wyoming.

the atmosphere (flared) but could be produced directly into the pipeline. Carbon dioxide that is produced by the explosion and mixed with the chimney gas would be released to the atmosphere.

Water produced with the gas initially will contain low levels of tritium. It may prove desirable to dispose of this water by reinjection underground, possibly into the same well from which it came.

The details of commercial gas stimulation will vary from field to field, depending on the gas-reservoir characteristics and operating conditions. Any specific concept must be based on maximizing the gas production-to-cost ratio and return on investment—consistent with safe and environmentally acceptable operating procedures.

CURRENTLY PROPOSED JOINT INDUSTRY-GOVERNMENT EXPERIMENTS

Two experiments sponsored jointly by industry and government have been proposed that embody the multiple explosive concept. We briefly summarize them here.

Rio Blanco Proposal

The CER Geonuclear Corporation has proposed a joint government/industry experiment called Rio Blanco.¹³ Figure 3 shows the cross section of this experiment. Three explosives, each with a nominal yield of 30 kt, are planned to be fired simultaneously at depths between 5700 and 6600 ft.

The company has proposed the following set of measurements that would con-

tribute to the technical understanding of nuclear gas stimulation:

- Determination of preshot reservoir properties;
- Gas production through the emplacement hole;
- Calculation of the fracture zone;
- Seismic motion measurements;
- Radioactivity measurements in the gas;
- Pressure measurements in the stemming.

To obtain further information we have proposed the following additional experiments:

- Measurement of chimney connections with tracers;
- Early gas-sample and chimney-pressure measurements;
- A postshot hole for measuring chimney radius, the effects of simultaneous detonation, and the reservoir pressure gradient.

The Rio Blanco experiment is in an advanced stage of preparation and is currently scheduled for execution during the first quarter of Fiscal Year 1973.

Wagon Wheel Proposal

The El Paso Natural Gas Company has proposed the Wagon Wheel experiment.¹⁴ In the initial planning phase considerable effort was devoted to predicting the cavity size and the crushed and shear fracture radii shown in Fig. 4.¹⁵ Note the small chimney size predicted at the chosen site, where the gas bearing formation is about 3000 ft thick. For eventual economic commercial production to be achieved, a way must be found to fracture through the entire gas-producing interval with a minimum number of explosives.

Fig. 3. Cross section of the Rio Blanco experiment. The dashed lines show the proposed postshot fracture and pressure monitoring hole.

Therefore, it is proposed to use five 100-kt explosives fired sequentially.

Figure 5 shows the conceptual design of the Wagon Wheel experiment. The measurements proposed by El Paso Natural Gas are:

- Determination of preshot reservoir properties;
- Gas production through the emplacement hole;
- Calculation of the fracture zone;

- Gas flow from each chimney with tracers;
- Seismic motion measurements;
- Radioactivity measurements in the gas.

The proposed LLL add-ons are to measure and interpret the following:

- Dynamic shock effects;
- Early chimney pressures;
- Chimney radius, chimney interconnections, and the fracture distribution caused by sequential firing;
- Reservoir pressure gradient.

Fig. 4. Predicted result of a 100-kt explosion at a depth of 10,000 ft in Wagon Wheel rock.

Fig. 5. Cross section of the Wagon Wheel experiment.

This experiment is planned for Fiscal Year 1974.

POTENTIAL FOR GAS STIMULATION

An assessment of the areas that may be suitable for gas stimulation has been

made by C. H. Atkinson of the Bureau of Mines.¹⁶ The regions presently judged to be most suitable are the basins of the Rocky Mountain states shown in Fig. 6. Table 2 gives an evaluation of the four basins. Atkinson estimated that only 20% of the potentially productive area may actually turn out to be amenable to gas stimulation. For these areas he further estimated that 40% of the total sand thickness contains recoverable gas and that in 20 yr of production 50% of the gas could be removed by use of nuclear stimulation. These estimates led him to conclude that the successful use of nuclear stimulation could make available about 317 Tcf of gas from these four major Rocky Mountain basins.

It should be pointed out that it is difficult to make such an estimate because of the very limited data available, and this figure should be taken as a rough approximation. More recent information seems to indicate that the Green River Basin may be overestimated, while the Piceance Basin may be underestimated.

Table 2. Estimated increase in reserves of natural gas assuming the effective use of nuclear explosives.^a

Basin ^b	Areal extent with productive potential (mi ²)	Assumed productive area (mi ²)	Number of known gas-bearing formations	Total sand thickness (ft)	Productive thickness (ft)	Increased recovery using nuclear explosives (Tcf)
Uinta	8,900	1800	4	1700	680	61
Piceance	3,900	800	4	1200	480	19
Green River	19,000	4000	7	2500	1000	199
San Juan	10,600	2000	3	1100	440	<u>38</u>
						317

^a Assumes that 20% of the total area will be productive, that 40% of total sand thickness contains recoverable gas, and that 50% of the gas will be recovered in 20 yr.

^b The large Paradox Basin is too sparsely developed to permit a reasonable evaluation.

Fig. 6. Low-permeability natural gas basins of the Rocky Mountain states. These basins contain reservoirs thick enough to be considered for nuclear stimulation.

A more accurate estimate of the gas potentially available in these regions is now in preparation as a part of the National Gas Survey being conducted by the Federal Power Commission.

RELATIONSHIP OF NUCLEAR STIMULATED GAS TO PROVED RESERVES AND POTENTIAL SUPPLY

Table 3 summarizes the Nation's proved reserves¹⁷ and potential gas supply¹⁸ during the last year and, for comparison, the supply that nuclear stimulation could make available. Proved reserves consist of gas that can be produced in the coming years from gas wells that are producing or have been subject

to conclusive formation tests. The proved reserves in the lower 48 states declined in 1970 from 275 to 264 Tcf because the production of 22 Tcf was greater than the additions to reserves of 11 Tcf. The large 1970 addition to U.S. proved reserves of 26 Tcf in Alaska will not be available to U.S. consumers until a gas pipeline is constructed from the North Slope. This gas is far from the markets in the contiguous 48 states and will require substantial investment to bring it to market. A pipeline to Chicago would cost about \$2 billion.²

The potential supply is the prospective quantity of gas yet to be found and proved by wells that may be drilled in the future under assumed conditions of adequate,

Table 3. Gas reserves, production, and supply (in Tcf).

<u>Reserves, Production, and Additions (1970)</u>			
Proved recoverable reserves as of December 31, 1969			275
Additions during 1970 (not including Alaska)			11
Less: Production during 1970			(22)
Proved recoverable reserves as of December 31, 1970 (lower 48 states)			264
Alaskan additions during 1970			26
Total proved U.S. reserves as of December 31, 1970			290
<u>Estimated Potential Supply^a</u>			
<u>Contiguous 48 states:</u>			
	<u>Onshore</u>	<u>Offshore</u>	<u>Total</u>
Probable	179	39	218
Possible	227	99	326
Speculative	<u>207</u>	<u>100</u>	<u>307</u>
Subtotal	613	238	851
<u>Alaska:</u>			<u>327</u>
<u>Total U.S. potential supply:</u>			1178
<u>Estimated Additional Supply Through Stimulation by Nuclear Explosives</u>			317

^a Assuming existing economic and operating conditions.

but reasonable, prices and normal improvements in technology. If a fundamental change in economics or technology occurs, estimates of potential would be changed.

Since the 317 Tcf of gas in tight formations are located in the contiguous 48 states, it would appear proper to

compare this volume with the 851 Tcf of potential conventional supply in the contiguous 48 states. Since a fundamental change in technology is required to make the 317 Tcf of gas available, by definition it has not been included in the proved reserves or estimated potential supply.

Gas Production from Nuclear Stimulated Wells

TECHNICAL FEASIBILITY

The most relevant data applicable to the gas-stimulation concept come from the two nuclear gas-stimulation experiments, Gasbuggy and Rulison. Gasbuggy was a joint Government/El Paso Natural Gas Company experiment in which a 29-kt explosive was fired on December 10, 1967, at a depth of 4240 ft in the San Juan Basin of New Mexico.¹⁹ Past production data and analyses of cores were used to select the Gasbuggy site. Permeability measurements made on the cores gave 0.14 millidarcy (md), but preshot production and laboratory measurements made under lithostatic overburden pressures indicated an in situ permeability of about 0.010 md.

Postshot drilling and production have yielded data on which the fracture interpretation given in Fig. 7 is based. Explosion-produced fractures were observed as far as 700 ft from the shot point, but basic matrix fracturing appeared to occur out to about 280 ft from the shot point (about $3\frac{1}{2}$ cavity radii). The gas was produced by reentering the emplacement hole; Fig. 8 presents the production data. In 17 months, 280 million ft³ (MMcf) were produced. This number should be com-

pared with 8 years' production of about 70 MMcf in the nearest conventional well.

Nuclear explosions in other types of rocks and at greater burst depths can be expected to fracture differently. In Rulison, a joint Government/Austral Oil Company experiment, a 43-kt nuclear explosive was detonated in September 1969 at a depth of 8427 ft in the Piceance Basin in Colorado.²⁰ Figure 9 shows an interpretation of the Rulison fracture system; Fig. 8 compares the first 9 months' production from the Rulison well with almost 8 years' production from the nearest conventional well. Thus, both Gasbuggy and Rulison have proved experimentally that nuclear stimulation can increase gas production dramatically.

GAS FLOW ANALYSES OF NUCLEAR STIMULATED WELLS

Extensive computational simulations of the pressure and gas flow results of Gasbuggy and of Rulison have been made.^{11,21-24}

The Rulison flow analysis given by Montan¹¹ (see Fig. 10) serves as an example. Analysis of the well performance was made by fitting a simple model of the chimney, gas sands, and explosively created fracturing to the two experimentally

Fig. 7. Postshot cross section of the Gasbuggy experiment.

Fig. 8. Gas production from the Gasbuggy and Rulison experiments.

Fig. 9. Postshot cross section of the Rulison experiment. R_c = cavity radius; D.O.B. = depth of burial.

Fig. 10. Gas flow from the Rulison experiment. The data cover the period from the time of the shot (September 1969) to June 15, 1970. The formation pressure is 3200 psia. The parameters assumed were: ϕh (porosity $\times$ height) = 3.0 ft, the permeability $\times$ height of the undisturbed formation $[(kh)_0]$, where k is the permeability and h is the height = 680 μ d-ft, and the postshot variation in kh as a function of distance from the shot point is shown in the inset graph. The cavity radius is 76 ft.

measured variables, flow rate and chimney pressure. The gas flow calculations for various trial models were made by a finite-difference solution to the nonlinear partial differential equation for radial Darcy flow. The TRUMP^{25,26} computer program was used to perform the numerical calculations. The model consisted of a central zone representing the chimney surrounded by a number of concentric zones representing the formation. The effect of explosive fracturing was simulated by increasing the permeability in the zones near the central zone; this increased-permeability region was represented by a 33-fold increase over the undisturbed formation permeability

extending from the chimney wall out to a radial distance of a 2.75 chimney radii.

These calculations were repeated until the calculated and measured pressures were in good agreement. The parameters that were varied during modeling that gave the best fit are given in the caption to Fig. 10.

