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**THE USE OF MULTIPLE EXPLOSIVES FOR
NUCLEAR GAS STIMULATION**

Milo D. Nordyke

November 10, 1970

**This paper was prepared for submission to the American Nuclear
Society Meeting, November 15-19, 1970, Washington, D.C.**

THE USE OF MULTIPLE EXPLOSIVES FOR NUCLEAR GAS STIMULATION*

Milo D. Nordyke

Gasbuggy and Rulison are now history. They have proven that nuclear explosives can be used to stimulate the productivity of natural gas from tight gas reservoirs. However, a number of problems remain to be solved before nuclear gas stimulation is an economically attractive business venture. The solutions to these problems are of crucial importance to the question: "Can you make money by using nuclear explosives to stimulate gas wells?" In this report the concept for using multiple nuclear explosives for gas stimulation is analyzed, the results of an economic analysis of a specific situation are summarized, and the problems that must yet be solved are discussed.

Simultaneous vs Sequential Multiple Explosions

Because deep reservoirs (>6000 ft) have high pressures and hence large quantities of gas in place, they are the most attractive sources of gas. However, the great depths also lead to very low permeabilities and very expensive holes. Therefore, it is of utmost importance to have each hole drain as much gas from the formation as possible. Primary interest is thus in formations where the aggregate thickness of the gas-containing sections is large (>1000 ft). Detonation of a nuclear explosive in such a hole produces a large region of increased permeability which can be considered a greatly enlarged well bore for drawing gas from the formation.

Fig. 1 shows the concept of nuclear gas stimulation in a thick, deep gas reservoir modeled after the Green River Basin in Wyoming. Each explosive produces a region of broken rock, called a chimney, and a fracture system which surrounds and is connected with the chimney. This concept envisages that the emplacement hole would be reentered after the detonation and used to produce the gas. The number of explosives, their yields

*Work performed under the auspices of the U.S. Atomic Energy Commission.

and spacings must be chosen so that: 1) the maximum possible thickness of gas section is stimulated, 2) the maximum yield does not exceed the "seismic limit" for the area under consideration, 3) the total cost is minimized, and 4) the chimneys are interconnected by means of intersecting fractures, or alternatively, a method is devised to keep the emplacement hole open between chimneys.

The larger the individual explosive yields, the larger are the horizontal and vertical fracture dimensions and the more gas produced. While the horizontal fracture dimension is important, the amount of gas produced by a single explosion depends much more strongly on the total thickness of the formation fractured vertically. The limitation on explosive yield depends on the remoteness of the site relative to surrounding towns. Some seismic damage to structures can probably be tolerated, but if financial compensation becomes large, the utilization of nuclear stimulation could be hampered by increased costs as well as adverse public reaction.

While it seems clear that multiple explosives will be required, either simultaneous firing with various numbers and yields of explosives or sequential firing can be considered. Simultaneous is defined to be firing all the explosives whose aggregate yield equals the seismic limit in a time short compared to the time required for the ground shock generated by one explosive to reach another. Sequential firing would introduce a time delay between explosions in a series which is long enough to prevent the seismic signals from adding to each other in the region of concern for seismic damage (perhaps 5 min.). Sequential firing would, of course, permit each explosive to be equal to the seismic limit.

Simultaneous firing of a vertical array of explosives will lead to interaction of the shock waves in the region between charges greatly increasing the peak compressional stress experienced by the rock which should result in increased fracturing of the rock. Addition of stress components perpendicular to the cylindrical axis should also lead to increased lateral motion with the development of vertical tension fractures which would be very beneficial to gas production and interconnection of

chimneys. The rock in the chimneys should suffer more fragmentation and be accelerated downward by the overlying shots leading to decreased bulking and hence higher chimney dimensions. Sequential firing would not have these advantages of shock interaction, but would benefit from the presence of the cavity or chimney and fracture zone from the previous shots. Reflection of the shock waves from these discontinuities should lead to significantly greater tensile failure in the region between explosives and a proportionate increase in gas production. While both alternatives would significantly improve the production over that projected by simple linear addition of the effects of single explosions, quantitative evaluation of these rock mechanics effects cannot be made without actual data from field experiments involving multiple explosions.

