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**COST AND FEASIBILITY
OF STIMULATING TIGHT GAS RESERVOIRS
WITH CHEMICAL EXPLOSIVES**

G. H. Higgins
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January 16, 1973

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309

COST AND FEASIBILITY OF STIMULATING TIGHT GAS RESERVOIRS WITH CHEMICAL EXPLOSIVES

Abstract

Long, continuous, cylindrical charges of high explosives are considered as alternatives to nuclear explosives or massive hydraulic fracturing for the stimulation of gas production in tight gas formations. The calculational method was that used previously for nuclear stimulation; it was verified by comparison of the calculated and observed gas production from Rulison. The calculations indicate that charges of high explosives 24 inches in diameter and 2000 feet in length (the height assumed for the gas-bearing sands) detonated in four wells per section would be comparable in cost and effectiveness to

estimates for one well stimulated by three 100-kiloton nuclear explosions. Stimulation by high explosives would require special development of the explosives (probably with ammonium nitrate as the base) to be suitably sensitive, temperature-resistant, and compatible with the gas-reservoir rocks; the required work appears to be straightforward, however. Comparative field testing is required to determine the optimum method (chemical or nuclear explosives or hydraulic fracturing) for a given region and to confirm that gas can be produced profitably for between 25¢ and 80¢ per Mcf.

Introduction

This report describes a theoretical investigation of stimulation of tight gas reservoirs with very large high explosive charges as an alternative to massive hydraulic fracturing and to nuclear stimulation. The results indicate that long cylindrical charges of high explosives detonated in gas reservoirs of very low permeability will significantly stimulate commercial gas production. Since there is very little experimental information on the amount of fracturing produced by high explosives detonated deep in the earth, we have calculated the amount of fractur-

ing to be expected. Calculations of the same kind have been done for nuclear explosions in tight gas reservoirs; the calculational method was verified by comparison of the observed and calculated gas production from Rulison.

The qualitative effect of the explosion in a well is to increase the effective radius of the well bore so that gas can flow into it more readily. If one considers that the gas that flows into the well must flow from all directions, then flow paths from hundreds of feet away must all converge at the well bore. Increasing

Fig. 1. Scheme for high-explosive stimulation of gas reservoir. Diagram shows the 12-inch well-bore underreamed to 24 inches through the gas-bearing sands. Inset: enlarged view of section of the cavity after detonation, showing fracturing in the surrounding 30-foot section.

the size of the well bore therefore enhances the well's production. The physical concept is illustrated diagrammatically in Fig. 1. A hole with a nominal diameter of 12 inches is to be drilled to the bottom of the lowest gas-bearing sand and then under-reamed to 24 inches from the top of the uppermost gas sand to the bottom of the lowest sand. Low-cost explosives, for example a slurry of sensitized, temperature-stabilized ammonium nitrate in diesel oil, is then to be pumped into the hole and stemmed with water or drilling mud. The well is to be left open for the firing of the explosive. Upon detonation, the stemming material should be expelled after about 20 seconds, and the well should then be ready to be placed in production. In a reservoir similar to Rio Blanco, stimulation of such a well should produce about 1.4 MMcf per day during the first year and a total of 6.5 Bcf during the first 20 years. The total cost is estimated to be of the order of \$0.5 million.

The importance of gas stimulation and the need for additional gas supplies have been discussed in many papers, for example Ref. 1. It is estimated that tight gas-bearing formations in the western states might yield as much as 300 Tcf of gas and those in other areas of the United States might yield another 300 Tcf. Thus, the potential additional gas production might be 600 Tcf, about twice the conventional reserves estimated² December 31, 1970 and about 25 times the present annual rate of consumption.

There are three possible means of recovering this gas: nuclear stimulation, chemical-explosive stimulation, and massive hydraulic fracturing. It seems likely that thorough evaluation will show that no one method is best in all areas; each should have its place in producing additional gas. Only the nuclear method has been demonstrated in tight sands; the other two methods must be evaluated in future field tests.

Theoretical Concepts

Since the Gasbuggy nuclear stimulation experiment (a 29-kiloton nuclear explosive fired in the San Juan Basin on December 10, 1967),³ attempts have continued to relate explosion effects such as shock pressure, cavity size, and shear strain to the stimulation of gas flow. The details of the effort are summarized by Rubin *et al.*,¹ for Gasbuggy and Rulison (a 43-kiloton nuclear explosion in the Mesa Verde Formation of the Piceance Basin, fired September 10, 1969). The analysis indicates that if initial reservoir permeability is k_0 and the cavity produced by the

explosion has sprung radius R_c , a satisfactory model consistent with actual production is found when the postexplosion permeability of the rock is essentially infinite out to a distance of one R_c , is $33.3 k_0$ between $1 R_c$ and $2.75 R_c$, and is equal to k_0 beyond $2.75 R_c$.

