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Elastic-wave stimulation of oil production: A review of methods and results

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ABSTRACT

Numerous observations accumulated principally during the last 40 years show that seismic waves generated from earthquakes and cultural noise may alter water and oil production. In some cases wave excitation may appreciably increase the mobility of fluids. The effect of elastic waves on the permeability of saturated rock has been confirmed in numerous laboratory experiments. Two related applications have arisen from these findings. In the first application, high-power ultrasonic waves are applied for downhole cleaning of the near-wellbore in producing formations that exhibit declining production as a result of the deposition of scales and precipitants, mud penetration, etc. In many cases, ultrasound effectively removes the barriers to oil flow into the well. The ultrasonic method is reported to be successful in 40-50 percent of the cases studied. In the case of successful treatment, the effect of improved permeability may last up to several months. Whereas this method has a very local effect, a second application is used to stimulate the reservoir as a whole. Here seismic frequency waves are applied at the earth's surface by arrays of vibroseis-type sources. This method has produced promising results; however, further testing and understanding of the mechanisms are necessary.

INTRODUCTION

Declining production in oil recovery operations is of major concern in the oil producing industry. Typically, the natural pressure in the reservoir generally results in no more than 10 percent recovery of the existing oil contained in the formation. The residual oil is difficult to produce because of its very low mobility. Commonly applied methods for enhanced oil recovery (EOR) include steam, water, and gas flooding; hydraulic and explosive fracturing; injection of surfactants; and layer burning. In the most successful cases, oil recovery can be enhanced up to 50-70 percent of the total oil in place. Another cause of declining production is that reservoir permeability may decrease locally around the producing wellbore owing to the deposition of scales and precipitants during exploitation that form an impermeable barrier to fluid flow. To combat local deposits, different methods are used, including solvent and acid injection, treatment by mechanical scrapers and high pressure fracturing.

Each of these enhanced oil recovery methods has a number of limitations, as well as some undesirable side effects. For example, some methods are costly, require shutting in production, or may create harmful ecological consequences. Such problems have led engineers and geophysicists to search for new methods of stimulation. In particular, the use of elastic-wave stimulation has been suggested, not as a substitute for conventional EOR methods, but as an alternative or complimentary tool which, in certain instances, may make conventional methods more effective.

In this paper, we will review the methods and results of enhanced oil recovery achieved by application of relatively weak elastic waves. This problem first attracted the attention of researchers in the US and USSR in the late 1950s. The peak of activity dates to the early 1970s in the US, and the 1970s and 1980s in the USSR. Most of the work in this area has been conducted by several Soviet research and industrial institutions, principally, the Institute of Physics of the Earth of the USSR Academy of Sciences, the Krylov Institute of Oil and Gas (VNII), and the Institute of Nuclear Geophysics and Geochemistry (VNIIYaGG) (currently VNIIGeosystem), all in Moscow, as well as the Special Design Bureau of Applied Geophysics of the Siberian Branch of USSR Academy of Sciences in Novosibirsk. In addition, this review includes an outline of the results

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published in the Russian literature not readily accessible to western researchers.

We are not concerned in this review with the use of explosives for oil recovery, in which high reservoir permeability is achieved by explosive fracturing of rock, by use of both chemical and nuclear explosions. There are separate, exhaustive reviews in this area (Prikhod'ko and Nekrasov, 1976; Bakirov and Bakirov, 1981; Prikhod'ko et al., 1981).

The paper is organized in chronological order of application development. In the next section we address observations showing the influence of earthquake and traffic-induced seismic waves on in-situ fluids, oil and water production. Following that, we address general mechanisms of elastic wave effects on saturated media. The third section is devoted to laboratory studies. The corresponding investigations of the effect of sonic and ultrasonic excitation on liquid flow through porous media are then reviewed because these studies generally preceded industrial applications. Case histories of field applications of ultrasonic reservoir treatment are given in the next section regarding acoustic treatment of productive wells. We then discuss the relatively recent investigations in which surface-based excitation is applied to stimulate reservoirs. The closing section provides a brief discussion with conclusions.

In this paper, we do not attempt to provide an exhaustive critical review of the work presented. This would be extremely difficult because much of the experimental detail is missing from many of the papers reviewed. Rather, we present all available publications and summarize their results so that researchers will know what has been tested and where to find the publication. We provide interpretation where the author has chosen to do so, and empirical results of under what conditions stimulation appears to improve production.

OBSERVATIONS OF SEISMIC WAVE INFLUENCE ON IN-SITU FLUIDS

Water level changes in wells

Interest in the effect of elastic waves on water, oil, and gas production dates back to observations made on the correlation between water well level and seismic excitation produced from cultural noise and earthquakes. For example, Figure 1 shows the sharp changes in water level in a 52-m deep well in Florida caused by nearby passing trains and a remote earthquake (Parker and Stringfield, 1950). The fluctuations caused by trains were approximately l-2 cm and were comparable with the fluctuation caused by the earthquake. Unfortunately, the distances from the sources are not indicated in this paper. The low-frequency fluctuations were caused by changes of atmospheric pressure and earth tides. In the same work, a 1.4-m fluctuation in the water level from a different well in Florida was reported as a consequence of an earthquake originating 1200 km away.

Barabanov et al. (1987) studied the influence of seismic waves produced by a vibroseis-type source on water level in 100-300-m deep wells, applying excitation frequencies in the range of 18-35 Hz. Kissin (1991) summarized the results of these experiments. The seismic waves produced fluctuations in water level of l-20 cm. In addition to the short-term fluctuations, longer-term changes in water level induced by the seismic source were observed for periods of up to five days. The presence of resonance frequencies, to which the aquifer responded sharply, is noted. Barabanov et al. (1987) observed that effects of vibroseis-type sources on aquifers were comparable to the effects of teleseismic earthquakes. A sharp fluid pressure response in the aquifers in California associated with the Landers earthquake was reported recently (Galloway, 1993). Observations from this earthquake show a co-seismic 4.3-fold increase in the fluid pressures that decayed exponentially for several days to weeks. It is worth noting that the decay rate is consistent with the one observed by Barabanov et al. (1987) after vibratory action.

The extensive study of hydrogeological effects produced by the Alaska earthquake of 1964 throughout the world revealed a significant influence on fluid level in wells (Vorhis, 1968). The earthquake was purported to have produced observed changes in well levels in Canada, England, Denmark, Belgium, Egypt, Israel, Libya, the Philippine Islands, South-West Africa, and Northern Australia, immediately following the passage of seismic waves. An astonishing 7-m fluctuation in a well in South Dakota was reported (Vorhis, 1968). A change of about 1 m was recorded in a well in Puerto Rico (Vorhis, 1968). Noticeable fluctuations in water level caused by teleseismic and local earthquakes are reported for numerous wells by other investigators (Leggette and Taylor, 1935; Blanchard and Byerly, 1936; La Rocque, 1941; Eaton and Takasaki, 1959; Katz, 1961-63; Rexin et al., 1962; da Costa, 1964; Gordon, 1970; Sterling and Smets, 1971; Kovach et al., 1975; Wakita, 1975; Roeloffs and Bredehoeft, 1985; Igarashi and Wakita, 1991; Matsumoto, 1992).

The fact that pore pressure may undergo variations under the influence of seismic waves is well known to geotechnical engineers. Raju and Neidhardt (1991) report that the pore water pressure rose by a factor of 1.5 at a depth of 2.2 m in response to a surface vibrator producing a maximum force of 400 kN (40 metric tons) with a frequency of about 30 Hz. Dobry et al. (1989) report that pore pressure measured at a depth of 3-6 m in a sedimentary layer increased by an order of magnitude in response to a local earthquake. Shen et al. (1989) measured a response of pore water pressure to two

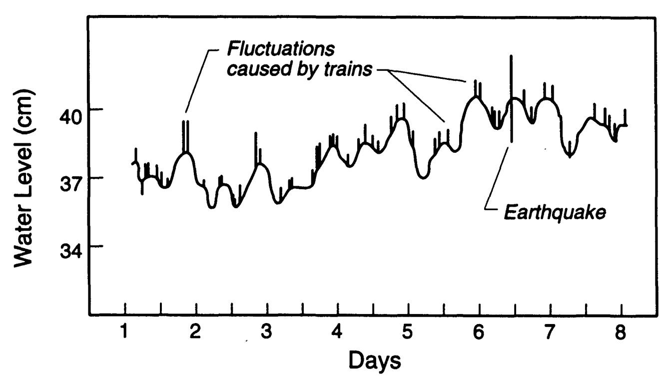

FIG. 1. Fluctuations of water level in a 52-m deep well induced by seismic waves excited by passing trains and an earthquake. The effect of trains is comparable to the effect of the earthquake. The earthquake epicentral distance is not reported (Parker and Stringfield, 1950).

local earthquakes (magnitudes of 6.2 and 7.0 and epicenters at 6 and 80 km, respectively) in Taiwan using sensors installed at depths of 2-16 m in relatively loose silty sand and sandy silt deposits. The maximum co-seismic increase in pore water pressure was 27 percent in a maximum period of 24 s. The time interval for a 50 percent decrease of the induced pore pressure post-excitation varied from several to 207 s. Engineers generally attribute the induced pore pressure to a volumetric strain caused by seismic excitation.