The use of these parameters to calculate the 20-yr cumulative production of Rulison leads to a result of 1.8 Bcf. Essentially the same result is obtained by Bray.²⁴ DeGolyer and McNaughton²³ calculate a higher figure, 4.5 Bcf, primarily because they assumed a higher formation permeability and a time-varying water barrier in the fractured

region. As mentioned previously, additional experimental data would help to resolve the issue. Nonetheless, some prediction confidence results from these independent calculations.

GAS PRODUCTION FROM SINGLE WELLS

Using the same distribution of fractures and zones of increased permeability as inferred from Rulison, calculations have been made of the rates of flow and ultimate gas production to be expected from typical commercial wells in the Piceance and Green River Basins. Table 4 gives the reservoir properties characteristic of the two basins used in the calculations.

The most critical characteristic for these calculations is the effective undis-

turbed formation permeability. To evaluate the effect of variations in permeability, we have used two representative values for each basin. We took the assumed quantities of gas in place per section from a paper by the Atomic Industrial Forum²⁷; different companies having leases in these areas have suggested both higher and lower numbers. We have used a spacing of one well per section for convenience of calculation. More wells per section would recover a higher percentage of the gas in place, which is important from a national resource point of view.

For the Green River Basin we assumed that the region of fracturing extended 2.5 cavity radii above the shot. Thus, a 100-kt explosive would produce a cylindrical zone of very high permeability with

Table 4. Assumed formation properties and nuclear well characteristics.

<u>Reservoir properties</u>	<u>Green River Basin</u>	<u>Piceance Basin</u>
Reservoir thickness (ft)	2,400	2,000
Depth to midpoint (ft)	11,000	6,200
Effective <u>in situ</u> permeability (μ d)	5 and 10	10 and 40
Specific gravity of gas	0.6	0.6
Temperature of formation ($^{\circ}$ F)	200	200
Gas-filled porosity (%)	4	4 and 5
Gas-field pressure (initial) (psi)	6,000	3,000
Bottom-hole pressure during production (psi)	750	750
Gas in place per section per gross ft of height (MMcf)	70	20
Gas in place per section (Bcf)	170	100
Well spacing (wells/mi ²)	1	1
20-yr gas production (Bcf)	21 - 35	14 - 31
<u>Nuclear characteristics</u>		
Number of explosives	3 or 4	3
Yield per explosive (kt)	100	100
Cavity radius (ft)	88	98

a radius of 350 ft and extending 385 ft above the shot point and 220 ft below. To stimulate a 2400-ft thick section, four such explosives would be required (see Table 4). The calculated gas production, using permeabilities of 5 and 10 μ d, is shown in Fig. 11.

Fig. 11. Calculated production from a gas reservoir in the Green River Basin stimulated by four 100-kt nuclear explosives. Curves are shown for two different permeabilities of the undisturbed formation.

In addition, we considered a case in which more extensive fracturing in the vertical direction was assumed. Such extensive fracturing may result when the shock wave is reflected from the chimneys and fracture systems of earlier shots, as would be the case in sequential firing. With a larger fracture system, it would be possible to stimulate the entire 2400-ft section with only three 100-kt explosives. The amount of gas produced would be the same as for the four 100-kt explosives, but the cost would be less by one explosive if such effects are observed.

We made similar calculations for gas production from a well in the Piceance Basin. In this case we considered that at the shallower depth of burial the larger chimneys from three 100-kt explosives would be sufficient to fracture the 2200-ft interval. Figure 12 presents cumulative production from a typical Piceance Basin well using permeabilities of 20 and 40 μ d with three 100-kt explosives.

Fig. 12. Calculated production from a gas reservoir in the Piceance Basin stimulated by three 100-kt nuclear explosives. Curves are shown for two different permeabilities of the undisturbed formation.

COMPARISON WITH CONVENTIONAL WELLS IN THE SAME REGION

Information provided by the Austral Oil Company²⁸ indicates that for several conventional gas wells located in the Rulison gas field the average projected 20-yr cumulative production will be 0.26 Bcf per well. These wells cost approximately \$200,000 to \$300,000; taking the lower cost we find that the

required investment was at least \$750,000 per billion cubic feet of gas. Two additional wells that have been treated by modern hydrofracturing methods are projected to have a 20-yr production averaging 0.4 Bcf. Using a conservative cost of \$300,000 for these wells leads to the same investment requirement—about \$750,000 per billion cubic feet. By comparison, an investment of \$2.41 million in a Piceance Basin nuclear stimulated well is projected to result in a 20-yr cumulative production between 14 and 31 Bcf—a unit cost of \$78,000 to \$172,000 per billion cubic feet.

Therefore, it appears that the average required investment in nuclear stimulated wells would be between one-fourth and one-ninth as large as in conventional wells for the same total production from these tight formations.

POSSIBLE SCHEDULE FOR COMMERCIAL PRODUCTION OF GAS BY NUCLEAR STIMULATION

A 5-yr research and development program remains to be completed before full-scale industrial field development can begin. Details are presented beginning on page 46. The successful execution of Rio Blanco and Wagon Wheel would be followed by a period of production testing and evaluation. A group of three or five pilot development wells in each basin might follow about 2 yr later, and upon successful completion and evaluation of these wells full-scale commercial development could begin, perhaps as early as 1977 in the Piceance Basin.

We assume here that industrial drilling, field construction, and explosive firing

teams will be assembled whose capabilities could rise to a level of constructing 30 to 40 wells per year. Such a rate of firing would not be greatly different from the announced rate of 39 nuclear events conducted during Fiscal Year 1970 at the Nevada Test Site. It is envisioned that two teams would operate in the Green River Basin, one building up to a construction level of 30 wells per year and one to 40; a third team would build up to 30 wells per year in the Piceance Basin. Table 5 gives a possible schedule for commercial development, together with the required number of explosives per year.

Using the annual gas production rates for the Green River and Piceance wells with permeabilities of 10 μ d and 40 μ d, respectively, as representative of well productivities for these regions, we calculated annual production rates for total gas from the Green River and Piceance Basins. These are shown in Fig. 13 and Table 6. No allowance was made for reduced production due to field use; in practice a few percent reduction would probably occur.

Although the calculations indicate that in 20 yr only 20% of the Green River and 31% of the Piceance gas originally in place will be produced per well, for simplicity the assumption is made here that the wells have a 20-yr life. (This assumption may have some validity because of the lenticular nature of the gas-bearing sands, which inhibits communication with the outlying areas. However, there is no present data on this topic.) On this basis the total production rate of nuclear stimulated gas would rise from 85 Bcf in 1976 to 2.5 Tcf

Table 5. Possible commercial production plan for nuclear-stimulated gas wells.

<u>Fiscal Year</u>	1977	1978	1979	1980	1981	1982	1983
<u>Number of wells detonated (per year)</u>							
Green River Basin A	—	10	20	30	40	40	40
Green River Basin B	—	—	10	20	30	30	30
Piceance Basin	20	20	30	30	30	30	30
Total	20	30	60	80	100	100	100
<u>Number of explosives required (per year)</u>							
	60	100	210	290	370	370	370

Fig. 13. Calculated annual gas production rates from the Green River and Piceance Basins.

explosive cost was based on the schedule of charges recommended by the AEC for use in evaluating potential Plowshare applications.²⁹ As summarized in Table 7, we have estimated the costs per well as \$2,410,000 and \$3,340,000 for the two basins, respectively. The cost of the Green River well with one fewer explosive would be reduced by \$460,000.

The actual number of explosives required, and therefore the total costs, will depend on which assumption regarding the extent of fracturing from multiple explosions is supported by experience. It should be noted that these costs do not include the cost of acquiring or proving out the lease nor the expenses incurred in collecting and transporting the gas to a transmission system.

SINGLE-WELL REVENUE ESTIMATES

Table 8 summarizes the revenue and expenses from a single nuclear gas well in the Green River Basin over a 20-yr period. Similar revenue calculations have been made for production from the Piceance Basin well. In this analysis we have obtained gross revenue by deducting 12.5% of the gross production for royalties paid, principally to the federal government that owns the land, and have used a wellhead gas price of 40¢ /Mcf for the remaining gas. Future net revenue was obtained by deducting state and local taxes (consisting of severance and ad valorem taxes in Wyoming at 6.5% and in Colorado at 12.5%), administration expenses at 3%, and operating expenses at \$500 per month per

Table 8. Economic analysis for single-well development in the Green River Basin. This assumes a permeability of 10 μ d, a wellhead gas price of 40¢/Mcf, and the use of three or four 100-kt explosives.

Year	Production (MMcf)		Revenue and expenses (thousands of dollars)					
	Gross	Net (87.5% of gross)	Gross revenue	Severance tax (1%)	Ad valorem tax (5.5%)	General and administration expense (3%)	Lease operating expense (\$500/month)	Future net revenue
1	4837	4232	1693	17	93	51	6	1526
2	2413	2111	844	8	46	25	6	758
3	2110	1846	738	7	41	22	6	662
4	1945	1702	681	7	37	20	6	610
5	1837	1607	643	6	35	19	6	576
6	1755	1536	614	6	34	18	6	550
7	1692	1480	592	6	33	18	6	530
8	1637	1432	573	6	32	17	6	512
9	1589	1391	556	6	31	17	6	497
10	1546	1352	541	5	30	16	6	484
11	1505	1317	527	5	29	16	6	471
12	1467	1284	514	5	28	15	6	459
13	1432	1253	501	5	28	15	6	448
14	1398	1224	489	5	27	15	6	437
15	1366	1195	478	5	26	14	6	427
16	1335	1168	467	5	26	14	6	417
17	1306	1142	457	5	25	14	6	408
18	1277	1118	447	4	25	13	6	399
19	1250	1094	437	4	24	13	6	390
20	1224	1071	428	4	24	13	6	382

Table 5. Possible commercial production plan for nuclear-stimulated gas wells.

<u>Fiscal Year</u>	1977	1978	1979	1980	1981	1982	1983
<u>Number of wells detonated (per year)</u>							
Green River Basin A	—	10	20	30	40	40	40
Green River Basin B	—	—	10	20	30	30	30
Piceance Basin	20	20	30	30	30	30	30
Total	20	30	60	80	100	100	100
<u>Number of explosives required (per year)</u>							
	60	100	210	290	370	370	370

Fig. 13. Calculated annual gas production rates from the Green River and Piceance Basins.

Table 6. Proposed schedule of commercial gas production by nuclear stimulation.

