Testing Exploration Wells by Objectives
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ABSTRACT

Many papers have been published extending the theoretical understanding of pressure transient analysis. Most of these papers have concentrated on analysis of buildup tests for reservoir permeability, wellbore damage, and reservoir pressure. In many cases, the state of the art of analytical methods is far superior to the quality of the data obtained with present day procedures and instrumentation. This paper reviews the state of the art of testing exploration wells and presents a systematic approach to better formation evaluation. This systematic approach consists of establishing specific objectives for obtaining formation evaluation from well testing. Once the objectives are set, guidelines are given to design the test to meet all the objectives. The responsibility of test design rests on a well trained test engineer who also has the responsibility of test supervision, data quality control, data analysis, and test documentation. Guidelines are presented for procedures and instrumentation and a specific field example is presented that illustrates how to plan and conduct an exploration well test.

INTRODUCTION

Much useful reservoir information can be gathered from a production test of an exploration well. Frequently however, much of the important data is lost due to improper planning or poor choices of procedures and equipment. Proper test design and procedures should maximize the quality of information obtained from a test. This paper explores the practical aspects of well test planning resulting from over 20 years of our experience testing exploration wells worldwide.

Before any test can be designed, the objectives of the test must be clearly and completely stated. Throughout various phases of the test -- design, implementation, data collection, and analysis, all personnel involved should be aware of the test objectives and should strive to fulfill them.

TEST OBJECTIVES

While it is not possible to compose a list of objectives which will suffice for every test, six objectives seem to occur in most exploration wells. The common exploration well test objectives are:

1. To determine the nature of the formation fluids.
2. To measure the productivity of the well.
3. To measure the reservoir temperature and pressure.
4. To obtain suitable samples for laboratory analysis.
5. To obtain reservoir description (permeability, reservoir heterogeneities).
6. To estimate completion efficiency.

Testing should never become a mindless exercise in which operations personnel blindly follow procedures written by others. The people who are implementing the test should be actively trying to achieve the test objectives. It is often difficult or impossible to predict how to best achieve the test objectives. Often it will be necessary to alter test procedures to conform to well performance, equipment, problems, weather, or other unforeseen events.

The test engineer's role is central to successful testing. It is important for one person to be responsible for test design, equipment, procedures, data collection, data quality control, test analysis, and presentation of results. When several people perform these functions, often important data are lost or forgotten and several of the test objectives may be overlooked. In addition, if the same individual runs the test and analyzes the data, he should be in the best position to ensure all of the data are collected and to explain the test results.

Successfully testing exploration wells requires constant attention to detail. A successful test requires good test design and careful data quality control. As a result, it would be very difficult indeed to run one exploration well test without first stating the test objectives.
Safety has not been included in this list because it is understood to be of paramount importance in every operation.

The determination of formation fluids is important in any wildcat well. The first question to be answered is: does the formation contain oil, gas, or water and how much of each can be produced. Testing is often curtailed when water is produced.

Closely connected to the first objective is the measurement of the formation productivity. The flow rates of oil, gas, and water are important to each test. These measurements of well productivity will be used primarily to evaluate the reservoir.

The third objective, measuring reservoir temperature and pressure, is probably the most difficult. The reservoir temperature is needed for fluid property determination, while the reservoir pressure will be used not only for pressure transient analysis, but also in later reservoir engineering studies. Attempted measurement of the initial pressure is frequently unsuccessful, but this information is often vital to test analysis.

Samples of produced fluids are needed not only for laboratory analysis, but also for fluid property information. When stable flow has been achieved, separator samples are often adequate. However, bottom-hole samples may be needed to meet this objective.

Most of the information available in the literature is aimed at the fifth objective. To obtain reservoir description, bottom-hole flowing and shut-in pressures are analyzed. These data can be interpreted to give permeability-thickness, to estimate flow efficiency, and to indicate heterogeneities in the formation. The quality of the conclusions drawn from these data is only as good as the data itself.

The completion efficiency, which is very important in production wells is of lesser importance in exploration wells. In many cases, little effort is made to minimize damage or stimulate the well. [PTL] After it is known that valuable hydrocarbon reserves exist, the degree of damage may however be important for subsequent planning of development wells.

One important item, estimation of reserves, has been omitted from our list of objectives. It is important to know the size of reserves; however, it is often impractical or impossible to determine the reserves from short flow tests. Reserves which can be determined solely from a short exploration well test are small and typically have negative impact on the development of a prospect. Extended production tests to evaluate reserves are not normally part of exploration well testing.