The economic advantages of simultaneous firing vs sequential firing can be evaluated for an idealized case in which one assumes a continuous gas section of height $H_{\max}$ which is to be stimulated with n explosives of yield W_n under a seismic limitation $W_{\max}$. It is further assumed that the seismic wave from n simultaneous explosions of yield W_n is the same as from a single explosion of yield nW_n . Fig. 2 summarizes the geometry assumed for the problem where:

H_n = vertical spacing criteria

R_n = effective horizontal fracture radius, and

R_D = drainage radius = 1/2 mile

For this calculation I have assumed $R_n = 2.5 \times$ cavity radius and $H_n = 6.8 \times$ cavity radius. Using simple Darcy flow, the relative rate of gas production, Q_n , will be given by

$$Q_n = \frac{(nH_n)C}{\ln(R_D/R_n)}$$

where

C = constant

If we consider the total cost of producing this nuclear stimulation in a commercial production situation, we have (in millions of dollars)

Fig. 2

$$C_n = .85 + n(.01 + C_{\text{exp}})$$

I have used here for the non-explosive costs a value of \$850,000 + .01n which will be discussed in a later section. C_{exp} is the nuclear explosive service charge released by the AEC several years ago.¹

Thus, we can calculate

$$\text{Relative gas produced per dollar invested} = \frac{Q_n}{Q_0 C_n}$$

where Q_0 is a normalizing constant equal to Q_n/C_n for one 50 kt explosion.

For simultaneous explosions the choices for n and W_n are limited by the boundary conditions

$$\text{B.C. 1: } nW_n \leq W_{\text{max}}$$

$$\text{B.C. 2: } nH_n \leq H_{\text{max}}$$

As n increases from 1 where $W_n = W_{\text{max}}$, B.C. 1 controls until the total height of the chimneys, nH_n , equals the height of the section to be stimulated, H_{max} . As n further increases, B.C. 2 controls and the total yield, nW_n , decreases from the seismic limit, W_{max} . Details of the calculation are given in Appendix A.

Fig. 3 summarizes the results of a representative calculation using a seismic limit of 50 kt. Fig. 4 shows a similar calculation for $W_{\text{max}} = 100$ kt. If we follow the solid curve in Fig. 3 or Fig. 4 (without regard for H_{max}), we see as the number of simultaneous explosives increases, the yield of each explosive decreases and the "gas/dollar" increases to a maximum for $n = 3-5$ and then decreases as n is increased further. If the cost of the explosives were smaller in relation to the other fixed costs, the curve would rise more steeply and have a peak at a larger value for n . Of course, when we impose the second boundary condition, we must follow the dashed curve and we see for $W_{\text{max}} = 50$ kt and $H_{\text{max}} = 1000$ ft, that there is no gain but rather a sharp decrease if n is increased beyond 3. However, it should be pointed

¹ N.D. Nurdyke, Peaceful Uses of Nuclear Explosions, Review Paper from Peaceful Uses of Nuclear Explosions, Phenomenology and Status Report, 1970, IAEA-PL-388/12, Vienna (1970).

Fig. 3

Fig. 4

out for this case that increasing to $n = 4$ does have one advantage: the total simultaneous yield drops from 50 kt to about 25 kt. Similarly, for $W_{\max} = 100$ kt (Fig. 4), there is no economic advantage to increasing n beyond 2 for $H_{\max} = 1000$ ft and 8 for $H_{\max} = 2400$ ft.

However, when we consider sequential explosives, a quite different picture emerges as shown by the dotted curves in Figs. 3 and 4. For these curves, $W_n = W_{\max}$ and we can see that the "gas/dollar" increases very steeply particularly for the thicker sections. Table I summarizes the conclusions that can be drawn from these curves and shows the clear economic advantage to be gained from sequential detonation. While the conclusions depend to some extent on the assumptions made for the various dimensions, they are most sensitive to the ratio of explosive related costs to non-explosive related costs. Decreasing H_n reduces the slope of the curves but doesn't change their interrelationship significantly.