Recently, Schatz,⁴ using the SOC73 explosion code, correlated a parameter called "failure shear strain" (ϵ_f) with the failure and deformation observed by Borg⁵ in granite from close to the Hardhat nuclear explosion. Schatz found that an ϵ_f of 0.01 correlated with the detectable

grain failure found at a distance somewhat less than the height of the collapsed chimney. At ϵ_f values of about 0.1, failure and fracturing were intense. He was careful to point out that there may be no direct physical relation between failure shear strain and permeability, but intensely fractured rock would be expected to be "highly permeable" with "significant enhancement" of permeability out to the distance at which ϵ_f is approximately 0.01. At $2.75 R_C$, the distance to which permeability apparently was enhanced about 30-

fold by Rulison, the calculated value is almost exactly 0.1, corresponding to the intensely fractured region. The gas production calculated for this permeability distribution from Rulison was compared with the well-test data¹ as shown in Fig. 2. The permeability distribution that would reproduce the test data cannot be uniquely defined, but it would appear that the stimulation effects from an explosion would be adequately described where $k_x \approx 30 k_0$ out to a distance where either $2.75 R_C$ or $\epsilon_f \approx 0.1$.

Fig. 2. Gas flow from the Rulison experiment from the time of the shot (September 1969) to June 15, 1970. The formation pressure is 3200 psia. The parameters assumed were ϕh (porosity X height) = 3.0 feet, $(kh)_0$ (permeability X height of the undisturbed formation) = 680 microdarcy feet, and cavity radius = 76 feet. Inset: postshot variation in kh as a function of distance from the shot point; this model for permeability distribution was used for the calculations.

Calculation of Gas Flow

The flow of gas from a stimulated well can be calculated using a two-dimensional fluid flow computer code.⁶ Montan performed a series of calculations⁷ for a hypothetical gas reservoir with the properties shown in Table 1. The results are

Table 1. Assumed reservoir properties.

Formation permeability k_0	20 μ D
Formation temperature T_f	200°F
Formation pressure P_f	3000 psi
Gas specific gravity G	0.6
Flowing well pressure P_w	500 psi
Permeability of formation after fracture k_r	
$f(k_r) R < R_c$	$k/k_0 > 100$
$f(k_r) R_c > R > 2.75 R_c$	$k/k_0 = 33.3$
$f(k_r) R > 3.00 R_c$	$k/k_0 = 1.00$
Net pay sand h	100 ft
Gas in place GIP	24.53 Bcf/section

shown in Fig. 3 for wells of sprung radius from 3 to 100 feet and for 160-acre and 640-acre spacing of wells. One well per section (640-acre spacing) is seen to produce from 11% to 37% more gas than one well per quarter section (160-acre spacing). For the same well cost, it would thus appear less profitable to drill more than one well per section. However, one well per section, even though it would be less costly, would deliver a smaller fraction of the total gas in place. The optimal economy-recovery combination must be determined by more detailed considerations. For any one well, increasing the sprung well bore radius from 3 feet to 90 feet would increase the production during the first 20 years by a factor of 2.3 to 2.9.

Fig. 3. Cumulative gas production in 20 years from explosives-stimulated wells as a function of sprung cavity radius R_c . The reservoir properties are those shown in Table 1.

The sprung cavity radii calculated for a depth of 7000 feet in a typical reservoir rock are shown in Fig. 3 (arrows) for massive high explosives and for 1-kiloton and 100-kiloton nuclear explosions. The increase in gas production between a 1-kiloton stimulation (where $R_c = 18$ feet) and a 100-kiloton stimulation (where $R_c = 86$ feet) is between 1.6-fold and 1.9-fold. Nuclear stimulation of thick multiple gas-sands reservoirs would be accomplished by sequential or simultaneous detonations of a number of point charges, with adjacent charges separated by about five to seven times R_c . Thus, for 1-kiloton charges the separation would be about 100 feet, and a 2000-foot interval would require up to 20 such charges; for 100-kiloton charges, three or four should be adequate. Since a considerable part of the cost of nuclear stimulation is associated with the explosives, the minimum number is generally desirable even though it implies maximum energy and corresponding seismic motion. There are significant differences in expected production among wells with sprung radii of 3, 20, and 90 feet, but only small differences among cavities with radii of 2, 3, and 4 feet (1.45, 1.62, and 1.72 Bcf). Therefore, small discrepancies between the sprung

radii calculated in the next section and the actual radii would make little difference in the reliability of this gas stimulation method.