Oil production changes

Numerous investigations also show the effects of earthquakes on oil production. Table 1 outlines the following observations for an overview comparison. Items are given in chronological order. Steinbrugge and Moran (1954) described variations in oil production in Kern county during the Southern California earthquake of July 21, 1952. Several of the wells showed increased casing pressure many times above normal in the first few days following the earthquake. However, several wells in the same field did not show changes, indicating a complex nature to the effect. One example is cited where two neighboring wells behaved very differently. One well showed increased production from 20 bbl/day to 34 bbl/day (1 bbl of oil = 159 x 10^{-3} m^3) immediately after the earthquake, whereas another dropped in production from 54 bbl/day to less than 6 bbl/day. Simkin and Lopukhov (1989, 14) cite an example from the Starogroznenskoye oil field in the Northern Caucasus (regions of the former USSR mentioned in this paper are shown on the map in Figure 2), where production increased by 45 percent following the earthquake of January 7, 1938. Unfortunately, they do not give any other quantitative details.

In quantifying earthquakes in Table 1 and below, we use a 12-point intensity scale as cited in the original references. We are aware that there are at least three definitions of such a scale. Unfortunately, most of the references do not specify the scale applied and therefore the cited intensity values may differ from study to study.

An earthquake of magnitude 6.5 (intensity at epicenter of 8-9) occurred in the Daghestan Republic (USSR) on May 14, 1970. This area has a number of productive oil fields, and careful studies were made on the correlation between the occurrences of the earthquake and its aftershocks and changes in oil production (Voytov et al., 1972; "Daghestan Earthquake of May 14, 1970. Seismology, Geology, Geophysics," 1980; Osika, 1981). Immediately following the shock there was a sharp increase in production. Production generally decreased as the aftershock activity diminished. The strongest aftershocks were followed by increases in production. Variations in oil yield corresponding to seismicity continued over several months. The largest changes in oil production were displayed by wells located in the vicinity of known (inactive) faults. On the day following the May 14 earthquake, oil and water outflow were observed from abandoned wells within the zone of seismic intensity 7. The oil outflow from these wells had terminated several years before the earthquake. Outflow continued through 1974.

The behavior of individual wells in several oil fields was reported for this earthquake. The Gasha oil and gas field is located 50 km from the epicenter. Figure 3 shows the

Table 1. Summary of case studies of influence of earthquakes on oil production.

Case history No.	Reference	Field location	Earthquake magnitude	Seismic intensity in oil field (12-pt. scale)	Epicentral distance (km)	Observed effect	Duration of effect
1	Steinbrugge and Moran (1954)	Kern County, California	7.6	8–11	80	mixed effects of increased and decreased oil production, increased casing pressure	
2	Smirnova (1968)	Cudermes field, Northeastern Caucasus	3.5 and 4.5	5–7	10–15	increased oil production, largest effect near faults	less than a month
			4.5 and 4.2	5	10–15	increased oil production	
3	Voytov et al. (1972); "Daghestan earthquake of May 14, 1970" (1980); Osika (1981)	Different fields in Daghestan and Northern Caucasus	6.5	4–7	50–300	large changes in oil production, renewed production in abandoned wells; changes in production associated with passive faults	several months to three years
4	Osika (1981)	Anapa, Northern Caucasus	5.5	3–5	100	increased oil production from some wells, pronounced near anticlines; increased reservoir pressure	
5	Simkin and Lopukhov (1989)	Starogrozenenskoye field, Northern Caucasus	4.8	6	30	45% increase in oil production	

response of well no. 23 to the earthquake. In response to the main shock, production immediately increased by one order of magnitude. The water yield from the same well increased by three times, as is also shown in Figure 3 (Voytov et al., 1972). There is a delay in water flow relative to the oil production increase that is not addressed by these authors. The Eldar oil and gas field is located 220 km from the epicenter. Well no. 58, drilled in the vicinity of a fault, responded with a sharp increase in production, yielding a rate of production characteristic of the entire field before the earthquake. In the first half of May 1970, the production amounted to 3.3-3.4 x 10^6 kg/day. After numerous aftershocks the oil yield increased to 4.3 X 10^6 kg/day (Osika, 1981, 25). The increase in production may have been even larger had it not been restricted artificially so as not to exhaust the reservoir. The average production yield increase in this well was about 15 percent. Unfortunately, the total period over which the effect lasted was not reported.

Osika (1981, p, 26-34) examined data from several other earthquakes in the Caucasus. He gives an example of an earthquake in 1966 with an epicenter in the Black Sea near Anapa (intensity at epicenter 6-7). Effects of this earthquake were manifested in the Abino-Ukrainskaya oil field located 100 km from the epicenter, where some wells showed increased production. Osika points out that hydrodynamic effects of earthquakes were observed even in zones with a seismic intensity as small as 3 and 4. In particular, the Kolodeznoye oil field is located 300 km away from the epicenter of the Daghestan earthquake ("Daghestan Earthquake of May 14, 1970. Seismology, Geology, Geophysics," 1980, 200-202). Oil production from well no. 5 increased from 51.8 to 73.6 m3/day immediately after the earthquake. The reservoir pressure in well no. 162 increased by 10-l5 percent after the earthquake. The liquid level in well no. 130 rose by 9 m, then gradually returned to the initial level. The effect was not observed in all wells and was more pronounced near anticline domes. Osika notes that establishing quantitative relationships was difficult in many cases because measurements of the oil yield were not performed regularly.

Smirnova (1968) studied the influence of several earthquakes on oil yield in the Gudermes Field in the Northeastern Caucasus. One of the wells under study, located at 10-l5 km from the epicenter of two earthquakes occurring on March 23, 1950 (M = 3.5 and 4.5). showed an increase in production of more than 30 percent on the day the earthquakes took place. Following two other earthquakes, occurring in August 1955 (M = 4.5 and 4.2, seismic intensity of 5 at the field), all the wells showed immediate or delayed changes in production. The effect of the earthquakes did not last for more than a month. Again, the effect was more pronounced in wells located near anticlinal inactive faults. Investigations showed significant variability of the effect of earthquakes throughout the oil field. Some wells definitely showed increased production, while some of them exhibited no changes.

General remarks

We found a significant number of observations regarding the effect of local and remote earthquakes on the water level in wells. Such observations prove that even relatively weak

FIG. 2. Map of part of the former USSR showing regions mentioned throughout the paper.

seismic waves can alter yields by changing fluid pressures in the aquifers. In contrast to this, observations of the influence of seismic waves on oil and gas production are far more contradictory. In part, these contradictions can be explained by the relatively scarce number of reliable observations of oil and gas reservoirs compared with the abundance of water well responses. Accurate, daily measurements of production, which are indispensable for inferring the relationship of oil production with earthquake occurrence, are not published and often not recorded. Consequently, investigators note the inconsistency of the observed effect, so that the response of a particular well can hardly be predicted. In addition, if increased production is observed in response to a local earthquake, it remains unclear whether it is caused by the actual elastic wave effect or by rupture within the reservoir. Steinbrugge and Moran's (1954) overview is an example of such an uncertainty.

GENERAL DESCRIPTION OF MECHANISMS

Proposed mechanisms of the effect of weak elastic waves on saturated media are considered in detail in a number of publications (Bodine, 1954a, 1954b, 1955; Duhon, 1964; Surguchev et al., 1975; Gadiev, 1977; Wallace, 1977; Kuznetsov and Efimova, 1983; Kissin and Stklianin, 1984; Vakhitov and Simkin, 1985; Sadovskiy et al., 1986; Simkin and Lopukhov, 1989; Kuznetsov and Simkin, 1990; Kissin, 1991; Simkin and Surguchev , 199 1). Fundamentally, gravitational and capillary forces are principally responsible for the movement of fluids in the reservoir (Simkin, 1985; Odeh, 1987). Gravitational forces act on the difference in density between phases saturating the medium. Residual oil in a typical depleted reservoir is generally contained in the form of droplets dispersed in water. Density differences induce the separation of oil from water. Capillary forces play an important role in liquid percolation through fine pore channels. Liquid films are adsorbed onto pore walls during the percolation process. These films reduce normal percolation by reducing the effective diameter of pore throats. If the pore size is small, the boundary film may block percolation altogether. Percolation may resume only when some critical pressure gradient is applied. Furthermore, the presence of mineralization in the percolating fluid changes fluid film thickness. Calculations show that the average thickness of the surface film of water in a porous channel is inversely proportional to the salt concentration, and ranges from 5 μ (NaCl solution with a concentration of 100 g/l) to 50 μ (concentration 1 g/l) (Kuznetsov and Simkin, 1990, p. 123), where μ represents microns. Throat diameter in reservoir rocks can vary from 2 to 100 μ (Fairbanks and Chen, 1971; Dawe et al., 1987).

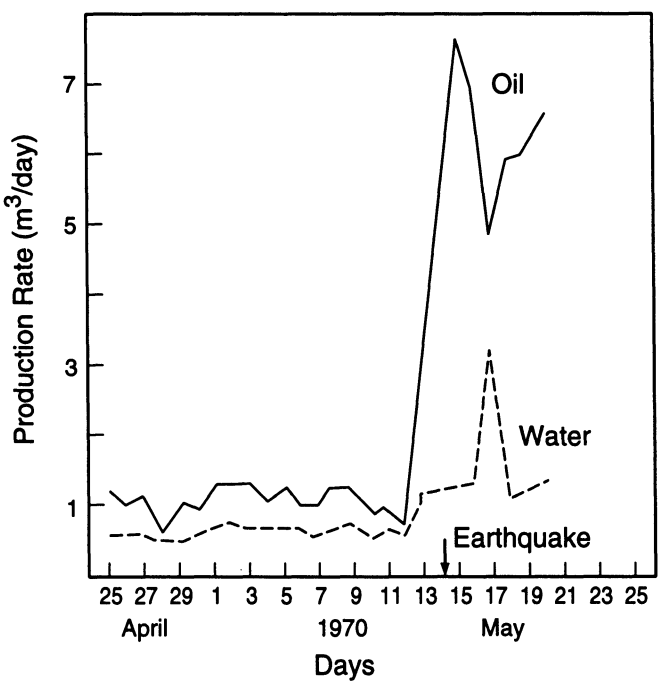

FIG. 3. Response of daily oil and water production from a well in an oil field in Daghestan to an earthquake of $M = 6.5$ and intensity at the epicenter of 8. The well is located 50 km from the epicenter. Note the increase in oil production appears to take place before the earthquake. This apparent effect is not real but results from the low sample rate and the fact that the sample points are connected by straight lines (Voytov et al., 1972).