Table I

Maximum Relative Gas Production per Dollar Invested*

Type	$W_{\max} = 50$ kt	
	$H_{\max} = 1000$ ft	$H_{\max} = 2400$ ft
Simultaneous	1.2	1.0
Sequential	1.5	2.1
	$W_{\max} = 100$ kt	
	$H_{\max} = 1000$ ft	$H_{\max} = 2400$ ft
Simultaneous	1.5	1.5
Sequential	1.7	2.6

* $\frac{Q_n}{Q_{on}} = 1$ for 1 50-kt explosion.

Quantitative Economic Analysis

While the above provides a qualitative evaluation of the best methods of using multiple explosives, a more quantitative analysis is needed to judge the value of nuclear gas stimulation as a potential technique for helping to solve our nation's natural gas shortage. This projection is

based on the assumption that the remaining technical and administration problems have been solved, that sufficient experience in the field has been gained to implement a number of reductions in safety programs, and that the safety and operational costs of an individual well can be averaged over many wells in the same field being developed at a rate of 10-20 per year.

For this example, we have used reservoir properties characteristic of the Green River Basin in western Wyoming. The most critical characteristic for these calculations is the effective in-situ permeability. In order to evaluate the effect of variations in permeability, two representative values [10 and 5 microdarcy (μ d)] have been used. The assumed quantity of gas in place per section has been taken from a recent paper by the Atomic Industrial Forum.² The assumptions that were used in the calculations are given in Table II and are believed to be appropriate for the Green River Basin.

The average quantity of gas in place and permeability of the gas-bearing sands in the Green River Basin are not well known. Both higher and lower numbers have been suggested by different companies having leases in the area. We have used a spacing of one well per section for convenience of calculation. It is appreciated that more wells per section would recover a higher percentage of the gas in place which is important from a national resource point of view.

The fracture zone produced by a nuclear explosion, insofar as it affects gas production, is assumed to extend to 2.5 times the cavity radius (R_c) in a horizontal direction, to $4.4 R_c$ in a vertical direction above the shot, and to $2.4 R_c$ in a vertical direction below the shot. These values are based on Gasbuggy data and are basically verified by the Soviet experience.³ Thus, a 100-kt explosive would produce a cylindrical zone of very high permeability with an effective radius of 220 ft and extending 385 ft above the shot point and 215 ft below. To stimulate a 2400 ft thick section, four such explosives

²Economic Subcommittee - Plowshare Committee of the Atomic Industrial Forum, "Economics of Stimulating Natural Gas Reservoirs with Nuclear Explosives," December 1969, Draft.

³I.D. Morokhov (Ed.), Atomic Explosions for Peaceful Purposes, Atomizdat, Moscow (1970).

Table II

Assumptions Used in Economic Analysis

Reservoir Properties

Reservoir thickness	2,400 ft
Depth to midpoint	11,000 ft
Effective in-situ permeability	10 and 5 microdarcy
Viscosity	0.017 centipoise
Gas-filled porosity	5%
Gas field pressure (initially)	6,000 psi
Bottom hole pressure (during production)	750 psi
Gas in place per section	70 MMcf/gross ft of height
Gas in place per section per 2400 ft	170 Bcf
Well spacing	One well/square mile

Nuclear Properties

Number of Explosives	4	5	6	7	3	5
Yield per explosive, kt	100	50	30	20	100	100
Cavity radius, ft	88	70	59	52	88	88
Horizontal fracture radius for production calculation, ft	220	175	148	129	220	132
Vertical height above shot, ft	385	305	257	225	515	310
Vertical height below shot, ft	215	170	143	126	385	170

would be required (see Table II). To consider the effect on production should seismic damage considerations require using a larger number of smaller yield explosives to stimulate the same vertical section, three other cases were calculated, assuming five 50-kt, six 30-kt, and seven 20-kt explosives.

Two other cases looking at variations in the assumptions regarding fracturing were also calculated. In the first case, more extensive fracturing in the vertical direction was assumed. This more extensive fracturing may result when the shock wave is reflected from the chimney and fracture system 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. The second case is the pessimistic one that anticipates that either due to increasing depth or clay content, the fractures tend to heal. Hence, an effective well radius of 1.5 times the cavity radius is assumed with five 100-kt explosives required to stimulate the 2400 feet. In summary then, to stimulate 2400 ft, four 100-kt explosives are expected. However, if more extensive fracturing occurs, only three would be required, and if less extensive fracturing occurred, five would be needed.

