Lawrence Livermore Laboratory

AN ANALYSIS OF NUCLEAR STIMULATION OF RESERVOIR A, U.S.S.R.

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UOPKL 72-30

M E M O R A N D U M

TO: John Toman
FROM: Jack Howard
SUBJECT: An Analysis of Nuclear Stimulation of Reservoir A, U.S.S.R.

This memorandum and its appendix, "Nuclear Stimulation of Reservoir A, U.S.S.R." reviews the economics of nuclear stimulation of this reservoir and also discusses possible mechanisms which would account for improved production.

It is very significant that, from a businessman's point of view, nuclear stimulation of Reservoir A was very profitable. According to my analysis, the Soviet investment in nuclear stimulation (ca. $\$2.9 \times 10^6$) yielded an internal rate of return of 30%. (Note: Rubin, Montan, and Ballou have already pointed out this conclusion in SDK 71-9.)

This memorandum is a progress report and additional work needs to be done. The most important areas which require additional work are given below:

1. Chemical problems. There is a need to know more about the gaseous phases developed by a nuclear explosion, how these phases interact with the indigenous rock-fluid system, and how they are dispersed from the chimney cavity into the country rock. Are gases other than carbon dioxide generated? Do they affect the viscosity of the hydrocarbon? Do they affect the acidity on the connate water? Do the acidic water phases leach the pore network? Someday we may have to be able to determine the effect of carbon dioxide on the viscosity of any crude and thus be able to generate data such as that shown in Figure 6.

2. Fracture mechanics problems. We should perform a SOC or TENSOR calculation of the Soviet explosions in order to evaluate the zone of fracturing

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one might expect about the shot point. The Soviet shots were in a dolomite-carbonate sequence.

3. Reservoir engineering problems. Reservoir A, a solution gas drive reservoir, did not experience the pressure decline in its late history which is typical of such reservoirs. There is a literature on the performance of solution gas drive reservoirs, and it would be worthwhile to synthesize this information in order to have a frame of reference with which to compare the performance of Reservoir A.

Reservoir A involves two-phase flow. Eventually we should have the capability to model two-phase flow possibly using a modification of the TRUMP code. We should then try to simulate the postshot reservoir performance of the field in order to see if we can match the reported reservoir performance to the effects of nuclear stimulation, as we understand them.

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APPENDIX - UOPKL 72-30

NUCLEAR STIMULATION OF "RESERVOIR A", U.S.S.R.

PURPOSE

Following stimulation by three nuclear explosives, the field rate of production of "Reservoir A", U.S.S.R., increased very significantly. This memorandum makes note of the potential profitability of projects such as Reservoir A and reviews some of the possible causes for the increased rate of production.

SUMMARY

1. The field rate of production for "Reservoir A" was enhanced by a factor of about 1.3 following nuclear stimulation.
2. The improvement may have been brought about by an increase, due to fracturing, of 22 md permeability in the average well reported to have been affected by the nuclear shots.
3. Although an average improvement of 22 md per well affected by the nuclear shots is reasonable, it is puzzling that all but three affected wells lie beyond the radius of fracturing which we would expect from the nuclear shots. (Note: Soviet scientists^{1,2,3} report fracturing at distances which include all affected wells.)
4. Carbon dioxide generated by the nuclear explosions, which took place in carbonate rocks, aids to some extent in improving the rate of production. However, the volume of carbon dioxide generated appears by itself to be too small to account for the improved rate over the time interval the improved rate has operated.
5. With continued production following nuclear stimulation, the average reservoir pressure did not decline in the manner that solution gas drive reservoirs generally do. Rather, the pressure declined at a markedly lower rate. The cause for this lower rate of pressure decline is not known at this time.

GEOLOGIC AND RESERVOIR ENGINEERING DATA ON "RESERVOIR A"

The most significant geologic features of Reservoir A are 1) that it is small (3.5 km² in area), 2) "insulated" from fluid flow with the surrounding rocks and 3) that the reservoir rock is carbonate.^{1,2,3,4} The most important aspects of the reservoir engineering are 1) the significant improvement in production capacity of the reservoir following nuclear stimulation and 2) the fact that only wells in the area of nuclear stimulation showed a response to the nuclear explosions.* Figure 1, which plots field rate of production vs time for Reservoir A, shows a marked change in decline rate following nuclear stimulation. Figure 2 (which is the key figure as far as prospects for nuclear stimulation of oil reservoirs is concerned) shows present worth of the increased hydrocarbon production vs various discount rates.⁵ The investment in nuclear stimulation was successful not only from a conservational point of view (Figure 1) but also from an economic point of view. The investment, according to our analysis, yielded an internal rate of return of about 30% and a present value percent profit discounted at 10% of about 185%.