In saturated reservoirs the water and oil phases are intermixed and dispersed within each other. The important attribute of the relative permeabilities between phases, which governs the oil yield factor, is the existence of a threshold oil saturation level S_o below which the oil is immobile (Odeh, 1987; Nikolaevskiy, 1989). At lower oil saturations, oil breaks down into isolated drops. As a result, the oil yield of a water-bearing stratum exhibits a physical limit equal to 1 - S_o. For instance, if $S_o = 0.3$, then only 70 percent of oil can be extracted using its natural mobility.

Nikolaevskiy (1989) speculates that excitation by elastic waves can change the phase permeability, thereby increasing the mobility of oil below S_o. Elastic wavefields may considerably reduce the influence of capillary forces on oil percolation, resulting in an increased rate of migration through the porous medium. This appears to be because of the fact that vibration of the surface reduces the adherence of fluid to it. Mechanical vibrations destroy the surface films adsorbed on the pore boundaries, thereby increasing the effective cross-section of pores. The destruction of films occurs both in weak and intense wavefields. In the latter case a number of different nonlinear effects produced by intense ultrasound such as in-pore turbulence, acoustic streaming and cavitation (Kuznetsov and Simkin, 1990, 126-127) may also contribute to this effect. Another effect increasing percolation is the reduction of surface tension and viscosity of liquids in the ultrasonic field, which apparently is caused by heating of the medium as a result of ultrasound absorption (Johnston, 1971).

Low-frequency waves are less likely to produce nonlinear elastic effects because the wave intensity (density of energy flux) is proportional to frequency squared (Nosov, 1965, 5). However, in the presence of an alternating pressure field with a wavelength exceeding the diameter of oil droplets and gas bubbles in water, droplets are induced to move because of their different densities (Kuznetsov et al., 1986; Sadovskiy et al., 1986). A theory describing this effect was developed by Vakhitov and Simkin (1985, 189-191), and

Kuznetsov and Simkin (1990,220-222). Because gas bubbles usually adhere to the surface of oil droplets, they carry oil droplets in response to the oscillatory field (Simkin, 1985).

Bjerknes forces, which are attractive forces acting between the oscillating droplets of one liquid in another, induce the coalescence of the oil droplets (Nosov, 1965, 13; Kuznetsov and Simkin, 1990, 129). Thus, as shown schematically in Figure 4, continuous streams of oil capable of Row may be formed out of dispersed oil droplets with wave excitation.

Most of the mechanisms described above apply to the effects of relatively weak elastic waves on fluid percolation. Major mechanisms involved in cases of weak and strong excitation seem to be essentially different. For instance, in the procedures proposed for removing wellbore damage formed by scales and precipitants, high-intensity ultrasound is used. The effect produced in this case is purely mechanical destruction of the local deposits, and has nothing to do with enhanced oil mobility. What is missing in the present state of the investigation of the effect of weak elastic waves on saturated media is a quantitative description of the major mechanisms and the theory or numerical model that could predict the result.

LABORATORY STUDIES

Effects produced by ultrasound are extensively used in the chemical industry for separation of mixtures, removal of contaminants, extraction of impurities, recovery of valuable materials from wastes, etc. (Nosov, 1965). Many of the experiments demonstrating the possibility of application of ultrasound in geophysics originated from this area. Table 2 provides a summary of the results of the influence of ultrasound on permeability of porous media obtained from laboratory work.

Influence of ultrasound on oil and water percolation and water Roods

To our knowledge, the first comprehensive laboratory study regarding the influence of ultrasonic energy on liquid Row through porous media was carried out by Duhon (1964). Duhon studied the characteristics of oil displacement by water in the presence of ultrasound. The author observed an increase in oil recovery from sandstone as a result of ultrasonic excitation. Additional recovery after a conventional water flood ranged from 6.4 to 14.7 percent for different frequencies (Duhon, 1964). Figure 5 demonstrates the effect of ultrasound on the ratio of water and oil permeabilities during the flood experiment. The permeability ratio K_{water}/K_{oil} in the absence of sound (I in Figure 5) was greatly reduced when sound was applied (2-4 in Figure 5). The author notes that the amount of oil recovered increased with decreasing oil viscosity. Ultrasound excitation also created an increase of the flow rate into the injection well. Regarding the possible mechanisms responsible for the observed effects of improved permeability, the author cites

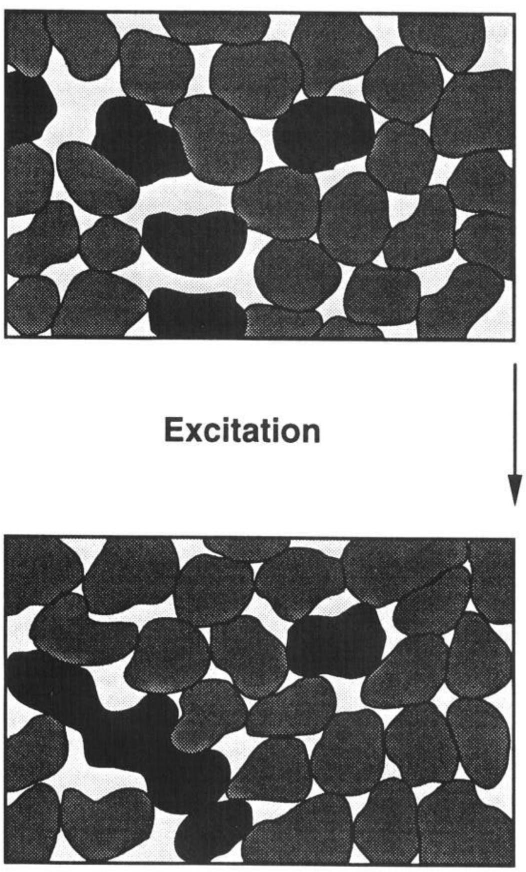

FIG. 4. Vibrations cause the coalescence of dispersed oil droplets, in turn forming streams of oil in the porous space. As a result, the oil mobility increases.

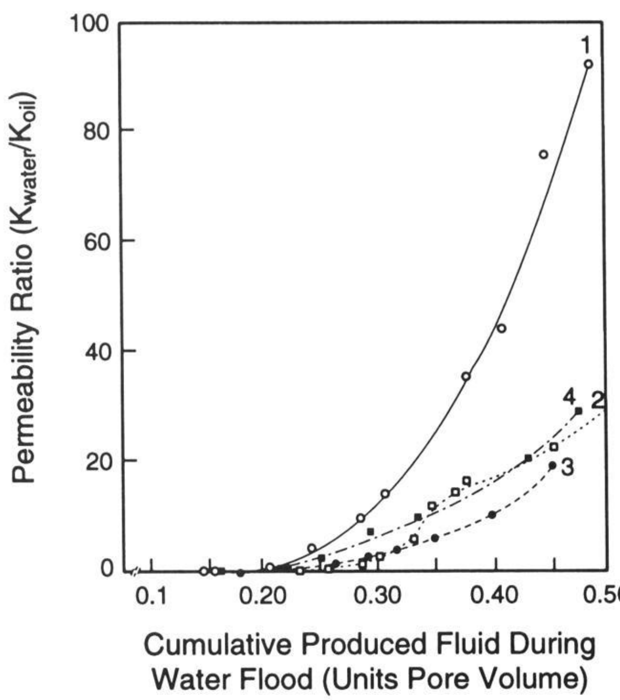

FIG. 5. Effect of ultrasound with different frequencies on water/oil permeability ratio: (I) water flood without application of ultrasound; (2, 3, 4) water flood with application of ultrasound with frequencies I, 3.1, and 5.5 MHz, respectively. Ultrasound considerably reduces the water/oil permeability ratio (Duhon, 1964).

cavitation and radiation pressure produced by the ultrasound. Note the very high frequencies of several MHz used in Duhon's experiment (Table 2).

Fairbanks and Chen (1971) measured percolation of oil through sandstone at different oil temperatures in the presence of an acoustic field. Increased percolation rates in the presence of ultrasound were noted at all temperatures, but were largest (increase by a factor of up to 18) at temperatures between 100 and 110 degrees C (Figure 6). The authors do not provide a quantitative explanation of this change. The dependence of the effect on temperature may be caused by changes in oil viscosity; however, independent control of the oil physical properties was not carried out during the experiment. Based on the observed laboratory effect, the authors proposed to use acoustic horns to boost recovery yields from reservoirs ("Sonic well stimulation research pushed," 1970).

Similar effects were reported by Gadiev (1977). He conducted laboratory experiments in saturated, unconsolidated

Table 2. Summary of laboratory studies of influence of sound/ultrasound on permeability of porous media.

