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AN ANALYSIS OF NUCLEAR GAS STIMULATION

G. C. Werth, B. Rubin, L. Schwartz, and D. Montan

February 16, 1972

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This paper with its figures is the summary of a talk presented by Dr. G. C. Werth at the 71st National Meeting, American Institute of Chemical Engineers, on February 22, 1972, in Dallas, Texas.

It is also the summary of a more complete document by the above authors on this subject to be issued within the next several weeks.

AN ANALYSIS OF NUCLEAR GAS STIMULATION*

G. C. Werth, B. Rubin, L. Schwartz, and D. Montan

It is becoming increasingly clear that the demand for gas 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 considered, major deficits will still exist in some geographic areas. 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 Bureau of Mines has estimated that 317 trillion cubic feet (Tcf) of gas is potentially available using nuclear explosive gas stimulation techniques. This figure should be compared to the proved reserves of 290 Tcf that are currently being produced at the rate of over 22 Tcf/year.

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

The key to commercial nuclear explosive gas stimulation lies in obtaining sufficient gas production at a cost which 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.

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

It is expected that the gas will be produced by reentering the emplacement hole after the detonations. The degree of stimulation is dependent 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 which will employ multiple explosives. In the Rio Blanco experiment, three 30-kt explosives will be simultaneously detonated at a depth near 6000 ft in the Piceance Basin in Colorado. 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.

For the present study, the fracture radius for production calculations was developed by matching the early production from Rulison and consists of a high permeability zone extending out to 2.75 times the initial cavity radius. This is consistent with the extent of fracturing measured in Gasbuggy.

Gas productivity calculations were made 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 section in the Piceance Basin containing 100 billion cubic feet (Bcf) of gas, and four 100-kt explosives were assumed for a 2400 ft vertical section in the Green River Basin containing 170 Bcf per section. Permeabilities of 10 to 40 microdarcies (μ d) and 5 to 10 μ d were assumed for the two regions, respectively. The corresponding 20 year gas production from single wells in the two basins ranges from 14 to 31, and 21 to 35 Bcf, respectively.

Based on these typical gas production rates, a plan has been postulated for commercial development of the two basins. It is assumed that upon completion of a five year 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. Using gas productivities corresponding to permeabilities of 40 and 10 μ d in the Piceance and Green River

Basins respectively, and on the conservative assumption that the wells would produce for only 20 years, gas production would start in 1977 and rise to a steady state production rate of 3.4 trillion cubic feet per year by the year 2000.

An economic evaluation is made of the production from single wells in the two basins. In this analysis, the federal royalty, severance and ad valorem taxes, administrative costs, and lease operating expenses are considered 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. Using this cost and a price of 40¢/thousand cubic feet (Mcf), the internal rate of return on invested capital varies from 7.5 to 28.5 percent, depending on the permeabilities encountered. If depletion allowance, depreciation, and corporate federal income tax are included and it is assumed that the loss in the development years can be written off against other corporate profits, the internal return on investment is slightly increased.

In a comparison of nuclear stimulation with the several alternative ways of increasing gas availability, it is seen that the cost of R&D, the required capital investment and time needed to achieve a new production capability of one trillion cubic feet per year are less than, or competitive with conventional exploration, coal gasification or import of liquefied natural gas. Gas sales prices from nuclear stimulation should be lower than from all other sources 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 state of California demand could be supplied in the year 2000.

Two methods of distribution of this gas in California are considered in order to evaluate the radiation exposure to the population resulting from low

levels of radioactivity in the gas. 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 less than 0.45 millirem (mrem) per year. The maximum individual exposure would be less than 0.7 mrem per year, and the population dose would be less than 14,000 man-rem per year. 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/year maximum permissible exposure to individuals in the population at large as recommended by the former Federal Radiation Council (now a part of the Environmental Protection Agency). They should also be compared with background exposures of 20 to 25 mrem/year from the radioactivity in the human body, 30 to 80 mrem/year from the average radiation from the soil, and a 3 to 7 mrem exposure from a roundtrip, coast-to-coast jet aircraft flight. The California population exposures should be compared to doses from natural sources of 2.3 to 3.5 million man-rem per year or doses from medical sources of 2 to 5 million man-rem per year.

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 per 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 would 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 range of \$100,000 to \$200,000 per year in each of the two basins.

Minimal amounts of radioactivity would be released in the local environment which 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 re-injection 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. A prototype explosive (characterized by the name Diamond) was tested successfully 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 which 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 which permits commercial use of nuclear explosives, and must announce how much is to be charged for these explosives. Also, pricing policies for sale of the gas, and regulation guidelines for 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 non-profit 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. 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.