Figure 3 is plotted with the sprung cavity radius R_c as the independent variable because R_c is easily and reliably calculated, but the effect that should be directly related to gas production is the enhanced permeability radius. Thus, Fig. 3 cannot be used to evaluate unstimulated wells with diameters equal to R_c . However, such an unstimulated well can be evaluated very roughly from Fig. 3 by taking as R_c the drilled well radius divided by 2.75. Thus, an unstimulated well of 3-inch radius would have $R_c = 0.25/2.75 = 0.091$ feet and would produce approximately 0.5 to 1 Bcf in 20 years (between 60 and 150 Mcf per day). It is not possible to drill a well without causing formation damage, but gas production from conventionally drilled and completed wells in the Rio Blanco area ranges up to 100 Mcf per day, consistent with the calculation. The well stimulated to an R_c of 3 feet (640-acre spacing) would be expected to produce about 2.5 times as much, and that stimulated to 90 feet about 7 times as much, as the unstimulated well.

Cavity Size

We have attempted to calculate the cavity radius to be expected from the detonation of cylindrical chemical explosive charges 1000 feet or more in length—sufficient to span all the gas sands. We used two calculational methods and an empirical formula for rock-breaking with

high explosives. The simplest method for calculating the radius of an explosion-produced cavity is to compute the charge density or specific volume and the pressure immediately after detonation, and then to assume adiabatic expansion to a pressure equal to that exerted by the

overlying rock or to some multiple of that pressure, for example twice the overburden pressure. To permit comparison of costs between this method and nuclear stimulation, we assumed the depth and density to be equal to those of the Rio Blanco reservoir, which was analyzed previously.¹

There appears to be no adequate gas expansion coefficient γ for the slurry-type explosives proposed. However, both nitromethane and a proprietary commercial explosive have been examined; the expansion equations of both can be approximated by

$$PV^{1.44} = \text{constant.}$$

Thus, $P_0 V_0^{1.44} = P_c V_c^{1.44}$ where P_0 and V_0 are the detonation pressure and explosive specific volume, P_c and V_c are the pressure and volume of the final cavity, and

$$\frac{V_c}{V_0} = \left(\frac{P_0}{P_c} \right)^{1/1.44},$$

and for cylindrical expansion

$$\frac{V_c}{V_0} = \frac{R_c^2}{R_0^2},$$

whence

$$R_c = R_0 \left(\frac{P_0}{P_c} \right)^{1/2.88}$$

This equation gives about the same results as a slightly more accurate polynomial expression for the pressure-volume relationship.

Fig. 4. The ratio R_c/R_0 versus depth of burial of the center of a long (length $\gg 10 R_c$) high-explosive charge. Curves A, B, and C are discussed in the text; arrow, value selected for economic analysis.

Figure 4 indicates the calculated ratio of cavity radius R_c to the initial charge radius R_0 as a function of depth of the center of the explosive charge. Curve A was calculated with the equation above, curve B was calculated with the polynomial adiabat for nitromethane, and curve C was calculated with the SOC73 computer code⁴ using the equation-of-state for Rio Blanco rock and the expansion adiabat of nitromethane. Calculations B and C were performed using the properties of nitromethane, but the results were adjusted to account for the greater initial explosive density (1.41 g/cm³) of the slurry explosives relative to nitromethane (~1.15 g/cm³). The proposed explosive is a mixture of ammonium nitrate, nitromethane, and aluminum powder that will have a higher density and a higher specific energy than nitromethane. Both of these differences indicate a "real" behavior more like curve A, but to be conservative we have used curve C to calculate

gas production. A cavity radius of approximately 3 feet would require a charge radius of 1 foot.

The radius for which the SOC73 code gave ϵ_f between 0.01 and 0.02 was the same as the radius of "breaking" calculated from an empirical equation for rock-breaking given by Langfors and Kihlstrom.⁸ The radius for which ϵ_f was 0.1 was indeed about 2.75 times the cavity radius shown in curve C of Fig. 4 as in the calculations for Rulison; the radius for which ϵ_f was 0.01 was closer to $10 R_c$. Hence, we expect that the use of curve C of Fig. 4, with enhanced permeability out to a distance of $2.75 R_c$ will underestimate the actual behavior of a gas reservoir.

