HYDRAULIC FRACTURING

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Hydraulic Fracturing

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DEDICATION

We wish to dedicate this book to our wives, Anne and Virginia, without whose cooperation this book would not have been possible.

judging the relative merits of various hydraulic fracturing treating procedures and the results to be expected from such a stimulation method. In other words, this Monograph is a *basic* reference book and a *working* text for the practicing engineer.

1.3 Historical Background

The fact that injection pressure decreases when water, acid, cement or oil is pumped into a formation at a high rate and at a high initial pressure has been the subject of a number of studies.

Acidizing of Oil and Gas Wells

The Pure Oil Co. in cooperation with Dow Chemical Co. performed the first acidizing of an oil well (Feb. 11, 1932) on Pure's Fox No. 6 well in Midland County, Mich. A 15 percent (by weight) hydrochloric acid with an arsenic inhibitor was used. By 1934, acidizing was an accepted practice for well stimulation in areas where the producing formation was limestone.

From 1945 to 1963, the technological improvements in acidizing were basically limited to the development of acid fracturing techniques and materials, and to the use of surface active agents. No change in acid composition was noted during this period. As a result of the development of high-pressure, high-rate pumping equipment, oil and gas wells were acidized at fracture inducing rates and pressures.[1,2]

Fitzgerald. In his comments on J. B. Clark's paper on the Hydrafrac process[3], P. E. Fitzgerald reflected the thinking of many engineers when he stated that pressure parting or formation lifting played an important part in the treatment of many wells where fluids were injected.

The pressure parting phenomenon had long been recognized in well acidizing operations. For example, at pressures below those required to lift the overburden, the formation would take substantially no fluid, but when a pressure high enough to part or fracture the formation was reached, the rate of fluid injection could be raised with little or no increase in the injection pressure.

After the acid entered the formation the chemical reaction dissolved the formation, thus further enlarging the established fracture. Since the characteristics of the rock are not uniform, more rock was dissolved by the acid in some places than in others, so that when the treatment was concluded the pressure-parted fracture could not completely close, and remained open to serve as a flow channel to the well.

Water Injection

Dickey and Andersen. From their study of water input wells, Dickey and Andersen[4] concluded that when the pressure at the bottom of an input well was raised above a certain value, the well took much and eastern Illinois oil and gas fields (260 to 2,075 ft).

The critical pressure also was observed to vary with depth and was, therefore, some function of the weight of the overlying rock. Assuming the specific gravity of water-saturated sedimentary rocks to be about 2.2, the pressure of the overburden would be approximately 1.0 psi per foot of depth.

Dickey and Andersen concluded that these breakthroughs, or breaks in injection pressure, were the result of a rupture or fracture of the formation.

Grebe. In the same vein, Grebe[5] reported in 1943 that a sand formation in a well 810 ft deep was broken down with a brine solution at a surface pressure of 720 psi. Backflow tests indicated that there was an exact balance at 360 psi (surface pressure) at which water would go in or out of the formation with very little pressure change. The weight of the earth above the point of formation fracture was determined by adding 360 psi to the head of 810 ft of brine. The average density of the earth proved to be about 2.2 (0.9548 psi/ft).

Grebe cited another case: a well 3,000 ft deep in which a formation breakdown was observed at a surface pressure of 1,500 psi while the well was being acidized. The formation lifting factor was calculated to be 0.968 psi/ft.

Yuster and Calhoun. In their study of pressure parting of formations in waterflood operations, Yuster and Calhoun[6] observed that overburden lifting does not mean that the entire overburden from a given input point to the surrounding producers is lifted by the water and actually floated on it. (While such a situation is theoretically possible, it would be the very rare exception rather than the rule.) Lifting of the overburden was defined as the parting of the rock or matrix at any bedding plane by the injection of fluid at pressures in excess of those tending to hold the formation together.

The implication that the downward force in a lifting process is the complete weight of the overburden does not necessarily hold true at all times. The force depends upon the physical condition of the overlying strata and is controlled by such factors as plasticity, compressibility, elasticity, and attitude of the strata. An analogy may illustrate this point. If the overburden were made up of a series of pillows topped by a series of books, it would be possible to part the formation locally by compressing the pillow or pillows upward and/or downward without lifting the entire overburden. The point or elevation of the wellbore where the formation has the lowest tensile strength will break first, while other fractures may occur if the pressure is great enough.

If a fracture initiated by excessive pressures has impermeable boundaries, it will continue to advance excessive pressure were permeable, the fracture would extend into the formation until the friction of the fluid flowing into it caused just enough drop in pressure to create a balance between the pressure in the liquid and the combined counter-force of the tensile strength of the formation and the downward pressure of the overburden.