ANALYSIS OF IMPROVED RESERVOIR PERFORMANCE

Darcy's Law and Improved Reservoir Performance

The purpose of any reservoir stimulation technique is to improve the capability of all or part of a reservoir to flow hydrocarbon. In analyzing the success of Reservoir A, we have focused on the law which describes flow in porous media, namely Darcy's Law.⁶ For radial flow, neglecting gravity, Darcy's Law may be written:⁷

$$u_r = \frac{-\kappa_r}{\mu} \frac{\partial p}{\partial r} \quad (1)$$

Here u_r is the volumetric rate of flow per unit cross-sectional area in the radial direction. κ_r is permeability of the rock in the radial direction. μ is viscosity. p symbolizes pressure which varies spatially.

*Two 2.3 kt devices were simultaneously detonated about the center of the reef at year 7.2 since initiation of field exploitation. One 8 kt device was detonated at year 7.5. See also Figure 5.

r is the radial spatial coordinate. The minus sign accounts for flow from high pressure to low pressure.⁶ Darcy's Law calls for an increased rate of flow (i.e. $u_r A$ where A is unit cross-sectional area) for increased permeabilities and pressure gradients and for decreased viscosities. Thus, if we can relate detonation of a nuclear device to suitably large changes in these parameters -- and the changes that they will have through time -- we ought to be able to account for the improved performance reported for "Reservoir A".

Estimates of the Magnitude of Factors Controlling Improved Flow Rate.

Flow Rate. From data on the change in productivity index for the field^{*} we can to some extent evaluate the magnitude of the factors which control the field flow rate at Reservoir A; namely κ_r , μ , and $\frac{\partial p}{\partial r}$. The productivity index for the field may be defined as the ratio:

$$\overline{PI} = \frac{\overline{q}}{\overline{p} - \overline{p}_{wf}} \quad (2)$$

where $\overline{q}$ is volume rate of flow, $\overline{p}$ is the average reservoir pressure; and $\overline{p}_{wf}$ is pressure at the well face of the average well. In view of the fact that no pressure changes were reported in the reservoir following nuclear stimulation,² we can argue that ratio of productivity indices for the field after and before stimulation is equal to the ratio of permeability and viscosity after and before stimulation:^{**}

^{*} There is no information on production characteristics of individual wells in the field.

^{**} The productivity index is the ratio of rate of production, q , to "draw-down", i.e. the difference between reservoir pressure and pressure at the producing well bore. The quantity, q , in turn is directly proportional to the pressure change between reservoir and well; to permeability, κ , and to surface area of the well bore, $2\pi r_w h$, and inversely proportional to viscosity, μ and to the ratio of radial drainage distance, r_d (i.e. the distance at which the average reservoir pressure is realized) to radius of the well bore. The productivity index may be thought of as a "field index" if the various quantities on which it depends are conceived as field averages. We do not expect r_d , r_w or h to change on the average following nuclear stimulation, and as noted in Reference 2, $\overline{p}$ and $\overline{p}_{wf}$ did not change.

$$E = \frac{\overline{PI'}}{\overline{PI}} = \frac{\overline{\kappa'}}{\overline{\mu'}} / \frac{\overline{\kappa}}{\overline{\mu}} \quad (3)$$

where the primes refer to values after stimulation; bars symbolize field averages; and E may be thought of as an enhancement coefficient. Figure 3 shows the field productivity index as a function of time. According to this figure,

$$\overline{PI} \approx 0.42$$

$$\overline{PI'} \approx 0.54$$

and therefore,

$$E = 1.29$$

The ratio of average permeability to average viscosity before stimulation is estimated as²:

$$\overline{\kappa} = 30 \text{ md.}$$

$$\overline{\mu} = 15 \text{ cp}$$

$$\overline{\kappa}/\overline{\mu} = 2 \text{ md/cp}$$

Hence, after stimulation the ratio of average permeability to average viscosity must be:

$$E \overline{\kappa}/\overline{\mu} = \overline{\kappa'}/\overline{\mu'} = 2.58 \text{ md/cp}$$

This is a reasonable number. It could for instance, be brought about by an average increase of about 22 md permeability in the 16 wells which were affected by the nuclear shots. Or, it could be brought about by an average decrease in viscosity of about 9 cp in the affected wells. These estimates assume that all factors other than permeability or viscosity of produced oil are the same in all the wells. As explained in more detail in the next section, it may be reasonable to expect such an increase in permeability due to fracturing. However, from information we now have, it appears very unlikely that viscosity reduction alone can account for the improved production.