The calculations were made assuming simple Darcy flow of the gas from a 5 or 10 μ d rock into a cylindrical region of varying size having infinite permeability, at a pressure of 750 psi. The horizontal fracture radii were selected to be less than the observed fracture radius, to compensate for the real variation of permeability with radius that occurs in reality. Fig. 5 presents cumulative production from the formation as a function of time, as a result of using 100-kt explosives for the two values of permeability. At almost all times, the 10 μ d case produces about 60% more gas than the 5 μ d case. Fig. 6 shows the variation in cumulative production vs time for the four different yields, all at 10 μ d. It can be seen that the total variation between the four 100-kt and seven 20-kt cases is about 18%. Far more significant is the effect of permeability shown in Fig. 5.

Fig. 5

Fig. 6

Table III presents a summary of the estimated costs of stimulating a gas well as part of a field development effort, assuming the use of three, four, or five 100-kt explosives. Similar field construction, support, and safety costs would apply to the five, six, and seven explosive arrays, but different explosive charges would apply. 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 hypothetically fail, making removal of the gas below much more difficult and expensive, we have assumed 2% of the gas would be lost. We have reflected this loss in the quantity of gas recovered, but it could be reflected equally well in the nuclear explosives cost. The nuclear explosive cost used is based on the schedule of charges recommended by the AEC for use in evaluating potential Flowshare applications. It should be noted that the total costs in Table III do not include the cost of acquiring or proving out the lease or expenses incurred in collecting and transporting the gas to a transmission system.

Table IV presents a summary of the revenue and expenses from a single nuclear gas well over a 20 year period in terms of 1970 dollars. In this analysis, we have obtained gross revenue by deducting 12.5% of the gross production from the 10 md curve in Fig. 5 for royalties paid, principally to the federal government that owns the land, and have used a wellhead price of 30¢/Mcf for the remaining gas. Future net revenue was obtained by deducting state and local taxes in Wyoming, consisting of severance and ad valorem taxes at 6.5%, general and administration expenses at 3%, and operating expenses at \$800/mo/well from the gross revenue. The last two columns in Table IV present the future net revenue for each year and the cumulative future net revenue over a 20 year period. Fig. 7 is a graph showing undiscounted future net revenue as a function of time.

In order to compare this future revenue with the investment required to create such a producing well, the present worth of this revenue has been calculated for various discount rates in Fig. 8. Both the 10 and the 5 md case are presented. Utilizing the well development costs for four explosives given in Table III, the present worth of such a well computed at an

Table III

**Estimated Cost per Well
Commercial Gas Stimulation - Green River Basin**

		Number of 100 kt Nuclear Charges		
		Three (\$K)	Four (\$K)	Five (\$K)
1.	<u>Emplacement Hole</u>			
a.	Includes site access and grading and a 12,000 ft emplacement hole cased in the upper few thousand feet. The hole will be uncased at total depth and mud-filled upon completion.	450	450	450
b.	Allowance for drilling problems in development of field (unable to complete one out of five emplacement holes).	100	100	100
2.	<u>Detonation Service Manpower</u>			
	Includes technical personnel to supervise explosive emplacement and stemming and to set up and operate firing equipment. Based on field development rate of one well/month	30	30	30
3.	<u>Explosive Emplacement and Stemming</u>			
	Includes equipment and personnel to emplace and stem explosives. Includes cost of all downhole hardware and stemming material.	150	160	170
4.	<u>Reentry and Completion</u>			
	Includes equipment and personnel to reenter emplacement well and wellhead hardware to complete well for production.	50	50	50
5.	<u>Safety Program</u>			
	Includes personnel to evaluate hazards and perform those activities necessary to ensure the health and safety of the general public and project personnel. Includes equipment to monitor and document radioactivities during production. Based on field development rate of one well/month.	100	100	100
	Subtotal without explosives	\$880	\$890	\$900
6.	<u>Nuclear Explosives</u>			
	Includes required number of complete explosives with provision for sequential firing. Includes temperature and pressure protection to 350°F and 15,000-psi environment, and all firing components. 2% of gas subtracted as penalty for 99% explosive reliability.	1380	1840	2300
	Total estimated cost per nuclear-stimulated well with allowance for lost holes in field development	\$2260	\$2730	\$3200

Table IV

Economic analysis for single well development.