Case history No.	Reference	Observed effect caused by sound/ultrasound	Frequency range	Sonic field intensity	Duration of excitation	Duration of the effect after end of excitation
1	Duhon (1964)	increased oil recovery during water flood; reduction of water/oil permeability ratio; increased flow rate into injection well	1–5.5 MHz	50 W (power of transducer)	6–9 hours	
2	Nosov (1965)	decrease of viscosity of polystyrene solution	300 kHz	$(20–120) \cdot 10^3$ W/m^2	20 min.	irreversible
3	Komar (1967)	100 percent paraffin removal			12.5–23.1 hr	
4	Fairbanks and Chen (1971)	temperature dependent increase of oil percolation rate	20 kHz	150 W (power of transducer)		
5	Johnston (1971)	decreased viscosity of epoxy resins, polyamids	47 kHz, 880 kHz	80 W, 50 W (power of transducers)	30 sec to 45 min	up to 48 hours
6	Abad-Guerra (1976)	removal of paraffin			0.5–1 hour	
7	Cherskiy et al. (1977)	sharp increase of sample water permeability	26.5 kHz	$(2–9) \cdot 10^3$ W/m^2		several minutes
8	Gadiev (1977)	increase of efficiency of oil displacement by water; decrease of surface tension of transformer oil; decrease of viscosity of polycrylamid solution	40Hz–15kHz; 400–800 Hz; 30–60 Hz	10–40 W (power of transducer); 10^{-1} W/m^2	1–5 hours	
9	Neretin and Yudin (1981)	increase of the rate of oil displacement by water	50–80 kHz	$(0.8–1.2) \cdot 10^3$ W/m^2	6 hours	
10	Sokolov and Simkin (1981)	decrease of oil viscosity	18 kHz	$8 \cdot 10^3$ W/m^2	30–60 min.	120 hours
11	Snarskiy (1982)	frequency dependent increase of the rate of oil displacement by water	9–40 Hz	$2 \cdot 10^3$ W/m^2		
12	Medlin et al., (1983)	increase of the rate of oil displacement by carbon dioxide	100 Hz	10^{-4} W/m^2	20 hours	
13	Ashiepkov (1989)	increase of oil percolation rate through sample	30–400 Hz	10^{-4} –10^3 W/m^2		
14	Dyblenko et al. (1989)	increase of the rate of kerosene displacement by water	200 Hz	88 W/m^2		
15	Pogosyan et al. (1989)	acceleration of gravitational separation of kerosene and water	120 kHz	10^4 W/m^2	2 hours	
16	Kuznetsov and Simkin (1990)	increase of oil mobility	1.2 Hz	10^{-3} W/m^2	48 hours	
17	Simkin et al. (1991)	increase of the rate of kerosene displacement by water		7.8 m/s^2 (particle acceleration in sound field)	51–92 hours	
18	Simkin and Surguchev (1991)	coalescence of oil droplets			2 minutes	

sand that was exposed to vibration created by an electromagnetic shaker. Excitation considerably accelerated the process of the penetration of liquids into capillaries (this is known as the sono-capillary effect). As a result, the efficiency of oil displacement by water during excitation increased by 10–15 percent, and the displacement duration was three times less than the duration in the absence of excitation. However, it is difficult to assess the veracity of Gadiev's results because he does not provide enough details to compare his data with the results of other experiments.

Cherskiy et al. (1977) measured the permeability of core samples saturated with fresh water in the presence of an acoustic field. According to their description, within a few seconds after the beginning of the pulse-mode treatment, the permeability of the sample increased sharply (by a factor of 82); however, a few minutes after removal of the sound field permeability decreased to the value before stimulation. Figure 7 shows the results for both pulse and continuous wave (cw) mode excitation, as a function of sound intensity. In pulse mode, the same permeability values were obtained as those in continuous mode applying intensities 10 to 15 times lower, but no explanation for the difference is given.

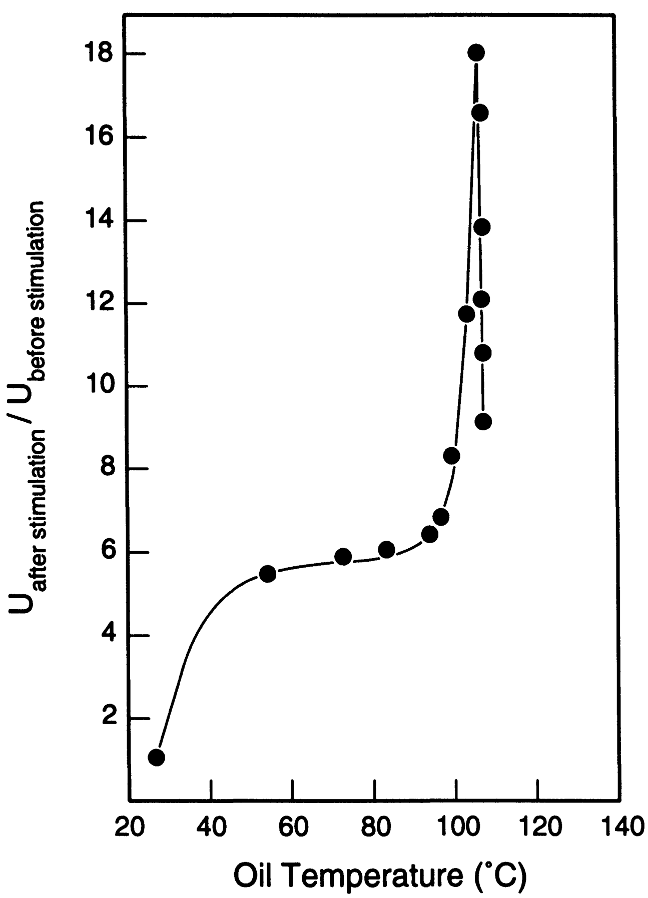

FIG. 6. Change in oil flow rate through sandstone after acoustic excitation at different oil temperatures. The vertical axis shows the ratio of percolation rate after stimulation U_{after} to the rate before stimulation U_{before}. An increase of up to 18 times was observed. The frequency and the ultrasonic transducer power were 20 kHz and 70 W, respectively (Fairbanks and Chen, 1971).

The pulse mode duty cycle is also not mentioned. The authors suggest the destruction of boundary water films as an explanation of the effect obtained. However, the authors did not provide a sufficient description of the experimental setup and verification procedures used.

The effect of the continuous wave acoustic field on the displacement of immiscible fluids was studied by Neretin and Yudin (1981). During the displacement of hydrocarbons by water through loose sand under the influence of ultrasound, the time displacement was reduced (the exact figure is not given), and the hydrocarbon yield increased from 65 to 85 percent.

Simkin and Surguchev (1991) observed the intense growth of oil droplets for two minutes after the beginning of cw excitation in a laboratory experiment. Frequency and intensity of radiation are not provided. They attributed the growth to sonically induced coalescence.

Estimations based on the equations of hydrodynamics show that the segregation rate of oil and water, which is considerably slowed down by capillary forces, may be increased by 2-3 orders of magnitude by applying sound (Simkin, 1985; Simkin and Lopukhov, 1989, 18; Kuznetsov and Simkin, 1990, 219–223). There are experiments confirming this effect. Pogosyan et al. (1989) studied the gravity-induced separation of saline water and kerosene impregnating the cemented mixture of quartz sand and marshallite. They applied a continuous transverse wave excitation with an amplitude of 0.1 mm. The elastic wavefield accelerated the gravitational phase separation by a factor of approximately 500 compared with the natural rate.

Viscosity and surface tension of fluids under the influence of vibration

Sokolov and Simkin (198 1) measured the dynamic viscosity of oil in the presence of an acoustic field. Immediately after the 30–60 minute-long treatment, the oil viscosity

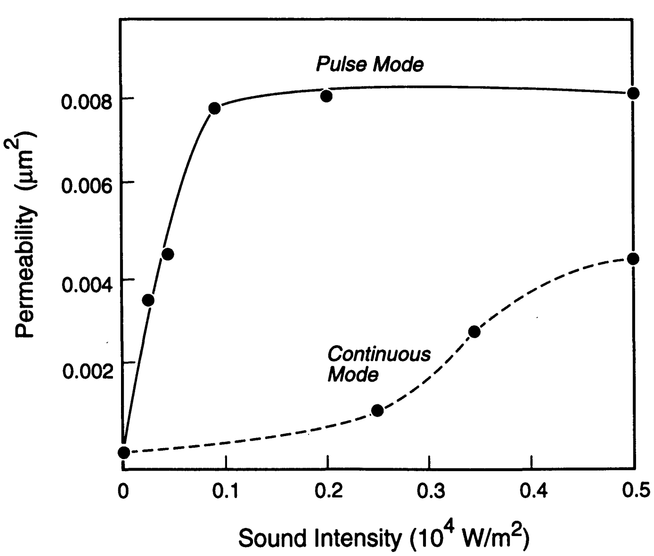

FIG. 7. The response of water permeability in a core sample to application of an acoustic field with varying intensity. The frequency was 26.5 kHz. The treatment in pulse mode proved to be more effective (Cherskiy et al., 1977).

dropped by 20-25 percent, then gradually returned to the pretreatment level during approximately 120 hours. Gadiev (1977, 30), in a review, notes that ultrasonic radiation may reduce the viscosity of high-polymeric liquids by up to 18-22 percent. In addition, Gadiev carried out measurements of the change in surface tension of transformer oil as a function of applied frequency and the duration of excitation. He observed a surface tension decrease with both frequency and time (Gadiev, 1977, 41). An extensive study of the influence of ultrasound on polymer viscosity was carried out by Johnston (1971). In the polyamid system used, Johnston exposed the fluid to a cw wavefield of 880 kHz for 20 minutes, inducing a six-fold decrease of viscosity, with no detectable degradation or polymerization. Similar reductions of fluid viscosity in the presence of an ultrasonic field are reported by Nosov (1965).