Year	Piceance Basin			Green River Basin A			Green River Basin B			Total		
	Wells in production	First-year gas (Bcf/yr)	Total gas (Bcf/yr)	Wells in production	First-year gas (Bcf/yr)	Total gas (Bcf/yr)	Wells in production	First-year gas (Bcf/yr)	Total gas (Bcf/yr)	Wells in production	First-year gas (Bcf/yr)	Total gas (Bcf/yr)
1977	20	85	85							20	85	85
1978	40	85	130	10	48	48				50	133	178
1979	70	127	212	30	97	121	10	48	48	110	272	381
1980	100	127	272	60	145	214	30	97	121	190	369	607
1981	130	127	327	100	193	326	60	145	214	290	465	867
1982	160		378	140	193	409	90	145	289	390	465	1076
1983	190		427	180	193	485	120	145	337	490		1249
1984	220		474	220	193	558	150	145	392	590		1424
1985	250		520	260		626	180		444	690		1590
1986	280		563	300		693	210		494	790		1750
1987	310		605	340		758	240		543	890		1906
1988	340		647	380		820	270		591	990		2058
1989	370		684	420		881	300		637	1090		2202
1990	400		720	460		940	330		682	1190		2342
1991	430		758	500		997	360		725	1290		2480
1992	460		792	540		1054	390		767	1390		2613
1993	490		824	580		1108	420		809	1490		2741
1994	520		858	620		1161	450		849	1590		2868
1995	550		886	660		1215	480		888	1690		2989
1996	580		918	700		1266	510		927	1790		3111
1997	590		930	740		1316	540		965	1870		3211
1998	600		938	770		1353	570		1002	1940		3293
1999	600		938	790		1378	590		1026	1980		3342
2000	600		938	800		1392	600		1038	2000		3368
2001												
2002												
2003												
2004												
2005	600	127	938	800	193	1392	600	145	1038	2000	465	3368

in 1990 and reach steady state at 3.4 Tcf in the year 2000.

Depending on the total areas available for development in the two basins, this rate might continue for many years. If it is proved valid that an estimated 300 Tcf

of total reserves is recoverable by nuclear stimulation, it would take about 80 yr at the above rate to recover it all. Thus, it should be appreciated that nuclear stimulation can make an appreciable and long-lasting contribution to the nation's gas supply.

Economics of Gas Production by Nuclear Stimulation

ESTIMATED COST OF COMMERCIAL GAS STIMULATION

Table 7 summarizes the estimated costs in 1976 of constructing a nuclear stimulated well as part of a field development effort in each of the two basins, assuming the use of three 100-kt explosives in the Piceance wells and four in the Green River wells. Allowance has been

made for problems encountered in drilling the emplacement holes and for failure of 1% of the nuclear explosives. Since it cannot be predicted which explosive in an array might fail, making removal of the gas below much more difficult and expensive, we have assumed 2% of the gas would be lost.

Construction costs were inflated from 1971 costs at 5½% per year; the nuclear

Table 7. Estimated costs per well for commercial gas stimulation (thousands of 1976 dollars).^a

	Piceance Basin ^b	Green River Basin ^c
<u>Emplacement hole</u>		
Includes site access, grading and a 10-3/4-in.-o.d. cased emplacement hole 7000 ft deep in Piceance Basin and 12,000 ft deep in Green River Basin	520	900
Allowance for drilling problems in development of field (unable to complete 1 of 6 emplacement holes)	90	150
<u>Detonation service manpower</u>		
Includes technical personnel to supervise explosive emplacement and stemming and to set up and operate firing equipment; based on a field-development rate of 1 well/mo	40	40
<u>Explosive emplacement and stemming</u>		
Includes equipment and personnel to emplace and stem explosives; includes cost of all downhole hardware and stemming material	190	210
<u>Reentry and completion</u>		
Includes equipment and personnel to reenter emplacement well and wellhead hardware to complete well for production	60	70
<u>Safety program</u>		
Includes personnel to evaluate hazards and perform those activities necessary to ensure health and safety of general public and project personnel; includes equipment to monitor and document radioactivities during production; based on a field-development rate of 1 well/mo	130	130
<u>Subtotal without explosives</u>	1030	1500
<u>Nuclear explosives (AEC-announced charge for 100-kt)</u>		
Includes required number of complete explosives with provision for sequential firing; includes temperature and pressure protection to 350°F and 10,000 psi and all firing components; 2% of gas subtracted as penalty for 99% explosive reliability	1380	1840
<u>Total estimated cost per nuclear-stimulated well with allowance for lost holes in field development</u>	2410	3340

^aCosts inflated from 1971 to 1976 at 5.5% per year.

^bThree 100-kt explosives per well.

^cFour 100-kt explosives per well.

explosive cost was based on the schedule of charges recommended by the AEC for use in evaluating potential Plowshare applications.²⁹ As summarized in Table 7, we have estimated the costs per well as \$2,410,000 and \$3,340,000 for the two basins, respectively. The cost of the Green River well with one fewer explosive would be reduced by \$460,000.

The actual number of explosives required, and therefore the total costs, will depend on which assumption regarding the extent of fracturing from multiple explosions is supported by experience. It should be noted that these costs do not include the cost of acquiring or proving out the lease nor the expenses incurred in collecting and transporting the gas to a transmission system.

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Table 8 summarizes the revenue and expenses from a single nuclear gas well in the Green River Basin over a 20-yr period. Similar revenue calculations have been made for production from the Piceance Basin well. In this analysis we have obtained gross revenue by deducting 12.5% of the gross production for royalties paid, principally to the federal government that owns the land, and have used a wellhead gas price of 40¢/Mcf for the remaining gas. Future net revenue was obtained by deducting state and local taxes (consisting of severance and ad valorem taxes in Wyoming at 6.5% and in Colorado at 12.5%), administration expenses at 3%, and operating expenses at \$500 per month per

Table 8. Economic analysis for single-well development in the Green River Basin. This assumes a permeability of 10 μ d, a wellhead gas price of 40¢/Mcf, and the use of three or four 100-kt explosives.

Year	Production (MMcf)		Revenue and expenses (thousands of dollars)					
	Gross	Net (87.5% of gross)	Gross revenue	Severance tax (1%)	Ad valorem tax (5.5%)	General and administration expense (3%)	Lease operating expense (\$500/month)	Future net revenue
1	4837	4232	1693	17	93	51	6	1526
2	2413	2111	844	8	46	25	6	758
3	2110	1846	738	7	41	22	6	662
4	1945	1702	681	7	37	20	6	610
5	1837	1607	643	6	35	19	6	576
6	1755	1536	614	6	34	18	6	550
7	1692	1480	592	6	33	18	6	530
8	1637	1432	573	6	32	17	6	512
9	1589	1391	556	6	31	17	6	497
10	1546	1352	541	5	30	16	6	484
11	1505	1317	527	5	29	16	6	471
12	1467	1284	514	5	28	15	6	459
13	1432	1253	501	5	28	15	6	448
14	1398	1224	489	5	27	15	6	437
15	1366	1195	478	5	26	14	6	427
16	1335	1168	467	5	26	14	6	417
17	1306	1142	457	5	25	14	6	408
18	1277	1118	447	4	25	13	6	399
19	1250	1094	437	4	24	13	6	390
20	1224	1071	428	4	24	13	6	382

well from the gross revenue. The last column in Table 8 gives the future net revenue for each year.

Figures 14 and 15 show the discounted cash flow rates of return on these investments as a function of gas sales price (before depletion, depreciation, and federal income tax) for the respective permeabilities and numbers of explosives appropriate to the wells in the two basins. One can see that at a gas sales price of 40¢ /Mcf the rate of return on investment in a Piceance Basin well varies from 7.4 to 28.5%, depending on the permeability; the rate of return on investment in a Green River Basin well varies from 10.5 to 27.9%, depending on permeability and the required number of explosives.

The rates of return in these figures do not include items such as federal income tax, depletion, depreciation, and intangible

Fig. 14. Discounted rate of return of a nuclear-stimulated gas well in the Green River Basin for two different permeabilities (1976 dollars).

development expenses because their impact on the profitability of a development varies from company to company. As an example of the effect of taxes on profitability, in

Fig. 15. Discounted rate of return of a Piceance Basin gas well stimulated with three 100-kt explosives (1976 dollars). Curves are shown for three different permeabilities.

Table 9 we present a possible summary of the cash flow derived from the revenue of Table 8 with 20% of the well-development cost capitalized and straight-line-depreciated over a 20-yr period, a 22% gross revenue depletion allowed, and a 48% federal income tax rate applied. Depreciation and depletion are added back to income after tax to obtain the cash flow. The remaining 80% of the well cost is treated as an expense and deducted from other taxable income of the company. About 60 to 70% of conventional-well costs qualify for treatment as an intangible

expense, and the explosive charges would appear to qualify in this category. The effect would be to increase this fraction to at least 80%. The resulting tax credit of \$1.28 million then gives a net investment cost for well development of \$2.06 million. Discounting the tabulated revenue cash flow indicates a rate of return of 25%. This compares closely with the 22.5% rate of return (before federal income taxes) indicated in Fig. 14 for the same well with four explosives at a permeability of 10 μ d. The same type of calculation for all the possible wells shown in Figs 14 and 15 gives rates of return after depletion and federal income taxes about 2 to 3% higher than the returns before taxes. This indicates that income tax, depreciation, depletion, and tax credits effectively cancel insofar as the rate of return is concerned.

COST COMPARISONS OF ALTERNATE GAS SUPPLIES

We now are in a position to compare some of the economic factors related to alternative methods of obtaining increased gas supplies. To place the methods on an equivalent basis for comparison, we have estimated the time and relative investment costs required to develop the more probable sources so as to attain an additional gas supply capability of 1 Tcf/yr (see Table 10). The table also indicates the approximate magnitudes of current or currently proposed investments, the likely ranges of gas sales prices, and the research and development funding required (if any) to bring these sources to commercial production.

Table 10 shows that gas produced from nuclear-stimulated wells has the potential of being more economic than all other sources except conventional

Table 9. Economic analysis for single-well development in the Green River Basin, including federal income tax, depreciation, and depletion (thousands of dollars). This assumes a permeability of 10 μ d, a wellhead gas price of 40¢/Mcf, and four 100-kt explosives.

Year	Gross revenues	Future net revenue	Less depreciation (20% of cost)	Taxable income	Less depletion allowance (22% of gross)	Net taxable income	Less federal income tax (48%)	Income	Add back depreciation	Add back depletion allowance	Cash flow
1	1693	1526	33	1493	372	1120	538	583	33	372	988
2	844	758	33	725	186	539	259	280	33	186	499
3	738	662	33	629	162	466	224	243	33	162	438
4	681	610	33	577	150	427	205	222	33	150	405
5	643	576	33	542	141	401	192	209	33	141	383
6	614	550	33	517	135	381	183	198	33	135	367
7	592	530	33	496	130	366	176	190	33	130	354
8	573	512	33	479	126	353	169	184	33	126	343
9	556	497	33	464	122	342	164	178	33	122	333
10	541	484	33	450	119	331	159	172	33	119	325
11	527	471	33	437	116	321	154	167	33	116	316
12	514	459	33	425	113	312	150	162	33	113	309
13	501	448	33	414	110	304	146	158	33	110	302
14	489	437	33	404	108	296	142	154	33	108	295
15	478	427	33	393	105	288	138	150	33	105	288
16	467	417	33	383	103	281	135	146	33	103	282
17	457	408	33	374	101	274	131	142	33	101	276
18	447	399	33	365	98	267	128	139	33	98	270
19	437	390	33	357	96	260	125	135	33	96	265
20	428	382	33	348	94	254	122	132	33	94	260

Table 10. Costs for alternative gas supplies.