In a second article on waterflooding, Yuster and Calhoun[7] concluded that the parting of formations in waterflood operations is indicated by a sudden increase in the rate of input without a corresponding increase in pressure. A graph of water input rate vs pressure might even show, at the point where parting or fracturing of the formation occurs, a definite decrease in injection pressure.

The formation parting factor for injection wells in the Bradford and Allegheny fields in Pennsylvania varied from 0.8 to 1.4 psi/ft. The low parting factors were confined generally to wells on the crest of the structure while the higher parting factors were associated with wells low on the structure. A plot of these factors vs depth indicated a trend of decreasing factors with increasing depth.

As a side-light to their study of waterflooding, Yuster and Calhoun noted that for successful acidizing and squeeze-cementing operations, pressures must be high enough to part the formation.

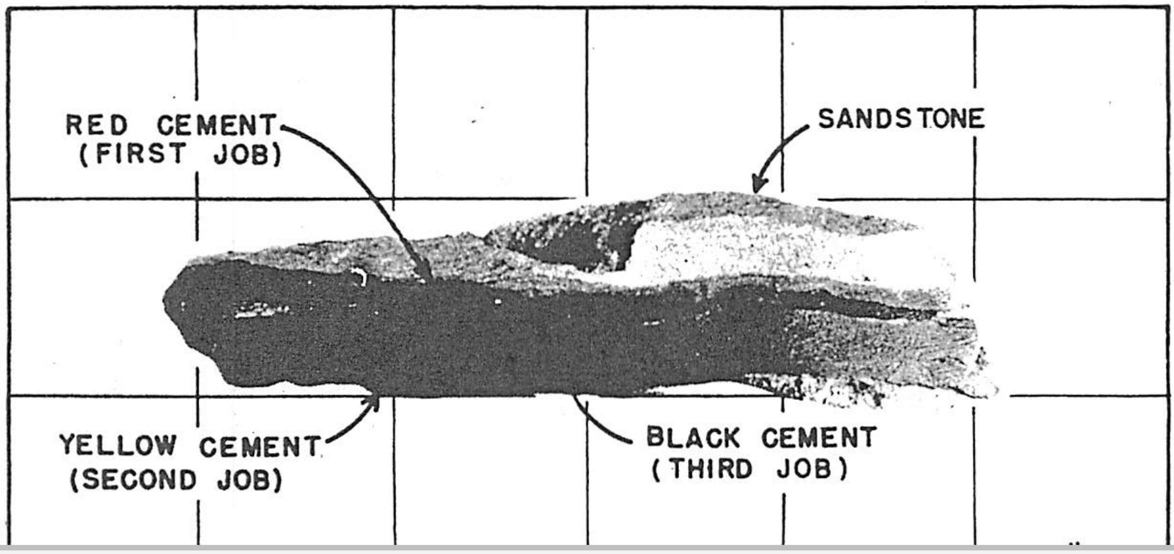
Squeeze Cementing

Torrey. Early recognition of the fracturing phenomenon in squeeze cementing was reported by P. D. Torrey.[8] He presented geological and engineering information to show that the fluid pressures involved in squeeze cementing part the rocks, generally along bedding planes or other lines of sedimentary weakness. The fracture formed provides channels or passageways in which the cement slurry can lodge beyond the wall of the hole. This phenomenon has been confirmed from cores of sand formations in sidetracked holes adjacent to sections of hole that have been squeezed previously. The cores reveal that the cement slurry sets as relatively thin laminations between the individual sand beds.

Rock samples (Fig. 1.1) recovered in shallow well squeeze-cementing tests[9] illustrate this parting of the formation.

Teplitz and Hassebroek. In their investigation of squeeze cementing, Teplitz and Hassebroek[10] observed that to inject the cement slurry injection pressures must be great enough to lift the overlying formations. This allows the cement slurry to flow into the parting between the formations in a pancake shape and form a barrier to vertical movement of fluids in the formation surrounding the casing. Teplitz and Hassebroek reasoned that it would be advisable to stop the injection of cement shortly after the pressure against the formation has exceeded that of the overburden, and after a reasonable quantity of cement has been forced out, since prolonged injection of cement at high pressure can only fracture the zone to a degree detrimental to the well. The sand core pictured in Fig. 1.2 demonstrates the results of such harmful action. This core was obtained from the producing horizon in a sidetracked well after the original hole had been subjected to a number of squeeze jobs. According to the best estimates, the lateral displacement of this core from the squeeze zone in the original well was approximately 21 ft. It should be noted that the prominent cement vein runs perpendicular to the plane of bedding in the sand.

A microscopic examination of the core revealed a thin filter cake, containing barites, between the cement and the face of the sand; but no trace of cement or mud



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