WATERFLOOD SURVEILLANCE

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ORGANIZATION

Surveillance, in order for it to be effective, should be implemented through an organization with adequate staffing and technology. Engineering and field operations organizations should be complementary, providing for specific lines of communications, and yet at the same time encouraging informal personal exchanges between both groups. Surveillance of a waterflood project requires constant cooperation between the two groups in order to collect, document, and analyze an immense quantity of data, and carry out an efficient operation.

Engineering Group

It is highly desirable for the engineering organization responsible for a group of waterflood projects to be modeled on the concept of "project engineering". The engineering group should be largely self-sufficient and should be comprised of various disciplines under a section or project leader who should have the overall responsibility for flood design, modification, and surveillance. The staff should include production, geological and reservoir engineering expertise to enable the group to handle drilling and remedial prognoses, day-to-day production/injection surveillance, and overall flood planning and modifications. The appropriate clerical and engineering technician support should be available to the group.

Field Operations Group

The field organization should be headed by the production superintendent with appropriate support from production foremen, maintenance foremen, and field operating personnel.

Well Analysis Group

This group, consisting primarily of engineering technicians, is normally relegated to a secondary position in most organizations. In actuality, this group plays a vital role in flood surveillance. The well analysis group should be responsible for gathering, documenting and analyzing operating fluid levels, Delta II dynamometer surveys, temperature surveys, and pressure surveys (statics, buildups, fall-offs) on a regularly scheduled basis or upon request by operations or engineering. This group can be set up either as a part of the engineering or the operations organization.

Above all, in this type of an organization, one-to-one contact between the engineering and field operations groups should be engendered and encouraged.

PROJECT WELL REVIEW

As is customary in many oilfield operations, project well reviews are held periodically to determine if the wells are performing satisfactorily. In the opinion of the author, the periodic well review is an integral part of flood surveillance and is a highly practical method of (1) keeping ahead of a waterflood project, instead of continually "putting out brush fires", and (2) bringing together the expertise of the engineering, field operations and well analysis groups in an action-oriented session. Prior to the review, the well analysis group should shoot fluid levels on all producing wells and provide a comprehensive well data sheet to all participants. Wells with high or changing fluid levels should be analyzed with the Delta II instrument. The minutes of the previous well review, and note sheets listing all wells grouped preferably by patterns and with pertinent comments should be available at the review.

The responsible surveillance engineer should update a well-location plat showing latest production test, gas-oil ratio, pressure, and related data. Injection curves should be updated and available for participants. Injection well profile history bar diagrams should also be available. The engineer should insure that all maps, curves, and tabular data which have a bearing on the discussion of each well (or a group of wells by patterns) are current and available.

Field operations' preparation should include having up-to-date well tests, well mechanical condition reports, and both specific and general operational observations.

Participants should include the superintendent, production foremen, the directly-involved maintenance foremen and lease operators for both the production and the injection systems, the well analysis group section leader and his responsible staff, and the production engineering section leader and his responsible staff (including the surveillance engineer assigned to the particular project).

After general comments about flood performance, each well (producer or injector) should be discussed individually and in relation to patterns and offsets. Each production well's performance curve along with well pulling, workover, and production test data should be reviewed. Data for review of injection wells (including those in adjoining areas which influence producers under study) should comprise rate, pressure, profile, and voidage replacement. When a problem or potential for improvement is apparent, a specific assignment for action should be made at the well review. The minutes of the review should be furnished each person in attendance for assignment and follow-up. Action can be initiated by the assigned group or by any of the interested parties. Prognoses written as a result of the well review can be processed quickly because of the familiarity of the project by the individuals involved. Success or failure of actions thus taken will influence decisions for similar wells within the project. Accountability for the assigned work should occur at the next scheduled well review for the project.

SURVEILLANCE TECHNIQUES AND PROCEDURES

Surveillance, stated simply, is answering questions about what is (or is not) happening in the supplemental project in relation to predicted or comparative performance. Because these data interrelate and are dynamic in nature, continual updating and analysis are required. Use of computer programs to gather, sort, plot and manipulate the needed data should be encouraged.

Production Wells

Questions frequently arise concerning individual producing wells because conditions change rapidly in an on-going drive project. Some of the questions which must be answered are:

1. Downhole Conditions

Is all correlative pay open? Detailed correlation work among offsets with the aid of structure maps and cross sections can insure that appropriate zones are open.

Is the well deep enough? Because original completions in many waterflood projects (particularly carbonate floods) were openhole-type, operators stayed short of the oil-water contact. As a result, many wells have been successfully deepened and pay zones have been exploited below the historic oil-water contact in several waterflood projects.

Has the well been properly stimulated? If not, what type of stimulation prognosis should be written to enhance the well's productivity?

2. Type of Production

Is a high gas-oil ratio in a production well the result of low reservoir pressure? If so, offset injection well profiles should be studied and corrected or additional injection points should be provided in flood plan modification. Injection-voidage balances must be maintained within patterns for the successful operation of a waterflood.