Improved Flow Rate From Fracture Induced Permeability Changes.

Fractures are highly permeable. If we liken flow in a fracture to flow in a long thin plot (see Figure 4) we can get some insight into the fracture system necessary to bring about the improved flow rate at Reservoir A. Although details of the analysis will not be presented here, it can be shown (Don Montan, personal communication, 1972) that the increment in permeability due to explosion induced fracturing, κ' , can be estimated from the relation that

$$\kappa' = \frac{w^3}{12s}$$

This expression applies to the geometrical arrangement shown in Figure 4, namely one in which cracks of wall-to-wall width, w , are parallel and spaced a distance, s , from one another. The increment in permeability has been estimated as 22 md. Accordingly, we can determine values for w and s which will yield this permeability. For instance, a system of parallel fractures 0.13 mm wide spaced 10 meters apart would yield a permeability of 22 md.

Orudjev et al² report that a zone of additional fractures has been established to have spread "at the distance of 300-400 meters from the epicenter of the explosion, some fractures having been recorded at the distance of 800 m." If indeed this is the case, then additional fracturing can be expected in all wells which responded to the nuclear shots. Ten of sixteen wells which showed a response to nuclear stimulation lie within 400 meters map distance of the epicenter of the explosions (Figure 5). All sixteen lie within 600 meters. Although it seems reasonable to expect one 0.13 mm fracture per 10 meters of borehole per affected well, it is important to point out that the Soviets give no information on the width or number of fractures observed in any well, nor do they explain their method of observation. It is also important to point out that the radial distance of fracturing in Reservoir A is more than an order of magnitude greater than reported previously^{9,10} in connection with subsurface nuclear explosions. However,

our past experience has not included shots in carbonate sequences. Based on the fact that the Soviet experiment was in saturated, relatively brittle rock, Terhune (1972, personal communication) has suggested that such large radial distances of fracturing may not be unreasonable. Hence to this point our analysis indicates that nuclear explosion-induced fractures could conceivably account for increased production. However, we clearly need experimental data for fracturing of carbonate rocks by nuclear explosions and would like to know more about the Soviet method for fracture evaluation.

Increased Flow Rate From Viscosity Reduction Owing to Solution of Carbon Dioxide

The solution of one or two mole fractions of carbon dioxide in hydrocarbon substantially reduces the viscosity of the hydrocarbon.^{11,12} Nuclear explosions in carbonate bearing rocks are known to generate carbon dioxide, roughly in the proportion of 10^7 moles of carbon dioxide per kiloton of explosive yield. It is reasonable to hypothesize, therefore, that a nuclear explosion in carbonate rocks can lead to some viscosity reduction and ultimately to improved production rates.

In order to explain the increased production at Reservoir A based on viscosity reduction alone, we need reduce the viscosity of the affected wells from 15 cp to about 6 cp. To achieve such a viscosity reduction, it is necessary to dissolve approximately 0.1 mole of carbon dioxide in about 350 cm^3 of oil (Figure 6). This estimate assumes that we have reasonably extended the data given by Simon and Graue¹¹, and that the oil molecular weight is around 340, and its density is about 0.87 gm/cm^3 .² The reservoir contains approximately 80×10^6 barrels of oil.^{2,5} This is approximately equal to $1.3 \times 10^{13} \text{ cm}^3$ of oil. If 40% of this amount lies in the central portion of the reservoir (the Soviet suggest that most of the accumulation is there) then about $5.2 \times 10^{12} \text{ cm}^3$ of oil lies in the reservoir volume tapped by those wells which responded to the nuclear explosions. Altogether, the three nuclear explosions generated about 1.3×10^8 moles of carbon dioxide. This amount of carbon dioxide if dissolved at a concentration to reduce the viscosity from 15 cp to 6 cp (i.e. 0.1 mole fraction carbon dioxide per 350 cm^3 of oil), can treat only $4.6 \times 10^{11} \text{ cm}^3$. Thus only about