RULISON GAS PRODUCTION

Rulison postshot interpretation based on cores, logs, gas composition, and production.

RULISON GAS PRODUCTION

GAS STIMULATION
PRODUCTION - COST - INTERNAL RATE OF RETURN

EVENT:	<u>Gasbuggy</u>	<u>Rulison</u>	<u>Rio Blanco</u>	<u>Wagon Wheel</u>	<u>Commercial</u>	<u>Commercial</u>
BASIN:	San Juan	Piceance	Piceance	Green River	Piceance	Green River
EXPLOSIVES:	one 29-kt	one 43-kt	three 30-kt	five 100-kt	three 100-kt	three or four 100-kt
DEPTH (MIDPOINT) FT:	4,000	8,400	6,200	10,400	6,200	11,000
STIMULATED INTERVAL FT:	286	420	1,350	3,200	2,000	2,400
TOTAL GAS IN INTERVAL BCF/SQ MI:	18	15	75	210	100	170
PRESSURE PSI:	1,100	3,200	2,750	6,334	3,000	6,000
PERMEABILITY MICRODARCY:	6.8	9	40	3.4 - 6.8	10 - 40	5 - 10
20 YEAR PRODUCTION BCF:	.9	1.8	22	21 - 33	14 - 31	21 - 35
PRESENT NET WORTH 8% AT 40¢/MCF (MILLION \$):	.13	.33	3.7	3.7 - 5.9	2.3 - 5.2	3.7 - 6.1
COSTS (MILLIONS):	2.9	3.9	-	-	2.4	2.9 - 3.3
INTERNAL RATE OF RETURN %:	-	-	-	-	7.5 - 28.5	10.5 - 28

ECONOMIC ANALYSIS FOR SINGLE-WELL DEVELOPMENT IN THE GREEN RIVER BASIN

(10 md, 40¢/Mcf, THREE OR FOUR 100-KT EXPLOSIVES).

Year	Production		Gross revenue	Severance tax (1%)	Ad Valorem tax (5.5%)	General and administration expense (3%)	Lease operating expense (\$500/month)	Future net revenue	Cumulative future net revenue
	Gross (MMcf)	Net (87.5% of gross) (MMcf)							
1	4837	4232	1693	17	93	51	6	1526	1526
2	2413	2111	844	8	46	25	6	758	2284
3	2110	1846	738	7	41	22	6	662	2946
4	1945	1702	681	7	37	20	6	610	3557
5	1837	1607	643	6	35	19	6	576	4133
6	1755	1536	614	6	34	18	6	550	4682
7	1692	1480	592	6	33	18	6	530	5212
8	1637	1432	573	6	32	17	6	512	5725
9	1589	1391	556	6	31	17	6	497	6222
10	1546	1352	541	5	30	16	6	484	6706
11	1505	1317	527	5	29	16	6	471	7176
12	1467	1284	514	5	28	15	6	459	7635
13	1432	1253	501	5	28	15	6	448	8083
14	1398	1224	489	5	27	15	6	437	8520
15	1366	1195	478	5	26	14	6	427	8946
16	1335	1168	467	5	26	14	6	417	9363
17	1306	1142	457	5	25	14	6	408	9771
18	1277	1118	447	4	25	13	6	399	10169
19	1250	1094	437	4	24	13	6	390	10559
20	1224	1071	428	4	24	13	6	382	10941

ESTIMATED COSTS PER WELL FOR COMMERCIAL GAS STIMULATION

(1976 dollars)^a

	Piceance ^(b) Basin (\$1000)	Green River ^(c) Basin (\$1000)
<u>Emplacement Hole</u>		
Includes site access, grading and a 10-3/4" O.D. cased emplacement hole 7000 ft deep in the Piceance Basin and 12000 ft deep in the Green River Basin	520	900
Allowance for drilling problems in the development of the field (unable to complete one out of six emplace- ment 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 one well/month	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 the health and safety of the general public and project personnel. Includes equip- ment to monitor and document radioactivities during production. Based on a field-development rate of one well/month	130	130
<u>Subtotal without Explosives</u>	1030	150
<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 15,000 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

(a) Costs inflated from 1971 to 1976 at 5.5% per year.

(b) Three 100-kt explosives per well.

(c) Four 100-kt explosives per well.