Paraffin removal induced by ultrasound

A study of the influence of ultrasound on paraffin deposition in sandstone cores was carried out by Abad-Guerra (1976). He studied the improvement of oil permeability in the presence of ultrasound in samples whose initial permeability was reduced to zero by precipitating paraffin. The permeability improvement ranged from 7 to 51 percent (Abad-Guerra, 1976, 64). The author concluded that the principal factors causing the removal of paraffins in the formation were cavitation, which causes strong agitation of the fluid, and heating of the medium. For instance, during one excitation of 40 minutes duration, the temperature increased from 31 to 76 degrees C (Abad-Guerra, 1976, 67).

Successful paraffin removal from rock using ultrasonic waves was reported by Horblit (1951), and Dvali and Sumarokov (1968). Komar (1967) reports mixed results.

Effects produced by low-frequency excitation

The study of the effects on oil mobility produced by low-frequency waves is of special interest because of their potential application to the reservoir stimulation by surface-based vibrators.

Laboratory investigations show that enhanced oil mobility occurs when low-frequency waves are applied. Gadiev (1977) measured the flow time of a given volume of polycrylamid solution through viscosimeter as a function of the excitation time. Frequencies of 30, 50, and 60 Hz with the wave displacement amplitudes equal to 1 mm were tested. The liquid flow rate increased by a factor of 1.5-2 over approximately six hours of continuously applied sound, showing that the rheological properties of the polymeric solution may be changed by a relatively low frequency during the excitation period.

Dyblenko et al. (1989) applied sound at a frequency of 200 Hz to enhance the displacement of kerosene by water in a reservoir core sample. They measured an increased kerosene yield of 12 percent as a result of the applied sound. During the excitation the mobility of residual oil increased, and the permeability to water decreased. Simkin et al. (1991) studied the effect of sound on oil yield from experiments using a loose quartz sand impregnated with kerosene. The particle accelerations as a result of the sound field in their experiment were as high as 0.8 g (frequency not given). The effect of excitation led to a significant increase in kerosene yield from the sample. Because of natural fluid flow without excitation, 32 percent of the initial amount of kerosene was extracted over 300 hours, whereas 60 percent of kerosene was recovered during only 51 hours with the application of sound.

Snarskiy (1982) used fine-grained quartz sand to study oil displacement by water in the presence of a sound field. The frequencies were in the range of 9-40 Hz. He found that the displacement rate was 19 percent higher when the sample was exposed to the sound field. The effect was frequency dependent. Some frequencies did not produce any changes in the displacement characteristics. Another experiment is described by Kuznetsov and Simkin (1990). A loose sand sample with an oil weight fraction of 5 percent and a seawater fraction of 40 percent was exposed to continuous wave (CW) excitation with a frequency of 1.2 Hz and an amplitude of 4 μ. Before treatment, oil was observed to remain relatively stationary over 15 days, while oil began to be exuded within 48 hours after the treatment started. In the above experiments, post-excitation effects are not reported.

Even very weak seismic excitations have been observed to affect oil yield. Medlin et al. (1983) applied cw sound at an amplitude 10^{-8} m to an oil-saturated sandstone core. During the treatment, carbon dioxide flowed through the sample at rates as high as 0.18 cm^3/hour. Figure 8 shows the influence of the excitation on gas flow. Flow ceased when the excitation was turned off ("cradled") and commenced when excitation was resumed. The authors proposed to use the gas

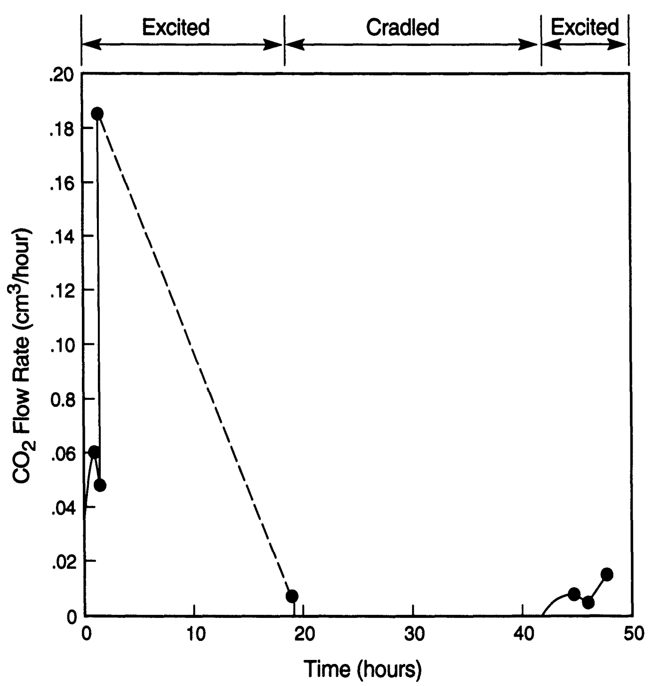

FIG. 8. The influence of weak, 100 Hz excitation of amplitude 10^{-8} m on oil displacement by carbon dioxide in oil-saturated sandstone. Wave-excitation enhanced gas flow through the sample up to as much as 0.18 cm^3/hour during the initial 19-hour test period. While the sample was clamped and unexcited (cradled), no flow was observed. When excitation was resumed, carbon dioxide flow recommenced (Medlin et al., 1983).

drive combined with weak seismic excitation as a method of enhanced oil recovery.

We should note that Medlin et al.'s claim is serious and needs thorough substantiation. Indeed, they used a remarkably low amplitude (equal to the observed amplitudes of microseismic noise at the earth's surface) to obtain an observable effect. If this is a valid effect, one should observe perceptible variations in oil production following the changes in the level of ambient seismic noise. We are not aware of such observations, although it cannot be excluded that this phenomenon exists. Moreover, the work cited is a patent containing reference to only a single experiment.

Nevertheless, one set of experiments may be supportive of Medlin et al.'s claim. Ashiepkov (1989) conducted similar laboratory studies of the effect of weak, low-frequency excitation on the percolation rate of transformer oil through porous core samples. The samples were exposed to CW excitation. Figure 9 shows the dependence of the oil percolation rate on sound intensity for different initial sample permeabilities. Permeability increased by 3-7 times as the intensity increased from 10^{-2} to 10^{3} W/m*. The author infers that this effect is because of a significant decrease of

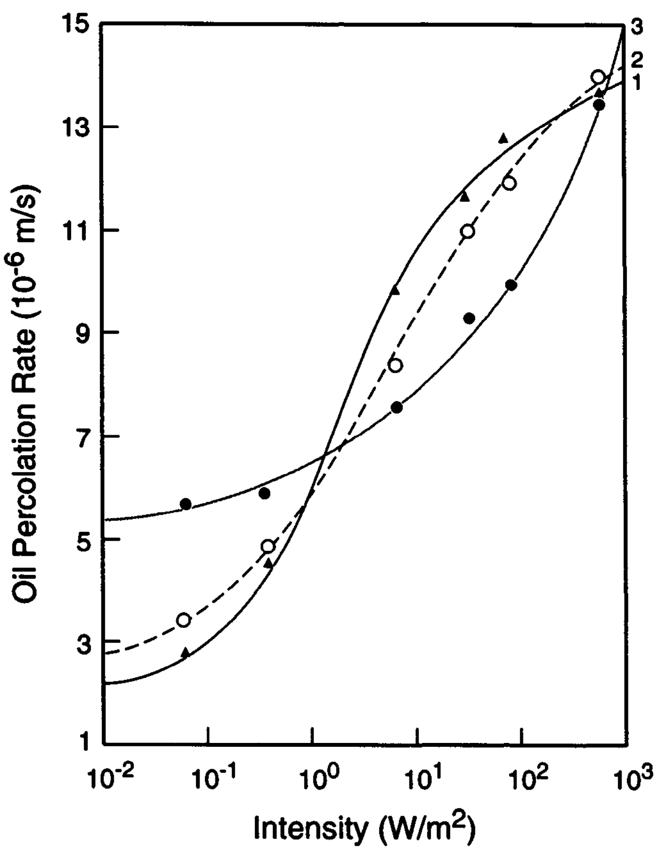

FIG. 9. Oil percolation rate dependence on low-frequency wave intensity in samples with different initial permeabilities: (1) 0.28 x 10^{-12} m^2, (2) 0.35 x 10^{-12} m^2, (3) 0.65 × 10^{-12} m^2. Samples were exposed to excitation vibrations in the frequency range of 30-400 Hz. Oil percolation improved by 3-7 times as the intensity increased from 10^{-2} to 10^{3} W/m^2 (Ashiepkov, 1989).

frictional forces between fluid and capillary walls caused by the excitation.

General remarks

The field of laboratory studies of the elastic wave effect on saturated media is the most exhaustive among the topics covered in this paper. Reported effects encompass frequencies ranging from several Hz to several MHz. It has been demonstrated in laboratory studies that high-frequency ultrasound can be used in applications for wellbore cleaning and accelerating fluid flow in reservoirs. There are fewer investigations in the low-frequency and low-intensity range, where the effects are questionable. However, it cannot be disregarded that reported pronounced fluid flow may take place from weak excitation, so further tests must be conducted.