The calculations of well production used to generate Fig. 3 were used also to provide the cumulative production curves shown in Fig. 5. This figure shows the expectation from the Rio Blanco reservoir from four wells stimulated by chemical explosives, each well with $R_c \approx 3$ feet covering a 2000-foot producing section between the 5200 and 7200 foot depths. The expectation is also given for one well with $R_c = 93$ feet and the same height of producing section⁹; the 93-foot radius and 2000-foot height imply stimulation with three 100-kiloton nuclear explosives spaced in the same 2000-foot vertical section. Note that the gross 2000-foot section is assumed to have 400 feet of net pay sand; Fig. 3 was calculated on the basis of 100 feet of net pay sand.

The abscissa of Fig. 5 is plotted in units of microdarcy years ($\mu D \cdot yr$). Thus,

for example, a nuclear well of 90-foot radius in a 20-microdarcy formation allowed to flow for 20 years ($400 \mu D \cdot yr$) would be expected to yield 20.5 Bcf of gas, and four chemical explosive wells with sprung cavity radii of 3 feet would yield 26 Bcf. Note that although 20 years is the usual well-life used to calculate return on investment, in this case the production from the four 3-foot wells during the second 20 years is 15 Bcf, and after 20 years 48% of the original 98 Bcf in place would be recovered from the 20-microdarcy formation.

Fig. 5. Cumulative gas production curves for a Rio Blanco reservoir with a 2000-foot producing section (between 5200 and 7200 feet). A, chemical explosives, four wells per 640 acres (160-acre spacing), $R_c = 2.901$ feet; B, nuclear explosives, one well per 640 acres, $R_c = 93.125$ feet.

Cost Analysis

The major elements contributing to cost are drilling, casing, explosive well completion, and field operation. These are estimated in the same way and the over-all economics are treated in the same way as by Rubin *et al.*¹; hence, the results should be directly comparable to cost estimates for nuclear stimulation.*

The costs are summarized in Table 2. Drilling requires a surface conductor and a 12-inch-diameter hole to 7200 feet, underreamed to 24 inches diameter be-

Table 2. Estimated costs of a gas well stimulated by chemical explosives.^a

Drilling	\$344,000
Underreaming	96,000
Casing and cement	40,000
Explosives (548,000 lb)	119,000
Service contract	9,000
<hr/>	
Total per well	\$608,000
Total for four wells	\$2,432,000

^aInflated to 1976 level by a factor of 1.45 times the 1971 estimates.

tween 5200 feet and 7200 feet. A plug-shoe would be set on nominal 7-5/8-inch casing at 5100 feet and this would be cemented to the surface. After the drilling through the shoe, the explosive would be run in under mud from 7200 feet depth to 5200 feet depth. The mud remaining above the explosive would be left in the

hole to provide stemming. Completion hardware would be installed at the surface and the explosive would be detonated.

The expanding high explosive gases should blow all the mud out after fracturing the formation, leaving the well ready for connection to a gathering line. Since the time required for ejection of the mud is long (~20 seconds) compared to the time for the explosive to have its effect, the stemming should be adequate. If the explosion gases are too hot after reaching the surface, they could cause ignition of the gas that follows. A more costly alternative would be to seal the surface until a few minutes after the explosion and then purge the stemming, but this might allow the mud to drain down and damage the explosion-produced fractures. Only experimental testing will indicate which alternative is better.

Future net revenues were calculated assuming the production curve for four wells (Fig. 5), capitalization of the well costs, a 20-year well life, 12.5% royalty, severance and ad valorem taxes of 12.5% (Colorado), administrative expense of 3%, and operating expense of \$125 per month per field well. We did not include depletion, depreciation, or Federal income tax. These calculations are summarized in Fig. 6, which shows the internal rate of return on the investment as a function of gas sales prices for three different field permeabilities. Also shown are the rates of return calculated¹ for the field stimulated by three 100-kiloton nuclear explosives.

From Fig. 6, we could expect a 20% return on investment for a sales price

* Due to very rapid recent inflation of drilling and casing costs, these estimates are as much as 50% too low; they should be used only for this comparison.