	Approximate time scale (yr to reach additional 1 Tcf/yr)	Approximate current or proposed investment (billions of dollars)	Approximate capital investment required to attain an additional 1 Tcf/yr (billions of dollars)	Gas sales price (1971 dollars per thousand ft ³)	Current R&D funding level (millions of dollars per yr)	Total required R&D funding (millions of dollars)
<u>Conventional exploration</u>						
Onshore	2-3	0.16 ^a		0.35-0.45 ^d		
Offshore	3-5	0.27 ^a	+1.0 ^b	0.50-0.65 ^e (Chicago)	0	Some
Alaska	8-10 ^f	0.21 ^a	+2.0 ^g	0.75-1.00 ^h (Chicago)		
Imports from Canadian Arctic	3-5 ^f	0.25 ^a +		0.75-1.00 ^e (Chicago)		
<u>Liquefied natural gas imports</u>						
	~5	0.1-0.2 ^f (1971-1975) 1.0/yr (1976-1980)	~3 ⁱ	0.68-1.00 ^d (East Coast)	0	Some
<u>Synthetic gas</u>						
Naphtha and heavy-oil gasification	5-7 ^j	~0.40 ^j	10 plants @ \$150 million - 1.5 ^j	0.85-1.60 ^j (at source)	0	Some
Coal gasification	~10-15 ^k	0.25 ^m	10 plants & mines - 2.9 ⁿ	0.70-1.00 ^e (at source)	15 federal 30 industry	300 ^p
<u>Nuclear stimulation</u>						
	10	No commercial investment	300 wells @ \$3.34 million - 1.0 160 wells @ \$2.44 million - 0.4	0.40-0.50 (1976 \$)	6.4 federal 6.0 industry	100-150
Total 1.4						

^aCurrent one-time only funding ³⁰^bNormal funding—based on costs of exploration for oil and gas as reported in Ref. 31. The costs for gas exploration were approximated by prorating the total costs for oil and gas exploration according to the costs of successful exploratory oil and gas wells.^cThis figure was estimated as follows: (1) Divide the average U.S. total reserves (275 Tcf for 1969) by the total U.S. productive capacity (36.5 Tcf/yr in 1969) to obtain the average reserve lifetime capability (7.6 yr in 1969); (2) divide this average lifetime into the average annual newly discovered additions to reserves (about 5.5 Tcf/yr from 1964 through 1970) to obtain the average change in productive capacity per year; (3) divide this number into the average total costs for gas exploration (see footnote b), which ranges from about \$690 million in 1965 to about \$950 million in 1969) to get the costs per unit change in productive capacity per year. The average for the years 1965 through 1969 is \$1.3 billion.^dReference 32. The price listed includes a transmission charge of 10-15¢/Mcf.^eReference 33.^fReference 8, p. 31.^gFor pipeline (Alaska only).^hNormal funding level unknown.ⁱFor ships, terminals, and storage facilities (Ref. 8, pp. 31 and 36).^jReference 34.^kReference 8.^mReference 35.ⁿReference 8, p. 54.^pReference 36.

exploration in terms of required investment, gas sales price, and research and development funding, and it is competitive with the others in terms of

the time needed to produce commercially worthwhile quantities. An expanded discussion of these topics is given in Appendix A.

Potential Markets and Delivery Schedule

Figure 16 shows the projected U.S. gas requirements by geographic region through 1995, assuming no constraints on supply. The production schedule we have proposed would reach 3 Tcf/yr by 1995. This would equal the total projected increase in the far western regions (8, 9, and 10 in

Fig. 16). Alternatively, this quantity of gas could supply half of the projected increase in the Great Lakes area (Region 4).

Figure 17 shows the projected State of California demand, the past production and consumption in California,³⁷ and our projected production of nuclear stimulated

Fig. 16. Future U.S. gas requirements by region. The 1970 data are the actual requirements; the 1975 data are estimates; the 1985 and 1995 data are projections. (Reproduced from Ref. 7 by permission of the Future Requirements Agency.)

Fig. 17. State of California gas consumption and production.

gas. One can see that by 1995 we could supply 80% of the total California demand.

Table 11 shows one possible schedule for delivery of the gas to California. A 36-in.-diam pipeline to Southern Cal-

ifornia would be provided to start deliveries in 1977. (We estimated pipeline capacities from figures given by Coates,³⁸ pipeline costs on the basis of average costs given by O'Donnell,³⁹ and compression station costs as 20%

Table 11. Possible schedule and costs for delivery of nuclear-stimulated gas to California.

	1972- 1977	1978- 1979	1980- 1981	1982- 1984	1985- 1990	1991- 2000
<u>Additional number of wells constructed</u>						
Piceance Basin	20	50	60	90	180	300
Green River Basin	—	40	120	210	420	700
<u>Well cost increment (millions of dollars)</u>	48	254	545	917	1834	3063
<u>Pipeline characteristics</u>						
Size	36 in.	48 in.	—	48 in.	48 in.	—
Capacity	0.5 Tcf	1 Tcf	—	1 Tcf	1 Tcf	—
Market	Calif.	Calif.	—	Calif.	Illinois	—
<u>Pipeline cost increment (millions of dollars)</u>	230	360	—	360	520	—
<u>Annual gas production at end of period (Tcf/yr)</u>	—	0.38	0.87	1.42	2.3	3.4
<u>Total cost increment (millions of dollars)</u>	278	664	545	1277	2354	3063

of pipeline costs.) This size of pipeline could handle up to 0.5 Tcf/yr. Because of the relatively assured supply, 48-in. pipelines capable of delivering 1 Tcf/yr would be added as required to handle the expected increase in total production rate. If the California market were being adequately supplied by 1983 from supplemental sources, a pipeline to take the final

1 Tcf/yr might be directed to the Great Lakes region.

Interestingly, the capital investment initially required for pipelines could be larger than that for the nuclear stimulated wells. Amortization of these pipelines, however, would not affect the wellhead gas price; the pipeline costs would be reflected in the price of gas delivered to the marketing region.

Radioactivity in the Gas

Based on the above plan for gas delivery, we have estimated the future dose commitment to the consuming population resulting from use of nuclear-stimulated gas.

Models based on data from Gasbuggy and Rulison have been used to calculate gas composition. Tritium production by the explosives is based on that expected

from a 100-kt Diamond explosive in a gas well environment.

Although gas was flared from Gasbuggy and Rulison and will be flared from Rio Blanco, Wagon Wheel, and probably several future experiments, we assume that well and field properties will have been established in the experimental phase

and that no flaring is expected for commercial field development.

Data from Gasbuggy⁴⁰ and Rulison⁴¹ identified tritium, krypton-85, and carbon-14 as the only radionuclides of significance in the gas vis a vis radiation exposure to potential consumers of stimulated gas when sufficient time is allowed between detonation and production of the gas (at least 3 mo). All of the krypton-85 was in the gas, whereas tritium was distributed among hydrogen-bearing species, principally water and natural gas, with only a small fraction available to the gas (about 5% for Gasbuggy and about 10% for Rulison). Carbon-14 is produced in such small quantities that its contribution to the potential dose to man is very small compared with that of tritium, even when the Diamond explosive, whose tritium production is minimal, is used.

Table 12 gives the expected tritium and krypton-85 concentrations in the gas (after water and carbon dioxide removal) as annual average concentrations for the expected rate of production from wells in the two basins. Small differences in

radionuclide concentrations in the gas from the two basins will result from differences in rock composition, depth, and temperature, as well as from the fewer explosives required in a Piceance Basin well. Due to the high early production rates, almost all of the contaminants in the gas will be removed from the well by the end of the first year, and second-year average radionuclide concentrations will be about 1/1000 of the first-year averages.

We will consider two alternative proposals for the delivery and use of the gas and the estimated population dose from each: (1) a uniform mixing model and (2) separate use of first-year gas from new wells for power generation.

California is the assumed market area for the stimulated gas, and we assume that the ORNL dose model for consumption of stimulated gas in Los Angeles⁴² is applicable for gas use throughout the state. The estimated future population was based on 1970 estimates* of 20 million

*The final 1970 population figures are 19,953,134 for the state and 7,032,075 for Los Angeles County.

Table 12. Average radionuclide concentrations in produced gas (after carbon dioxide and water removal).

Basin	No. of 100-kt explosives per well	Year	Annual average concentration (pCi/cm ³)	
			Tritium ^a	Krypton-85
Green River	4	1	11 ^b	71
		2	0.015 ^b	0.1
Piceance	3	1	<8 ^c	60
		2	<0.004 ^c	0.02

^aAssumes negligible exchange of tritium from water to methane after the start of production.

^bFrom Ref. 1.

^cBased on a <2000-Ci tritium residual for a 100-kt Diamond explosive in a gas well environment.

for California and 7 million for Los Angeles and a growth rate of 1.5%/yr. Dose equivalents are calculated for submersion, inhalation, and skin absorption only. Contributions from food chains are expected to be small relative to these direct modes of exposure. Whole-body dose calculations for krypton-85 are based on Hendrickson's model.⁴³

Figure 17 shows the stimulated gas supply from the proposed commercial field development compared with the projected demand for California, and Fig. 13 shows the supply of first-year gas from new wells. Figures 18 and 19 show the average and maximum radiation exposures to individuals (using upper-limit tritium concentrations) from these two methods of gas delivery to the California population, and Fig. 20 shows the population dose.* A more detailed discussion of these topics is given in Appendix B. These figures do not include the possibly higher doses to the small number of individuals using unvented gas heaters or appliances.

As shown, for the uniform mixing model, the highest average dose to individuals

would be less than 0.64 mrem/yr in 1981 and the highest maximum dose would be less than 1.0 mrem/yr. For the separate pipeline model, in which the first-year gas is delivered to power plants, the average dose to individuals would be less than 0.11 mrem/yr and the maximum dose would be less than 2.1 mrem/yr. Thus, the separate pipeline model results in a lower average individual dose but slightly increased maximum dose.* However, as shown in Fig. 20, the population dose would be decreased from about 15,000 man-rem/yr to the 1500-2000 man-rem/yr range. To keep exposures as low as "practicable," this alternative may be preferable if the extra complexity of handling the contaminated gas in a separate pipeline does not represent an unreasonable cost. However, even the exposures resulting from the uniform dilution model are a very small fraction of the natural background.

Table 13 summarizes the different possible doses to the California population from use of nuclear-stimulated gas and compares them with doses from natural

*The contribution to dose from the exclusive power plant usage of stimulated gas in Los Angeles was not considered in Ref. 42. Therefore, in this report we scaled (by the fraction of total gas usage represented by power plant consumption) the average ground-level concentrations from all sources indicated by Barton et al.⁴² to obtain conservative estimates of the average dose to the population resulting from only power plant use of first-year gas from new wells. The maximum dose to individuals downwind of power plants, however, was based on the peak ground-level concentration of 100 cm³ of gas per cubic meter of air calculated by Barton et al.⁴² Recently, T. V. Crawford of this Laboratory carried out preliminary calculations of the annual average ground-level air concentrations of combustion

products from the 10 Los Angeles power plants using a computer model that considers the frequency distribution of atmospheric stability categories as a function of wind direction, the actual wind speeds associated with the different directions and stability categories, and the effective plume height for each power plant. He used 5 yr of data from four weather stations in the vicinity of the power plants. Preliminary results⁴⁴ indicate that both the annual maximum dose to individuals and the average dose to the population will be at least one order of magnitude lower than those indicated in Fig. 19. This appears to invalidate the conclusion stated above that the separate pipeline model would result in a slightly increased maximum dose to individuals.