ACOUSTIC TREATMENT OF PRODUCTIVE WELLS

Acoustic treatment of productive wells has proven to be effective for restoring the permeability of productive zones that were damaged by mud penetration and by deposits of scales and salts and for removing paraffins and asphaltines from reservoir rock. The latter effect is a result of the melting of soft organic deposits in the vicinity of the wellbore as a result of the absorption of ultrasound and the resultant heating. Ultrasound has also been used for preventing salt precipitation on downhole equipment (Akhmetov et al., 1977; Makarov et al., 1978; Kuznetsov and Efimova, 1983, 155-175).

The first use of ultrasound for improved oil recovery dates back to the 1950s and 1960s. Sherborne (1954) proposed the use of sonic or ultrasonic wave excitation in an oil-bearing formation during liquid flooding or gas driving to enhance extraction efficiency. Bodine (1948; 1954a, b; 1955; 1959a, b; 1962; 1964; 1965a, b; 1967; 1968; 1971; 1976; 1981b) in a series of patents, proposed the use of acoustic waves to clean petroleum bearing strata, induce additional fracturing in reservoirs, and enhance oil mobility or achieve more effective penetration of injected chemicals into the formation. Employing sonic energy has been proposed to recover in-situ shale oil (Pelopsky et al., 1970; Bodine, 1981a). Similarly, the possibility of using elastic waves for secondary and tertiary recovery has been propounded by Phillips (1970), Keenan (1976), Fisher and Fisher (1977), Wallace (1977), Wright (1980), Williams (1984), and Ellingsen (1989). Note, however, that all of the above references are patents and do not contain serious field verification of the proposed techniques. We find most of the field case histories in the Soviet literature (Mikhailov et al., 1975; Cherskiy et al., 1977; Mikhailov et al., 1977; Dubinskiy et al., 1978; Mikhailov and Neretin, 1978; Neretin and Yudin, 1981; Sarkisian et al., 1981; Kuznetsov and Efimova, 1983; Efimova and Shubin, 1989; Simkin et al., 1990).

In the USSR, the first industrial tests of the acoustic method for reservoir stimulation began in 1975 (Simkin and Lopukhov, 1989). The method was used in a number of productive wells. The overall success rate of the treatments is reported to be about 52 percent (according to the advertising flyer issued by the VNIIGeosystem Institute). When the treatment is successful, the effect of increased permeability may last for 3-24 months, and has led to a significant increase in production in some cases.

Figures 10a and 10b show the daily oil yield and water cut in the produced fluids after acoustic treatment of productive wells at Samotlorskoye and Fedorovskoye oil fields in Western Siberia (Simkin et al., 1990) [Table 3]. The average yield and water cut before stimulation are also shown. The authors do not, however, give the time period over which these averages were calculated. The authors note that the increase of oil outflow from the reservoir was observed almost immediately after treatment. The water cut generally decreases. Figure 10a shows an example of a long-term effect, and Figure 10b shows an example of a short-term effect for a different well. In the first case the effect of the enhanced oil production lasted for more than a year, and the production gradually returned to the pretreatment level. In the second example, the effect lasted for 1.5 months and the production then dropped far below the initial level. For the Samotlorskoye and Fedorovskoye fields, the increased oil production rate was 8100 kg/day and 14 400 kg/day, and the percentage of successful treatments was 42 and 51 percent, respectively. Analogous results were obtained in the treatment of injection wells. Unfortunately, the geological characteristics of the reservoirs are not reported in this account. Also, we did not find an analysis of the factors that could be responsible for a high efficiency of the treatment in one case and its failure in another.

Results of acoustic treatment on productive wells are also reported by Kuznetsov and Efimova (1983, 146-148). This work is an example of a well-documented field history. One

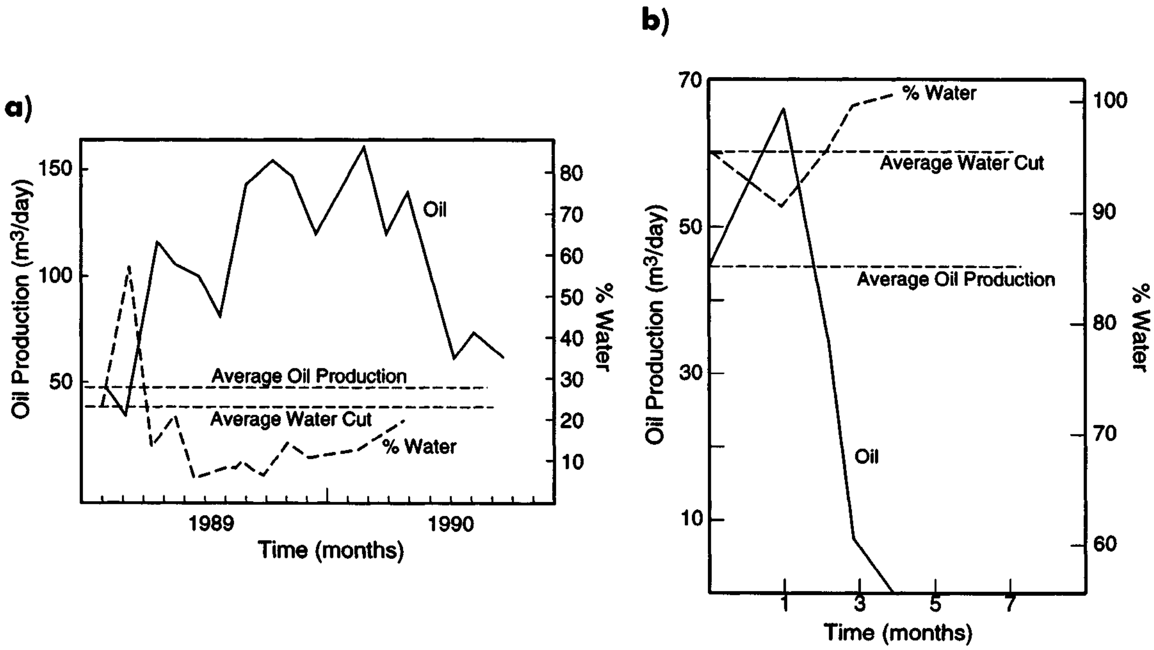

FIG. 10. Results of acoustic treatment of productive wells in Western Siberia. The long-term (a) and short-term (b) effects are presented. Improved production lasted for more than a year in the first case and 1-1.5 months in the second case. In the second case the oil production dropped far below the initial level within two months after treatment (Simkin et al., 1990).

Table 3. Summary of case studies on downhole reservoir ultrasonic stimulation.

Case history No.	Reference	Field location	Range of frequencies	Ultrasonic field intensity	Duration of excitation	Duration of the effect of increased permeability
1	Morris (1974)	Odessa, Texas	58 MHz	48 kW (tool power)	several minutes	
2	Kuznetsov and Efimova (1983)	Western Siberia	12.5–16.5 kHz	$(1.2–5) \cdot 10^3$ W/m^2	more than 5 days	
3	Simkin et al. (1990)	Western Siberia	5–50 kHz	$(1–10) \cdot 10^3$ W/m^2	several hours	94 days, 147 days on average for two different fields
4	Shaw Resource Services (1992)	Ventura County, California	200 Hz–10 kHz	3–5 kW (tool power)	1 month	10–15 days
		Bakersfield, California	200 Hz–10 kHz	3–5 kW (tool power)	4–6 hours	1 month

marginal well was stimulated in three stages. The producing reservoir rock was a fine-grained sandstone with a siliceous clay and carbonaceous cement. The layer depth was 162X8-1653.8 m. This region was perforated, and a. zone damaged by penetration of mud had been created during drilling and exploitation and had reached a thickness of 16 well diameters. The results of stimulation are shown in Figure 11. In the first stage (intensity I = 1.2 kW/m2, frequency f = 16.5 kHz), the reservoir was stimulated over a period of 69.5 hours. The production gradually increased from 37 X 10' to 62 x 10^3 kg/day. During the second stage lasting 24.5 hours (I = 4 kW/m2, f = 14 kHz), a further rise of production occurred reaching 78 x 10' kg/day, and an increased gas content was noted. The third stage lasted for only 1.5 hours (I = 5 kW/m^2, f = 12.5 kHz). The yield dropped somewhat because of the sharp increase of gas content in the reservoir. For this reason the treatment was terminated. This example shows that one negative effect of acoustic treatment may be significant degassing of the liquid. Nevertheless, as a result of this stimulation, the well productivity increased by 15 percent, as seen in Figure il. Another positive effect obtained was the extension of the pay thickness of the reservoir. Figure 12 shows the appearance of new producing intervals in the same experiment. The pay thickness increased from 3.4 to 6.8 m (Figure 12b). The most significant increase of the pay thickness occurred at the depth range between 1644 and 1649 m.

Morris (1974) describes the use of an ultra-high frequency tool which produced 2-s ultrasound pulses for cleaning sand and carbonate formations. The tool was moved at intervals during the operation to cover the entire producing zone. The time of treatment was two minutes per 30 cm. Because the sonic wavefield penetrates a short distance at such an ultra-high frequency, the principal effect produced in this case was purely mechanical destruction of wellbore scales. Total oil production from 21 wells studied before treatment was 774 bbl/day, increasing to 1098 bbl/day after the treatment, and producing a net increase of 324 bbl/day. Oil increases were realized from 14 of the 21 wells. A significant increase in total fluid was observed in 17 of the 21 wells, indicating an 81 percent success rate in removing wellbore permeability barriers, However, it remains unclear why the other 19 percent of the wells did not exhibit increased flow. The results of the application of a similar tool are reported in another study ("High-intensity sonic shock waves harnessed for effective scale removal system," 1976). On average, there was an increase in oil production of 29 percent and an increase of 25 percent in the production of total fluids. Of the number of the wells treated, 68 percent responded with an increase in oil production and another 15 percent responded with an increase in total fluids. The average increase was 8.3 bbl/day. Completion well types treated included open holes and wells with perforated casing and slotted liners.