PRESENT WORTH OF FUTURE NET REVENUE VS
INTERNAL RATE OF RETURN
(BEFORE TAXES)

PICEANCE WELL
40 μ d

PRESENT WORTH OF FUTURE NET REVENUE VS
INTERNAL RATE OF RETURN
(BEFORE TAXES)

GREEN RIVER WELL
10 μ d

POSSIBLE GAS STIMULATION DEVELOPMENT AND PILOT COMMERCIAL PROGRAM

Lawrence Livermore Laboratory
February 1, 1972

POSSIBLE COMMERCIAL PRODUCTION PLAN

Fiscal Year	1977	1978	1979	1980	1981	1982	1983
	Pilot Commercial Production						
	Commercial Production						
<u>Annual Number of Wells Detonated</u>							
Green River - A		10	20	30	40	40	40
Green River - B			10	20	30	30	30
Piceance	20		30	30	30	30	30
Total Annual Wells	20	35	60	80	100	100	100
<u>Annual Number of Explosives Required</u>	100	160	270	330	370	370	370

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February 1, 1972

CHART 6
FUTURE U.S. GAS REQUIREMENTS BY REGION, 1970, 1975, 1985, and 1995

PROJECTED GAS CONSUMPTION
STATE OF CALIFORNIA

AND STABILIZATION OF EXPLOSIVE DEGRADATION

TEMP. PLACEMENT AND
RE-ENTRY CASING

OPERATIONAL INFORMATION

YIELD RANGE - 20 TO 100 KT
DIAMETER - 48 INCHES

OPERATIONAL TITLES

TOTAL (EXPLOSIVE + INDUCED)
1000 TO 2000 CUBES

ENVIRONMENTAL CAPABILITY

PRESSURE - 10,000 PSI
TIME - > 4 WEEKS AT
RESERVOIR TEMPERATURES

7 INCH DIAMETER
40-50 FEET LONG

< 8 INCH DIAMETER
~ 35 FEET LONG

LOCAL ENVIRONMENTAL IMPACT

Emplacement Well Construction

Power Lines

Gas Pipelines

Access Roads

Ground Motions on Shot Day

SEISMIC DAMAGE SUMMARY

	GASUBGGY	RULISON	RIO BLANCO	PICEANCE COMM'L	WAGON WHEEL	GREEN P COMM'
Number of Structures Susceptible to Damage	(0-15 mi) few	(0-22 mi) 1,900	(0-28 mi) 300 (28-40 mi) 3,000	~300	(0-40 mi) 1,350	~1,350
Number of Claims Filed or Estimated	2	320	(0-28 mi) 85 (28-40 mi) 85 Total 170	~50	75 x 2 (2x for seq. det.) = 150	<10
\$ Value of Claims Paid or Estimated	-	\$93K	\$50K	~\$25K	\$65K	\$50K
\$ Value/Year Estimated for Commercial Operation (4 detonation days/year)	-	-	-	~\$100K	-	<\$200

Lawrence Livermore Laboratory
December 6, 1971

SEISMIC DAMAGE SUMMARY

GASUBGGY	RULISON	RIO BLANCO	PICEANCE COMM'L	WAGON WHEEL	GREEN RIVER COMM'L
(0-15 mi) few	(0-22 mi) 1,900	(0-28 mi) 300 (28-40 mi) 3,000	~300	(0-40 mi) 1,350	~1,350
2	320	(0-28 mi) 85 (28-40 mi) 85 Total 170	~50	75 x 2 (2x for seq. det.) = 150	<100
-	\$93K	\$50K	~\$25K	\$65K	\$50K
-	-	-	~\$100K	-	<\$200K

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GAS STIMULATION
BENEFITS TO GOVERNMENT

	Increment in Year			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, \$M	3468	700	992	3756
<u>Revenue to Government</u>				
County Ad Valorem ^a Taxes, \$M	16.7	33.7	48.0	180.5
State Severance ^b Taxes, \$M	3.1	6.1	8.6	32.8
Federal Royalty ^c , \$M	<u>43.3</u>	<u>87.6</u>	<u>124.4</u>	<u>468.7</u>
Total Government Revenue, \$M	63.1	127.4	181.0	682.0
<u>Balance of Payment Effect</u>				
Equivalent Cost of Imported Oil ^d , \$M	458	925	1315	4952
Equivalent Cost of Imported Liquefied Natural Gas ^e , \$M	606	1229	1741	6562

Notes

- a) Ad valorem taxes taken as 5.5% of net value after U.S. royalty.
- b) Severance taxes taken at 1% of net value after U.S. royalty.
- c) Federal royalty taken as 12-1/2% of gross production value.
- d) Cost of imported oil taken as \$3.00/bbl paid to foreign producers and shippers.
Energy equivalent of 1 bbl oil = 5680 Mcf of gas.
- e) Cost of imported liquefied natural gas taken as 70¢/Mcf paid to foreign
producers and shippers. U.S. price after vaporization would be 80¢/Mcf.
- f) Discounted at 8%.