10 md
30%/McF
Four 100-kt

Year	Production		Gross revenue	Severance tax (1%)	Ad Valorem tax (5.5%)	GMA (3%)	Lease operating expense (\$800/mo)	Future net revenue (FNR)	Cumulative FNR
	Gross	Net 0.875							
	MMcf	MMcf	\$1000	\$1000	\$1000	\$1000	\$1000	\$1000	\$1000
1	6128	5362	1609	16	88	48	10	1446	1446
2	3185	2787	836	8	46	25	10	747	2193
3	2585	2262	679	7	37	20	10	605	2798
4	2333	2041	612	6	34	18	10	545	3342
5	2183	1910	573	6	32	17	10	509	3851
6	2074	1815	544	5	30	16	10	483	4334
7	1986	1738	521	5	29	16	10	462	4797
8	1909	1671	501	5	28	15	10	444	5241
9	1840	1610	483	5	27	14	10	428	5668
10	1777	1554	466	5	26	14	10	412	6081
11	1717	1502	451	5	25	14	10	398	6479
12	1660	1453	436	4	24	13	10	385	6864
13	1607	1406	422	4	23	13	10	372	7236
14	1555	1361	408	4	22	12	10	360	7596
15	1506	1317	395	4	22	12	10	348	7944
16	1458	1276	383	4	21	11	10	337	8280
17	1412	1236	371	4	20	11	10	326	8606
18	1368	1197	359	4	20	11	10	315	8922
19	1326	1160	348	3	19	10	10	305	9227
20	1285	1124	337	3	19	10	10	296	9523

Year	Production		Gross revenue	Severance tax (1%)	Ad Valorem tax (5.5%)	GMA (%)	Lease operating expense (\$800/mo)	Future net revenue (FNR)	Cumulative FNR
	Net	0.875							
	Net	Net	\$1000	\$1000	\$1000	\$1000	\$1000	\$1000	\$1000
1	6128	5362	1609	16	88	48	10	1446	1446
2	3185	2787	836	8	46	25	10	747	2193
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19	1326	1160	348	3	19	10	10	305	9227
20	1285	1124	337	3	19	10	10	296	9523

Fig. 7

Fig. 8

8% interest rate corresponds to a present-worth-to-investment ratio of $1.5/2.7 = 2.0$ for the 10 μ d case, and $3.5/2.7 = 1.3$ for the 5 μ d case. Alternatively, the internal rate of return (before depletion and federal income tax) shows the sensitivity of the profit to the effective well radius, permeability, and number of explosives required.

Effective well radius	$\frac{2.5 R_c}{10}$	$\frac{1.5 R_c}{5}$		
Permeability (μd)	$\frac{10}{5}$	$\frac{10}{5}$		
<u>Number of Explosives</u>	<u>Rate of Return (Before FIT)</u>			
3	35%	18%		
4	27%	13%	18.5%	8%
5			15%	6%

Such items as federal income tax, depletion, depreciation, and intangible development expenses have not been included to this point because their impact on the profitability of a development varies from company to company. In Table V we present a possible summary of the cash flow derived from the revenue of Table IV, with 20% of the well development cost capitalized and straight-line depreciated over a 20 year period, and 22% of 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. While about 60% to 70% of conventional well costs qualify for treatment as intangible expense, 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 gives a net cash flow for well development of \$1682K. Discounting the tabulated revenue cash flow indicates a rate of return of 29.5%. This compares closely with the 27% rate of return (before FIT) shown in the above table, and indicates that income tax, depreciation, depletion, and tax credits effectively cancel insofar as rate of return is concerned.