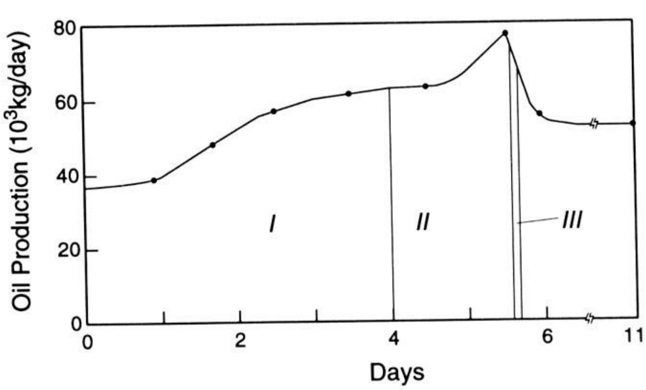

FIG. 11. Change in daily oil yield from a well at the Zapadno-Mortymyinskoye oil field in Western Siberia over three stages of acoustic treatment. Frequencies in the range of 12.5-16.5 kHz and intensities of 1.2-5 kW/m^2 were applied. Points represent data samples, and the curves connecting them were interpolated by the authors of the original paper (Kuznetsov and Efimova, 1983).

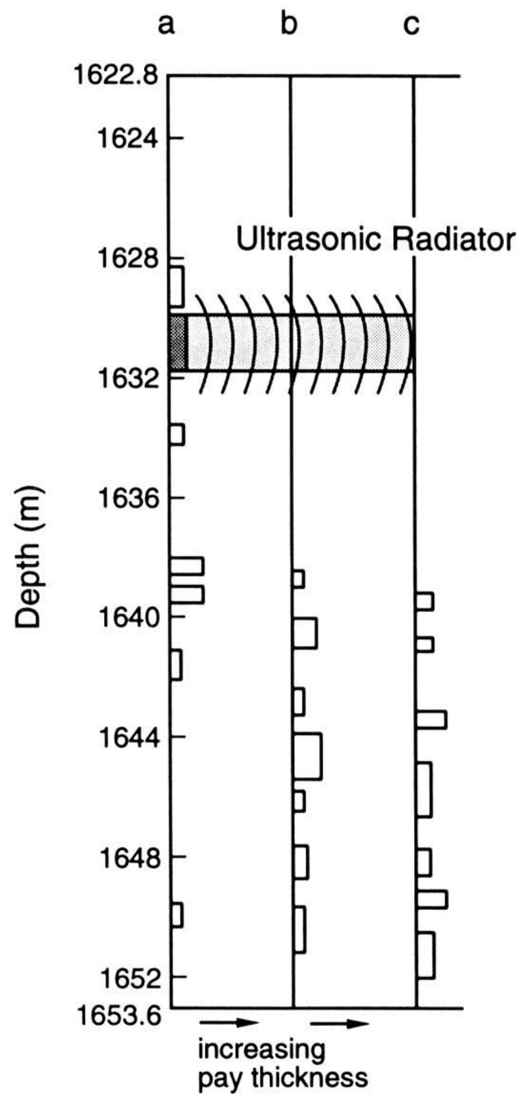

FIG. 12. Appearance of new producing intervals within a reservoir after acoustic treatment in the application described in Figure 11: (a) oil outflow profile before, (b) during, and (c) after the treatment. The length of the boxes is proportional to production. The position of an emitter is shown schematically. It was stationary during the entire experiment (Kuznetsov and Efimova, 1983).

Injection wells also responded favorably to treatment. No cement damage was reported.

Recently Shaw Resource Services, Inc. ("Sona-Tool test information," April 1992) issued a report on field tests of a piezoelectric sonic tool. The first test was performed on a single well over three months in 1983. During this period, two tools were intermittently activated for approximately two months total. The average rate of production while the tools were in operation was 37.9 bbl/day in comparison to an average of 31.8 bbl/day when the tools were not operating, an increase about 19 percent because of the stimulation. During 1991 Shaw Resource Services conducted tests on seventeen wells using the Sona-Tool. All of the wells showed declining oil and water production rates before stimulation. At intervals of 30 cm, the slotted liners were subjected to approximately three minutes of excitation. The success rate is reported to be between 40-50 percent, and the percent of additional oil produced ranges from 45 to 0. As can be concluded from the field data presented, the duration of the effect in the most effective cases can last for up to one month.

Kuznetsov and Efimova (1983), Simkin et al. (1990), and the above Shaw Resource Services (report) describe optimal criteria for the selection of wells for successful acoustic treatment. The independent experience in these references provides the following guidance:

1) The reservoir should show declining production. Indications should exist that the near-borehole zone is plugged by deposits. No improvement can be expected when a highly producing formation is treated.
2) The reservoir should not exhibit a significant decrease of internal pressure;
3) The reservoir characteristics should include:
   (a) porosity of not less than 5 percent,
   (b) significant gas content (more than 10 m^3 gas/m^3 total fluid),
   (c) viscosity not more than 10^{-2} Pa s.
4) The optimal frequency and intensity range for effective wellbore cleaning are 5-50 kHz and l-10 kW/m^2, respectively. Continuous treatment generally should last for several hours.

Cylindrical magnetostrictive tools were used most commonly in the Soviet work. The treatment was usually performed in perforated casing to achieve efficient coupling of the radiator with the reservoir rock and improve acoustic field penetration. We surmise that formation characteristics that do not meet with the above criteria may explain the negative results of those 50-60 percent of stimulation cases mentioned by different authors.

RESERVOIR STIMULATION USING SURFACE VIBRATORS

It was shown earlier that low-frequency seismic waves can also lead to an increase in the oil mobility of some reservoirs. Such waves may be applied from the earth's surface by means of seismic vibrators for stimulating reservoirs as a whole. Sadovskiy et al. (1986) conjecture that the weaker elastic wave effect produced may be compensated for to some extent by extending the time of application. However, they do not give quantitative estimates of this trade-off and this problem remains to be explored.

The possibility of oil production enhancement using surface excitation has been discussed by Bodine (1955), Snarskiy (1982), Medlin et al. (1983), Simkin (1985), Kuznetsov et al. (1986), Sadovskiy et al. (1986), Asan-Djalalov et al. (1988), Ashiepkov (1989), Ashiepkov et al. (1989), Dyblenko et al. (1989), Nikolaevskiy (1989), Simkin and Lopukhov (1989), Asan-Djalalov et al. (1990), Kuznetsov and Nikolaev (1990)) Riashentsev (1990)) Kissin (1991), Nikolaev (1991), and Simkin and Surguchev (1991). However, descriptions of real field applications are scarce, and only a few cases appear in the Soviet literature between 1988 and 1991.

Seismic vibrators of 20–30 tons (1 metric ton = 9.8 kN) are currently used in industrial seismic exploration for oil in both the US and Russia. Measurements with 10-ton vibrators showed the intensity in the field at a depth of 120 m to be about 0.1 W/m^2. Such exploration vibrators usually operate in the frequency range of 10-100 Hz. Stationary, 100-ton vibrators, capable of producing seismic wave intensities of up to 0.5 kW/m^2 in the near-source zone have been used in the Soviet Union (Sadovskiy et al., 1986; Ashiepkov et al., 1989; Simkin and Lopukhov, 1989, 20). Ashiepkov (1989) documents an intensity of 0.6-0.8 W/m^2 developed by a pair of such sources within a radius of 12-15 km. Sadovskiy et al. (1986) claim that by grouping sources, seismic waves equivalent to a seismic intensity of 4-5 can be produced. Stationary vibrators operate in a much lower frequency range with the upper limit around 15 Hz.

The method was tested using 20-ton vibrators at the depleted Abuzi oil field near the city of Krasnodar in the Northern Caucasus (Kuznetsov and Nikolaev, 1990; Kissin, 1991). The reservoir depth and thickness were 1200 and 10 m, respectively, and the water cut was 90-92 percent. The source was positioned 250 m laterally from the producing well. Figure 13 shows the results of the treatment. The average oil cut in the liquid produced before excitation was less than 10 percent. The average oil cut increased up to 20-25 percent after several days of stimulation, which com-

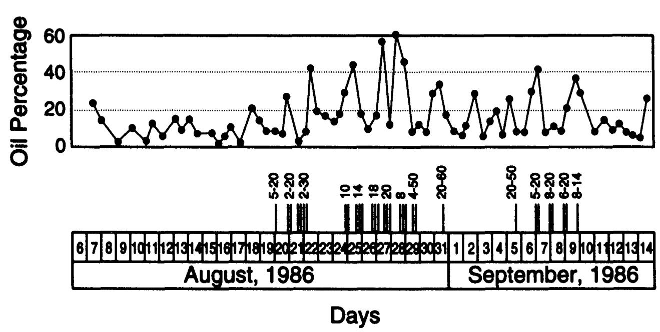

FIG. 13. Oil percentage in total liquid before and after stimulation by 20-ton vibroseis-type sources (Northern Caucasus). Vertical lines show times of excitation. The frequency of excitation or the frequency sweep interval in Hz is indicated above each line. The depleted reservoir was composed of interlayered sand and clay beds, 10 m thick, at a depth of 1200 m. The average oil percentage increased from 8-10 to 20-25 percent as a result of stimulation (Kissin, 1991).

prised a series of 20-minute vibrations each day. A similar effect was obtained at the same area one year later. The period of time when the oil/water ratio in the produced liquid exceeded the pretreatment level is estimated to be more than 60 days (Kissin, 1991).