Fig. 18. California per-capita exposure from tritium and krypton-85 assuming uniform mixing of nuclear-stimulated gas with the total gas delivered to the state.

Fig. 19. Individual exposures in the vicinity of power plants from tritium and krypton-85 assuming separate power-plant use of first-year gas from new wells.

Fig. 20. Upper-limit population exposure due to the use of nuclear-stimulated gas in California.

Table 13. Radiation exposure to population of California from various sources.

Source	1970 estimated individual exposure (mrem/yr av)	1970 estimated population exposure (man-rem/yr)	2000 estimated individual exposure (mrem/yr)		2000 estimated population exposure (man-rem/yr)
			Av	Max	
Natural background	114	2,300,000	114	—	3,500,000
All medical sources	98	2,000,000	160	—	5,200,000
Nuclear atmospheric tests	5	100,000	5	—	160,000
Nuclear power reactors	0.002	40	~0.2	—	6,000
Power-reactor fuel reprocessing	0.0008	16	0.2	—	6,000
<u>Gas Stimulation</u>					
General use of all gas	—	—	<0.45	<0.7	<14,000
Power plant use of first-year gas	—	—	<0.11	<2.1	<2,000

background and other man-made sources of radiation.⁴⁵

On a worldwide scale the long-lived tritium and krypton-85 from nuclear-gas stimulation are of concern as contributors to the general buildup of these radionuclides in the biosphere. Based on the above models for field development, the krypton-85 in the gas will be released at a steady rate of 0.85 MCi/yr after the fourth year. Worldwide buildup of krypton-85 from this source would approach a steady state value of 13 MCi by the end of this century. Assuming a uniform distribution in the atmosphere, the whole-body dose to individuals worldwide then would be about 8×10^{-5} mrem/yr.

Tritium in the gas will be released at a rate of less than 0.14 MCi/yr after the fourth year of production. This corresponds to a contribution to the worldwide tritium inventory at steady state of 2.5 MCi, which would be about 3 to 10% of the naturally produced inventory from cosmic rays. We expect that tritiated water produced from the stimulated wells (and removed from the gas before it enters the pipeline) will be disposed of in a manner that permanently isolates it from the biosphere by reinjection underground. If it cannot be so disposed, the rate of tritium release could be about four times the above rate.

Environmental Impact

WELL CONSTRUCTION

The permanent local environmental effects resulting from the construction of

a nuclear-stimulated well are essentially no different from those of a conventional gas well. Power lines, access roads, a leveled area for operation of the drill rig,

mud pits to contain drilling mud, and gas pipelines would be required. Items not needed after completion of construction, such as the mud pits, could be restored to their initial condition.

At the depths of burial contemplated for the nuclear explosives, no surface subsidence or other permanent disturbance should occur.

SEISMIC EFFECTS

The principal limitation on the maximum size of nuclear explosive that can be used for nuclear stimulation is due to the transient seismic shock immediately following the explosion. Based on the results from many underground nuclear experiments, methods have been developed for predicting the expected components of ground motion: peak vector acceleration, velocity, and displacement.⁴⁶ These methods take into consideration the effects of source, transmission path, and receiving-site geology.

In addition, the experience from such damage to structures as has been seen in Hattiesburg, Mississippi, from Salmon and in Mercury, Nevada, from many experiments at NTS and in Meeker, Colorado, from Rulison provides a measure of correlation between the expected ground motions and the degree of expected structural damage.

In the relatively remote Piceance and Green River Basin locations, the number of existing structures exposed to such damage will be low. Well sites will be constrained to those locations where the repair cost of such minor damage as does occur will be an acceptable cost to the operation.

For example, an estimate of \$50,000 has been made for the damage to be expected as a result of the Rio Blanco experiment in Colorado.⁴⁷ This estimate is primarily a result of architectural damage (e.g., plaster cracking, fallen bricks at residential and public structures). Figure 21 shows three examples of such minor damage experienced as a result of Rulison. Predetonation preventive maintenance probably will reduce this cost.

Table 14 presents the Gasbuggy and Rulison seismic damage experience and gives estimates of the expected costs for Rio Blanco, Wagon Wheel, and the commercial Piceance and Green River Basin wells.

To minimize the number of days on which local populations would be subject to this seismic nuisance, one possible mode of operation would be to construct a number of wells and detonate them all on the same day. Four detonation days per year should suffice for the 30 or 40 wells-per-year size of field operations we have postulated.

Inconvenience to the public on shot days may require suitable compensation. However, the expected annual costs for seismic damage are small (see Table 14).

SEISMIC AFTERSHOCKS

Underground nuclear explosions sometimes generate small aftershocks in the immediate vicinity. The specific mechanisms for generation of these small earthquakes are not known, but they are apparently related to residual stress changes produced by the explosion.

Rulison provided information on the aftershock susceptibility of an area that

Fig. 21. Typical seismic damage from an underground nuclear explosion: cracking of masonry foundation (upper left), dislodged bricks (lower left), cracking of plaster (right).

Table 14. Seismic damage estimates.

	Gasbuggy (actual)	Rulison (actual)	Rio Blanco	Piceance Basin commercial	Wagon Wheel	Green River Basin commercial
Number of structures susceptible to damage	Few (0-15 mi)	1900 (0-22 mi)	300 (0-28 mi) 3000 (28-40 mi)	~ 300	1350 (0-40 mi)	~ 1350
Number of claims expected	2 (claims filed)	320 (claims filed)	85 (0-28 mi) 85 (28-40 mi) Total 170	~ 50	75 × 2 (for sequential detonation) = 150	< 100
Estimated value of claims	—	\$93,000 (paid)	\$50,000	~ \$25,000	\$65,000	\$50,000
Annual claim estimate for commercial operation (4 detonation days/yr)	—	—	—	~ \$100,000	—	< \$200,000

statistically has a low frequency of earthquakes. The U.S. Geological Survey's National Center for Earthquake Research and the National Oceanic and Atmospheric Administration's Earth Science Laboratory both instrumented the Rulison area with seismographs.⁴⁸

Ambient seismic activity was monitored for several days before the detonation and no earthquakes were detected. Many small aftershocks were detected within a few minutes after the detonation; all originated within 3000 ft of the Rulison location. Further monitoring for 20 days at distances out to 60 mi indicated 27 seismic events; of these, 14 were less than 60 mi from the Rulison emplacement well, but the largest had a body-wave magnitude of 2.2.

On the basis of such experience, we expect that each explosion in the 100-kt yield range will generate no more than a few dozen such events, none having a Richter magnitude greater than 3 (compared with a Richter magnitude $5\frac{1}{2}$ body wave for each of the five detonations). These will cease within a few hours. The total seismic energy released will be substantially less than that from each 100-kt explosion. The ground motion they produce may be perceptible to an observer within a few miles of the detonation, but probably not farther away. They will present neither hazard nor identifiable impact on the environment.

In connection with earlier underground detonations, the argument has been raised that, while the innocuous small aftershocks described above are the expected effect, it is not impossible in principle that some future explosion, if

detonated in a region where high natural stress had built up, might trigger an earthquake with greater seismic energy and greater hazard potential than the explosion itself. However, because Colorado and the Green River area of Wyoming are not active seismic regions and have no history of destructive earthquakes, we do not believe that this will constitute a risk. There is no realistic prospect of prematurely setting off a major earthquake that might have been near the point of natural occurrence.

DISPOSAL OF RADIOACTIVITY IN THE CHIMNEY GAS

During the early stages of commercial nuclear stimulation development there will be a need to test the gas productivity of test wells constructed in previously untested geological formations and locations. This will require flaring both of the gas that fills the chimney after the detonation and some amount of the gas that continues to flow into the chimney from the surrounding formation as the well is produced.

Small amounts of radioactivity will be released to the environment during this flaring operation. However, we believe the exposures resulting from such releases can be held to acceptable levels. As an example, the statements regarding maximum exposures to man from flaring of the gas during production testing of Rio Blanco are quoted from the environmental statement⁴⁸:

"The calculations assume maximum radioactivity concentrations and a maximum rate of flaring.

The possible resulting radiation exposure to man from the production testing activity is found to be a small fraction of the natural background radiation. While the radiation exposure to man from dry deposition is estimated to be a small fraction ($\ll 1\%$) of the natural annual background there is the opinion held by some scientists that any exposure above annual background (approximately 140 mrem per year at the location of Rio Blanco) should be avoided.^[49-51] Other scientists maintain that these radiation levels have no somatic, physiological or genetic effect at all.^[52]"

Once the potential productivity at a particular area is determined, flaring of gas should not be necessary for normal commercial operations. However, the carbon dioxide and water vapor present in the gas must be separated from the methane before it can be delivered to the pipeline. Natural gas from conventional wells is normally processed through purification facilities to remove these constituents, which are then harmlessly discharged to the environment. However, 35-50% of the tritium initially present in the chimney may be in the water vapor, and this water, after condensation and separation from the methane, could have a specific activity in the range of 0.02 to 0.05 $\mu\text{Ci/ml}$. This is 20 to 50 times the ICRP-accepted standard for potable water.*

*The current radiation protection guideline value for tritium-containing water is 1000 pCi/ml, as established by the Federal Radiation Council (now a part of the EPA).

The best method for disposal of this water has yet to be determined. It is possible that the water could be reinjected into the producing well, thereby isolating it permanently underground in a location where it could not have access to aquifers.

The disposition of water containing low levels of tritium will be a continuing aspect of nuclear stimulation field operations. The final choice of disposition methods will depend on interactions between costs and the government policy of practicable and minimal releases of radioactivity to the environment.

GROUNDWATER EFFECTS

Detailed hydrologic studies of each local area selected for nuclear stimulation will be necessary in order to understand the conceivable pathways by which radioactive contamination might enter the groundwater and to assess the potential hazards. Such an assessment has been made for Rio Blanco.⁴⁸ While the conditions will be different for each specific location, the Rio Blanco analysis may be taken as indicative of the environments to be expected in developing these basins.

The U.S. Geological Survey has thoroughly studied the hydrology of the Piceance Creek Basin. The bottom of the lowest aquifer region containing mobile water is at least 3500 ft above the calculated top of the detonation-induced rock fractures. Therefore, no aquifer will have direct communication with the explosion produced chimney. Near the emplacement well, the water in this lowest aquifer (called the "B" aquifer) is sub-potable, containing about 3000 ppm of dissolved solids. Water moves through the "B" aquifer at

less than 1.2 ft per day. The nearest current-use point from this aquifer is 3.6 mi from the detonation site. If the water were assumed to be flowing towards this point, the radioactivity would take some 43 yr to arrive there, assuming also that it was first able to enter the aquifer. By that time, from radioactive decay alone and not assuming any dilution by uncontaminated water, the tritium concentration would be less than 1% of the current radiation concentration guides for water. The potential individual dose that could be accrued by drinking this water would be less than 1 mrem/yr.