The present average wellhead price of natural gas in interstate commerce is about 16¢/Mcf. However, most new contracts are being written for

Table V

Economic analysis for single well development (continued)

YEAR	GROSS REVENUES (from D-2a)	FUTURE NET REVENUE (from D-2a)	LESS DEPRECIATION 20% of Cost 20 Yr. S.Y.	TAXABLE INCOME	LESS DEFLECTION 22% of Gross INCOME	NET TAXABLE INCOME	LESS FEDERAL INCOME TAX @ 40%	INCOME	ADD BACK DEPRECIATION	ADD BACK INCOME DEFLECTION	CASH FLOW
1	1609	1446	27	1419	374	1065	511	574	27	354	935
2	836	747	27	780	184	596	277	279	27	184	490
3	679	605	27	578	149	428	206	223	27	149	399
4	612	545	27	518	135	383	184	199	27	135	361
5	573	509	27	482	126	356	171	185	27	126	338
6	544	483	27	456	120	336	161	175	27	120	322
7	521	462	27	435	115	320	154	166	27	115	308
8	501	444	27	417	110	306	147	159	27	110	297
9	483	428	27	401	106	294	141	153	27	106	287
10	466	412	27	385	103	282	135	147	27	103	277
11	451	398	27	371	99	271	130	141	27	99	268
12	436	385	27	358	96	262	126	136	27	96	259
13	422	372	27	345	93	252	121	131	27	93	251
14	408	360	27	333	90	243	117	126	27	90	243
15	395	348	27	321	87	234	112	122	27	87	236
16	383	337	27	310	84	225	108	117	27	84	229
17	371	326	27	299	82	217	104	113	27	82	222
18	359	315	27	288	79	209	100	109	27	79	215
19	348	305	27	278	77	201	97	105	27	77	203
20	337	296	27	269	74	195	93	101	27	74	193

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10¢-20¢/Mcf and there is much pressure for increasing the wellhead price to stimulate exploration for new gas supplies. Based on a 16¢/Mcf wellhead price for gas and \$2.75/barrel price for oil, gas costs about 16¢/million Btu of energy and oil costs about 50¢/million Btu of energy. The price of coal is about the same as for oil. This price differential, coupled with 1000 to 10,000 times less sulfur in gas than in oil or coal makes gas the preferred fuel of the three. Natural Gas Pipeline Company is buying gas for intrastate use at 28¢/Mcf in order to ease its supply emergencies.⁴ The price projected for coal gasification used by the American Gas Association in a recent report on this new technology is 60¢/Mcf.⁵ In view of all the above, the price of 30¢/Mcf appears to be a reasonable estimate of near-future market conditions.

Problems to be Solved

These projections are based on a number of assumptions that may be either too conservative or too optimistic. For example, well founded arguments can be made that at the large depths under consideration, the fractured region will be smaller than we have assumed and smaller spacing must be used. On the other hand, based on fragmentary data from the Pile-driver shot, the French and Russian experience, and theoretical considerations, it can be argued that multiple explosions, either simultaneous or sequential, will produce much larger fractured regions than simple superposition of single explosions would lead us to expect. Understanding the interaction of multiples could have a tremendous impact on the profitability of nuclear stimulation by reducing the number of explosives required by a factor of 1.5 to 2 or alternatively, permitting the use of explosives as small as 5 or 10 kt to stimulate thick gas sections (note that the yield required to stimulate a given height decreases as the cube of the vertical spacing parameter). An understanding of these effects will require a great

⁴Oil and Gas Journal, 68 (28), 1970.

⁵American Gas Association, Redex Committee on Acceleration of Commercial Gasification of Coal, 1970.

deal of careful experimental design, data collection, and rock mechanics calculations.

A large number of engineering problems must also be solved if the cost reductions discussed in Table III are to be realized and sequential firing is to be used. For example, a number of new approaches for stemming and reentering the emplacement hole for production have been designed but must be carefully and exhaustively evaluated in the field to determine which is best from a safety and cost point of view. The use of simultaneous explosives does not appear to pose any new engineering questions and can be utilized on any future experiments without any significant effort, but the use of sequential explosives would require extensive ruggedization of the explosives to withstand the shock from earlier nearby explosions. However, much work in this general area has been done as part of the development of nuclear weapons for national defense and the problem is largely one of applying that technology to the explosives currently being developed for gas stimulation. While this will be a significant engineering task, the economic benefits would appear to warrant this effort.

A number of other problem areas remain which all can have a first-order impact on the commercial profitability of nuclear stimulation:

- Developing a good technique for evaluating the effectiveness of the fracture zone for gas production, particularly in the case of multiple explosions.
- Developing methods of altering or optimizing the chemical environment to minimize the production of troublesome radio-nuclides.
- Developing the technical data that is crucial for the making of administrative decisions that are needed for commercial nuclear stimulation.
- Developing the nuclear explosives especially designed to meet the unique criteria required for nuclear stimulation.