Should the well be responding? Does production appear unrestricted? Study of the production and fluid level history coupled with knowledge of the injection well behavior in the particular pattern can normally detect productivity impairment.

Where is the water production coming from? It can normally be determined from water samples whether or not the water influx is injection breakthrough, if the source water and the formation water have different salinities. Uphole casing leaks are identifiable by chemical analyses of water samples and/or pressure tests. The tough problem usually involves identifying the particular pay member through which breakthrough is occurring. In old wells, a study of water bank radii or bubble maps and injection profiles normally will provide a reasonable estimate. In new wells, resistivity logs run in open hole will often locate potential breakthrough zones, if infill drilling has been carried out. If a water shut-off is deemed advisable, it should be tried.

3. Lift Equipment

Is the equipment properly sized? Is downhole displacement efficient? Is the equipment operating satisfactorily? A combination of well tests, fluid level shots, and Delta II surveys provides the data necessary to answer these questions for beam units, which can be placed where they will be most effective. Measured loads on the equipment should be compared to industry standards (e.g., the Permissible Load Concept initially proposed by Bethlehem Supply, in case high-slip motors are in use).

If submersible pumps are being used, equipment design should be based on IPR data. Surveillance of lift performance should consist of using well tests, ammeter charts and pumping bottomhole pressures for properly sizing and monitoring the units.

Injection Wells

Changes and problems in injection wells are normally more subtle and the resulting questions and solutions harder to answer or accomplish. Results of work done are usually not known for a considerable length of time.

1. Downhole Conditions

Is all correlative pay open? Is all open pay taking water and in the correct ϕh (porosity-thickness product) proportion? Injectors should be checked periodically by profile surveys. These data provide the bases for immediate evaluation and for generation of water bank radii or bubble maps. To improve receptivity in a specific zone, the normal approach might be re-stimulate and reperforate, if warranted. To reduce a zone's receptivity, methods which can be tried are mechanical plugbacks or plugbacks with sand or other plugging materials available in the industry.

2. Well Performance

Is the well taking water at expected rates and pressures? Have significant changes occurred? What is the fall-off pressure? These questions can be answered by analysis of regularly reported performance data and periodic fall-off pressure surveys. Fall-off surveys in injection wells gain increasing importance, as measurement of reservoir pressure in production wells becomes difficult after the installation of artificial lift.

Injection - Production Patterns

In a pattern flood project, a well's performance cannot be analyzed in isolation. A surveillance engineer needs to spend time and effort relating all wells within a specific flood pattern. Since patterns are not normally related to production batteries, this type of analysis extends throughout and often beyond the boundaries of the engineer's geographic area of responsibility, particularly in a large project. It is in pattern analysis that cross sections, pie maps (zonal completion maps), water salinity maps, and reservoir pressure maps play an important part. Most cases of abnormal performance can be explained and, hence, corrected, if available data are properly interrelated. This kind of work is laborious and without much glamour. Nevertheless, drive projects can drift into serious, sometimes irrevocable problems, if not analyzed in this detailed manner on a continuing basis. Furthermore, this type of pattern surveillance continually turns up profitable candidates for workovers and other adjustments. Injection-voidage energy balances should be calculated by patterns or by selective areas of interest, and then should be compared with actual performance for flood evaluation and prediction. In this regard, it is extremely important to monitor gas-oil ratio trends or changing injectivity profile behavior which might also be developing on a larger areal basis. The surveillance engineer must be continually cognizant of these aspects of flood operation. An additional pertinent area of periodic special emphasis is the gathering and analysis of shut-in bottomhole pressures in selected producing wells in the project.

CONCLUSIONS

There is no cookbook technique for flood surveillance. Surveillance is laborious, detailed work, and, often times, with little glamour. But its rewards are evident in successful project performance, prevention of loss of anticipated reserves, and addition of reserves not foreseen previously.

If one were to spell out a few salient lessons from the author's experience in flood surveillance as a guide to other supplemental projects, these would simply be:

1. Adequate staffing, in number as well as in experience, in both engineering and field operations
2. Rapport and good communication between the engineering and field operations groups
3. Periodic project well reviews geared to optimum monitoring, corrective action, and flood plan modification.

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APPENDIX

Limitations of space do not allow for inclusion of samples of the types of maps and tabular or graphical data which should be kept updated and should be utilized in the surveillance of a waterflood project. However, a listing of some of the items is shown below with comments as appropriate:

1. Individual well production performance curves showing plots of oil rate, water rate, gross fluid rate, water cut, cumulative oil, cumulative water, gas rate and gas-oil ratio versus time. Remedials, recompletions, producing fluid levels, shut-in pressure surveys, lift equipment changes and other related data should also be indicated on the individual curves.