Another example is given by Simkin and Surguchev (1991). They conducted an experiment at the Tchangirtash oil field in Kirghizia. The reservoir was at a depth of 410-540 m with a pay thickness between 5.745 m. The water cut was 90 percent. Several 50 kW vibratory generators continuously stimulated the reservoir during approximately one month in the first pilot area and two weeks in a second pilot area. In the second pilot, the vibratory stimulation was combined with a gas injection. Figure 14 shows the increase in the oil production rate after treatment in both cases. In the first one, the water cut was reduced by 25-30 percent. The second pilot stimulation resulted in a 1.6-fold increase in the average daily production; whereas, the water cut decreased by 20-25 percent. The information about the frequencies of excitation is not available.

Kuznetsov and Nikolaev (1990) include details of independent tests at three different oil fields with varying geological conditions and reservoir characteristics. Necessary baseline information as well as the post stimulation behavior of yields are provided. Simkin and Surguchev (1991) provide only those examples of field stimulation tests that we used in Figure 14. They confined themselves to a very concise description of the experimental conditions. Also note the scanty number of data samples.

Simple qualitative reasoning leads to the conclusion that vibrational treatment increases the mobility of the less abundant phase of the liquid inside the reservoir (Nikolaevskiy, 1989). Indeed, stimulation appears to make the dispersed phase coalesce and flow. Kuznetsov and Nikolaev (1990) describe an attempt to stimulate production of a well yielding almost purely oil before excitation. Excitation by 20-ton vibrators at frequencies of 17 and 18 Hz was used (information about the duration is not available). After several stimulations, the water percentage significantly increased, as shown in Figure 15. The authors describe a breakthrough of water into highly productive wells with a low water cut after they were stimulated. These results do not contradict the general understanding of the processes proceeding in the reservoir under excitation, and indicate that depleted reservoirs react most favorably to seismic stimulation. The excitation of nondepleted reservoirs may have a negative effect, increasing the water mobility. Other examples of successful vibroseismic treatments are given by Asan-Djalalov et al. (1988) and Asan-Djalalov et al. (1990), though in a very terse manner.

Kuznetsov and Nikolaev (1990) summarize the field experience leading to the highest efficiency of vibrational treatments. They provide several criteria for reservoir selection:

1) The depth should not exceed 1500-1700 m (for available surface vibrators with 20-30 tons of force).
2) Water percentage should not be less than 90 percent (use in depleted oil fields is most effective).
3) Oil viscosity small to moderate.
4) Reservoir resonant frequencies should be selected (a suggested approach to finding optimal frequencies is to measure fluid level oscillations in a given well while sweeping over a large range of frequencies).

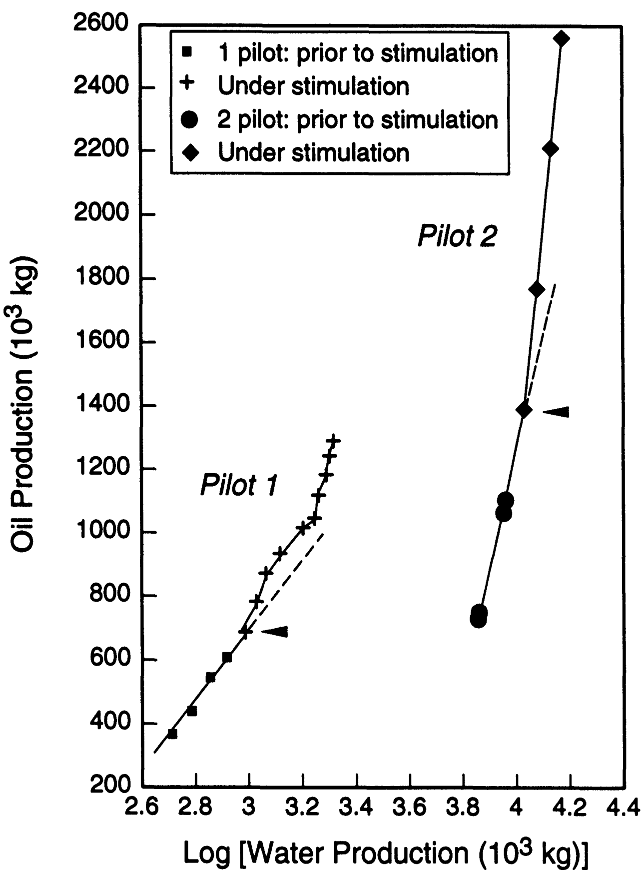

FIG. 14. Oil versus water production before and after stimulation by vibroseis-type sources above a depleted reservoir in Kirghizia. Pilot 1 and Pilot 2 refer to the stimulations of two different areas. The reservoir rock was a fine-grained sandstone with thin clay layers. Reservoir depth was 410-540 m and reservoir thickness was 25 m. The initial water cut was 90 percent. Note the increase in oil percentage in both cases (Simkin and Surguchev, 1991).

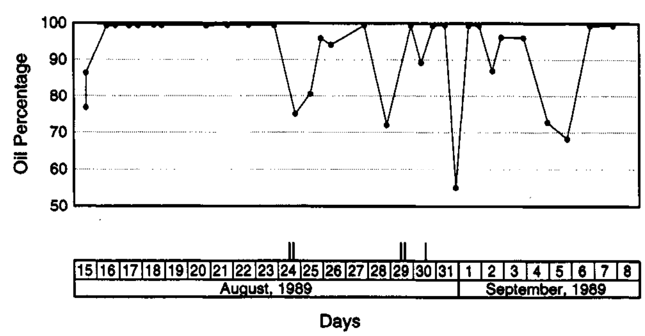

FIG. 15. Volumetric oil content in the total liquid before and after stimulation by a surface vibroseis-type source in the Northern Caucasus. Vertical lines show times of excitation. The reservoir was composed of a sequence of sandstone, sand, and clay layers. The depth was 2000 m and thickness was 130-140 m. This example shows the negative effect of excitation by increasing the water mobility, when the initial oil content was high (Kuznetsov and Nikolaev, 1990).

Investigations show that vibrational treatment may be effective in combination with gas or fluid injection in a producing formation (Sherborne, 1954; Medlin et al., 1983; Simkin, 1985; Kuznetsov et al., 1986). In the method proposed by Medlin et al. (1983) a low amplitude seismic excitation of an oil-bearing formation significantly enhances the displacement of oil by a carbon dioxide drive. However, these authors do not cite any field histories. Other works describe examples of industrial applications and also indicate that a combination of acoustic or seismic treatment with other conventional EOR methods, such as acidization, significantly increases their efficiency (Morris, 1974; Gadiev, 1977; Kuznetsov and Efimova, 1983, 152). Gadiev (1977, 131-132) notes in a summary of several years' field experience with a downhole hydraulic vibrator that the rate of oil production decline for wells treated by acid combined with vibrations is much less than for the wells subjected to standard acid treatment.

In spite of several observations of successful seismic stimulation of reservoirs, the number of tests cannot be considered satisfactory. The common shortcoming of all cited works is that no evaluation of the seismic field intensity is made at reservoir depths, so that we cannot compare this value with that achieved in laboratory experiments. An approach employing a sufficiently long measurement of background oil production characteristics before and after excitation, dense sampling of the production data, and the recording of in-situ seismic field characteristics should be used in further trials.

DISCUSSION AND CONCLUSIONS

It has been shown in laboratory studies that the application of elastic-wave excitation to saturated porous media can affect permeability and increase the extraction of hydrocarbons dispersed in the porous space. Similar observations have been obtained from the influence of earthquakes on the behavior of fluids in wells and reservoirs. Several patents for potential field service applying ultrasonic treatment of wells were granted in the 1950s and 1960s in the US and former USSR; however, most activity and the beginning of actual field service date to 1970s. Research at that time was concentrated on the creation and industrial application of ultrasonic tools capable of creating strong acoustic fields inside the wellbore for cleaning. Practice showed that such tools might be very effective in removing scales, paraffins, and asphaltines from the formation, reversing the effects of mud penetration into the reservoir, as well as in preventing precipitation of salts on well equipment. The percentage of successful treatments is between 40 and 50 percent. If treatment is successful, the effect of increased permeability may last for one day to 24 months.

Interest in whole-reservoir, low-frequency stimulation arose in the last ten years. Surface excitation by groups of vibroseis-type sources appears to be effective for stimulating relatively shallow reservoirs. An advantage of surface-based stimulation is the effect on a large volume of a given oil-bearing formation. The negative aspect of this method is that low amplitude waves reaching the reservoir produce a weak effect; however, the effect can be enhanced by use of source arrays and by extending the period of excitation. It was also shown that it is more effective to stimulate a reservoir at its resonant frequency.

The surface excitation method of reservoir stimulation requires that significant testing be done. The number of field tests is, as yet, insufficient. The attempts, to date, of using surface sources for oil production stimulation show both positive and negative results, depending on the reservoir characteristics. It would be premature to speak about large-scale industrial implementation. Further investigations, especially aimed at understanding mechanisms, are necessary to understand and optimize the method performance.

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