The last area is well on its way to solution. Solving the others will require a cooperative effort of all those active in the program to insure that no opportunity is lost to acquire the data the program needs. Only by such a cooperative effort where each experiment contributes to the total understanding of nuclear gas stimulation can we hope for success.

Acknowledgments

The economic evaluation presented here is largely drawn from UCRL-50966 and as such contains the contributions of many people. I should like to give particular credit to Don Montan, Lynden Ballou, and Glenn Werth, LRL, who made major contributions to that section.

Appendix A

VARIATION IN GAS PRODUCTION PER DOLLAR INVESTED AS A FUNCTION OF THE NUMBER OF EXPLOSIVES AND TYPE OF FIRING

Milo D. Nordyke

Consider the problem of stimulating a continuous gas reservoir section $H_{\max}$ high with one or multiple explosives. Consider also a seismic yield limit, $W_{\max}$, on a single explosive or group of explosives. If H is the height of the chimney or region of major increase of permeability produced by an explosive, W , and R is the horizontal radius of a cylinder which represents the effective bore hole resulting from nuclear stimulation, we have:

$$H = C_1 W^{1/3} \quad (1)$$

$$R = C_2 W^{1/3} \quad (2)$$

If H_1 and R_1 are the parameters for a single explosive, W_1 , and since $W_1 = W_{\max}$, we have:

$$H_1 = C_1 W_{\max}^{1/3} \quad (3)$$

$$R_1 = C_2 W_{\max}^{1/3} \quad (4)$$

As we increase the number, n , of explosives in the single hole, spacing them a distance H_n apart (see Fig. 1), we have:

$$W_n = \frac{W_{\max}}{n} \quad (5)$$

until

$$nH_n = H_{\max} \quad (6)$$

at which point if we further increase the number of explosives, their yield must be reduced in accordance with the constraint indicated by Eq. 6.

Thus, there are two regions, the first in which Eq. 5 is the constraint, and the second in which Eq. 6 is the constraint. The boundary between these regions occurs at $n = n_c$ where

$$\begin{aligned}
 n &= \frac{H_{\max}}{H_n} = \frac{W_{\max}}{W_n} \\
 H_n &= C_1 W_n^{1/3} = C_1 \left(\frac{W_{\max}}{n} \right)^{1/3} \\
 n &= \frac{H_{\max} n^{1/3}}{C_1^3 W_{\max}^{1/3}} \\
 n &= \left(\frac{H_{\max}^3}{W_{\max} C_1^3} \right)^{1/2} = \left(\frac{H_{\max}^3}{H_1^3} \right)^{1/2} \quad (7)
 \end{aligned}$$

For $n < n$, we will stimulate less than the total section and the gas flow will be given by

$$Q_n = \frac{C_3 n H_n}{\ln (R_D / R_n)} \quad (8)$$

where R_D = drainage radius.

$$\text{Since } R_n = C_2 \left(\frac{W_{\max}}{n} \right)^{1/3} \quad (9)$$

$$\text{and } H_n = C_1 \left(\frac{W_{\max}}{n} \right)^{1/3} \quad (10)$$

we have

$$Q_n = \frac{C_1 C_3 (W_{\max})^{1/3} n^{2/3}}{\ln (R_D n^{1/3} / C_2 W_{\max}^{1/3})}$$

If $R_D / C_2 = \alpha_0$ and $R_D / C_2 W_{\max}^{1/3} = \alpha_1$

$$\text{then } Q_n = \frac{C_3 C_1 n^{2/3} W_{\max}^{1/3}}{\ln \alpha_1 + 1/3 \ln n} \quad (11)$$

The height of the section stimulated is then

$$H_{\text{total}} = C_1 n^{2/3} W_{\max}^{1/3}$$

For $n = m$ we have

$$Q_m = \frac{C_3 C_1 m^{2/3} W_{\max}^{1/3}}{\ln \alpha_1 + 1/3 \ln m} \quad (12)$$