At the emplacement well, the "B" aquifer lies between 880 and 1650 ft below the surface. It is overlain by an aquitard—a flow-restricting formation. Still higher, between 245 and 845 ft below the surface, is the so-called "A" aquifer. The quality of the water in the "A" aquifer is better; it contains only 640 ppm of dissolved solids. If there were a small crack that ran from the chimney to the surface and radioactivity were to seep up that crack, only 1% of the activity would pass through the "B" aquifer and on to the "A" aquifer. Water flow velocity in the "A" aquifer averages less than 0.8 ft/day. The nearest well tapping the "A" aquifer is about 6.5 mi from the emplacement well (but in a direction that is almost perpendicular to the groundwater flow). Even assuming that the flow were towards this well, contaminated water would take 100 yr (at current flow velocities) to reach it. Thus, the tritium levels would have decayed to far lower levels than those quoted above for the nearest use point in the "B" aquifer.

Thus it may be concluded that no contamination of the groundwater near the Rio Blanco site is anticipated. Immediately following the detonation, some increase in turbidity may be experienced in water wells out to 10 mi due to shaking of the well cores, but this should subside in a few days. In addition, water wells and springs within 3 mi may show a slight temporary increase in flow due to a rise in the piezometric surface.

EFFECTS ON OTHER MINERAL RESOURCES

Concern has been expressed over the possible deleterious effects of gas stimulation detonations on other mineral formations that might render them unmineable by standard methods such as formation fracturing or increases in water intrusion.

For example, at the Rio Blanco site the major mineral resources are oil shale and sodium and aluminum-bearing minerals (nahcolite and dawsonite), located at depths of 440 to 2300 ft.

At a meeting of the Colorado Governor's Advisory Committee on Project Rio Blanco, the Oil Shale Corporation (TOSCO), Superior Oil Corporation, and Wolf Ridge Minerals Company each expressed their concern that the project would jeopardize development of the oil shale and sodium minerals.⁵³ Their concern is principally that the effect of the stress wave on the joints and the fractures in the Green River Formation might be such as to make mining more difficult or perhaps impossible. They also stated that the mineral resources in the area are potentially more valuable than the gas and that the possible loss of such large mineral resources is not worth the risk.

The possible mechanisms and extent of effects on the oil shale formations have been studied in some detail.^{54,55} These included fracturing of the rock by the outgoing shock wave, the possibility of motion induced on faults, the possibility of mine damage, and the possible increase of water intrusion due to increased permeability of the adjacent aquitards or transecting faults.

Theoretical calculations and comparisons with past detonations lead to the conclusion that there can be no fractures created by the Rio Blanco explosion between about 350 and 5000 ft below the surface.⁴⁷ The full extent of the mineral-bearing region falls within this range.

Motion along preexisting faults in the vicinity of nuclear detonations at NTS have been observed and reported. However, there is no surficial evidence that such motion has changed the permeability of these faults. By examining the explosion-induced fault motion, one would expect that no fault farther than about 7000 ft (measured on the surface) from a 100-kt detonation could be moved.⁵⁶ Since there are no known faults within $2\frac{1}{2}$ mi of Rio Blanco, no such motion is expected. However, the location of nuclear stimulated wells will need careful evaluation on the basis of proximity to major faults;

a criterion that no fault be closer than 7000 ft may be reasonable for future operations.

This Laboratory has obtained considerable experience relevant to potential mine and tunnel damage in connection with nuclear detonations in or near tunnel complexes at NTS. This experience indicates that even in the weak rock found at NTS no visible effects from an explosion of 100 kt would be expected in tunnels and mines more than about one mile from the detonation and, in the majority of cases, no visible damage would be expected farther than about one-half mile away.

Since no fault motion and no cracking in the region of occurrence of these mineral resources is expected, the increase of water intrusion does not appear to be a real possibility.

Similar considerations of these potential effects will need to be made in each location for which nuclear stimulation is proposed. However, on the basis of the Rio Blanco studies it would appear that no threat will be presented to the development of mineral resources in these areas and that future development of these gas reservoirs can be accomplished prior to, or concurrent with, mineral resource development using cooperation and good management techniques.

Public Acceptance

Public acceptance, both of the technical feasibility experiments and the subsequent commercial development of fields, will be a major factor in the development and use of the technology. The Gasbuggy experiment generated no oppo-

sition. In Rulison several injunctions were sought initially to stop the detonation and subsequently to prevent the post-shot flaring program. In all instances the courts ruled that the experiment could proceed, thereby clearly establishing

the propriety of AEC procedures and guidelines regarding release of radioactivity and carrying out peaceful nuclear explosions.⁵⁷

Since Rulison, considerable effort has been made to work with those groups in Colorado who opposed Rulison, as well as State advisory groups and environmental organizations, in an effort to acquaint them fully with planned precautionary measures and to acknowledge their criticisms. In addition, a series of public meetings on Plowshare, the Miniata test, and the publication of the Rulison results have re-

sulted in generally favorable public reactions.

Ultimately, public acceptance will revolve around a few key points: (1) a public awareness of the shortage of fuel and other natural resources; (2) a direct benefit (such as jobs or severance and ad valorem taxes) to those most directly inconvenienced by the detonations; (3) an awareness that the radioactivity associated with products from nuclear detonations is extremely small; and (4) the actual demonstration—through the carrying out of experimental projects—that the AEC can accurately

Table 15. Benefits to the government from nuclear gas stimulation.

	Increment in			Present value of cumulative total through 1991 ^f
	1980	1986	1991	
Gas Production (Tcf/yr)	0.867	1.750	2.480	—
Gas Value at 40¢/Mcf (millions of dollars)	347	700	992	3756
<u>Revenue to government (thousands of dollars)</u>				
County ad valorem taxes ^a	16.7	33.7	48.0	180.5
State severance taxes ^b	3.1	6.1	8.6	32.8
Federal royalty ^c	<u>43.3</u>	<u>87.6</u>	<u>124.4</u>	<u>468.7</u>
Total government revenue	63.1	127.4	181.0	682.0
<u>Balance-of-payments effect (millions of dollars)</u>				
Equivalent cost of imported oil ^d	458	925	1315	4952
Equivalent cost of imported liquefied natural gas ^e	606	1229	1741	6562

^aTaken as 5.5% of net value after U. S. royalty.

^bTaken as 1% of net value after U. S. royalty.

^cTaken as 12½% of gross production value.

^dTaken as \$3.00/bbl paid to foreign producers and shippers (energy equivalent of 1 bbl oil = 5680 Mcf of gas).

^eTaken as 70¢/Mcf paid to foreign producers and shippers; U. S. price after vaporization would be 80¢/Mcf.

^fDiscounted at 8%.

predict the effects of nuclear explosions and that its procedures do adequately protect the public health and safety and minimize impact on the environment.

Based on the schedules for commercial development proposed in this report, Table 15 presents the financial benefits to government over the next 20 yr from the sale of nuclear stimulated gas at 40¢ /Mcf.

If instead of producing this domestic gas the equivalent energy is provided to U.S. consumers by importing crude oil at \$3.00 per barrel, the balance of trade effect would result in an outflow of \$1.3 billion per year by 1991. If the requirement for this energy must be met by gas, the importing in 1991 of an equivalent quantity of liquefied natural gas at 70¢ /Mcf paid to foreign producers and shippers would result in an outflow of almost \$1.7 billion per year.

We have proposed that field development could start in 1977, increasing as shown in Table 5 to a continuing construction rate of 100 wells per year. Depending on the total area available in each locality for development, it may be expected that several hundred wells would be constructed over an extended period and that these wells would continue to produce gas for 20 to 50 yr.

Such a program would greatly affect the population levels and economic bases of these remote areas, since this level of long-term construction and operating activity might be expected to result in local populations of about 10,000 to 20,000 people. Thus, in addition to the tax revenues to local government from production of the gas, there would be a far larger stimulus to the local economies from the economic multiplier resulting from this new local industry.

Technical Development Programs for Achieving Commercial Usage

If nuclear gas stimulation is to be utilized for increasing the nation's supply of natural gas, a number of development programs must be undertaken. While we have answered a number of the most important questions regarding technical feasibility and safety, explosives must be designed to minimize the radioactivity problem, costs must be further reduced, the optimum use of multiple explosives must be determined, and operational procedures must be worked out. These efforts are described in the following sections.

DEVELOPMENT OF THE GAS-STIMULATION EXPLOSIVE

The explosives used in the Gasbuggy and Rulison experiments were existing designs developed to meet military weapons criteria. The explosive for commercial gas stimulation must be designed (1) to leave a minimum amount of tritium, (2) to fit into as small a drill hole as practicable, (3) to withstand the high temperatures and pressures existing in gas fields, (4) to be sufficiently rugged to withstand the shock from previous sequentially fired explosives, and (5) to be of minimal cost (i.e., to be easily manufactured and use

minimum quantities of fissionable materials).

These goals are difficult to meet simultaneously and are not met fortuitously by a weapon explosive. A common denominator for all these factors is cost, since desirable features always can be achieved for more money. Therefore, tradeoffs between features are essential to attain minimal costs.

An explosive that embodies most of these features has been designed; the word Diamond is intended to serve as the generic name for this class of explosives. Salient features of these design factors and their impact on the Diamond explosive are as follows.

Diameter

Diameter is important because of limitations of drilling technology and drilling cost. It is more difficult to design an explosive with the desired characteristics at a small diameter than at a large diameter. The cost of the explosive will generally increase as the diameter decreases. The diameter of the Diamond explosive canister is less than 8 in.; it can therefore be emplaced in a 9-5/8-in.-o.d. casing. Modification of the explosive for sequential firing may lead to a somewhat increased diameter.

Gaseous Radionuclide Production

The reduction of post-explosion tritium levels is the single most important technical consideration. Because a thermonuclear explosive can produce between 0.7 and 5 g of tritium per kiloton of yield, a fission explosive has an inherent advantage in that only about 0.1 mg of tritium is produced in ternary fission per kiloton of

fission yield. The Diamond explosive is designed with this factor in mind.

Additional sources of tritium are from neutron reactions with shielding materials or with constituents of the surrounding rock. An (n, T) reaction on ^{10}B and an (n, α) reaction on ^6Li are the two dominant sources. Since the lithium occurs naturally in the rock (and 0.5 to 3% of the neutrons entering the soil will form tritium for the range of gas-field soils for which we have analyses), it is advantageous to keep the neutrons from entering the soil.

The post-explosion tritium from each 30-kt Diamond explosive in the Rio Blanco Event is expected to be less than 0.1 g (1000 Ci). This low level of post-explosion tritium represents a significant step in the development of a gas stimulation explosive.

Krypton-85 is the other radioisotope of concern. It is a fission product and its presence is an unavoidable consequence of the use of the fission process.

Downhole Conditions

The explosive is designed to be capable of withstanding an external hydrostatic pressure of 10,000 psi and temperature as high as 350°F.

To protect against high temperatures there is a system (illustrated in Fig. 22) that utilizes the latent heat of vaporization of an internal water supply to provide the necessary cooling. The advantages of such a system are its simple operation, inexpensive components, and lack of need for surface power. The main disadvantage is that the system has a limited life; when the water supply is exhausted the explosive will heat up and become unusable.