Fig. 6. Internal rate of return on investment for different gas field permeabilities and gas sales prices for both nuclear and high explosives stimulations.

between 25¢ per Mcf and 80¢ per Mcf depending on the initial permeability of the formation. Since many of the methods proposed for creating new sources of domestic gas would result in costs of \$1.00 per Mcf to \$1.50 per Mcf, this technology appears attractive both from the producers' and the consumers' points of view. Also, it is interesting to compare the nuclear-stimulated wells with those stimulated by chemical explosives. For a formation of 40-microdarcy permeability, chemical explosives yield gas 22% cheaper than nuclear explosives. For a 20-microdarcy formation, however, the costs would be equivalent, and for a 10-microdarcy formation, nuclear stimula-

tion would yield gas 15% cheaper than chemical explosives. This is partial justification for the statement in the Introduction that the optimal method will depend on the region.

Several accidents have occurred with high explosives during attempts to use them for well stimulation. Therefore, we propose the use of a less energetic and safer explosive at the expense of larger holes and consequently higher drilling costs than would be required for a very energetic explosive (e.g., nitroglycerin). Another hazard is that about 25,000 pounds of carbon monoxide and 25,000 pounds of nitrogen oxides are expected to be vented during the first few

minutes of flow while the well is being purged of residual detonation gases. These are significant amounts, but development and testing programs should yield a suit-

able low-cost explosive that would produce less of these noxious gases. No other serious environmental impacts unique to this stimulation technique are now known.

Conclusions

The low-cost explosive suggested in the preceding paragraph should be examined to determine its equation-of-state, susceptibility to sensitization, formation compatibility, and sensitivity to higher temperatures (many reservoirs have temperatures above 300°F), as well as the reliability with which it can be detonated at depth and the ease and safety with which it can be processed, mixed, and pumped. This is a long list of requirements, but none of them is technologically difficult, and no great time should be required to develop a suitable explosive.

Stimulation of low-permeability gas reservoirs with long cylindrical charges of high explosives appears to be technically and economically competitive with other stimulation techniques and also cheaper than some alternative domestic gas supplies such as imported liquefied

natural gas and coal gasification. Stimulation with high explosives has never been tested at the proposed magnitude, even though many gas and oil wells have been successfully stimulated with considerably smaller charges; these wells were in shallow formations with thin net pay sands, where smaller charges were adequate.¹⁰ Hence, a field test of large charges should be performed. Ideally, the test site should be very close to a nuclearly stimulated well and to one stimulated by massive hydraulic fracture, so as to permit close comparison of the techniques. Further, tests in several reservoirs would be desirable to establish which of the methods is most appropriate for different permeabilities and different susceptibilities to formation damage. It seems clear that this technique will significantly raise our domestic reserves of natural gas.

References

1. R. Rubin, L. Schwartz, and D. Montan, An Analysis of Gas Stimulation Using Nuclear Explosives, Lawrence Livermore Laboratory, Rept. UCRL-51226 (1972).
2. Potential Supply of Natural Gas in the United States as of December 31, 1970, Potential Gas Committee, Colorado School of Mines Foundation, Inc., Golden, Colorado (1971).
3. A. Holzer, "Gasougy in Perspective," in Engineering with Nuclear Explosives, Proc. Am. Nucl. Soc. Symposium, Las Vegas, Nevada, January 14-16, 1970, vol. 1, p. 662 (1970). (AEC CONF/700101)
4. J. F. Schatz, Calculation of Extent of Shear Fracturing Using SOC73, with Implications Concerning Permeability Enhancement, Lawrence Livermore Laboratory, personal communication (1974).
5. I. Y. Borg, "Extent of Pervasive Fracturing around Underground Nuclear Explosions," Intern. J. Rock Mech. Min. Sci. 10, 11-18 (1973).
6. D. Montan, "Project Rulison Gas Flow Analysis," Trans. Am. Nucl. Soc. 14, 690 (1971).
7. D. Montan, Lawrence Livermore Laboratory, private communication (1974).
8. U. Langefors, The Modern Technique of Rock Blasting (John Wiley, New York, 1963).
9. T. R. Butkovich and A. E. Lewis, Aids for Estimating Effects of Underground Nuclear Explosions, Lawrence Livermore Laboratory, Rept. UCRL-50929 (1973).
10. R. E. Hurst, W. M. Zingg, and C. W. Crowe, "New Explosive Fracturing Method Is Safe, Effective," World Oil, January 1970, 131-135 (1970).