nine per cent of the reservoir oil in the central part of the reservoir will be affected sufficiently to bring about the improved production we are trying to explain. Although some wells may be very favorably affected, overall this amount seems too small to account in itself for the improved production of the reservoir. Even if for a time all production tapped only the lowered viscosity oil, which amounts to 2.9×10^6 barrels (i.e. $4.6 \times 10^8 \text{ cm}^3$), viscosity reduction still cannot explain the change in productivity for the number of years reported. For the production rates shown on Figure 1, this volume of reduced viscosity oil would be produced in about 3 years. In the absence of other favorable effects produced by the nuclear explosions, one would expect the field to return to the decline rate characterizing it before nuclear stimulation. In summary then, it would appear that the solution of carbon dioxide by itself cannot bring about the observed changes in production. The volumes of carbon dioxide created by the nuclear explosions are not adequately large to account for changes in production rate over the reported time intervals. However, the generation of carbon dioxide does contribute favorably toward improved production.

Comments on Pressure Decline Following Nuclear Stimulation

According to Muskat⁸, for solution gas drive reservoirs, reservoir pressures decline with continued production either almost linearly or else at an increased rate. Oredjev et al (their Figure 6), however, show that the rate of reservoir pressure decline following nuclear stimulation decreased. The fact that pressures did not decrease so fast as might be expected is important. According to Darcy's Law, volumetric rate of flow is proportional to the pressure gradient, e.g. $\partial p / \partial r$, which is proportional to the difference between the pressure of the reservoir and pressure at the bore. Whereas loss of reservoir pressure would reduce the magnitude of the pressure gradient, maintenance of reservoir pressure also permits maintenance of the pressure gradient.

The reasons for the relatively reduced rate of reservoir pressure decline are not given by the Soviet scientist involved with Reservoir A^{1,2,3}, if indeed they are known. Although such an analysis is beyond the scope of

this memorandum, we hypothesize at this time that the reservoir pressure may have been sustained to some extent by the influx of water from the gypsum and anhydrite beds surrounding the reservoir.

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FIGURES WITH FIGURE CAPTIONS

1. Field rate of production vs time for "Reservoir A", U.S.S.R.
Note the change in decline rate subsequent to the nuclear stimulation, which took place between 7 and 8 years since initiation of field exploitation.
2. Present worth of increased production due to nuclear stimulation vs nominal discount rate. The investment of \$2.9 million dollars in the stimulation yields an internal rate of return of 30%.
3. Reservoir A - productivity index vs time. The productivity index changed from a value of 0.42 to 0.54 subsequent to nuclear stimulation.
4. Geometry for an idealized fracture system used in evaluating changes in flow characteristics in Reservoir A.
5. Reservoir A, U.S.S.R. structure contour map and locations of emplacement of nuclear devices. Wells affected by the stimulation are shown with black dots. The shaded area describes the radial extent of fracturing we would have expected, based on our experience. Soviet scientists report fracturing up to 800 meters distant from the shot points. Heavy arrows show locations of emplacement holes.
6. Relationship between temperature, oil gravity, mole fraction dissolved carbon dioxide and viscosity (from Simon and Graue, 1965). The figure shows, for example, that at 100°F the viscosity of 20° API crude is reduced from over 100 cp to about 50 cp by the solution of 0.15 mole fraction carbon dioxide. Although data are not available for the crude from Reservoir A, the curves for a 33° crude with viscosity at surface conditions similar to that reported for Reservoir A have been plotted on Figure 5, according to the suggestion by Simon and Graue (1965, p. 105). This plot shows that the solution of about 0.1 mole fraction of carbon dioxide at 75°F (which is the estimated average reservoir temperature of reservoir) will reduce the viscosity of the hydrocarbon from about 15 cp to about 7 cp. (Other data by Simon and Graue indicate further than this mole fraction of carbon dioxide can readily dissolve in the hydrocarbon under reservoir temperature and pressure conditions.)

FIELD RATE OF PRODUCTION vs TIME - "RESERVOIR A", U.S.S.R

"RESERVOIR A", U.S.S.R.
PRESENT WORTH OF INCREASED PRODUCTION
DUE TO NUCLEAR STIMULATION vs NOMINAL DISCOUNT RATE

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