WAYS TO INCREASE GAS SUPPLIES

POSSIBLE ALTERNATIVES

	POTENTIAL QUANTITIES, TCF	COMMENTS															
<u>Conventional Exploration</u>	<table> <tr> <th>Proved</th><th>Potential</th><th>Total</th></tr> <tr> <td></td><td>613</td><td></td></tr> <tr> <td></td><td>238</td><td></td></tr> <tr> <td></td><td>327</td><td></td></tr> <tr> <td>290</td><td>1178</td><td>1468</td></tr> </table>	Proved	Potential	Total		613			238			327		290	1178	1468	Present reserves will last 8-10 years. Exploration now directed much deeper onshore, into deeper water offshore and into remote areas.
Proved	Potential	Total															
	613																
	238																
	327																
290	1178	1468															
Imports from Canada	53 22 75	Canada recently refused to permit additional sales to U.S. and will not do so until further discoveries are made.															
<u>Liquefied Natural Gas Imports</u>																	
South America	~50	Quantities listed are 1967 estimated total reserves; they are 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	Depends on availability of imported naphtha and heavy oil.	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	U.S. strippable coal reserves = 140 billion tons = 1750 TCF.	Based on conversion of all the strippable coal to gas at 50% efficiency.															
<u>Nuclear Stimulation</u>	317	There is a large uncertainty in this value. An improved estimate is being made by the current National Gas Survey.															

COSTS FOR ALTERNATIVE GAS SUPPLIES

	Approximate Time Scale, Years to Reach Additional 1 TCF/yr	Approximate Current or Proposed Investment \$ Billions	Approximate Capital Investment Required to Attain 1 TCF/yr Additional \$ Billions	Gas Sales Price \$ per Mcf (1971 \$)	Current R&D Funding Level \$ Millions/ yr	Total Required R&D Funding \$ Million
<u>Conventional Exploration</u>		(One (Normal Time + Fund- Only) ing)				
Onshore	2-3	0.16	\$1.5 to 2	0.35 to 0.45		
Offshore	3-5	0.27	(Pipeline, \$2.0)	0.50 to 0.65	0	Some
Alaska	8-10	0.21		0.75 to 1.00 (Chicago)		
Imports from Canadian Arctic	3-5	0.25 + ?		0.75 to 1.00 (Chicago)		
<u>Liquefied Natural Gas Imports</u>	~5	0.1 to 0.2 (1971 to 1975) 1.0/yr (1976 to 1980)	Ships, terminals, storage ~\$3	0.68 to 1.00 (East Coast)	0	Some
<u>Synthetic Gas</u>						
Naphtha and Heavy Oil Gasification	5-7	~0.40	10 plants @ \$150M = \$1.5	0.85 to 1.60 (Source)	0	Some
Coal Gasification	~10-15	0.25	10 plants & mines = \$2.9	0.70 to 1.00 (Source)	15 Federal 30 Industry	300
<u>Nuclear Stimulation</u>	10	No commercial investment.	300 wells @ \$3.34 = \$1.0 160 wells @ \$2.44 = 0.4 \$1.4B	0.40 to 0.50	6.4 Federal 6.0 Industry	125

	Years to Reach Additional 1 TCF/yr	Proposed Investment \$ Billions	Capital Investment Required to Attain 1 TCF/yr Additional \$ Billions	Price \$ per Mcf (1971 \$)	R&D Funding Level \$ Millions/yr	Required R&D Funding \$ Million
<u>Conventional Exploration</u>		(One Time + Fund-Only) (Normal ing)				
Onshore	2-3	0.16	\$1.5 to 2	0.35 to 0.45	0	Some
Offshore	3-5	0.27	(Pipeline, \$2.0)	0.50 to 0.65		
Alaska	8-10	0.21		0.75 to 1.00 (Chicago)		
Imports from Canadian Arctic	3-5	0.25 + ?		0.75 to 1.00 (Chicago)		
<u>Liquefied Natural Gas Imports</u>	~5	0.1 to 0.2 (1971 to 1975) 1.0/yr (1976 to 1980)	Ships, terminals, storage ~\$3	0.68 to 1.00 (East Coast)	0	Some
<u>Synthetic Gas</u>						
Naphtha and Heavy Oil Gasification	5-7	~0.40	10 plants @ \$150M = \$1.5	0.85 to 1.60 (Source)	0	Some
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<u>Nuclear Stimulation</u>	10	No commercial investment.	300 wells @ \$3.34 = \$1.0 160 wells @ \$2.44 = 0.4 \$1.4B	0.40 to 0.50	6.4 Federal 6.0 Industry	125