To protect against high pressures there is a high-strength steel canister over the

Fig. 22. Temperature controls for underground nuclear explosives.

explosive. In addition, the internal parts are designed to take as much load as possible. The main problem in the canister design arises in choosing a low-cost yet adequate-strength steel that is resistant to the corrosive effects found in deep holes.

Sequential Firing

Currently the Diamond explosive may be detonated only in the simultaneous mode. The sequential mode will require a substantial effort to develop an explosive capable of performing reliably after having been subjected to the stresses generated by the previous explosions.

Cost

As previously mentioned, all aspects of

the explosive design affect the cost. The cost factor was considered at every step in the design of the present Diamond explosive, and a continuing effort will be made to make the explosive as inexpensive as possible.

A Diamond explosive was tested in the Miniata Event at the NTS on July 8, 1971. The purpose was to verify that the explosive together with a simplified firing system would perform as designed.

The measured yield of about 82 kt is in excellent agreement with that predicted before the shot. Results indicate that the experiment was completely successful.

Although the purposes and constraints of this experiment as conducted at NTS

were not consistent with a meaningful direct measurement of postshot tritium levels, all diagnostic results are in harmony with the conclusion that the amount of tritium produced in a gas field environment would be as predicted.

NUCLEAR EFFECTS

As illustrated in the section on gas production, the cost of stimulating a given gas section and the amount of gas that can be recovered depends critically on an understanding of the fracturing effects of single and multiple explosions. Based on our data and those of the Soviets and the French, the fracture dimensions in a hard, brittle rock such as granite are quite well known. On the other hand, in salt there are no significant permanent fractures. Data from Gasbuggy indicate that the fairly high clay content in the gas-bearing Pictured Cliffs formation acted to inhibit the formation of permanent fractures. We believe that in a shale with less clay, as at Rulison and in the Green River Basin, larger permanent fracture systems will result. Whether such fractures will stay open at 10,000 to 14,000 ft is not known.

The use of multiple explosions should lead to the enhancement of fracturing, whether simultaneous or sequential firing is used. For simultaneous firing, the much higher stress level in the region of interaction, as well as the reinforcement of lateral movement in this region, should lead to more extensive compressive and tensile failure. For sequential firing, the presence of the chimney and the fracture zone resulting from the earlier shots will provide free surfaces for the generation of reflections and subsequent tensile

fracturing by the later shots. Whether simultaneous or sequential firing is superior from a fracturing viewpoint cannot be determined without experimentation. Such enhancement could reduce the costs of stimulating a given section by 20 to 50% and might increase gas production by comparable amounts.

Figures 3 and 5 show the locations of proposed postshot fracture-measurement and pressure-monitoring holes to be drilled into the fractured regions resulting from the Rio Blanco and Wagon Wheel experiments. Such measurements are necessary to achieve understanding of the effects of multiple chimneys and to achieve confidence in our ability to predict such effects from calculations based on experiments of this type.

Nuclear-effects data relative to understanding the role of fractures in gas production also should be obtained in subsequent nuclear production tests by adding instrumentation to such projects. The details of the type and frequency of such add-on experiments cannot be fully specified until the gas-production experiments are better defined.

Studies of the chemical interactions occurring in the chimney are of critical importance in understanding and predicting radioactivity behavior. Figures 23 and 24 show the radioactivity and gas composition from Gasbuggy and Rulison.^{40,41} It is evident that significant chemical reactions and exchange processes were going on inside the chimneys after the detonations. Since each chimney will present a somewhat different chemical environment, some variation in the chemical state of the tritium can be expected. These differences need to be understood so that

Fig. 23. Flow rate, composition, and radioactivity of Gasbuggy gas.

every measure can be taken to minimize the radioactivity produced in the gas.

While the seismic damage problem for single explosions is reasonably well understood at the present time, the use of multiple explosives, whether sequential or simultaneous, as well as the greater depths raises a number of new questions that must be answered. Therefore, additional research in the areas of seismic motion and damage must be undertaken as a part of any

program to reduce the cost of nuclear gas stimulation.

Obviously, there is a great deal of interaction between these development programs and the nuclear-explosives design effort described above, particularly in the area of environmental conditions and sequential firing.

Fig. 24. Composition and radioactivity of Rulison gas.

EXPLOSIVE OPERATIONS SYSTEM

To achieve the low fielding costs projected in Table 7, a major engineering program must be mounted to develop new operational procedures and techniques. For example, new and better methods of reentering the chimney region through the emplacement hole are required. To evaluate the concept of sequential emplacement and detonation of explosives one at a time, extremely reliable methods of retaining a sealed emplacement hole above each chimney will need to be developed.

A closely related area of engineering study is the operational system needed for carrying out emplacement and detonation. A recently developed concept, shown in Fig. 25, envisages the use of cement stemming immediately above the explosive to act as a pressure seal. Fluid stemming would fill the remainder of the hole to the surface. Removal of the explosive firing cable for subsequent reentry is the troublesome problem here; in this concept, high-strength cable immersed in the fluid stemming would break at the cement-fluid interface when stressed and could be pulled from the hole. Low-strength cable remaining in the cement could be drilled out with the cement. To minimize costs, a minimum number of vehicles would be used for explosive delivery, firing cable connection, and remotely controlled firing.

GAS-RESERVOIR PRODUCTION TECHNOLOGY

The best method of evaluating any gas well, whether it be conventional or nuclear stimulated is to produce gas from the well

for a period of time at several different rates and record the corresponding down-hole pressure. By matching these data with theoretical calculations of the flow process, an understanding of the extent of the fractures and the role they play can be gained. However, in the general case the interpretation is not unique and additional pressure data are needed in the fracture region, as well as beyond. As a result of many years' experience with conventional wells, a good deal of understanding of their results has been developed. However, the nuclear-stimulation case is significantly different in scale and kind, and so far only two nuclear wells are available for study.

To develop a good understanding of the fracture zone (particularly for multiple explosions) and the role it plays and to optimize the spacing and placement of the explosives, definitive experiments in gas-production engineering would appear very necessary. Figures 3 and 5 illustrate such proposed experiments in which an additional hole is drilled in the fracture zone of a multiple gas-stimulation application so that pressures can be monitored during production from the emplacement/reentry hole. The use of two such holes would be still better; such data make the solutions unique when matched by two-dimensional gas-flow calculations and should yield a very good understanding of the important parameters for nuclear gas stimulation. Since not all gas reservoirs are alike in their flow characteristics and because various spacings should be tried with nuclear explosives, several experiments may be necessary for a full understanding.

Fig. 25. Commercial fielding concept for a nuclear explosive for gas stimulation.

Policy Issues Requiring Government and Industry Action

There is no question that additional sources of gas for our nation's needs must be developed. It is also clear that development of no one single new source can meet the burgeoning demand; all potential sources must be considered and as many as appear practical developed.

Nuclear gas stimulation has been shown to be technically feasible but requires considerable technological development before it can contribute natural gas to our national supply in an economically attractive way. A number of actions must be taken by government and by industry for the technological development program to be accomplished and for the establishment of a nuclear-stimulated-gas industry.

GOVERNMENT ACTIONS

It must be recognized that for industry to assess accurately the required amount of capital investment and return on that investment, firm information is needed on (1) the prices to be charged by the AEC for the nuclear explosives, (2) the gas sales prices to be allowed by the Federal Power Commission, and (3) the levels of radioactivity in the distributed gas to be allowed by the AEC, as based on standards to be established by the Environmental Protection Agency. Present law permits the use of nuclear explosives in joint government-industry experiments. However, after the research and development program is completed, a law must be passed to permit commercial use of nuclear explosives. In addition, information such as canister diameter and quantity of internal and external radioactivity

produced per explosive will need to be declassified so that design of commercial production wells can proceed.

INDUSTRY ACTIONS

AEC Chairman J. R. Schlesinger in a recent speech⁵⁸ reminded industry that the role of the AEC is to provide service and support in nuclear matters but it is up to industry to provide the incentive and resources for the establishment of commercial nuclear enterprises. Nuclear-stimulated gas production still awaits the execution of a several-year technological development program that will involve substantial expenditures. Although a small number of companies have come forward to propose, fund, and execute a few joint industry-government experiments, it is apparent that a number of companies holding mineral leases on properties suitable for nuclear gas stimulation have not seen fit to commit their effort.

It is recognized that the funds required for such experiments may be too great for all but a few companies to risk on a unilateral basis. However, ways to pool funds from more than one company for such purposes are known; for example, the electric utilities industry is proposing to carry out research and development through a nonprofit foundation, and the gas industry is already conducting such research on coal gasification through the Institute of Gas Technology.^{59,60}

If the burden of industrial sponsorship for nuclear stimulation falls too heavily on only the presently participating companies while others wait for the technology

to be developed, completion of the development program may not occur and commercial production may never come to pass.

JOINT ACTIONS—THE TECHNOLOGICAL DEVELOPMENT PROGRAM

A 5-yr program of technological development will be required to achieve commercial gas production. One or two nuclear experiments will be required to measure the environmental conditions resulting from a nearby nuclear detonation and to test the successful operation of a hardened explosive fired in the sequential mode. Pilot development tests involving the construction of groups of three to five wells in each new location will be necessary to prove out the gas productivity and economics of nuclear stimulated wells using multiple detonations.

We suggest that the government's role would be to develop the explosives and the understanding of the nuclear effects of these explosives. Industry's role would be to join with the government by proposing specific joint experimental projects, funding a major share of the field test costs, and applying its research and development capabilities to the reservoir-production problems.

Should the government decide that nuclear gas stimulation is an alternative warranting its policy and funding support, we believe the development program could be accomplished in about 5 yr for \$100 to \$150 million, of which 60% might be funded by the government and 40% by industrial companies. Alternatively, if the development program were to be paced by industrial interest and funding, with the government contributing only the explosive

development and minimal research and development funds necessary for government contractors and safety, more experiments stretched over 6 or 7 yr would be required and the total cost would be increased.

The nuclear explosive will be continually improved as experience is gained in actual field use. The nuclear-effects data will be obtained primarily through government-funded research and development "add-ons" to specific projects. Building an understanding of the generation of the seismic waves and distribution of the radioactivity is necessary to minimize the chance of an unforeseen occurrence in future projects and to learn just how far it is prudent to go in cost-reduction proposals. Fracturing research will be an effort to find out how few explosives can be used to stimulate a given reservoir section and still be interconnected so that the emplacement hole can be used for reentry. Radiochemical and chemical work should help in understanding how the shot horizons can be selected to minimize CO₂ and tritium production and in deciding on the best methods for the disposal of tritiated water. While these issues are of interest to a specific project sponsor, the relevance is more toward being better able to apply the understanding of these effects to other areas and depths; hence the recommendation of government funding. The joint projects are obviously necessary to test for gas production and to learn how to efficiently carry out nuclear explosions in gas fields.

At the conclusion of this program, the costs for field development should be well established and the technical questions relating to nuclear stimulation should be answered.