2. Individual well injection performance curves showing plots of water injection rate, surface injection pressure, injectivity index and cumulative water injection versus time. Workovers, profile surveys and pressure fall-off surveys should also be indicated on the individual curves.

3. Structure, isopach and porosity-net pay thickness (ϕh) maps of total pay as well as individual pays within the total productive horizon, including gas-oil and oil-water contacts. Formation water salinity and oil-water contact maps, if the project has varying salinity and nonhorizontal oil-water contact, should be available. Gas-oil ratio maps and bottomhole pressure maps are also useful.

4. "Pie" or zonal completion maps showing all designated pay zones, gas-oil and oil-water contacts, casing cementing point and/or total depth, and interval open to production or injection for individual wells.

5. Cross sections (north-south, east-west, northeast-southwest and northwest-southeast), perferably with each well location shown through the appropriate line of section. Annotations of open zones and extent of water bubbles further enhance the value of the cross sections.

6. Individual well test data on each production and injection well with comments which include pressure, fluid level, well pulling, water sample analyses, lift equipment changes, remedial or other pertient information. Individual well completion data forms should also be available.

7. Computer capability to sort out and manipulate data. Examples are: listings by well names; ascending order of GOR, water cut, water rate, oil cut, oil rate, water injection rate, and injection pressure; groupings by patterns, infill programs, selective areas of interest, or production batteries.

8. Computer-generated water bank radii or bubble maps for individual zones for all injection wells showing, also, zones previously open or currently open to injection. During the fillup stage of water injection into a partially depleted reservoir, the water bank can be envisioned as moving away from the injection point until the leading edge of the concentric of bank breaks through at the offset producers. Using this concept, one can calculate the water bank radius in an individual pay zone or the total productive pay around an injector for a given volume of cumulative water injection by:

$$R_{WB} = \left[\frac{5.61\ (Q_W)}{\pi\ (\phi h)\ (1 - S_{WC} - S_{OR} - S_{GR})} \right]^{1/2}$$

Where:

R_{WB} = water bank radius (ft)

Q_W = cumulative water injection (bbl)

ϕ = porosity (decimal)

h = net pay thickness (ft)

S_{WC} = connate water saturation (decimal)

S_{OR} = waterflood residual oil saturation (decimal)

S_{GR} = waterflood residual gas saturation (decimal)

Although the water bank shapes may not be circular in a heterogeneous reservoir, the bubble map can serve as a useful guide to the advance of the flood front in an individual pay zone. The bank shapes may be modified in conjunction with directional permeability trends which might be existent in the reservoir.

9. Injection profile history bar diagrams based on periodic profile surveys for each injection well showing the percentage of water volume going into each zone as compared to the ideal profile constructed from the ϕh (porosity-pay thickness product) of each zone.

10. Millidarcy-feet (kh) maps by total zone constructed from pressure fall-off data in injection wells.

11. Computer capability to calculate injection-voidage balances by patterns or by selective groupings of production and injection wells. Nomographs depicting reservoir voidage versus oil and water production rates for varying gas-oil ratios and reservoir pressure levels. For example, reservoir voidage at a particular reservoir pressure level may be calculated by:

$$V = B_o q_o + B_g \text{ (PGOR) - (SGOR) } r_o + B_w q_w$$

where:

V = total reservoir voidage (BPD)
q_o = oil production rate (BOPD)
q_w = water production rate (BWPD)
B_o = oil formation volume factor (RB/STB)
B_w = water formation volume factor (RB/STB)
B_g = gas formation volume factor (RB/MCF)
PGOR = producing gas-oil ratio (MCF/RB)
SGOR = solution gas-oil ratio MCF/RB)

Injection-voidage balances by patterns or by selective areas in the project are extremely important in the surveillance of the drive response of a waterflood. The surveillance engineer must be constantly alert to recognizing inclining or declining gas-oil ratio trends, and making injection rate adjustments accordingly. Above all, the voidage must not be allowed to exceed the injection rate. This type of analysis (with appropriate assumptions in material balance theory for a closed system) can also be used for making performance predictions or for investigating the effects of changes in operating strategy, after the rate model has been history-matched with actual performance.

12. Project performance curves other than individual well curves discussed above are also quite useful in overall surveillance and flood predictions. These might consist of: cumulative oil, water and gas production vs. cumulative water injection; oil and water cut vs. time; injection voidage, produced oil/injected water, produced water/produced oil and produced water/injected water vs. time; cumulative water injection, produced oil/produced water vs. cumulative oil production; water and oil cut vs. cumulative oil production; produced oil/injected water and produced total fluid/injected water vs. cumulative water injection. Several of the above curves can also be plotted in terms of total pore volume, hydrocarbon pore volume or percent of original oil-in-place. Examples are: cumulative gross or net water injection as a fraction of total pore volume vs. cumulative oil production as percent of original oil-in-place; cumulative total fluid production as a fraction of total pore volume vs. cumulative oil production as percent of original oil-in-place.