For $n > m$ we have

$$\begin{aligned} H_n &= \frac{H_{\max}}{n} \\ R_n &= \frac{C_2 H_{\max}}{C_1 n} = \frac{R_1 H_{\max}}{n H_1} = \frac{R_1}{n} m^{2/3} \\ W_n &= \left(\frac{H_n}{C_1} \right)^3 = \left(\frac{H_{\max}}{nC_1} \right)^3 = \frac{R_1^2}{n^3} W_{\max} \end{aligned} \quad (13)$$

and using Q'_n for values of Q_n when $n > m$, we have from Eq. 8

$$\begin{aligned} Q'_n &= \frac{C_3 C_1 H_{\max}}{\ln (nR_D/R_1 m^{2/3})} \\ &= \frac{C_3 C_1 H_{\max}}{\ln (n/m^{2/3}) + \ln \alpha_1} \end{aligned} \quad (14)$$

$$\text{at } n = m, Q'_m = \frac{C_3 C_1 H_{\max}}{\ln \alpha_1 + \ln m^{1/3}}$$

Since $Q_m = Q'_m$, from Eq. 12 we can conclude that

$$C_3 H_{\max} = C_3 m^{2/3} W_{\max}^{1/3}$$

and

$$Q'_n = \frac{C_3 C_1 m^{2/3} W_{\max}^{1/3}}{\ln \alpha_1 + \ln n - \ln m^{2/3}} \quad (15)$$

The total yield is given by $nW_n = \frac{m^2}{n} W_{\max}$.

The cost of carrying out a nuclear stimulation service with n explosives can be broken down as:

$$C_n = C_o + nC_T.$$

C_T can be broken down into the published charges for a nuclear explosive service¹, C_{exp} , plus the cost of additional emplacement hardware. The published charge can be expressed in millions of dollars as:

$$C_{exp} = \$.240 + .048 \ln W_n; 10 \text{ kt} < W_n < 2000 \text{ kt} \quad (16)$$

I have assumed

$$C_{exp} = .350 \text{ for } W_n < 10 \text{ kt}$$

In Table III it has been estimated that the additional emplacement hardware would cost about \$10,000 per explosive and the constant cost, C_o , is \$850,000 per shot. Thus, we have for C_n , in millions of dollars

$$C_n = .85 + n(.01 + C_{exp}). \quad (17)$$

Two values for H_{max} , 1000 ft and 2400 ft, and two values for W_{max} , 50 kt and 100 kt, were used to evaluate Eqs. 11, 15, 16, and 17. The following assumptions were made for the other variables:

$$R_D = 2500 \text{ ft}$$

$$C_1 = \frac{H_n}{W_n^{1/3}} = 130 \text{ ft/kt}^{1/3} = 6.8 \text{ cavity radii at 11,000 ft}$$

$$C_2 = \frac{R_n}{W_n^{1/3}} = 48 \text{ ft/kt}^{1/3} = 2.5 \text{ cavity radii at 11,000 ft}$$

Figs. 3 and 4 summarize the results of these calculations. As the number of explosives increases, the gas per dollar increases until the entire section is stimulated (at $n = n$) and then decreases along the dashed line as the total yield, nW_n , decreases very markedly. For a 1000 ft section, this transition occurs between two and three explosives. For very thick sections, the "gas/dollar" will decrease before the entire section is stimulated when the decrease in the horizontal radius of stimulation becomes more significant than the added vertical stimulation.

To see the significance of the effective fracture radius C_2 , a number of parameter studies were done. Varying C_2 over a factor of 4 shifts the curve up or down by about 15%, but doesn't change the shape. Variations in R_D will have a similar effect as those variations in C_2 since they enter all the equations as a ratio.

The results of using sequential firing of a series of n explosives equal in yield to $W_{\max}$ are also shown in Figs. 3 and 4.

To explore the effect of varying the chimney height or vertical spacing, several problems were calculated with H_n decreased by 50%. All of the Q_n values were decreased by 50% and the values of m were significantly increased. However, the general picture including the economic advantages of sequential firing is about the same.

This exercise is primarily to graphically illustrate the relation of the various parameters and assumptions. One may quarrel with some of the numbers, but the general picture won't change very much. The curves and conclusions are not changed so long as the ratio between fixed and explosive costs remain constant. Significantly lower explosive costs relative to fixed costs would make the curves steeper and move the knee to the left.