BENEFITS

The primary beneficiary will be the American consumer, who would be provided a new supply of relatively low cost, convenient, clean fuel. The government's

investment could be returned many times in royalties. The return to the various state and local taxing jurisdictions ranges from $6\frac{1}{2}\%$ to $12\frac{1}{2}\%$. The companies involved would, of course, recover their expenses and derive their profit from the sale of the gas.

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Appendix A

ALTERNATIVE GAS SUPPLY METHODS

This discussion of the alternatives for obtaining increased gas supplies is an amplification of the topics in Table 10.

Conventional Exploration in the U.S. and Canada

Conventional exploration and drilling in geologically favorable locations represents the best method for increasing domestic gas supplies, and the petroleum industry has been spending about \$1 billion per year on gas exploration for the past few years.^{A-1} The gas transmission pipeline companies have committed approximately an additional \$1 billion during 1970-71 for this purpose because a ruling by the FPC allowed them to include in their rate base advanced payments to gas producers for exploration.^{30,A-2} However, the FPC recently stopped further advanced payments of this kind.^{A-3}

Much of the onshore U.S. down to 10,000 or 15,000 feet already has been explored; thus the favorable areas for new gas finds appear to be offshore, onshore at depths below 15,000 ft, or in more remote regions such as Alaska and the Canadian Arctic islands. Since these locations are more difficult to explore, finding and developing such gas supplies probably will take 2 or 3 yr longer than usual. Further delays may occur due to the current lack of availability of federal leases for offshore properties in favorable locations and recent procedural restrictions by the U.S. courts on granting of

such leases due to possible environmental effects.^{A-4}

Imports of gas by pipelines from Canada have been growing steadily over the past few years. Prospects for additional gas finds in Canada appear very favorable and considerable investment in exploration undoubtedly will occur. However, recent estimates indicate an import level of only 2.3 Tcf/yr by 1985,^{A-5} partly because of Canadian export restrictions.^{A-6} Delivery of gas to U.S. markets from remote northwestern Canada or Arctic island regions will be costly and will require additional pipeline construction.

Import of Liquefied Natural Gas

It is probable that import of LNG will grow very rapidly in the coming years. Large quantities of gas will be available from North Africa and the Middle East if sufficiently large investments are made in foreign liquefaction plants, special refrigerated tankers, and U.S. storage and regasification plants. The El Paso Natural Gas Company has filed for and obtained partial approval from the FPC for import of 0.36 Tcf/yr of LNG from Algeria.^{35,A-7} The disadvantages of this method are the higher gas sales price, the dependence of U.S. consumers on an easily interruptible foreign source, and the adverse effect on the U.S. balance of trade.

Development of the technology for liquefying, storing, and sea transport of LNG has been funded entirely by

industry.^{A-8} Commercial deliveries from Algeria to markets in Europe have been underway for several years,^{A-9} so that further developmental funding does not appear necessary.

Synthetic Gas

Gas can be synthesized by several routes from hydrocarbon fluids and from coal. Commercially proved processes for conversion of naphtha and light oil feedstock are readily available; as of December 1971 plans had been announced for construction of at least 13 gas synthesis plants by the gas transmission industry.³⁴ Although the capital investment for such plants is not excessive (\$30 million for 40 Bcf/yr), the cost of naphtha feedstocks is high and the resultant gas sales price probably will be more than \$1 per thousand cubic feet at the plant. In addition, domestic supplies of naphtha and light oil feedstocks are very limited because of competitive demand by the petrochemical industry. Import of naphtha further affects the balance of trade and may come under oil import restrictions. Therefore, most of these plants are planned for use on an intermittent, seasonal basis to meet peak demands. This source of gas does not appear to be a solution to the long-term supply problem.

Because the vast coal reserves of the U.S. represent a source of hydrocarbon fuels that should last for 200 or 300 yr, there can be no doubt that coal gasification eventually will come to supply a significant portion of our gas supplies.

The principal method for gasification of coal in current commercial operation is the Lurgi high-pressure process. Large plants of the Lurgi type have been in

operation in a number of different countries^{A-10} for as long as 30 yr. Although improvements in efficiency have been made, the process has operational drawbacks in its fixed-bed handling of coal and ash that cause it to be less efficient than more recently developed fluidized bed processes. At least five new processes (plus variants) are in the advanced stages of development; three of these are just entering or have entered the pilot plant stage and the other two may follow in about 2 yr.^{A-11} However, none of the advanced methods is expected to be in commercial production before 1978 to 1980; therefore, some companies with urgent supply needs may proceed with the construction of Lurgi process plants.³⁵ A coal gasification plant to produce about 0.08 Tcf/yr will cost about \$250 million; the coal mine required to supply it will cost about \$40 million.⁸ The amount of coal needed to supply such a plant is about 6 million tons/yr. Thus, an addition to gas supplies of 1 Tcf/yr would require 60 million tons/yr of coal—10% of the present U.S. total coal production.

A 5-yr joint government-industry research and development program to carry this technology from its present research status to commercial production was started in June 1971.³⁶ The planned government annual funding level of \$20 million was reduced to \$15 million for Fiscal Year 1972. Total government funding is expected to be about \$100 million.

Nuclear Stimulation

Our proposed commercial production schedule for nuclear stimulation of the Green River and Piceance Basins, as shown in Fig. 14, indicates that a gas

production rate of 1 Tcf/yr would be reached in 1982. The required capital investment in nuclear-stimulated gas wells to that date would amount to \$1.4 billion. It is anticipated that the needed funding to complete the 5-yr research and development program will range from \$100 to \$150 million, shared between government and industry.

Thus, it may be seen that gas produced from nuclear-stimulated wells has the potential of being better than all other sources except conventional exploration in terms of required investment, gas sales price, and level of research and development funding, and it is competitive with the others in terms of time scale needed to produce commercially worthwhile quantities.

Competition for Investment Capital

A striking feature of the entire U. S. energy industry is that it is very capital-intensive. Although the gross purchase value of energy (gas, coal, petroleum in all forms, and electricity) by consumers

is about 8% of the gross national product, the industry now utilizes more than 14% of the gross capital available for private investment—more than 26% of the amount spent annually in the U. S. for investment in new plants and equipment.^{A-12} A rough estimate of the capital requirements for the energy industry from 1970 to 1985 indicates that the gas industry needs are about 15% of the total.⁸ In view of the very large amounts of capital that will be required to meet currently projected energy needs and the increasingly stiff competition between different energy sources as well as from other demands for capital, concern has been expressed by officials of government and the banking community over the availability of sufficient funds to meet these requirements.^{A-13, A-14} Therefore, it will become increasingly important to choose for development those energy resources that not only show a profitable return but also require the smallest capital investment. In this regard, gas production from nuclear stimulated wells compares very favorably.

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Appendix B

RADIOACTIVITY IN THE GAS

Here we discuss additional details pertaining to radioactivity concentrations in the gas pipelines and to the assumptions used in the consumption models.

Uniform Mixing Model

In this model, as field development progresses, gas from new wells will be mixed with that from older wells in the field, and radionuclide concentrations in the pipeline will gradually decrease as shown by the broken curves in Fig. B-1, assuming complete mixing of gas from the two basins. It is further assumed that the gas will be uniformly diluted with all the other gas being delivered to California from out of state. (The projected out-of-state supply was assumed to be 80% of the total demand, which was the proportion in 1971).³⁷ The resulting radionuclide pipeline concentrations are shown by the solid lines in Fig. B-1. The annual-average whole-body doses to the California population from tritium and krypton-85 that result from burning the diluted gas are shown in Fig. 18. The lower curve represents the annual average exposure to individuals, which includes (1) the exposure from domestic use, with all heating and appliances vented except gas ranges, and (2) the population-weighted average exposure from outside air that contains combustion products from all sources. As shown, the average dose would be less than 0.64 to 0.45 mrem/yr. The upper curve shows the annual-average maximum exposure to individuals; this results from

exposure to maximum combustion product concentrations downwind of power plants. The maximum dose would be less than 1.0 to 0.70 mrem/yr. For the extreme case of individuals using unvented heating and appliances (which are illegal in many communities), the maximum exposure would be about five times that given by the upper curve in Fig. 18. The average exposures shown in Fig. 18 do not include

Fig. B-1. Radionuclide concentrations in gas distributed in California assuming uniform mixing with total gas delivered to the state.

the small fraction of individuals with un-vented heating and appliances.

If dilution with the entire out-of-state supply is not possible, individual exposures would increase in proportion to the lesser dilution. However, after the sixth year of production the stimulated gas would represent more than half of the estimated out-of-state supply; therefore, with no dilution after the sixth year, exposures would at most be a factor of two higher than indicated. After the nineteenth year, the stimulated gas supply slightly exceeds the estimated out-of-state supply, and the individual doses shown correspond to use of undiluted stimulated gas.

Separate Pipeline for First-Year Gas from New Wells

An alternative consideration is to separately collect all the first-year production from new wells and deliver it specifically for consumption in electric-power generating stations. The expected quantity of this gas at steady state (0.47 Tcf/yr after the third year) would be about 1.7 times the consumption of gas-burning power plants now in Los Angeles. The second-year and later gas then could be freely delivered with essentially no concern for its radioactivity content. (Since average concentrations in the second year are expected to be about 1/1000 of those of the first year, the corresponding dose for such gas usage would be about 1/1000 of the values in Fig. 18.)

Figure B-2 shows pipeline tritium and krypton-85 concentrations in the special pipeline before and after dilution with the current consumption by power plants in Los Angeles. After the third year the supply exceeds the current Los Angeles

Fig. B-2. Radionuclide concentrations in gas distributed to power plants in California assuming the plants receive only first-year gas from new wells.

power plant consumption and no dilution is assumed thereafter.

The atmospheric exposure model for Los Angeles⁴² has been scaled to estimate the exposure to individuals from exclusive power-plant consumption of stimulated gas. Figure 19 shows these estimates, which assume dilution during the first 3 yr; the population weighted average exposure would be less than 0.11 mrem/yr and the maximum exposure would be less than 2.1 mrem/yr.* The excess gas in the pipeline (about 70% of the current Los Angeles power-plant consumption) is assumed to be utilized in power plants

*See footnote on p. 34.

elsewhere in California under similar exposure conditions. Thus, individual doses would remain about the same, but the population at risk would be about 1.7 times that estimated for Los Angeles.

Population Dose

Figure 20 summarizes the man-rem population exposure in California for the two alternative delivery and use situations outlined above. For uniform mixing of the gas, the population exposure would be less than 15,000 man-rem/yr. Although the dilution assumed affects individual doses, the man-rem population exposure is approximately proportional to the total radioactivity released and the population exposed and is qualitatively independent of dilution. Both man-rem curves in Fig. 20 rise rapidly in early years due to

an increasing number of new wells brought into production during this period. The population used for the upper curve (uniform dilution model) was that of the entire state, because of uniform gas usage; that for the lower curve (power-plant use of first-year gas from new wells) assumed exposure of only the Los Angeles population during the first 3 yr and 1.7 times the Los Angeles population after the fourth year. In the latter model, if the power plants were located away from urban centers, the annual man-rem dose would be lower in proportion to the lower population at risk. Even with the assumed urban power-plant locations, the population dose from this alternative use of stimulated gas is a factor of seven to ten lower than for the uniform dilution model.

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