The list of objectives is neither comprehensive nor will all of these objectives necessarily apply. Since each well has its own objective, the objectives should be clearly stated before the test is designed and the equipment is selected.

TEST DESIGN

The test engineer should take the specified objectives and design a test to meet them. A dual-flow-dual-shut-in procedure shown in Figure 1, consisting of a short flow period with a shut-in to measure the initial pressure and a long flow period with a subsequent shut-in is typically used. Two other issues which must be addressed in the design are the selection of pressure gauges and the choice of shut-in techniques.

The initial flow and shut-in are designed to establish communication with the formation and measure the initial pressure. The initial flow period should be as short as possible. Long flow periods will require long shut-in periods to reach pressure stabilization. For gas wells, it is often advisable to surface gas to avoid the complication of phase segregation in the wellbore. The initial shut-in period should be at least one hour and at least four times the duration of the flow period. Surface recording bottom-hole pressure gauges are invaluable in obtaining accurate measurements of the initial pressure.

The major flow period should be long enough to evaluate a representative volume of the formation. For most formations of interest, a flow period of six to twelve hours is sufficient. This should encompass a period of at least six hours of stable operation to ensure a reasonable estimate of productivity and to obtain samples for analysis. The major shut-in period should be 1 1/2 to 2 times the duration of the flow period.

No provision has been made here for multirate testing. Multirate tests are designed to meet specific objectives such as measuring the turbulence factor in gas wells or evaluating different tubing strings. As a result, they are rarely needed in exploration well testing. However, if the test objectives call for multirate testing, the test should be so designed.

As part of the test design, the choice between surface and bottom-hole shut-in must be made. Surface shut-in has the advantages of simplicity and the opportunity to suspend surface-recording bottom-hole gauges in the well while testing. Bottom-hole shut-in has the advantages of lower surface pressure during shut-in and less wellbore storage. If high surface pressures during shut-in will pose a safety problem or if wellbore storage will distort valuable early time data, then bottom-hole shut-in should be used. However, in most cases the advantages of surface shut-in, particularly surface recording gauges, will dominate. Typical bottom-hole equipment for surface and bottom-hole shut-ins are shown in Figures 2 and 3.

Selection of pressure gauges is important. In general, select the best available gauges. Typically, this means using one of several high precision electronic gauges available. However, it is important to note that mechanical gauges are often sufficiently accurate to evaluate many wells. An acceptable evaluation is normally obtained when the sensitivity of the gauges is less than 10 percent of the anticipated slope on the semilog plot of pressure versus time. In addition to checking the gauge sensitivity,
It is important to run more than one gauge. It is highly embarrassing to fail to meet several objectives because the only gauge malfunctioned.

One of the potential variables to be considered in test design is the perforating technique. Where possible, underbalanced perforating gives better results. However, safety considerations, equipment limitations, or other factors may force overbalanced perforation with a casing gun.

The final step in test design is the specification of equipment. Typically, the equipment specified will consist of flow lines, a choke manifold, a heater, a 3-phase separator, test tanks, a transfer pump, and burners. It is important to consider the risk of hydrogen sulfide and to have hydrogen sulfide rated equipment whenever possible. When testing from a floating drilling vessel, the surface equipment will be augmented by a subsea test tree and possibly by a subsea lubricator valve. Typical surface equipment is shown schematically in Figure A. The test engineer should know the limitations of each piece of equipment in order to safely conduct the test.

DATA COLLECTION AND THE TEST ENGINEER

Now that the test has been designed to meet the specified objectives, the test engineer’s primary responsibility is to conduct a safe test, effectively gathering the data needed for analysis. In addition, he must monitor the quality of the data, check for proper equipment functioning, and ensure quality samples are taken.

The first step in the data collection process occurs before the test. The test engineer must be sure that all of the pressure gauges, flow meters, and thermometers are functioning and properly calibrated. Normally, thermometers are calibrated in ice water; pressure gauges are checked against a dead weight tester, differential pressure gauges are checked with a mercury manometer, and flow meters are calibrated with a tank both before and after a test.

Once the test begins, the test engineer tries to bring the well production to the maximum safe stable rate as quickly as possible. The desire is to have as long a stable flow period as is possible within test design limitations. A production plot, a plot of flow rate and tubing pressure or bottom-hole pressure versus time as shown in Figure 5, can be an invaluable aid in assessing the stability of the test.

After the test has started, careful documentation of data and events is as important as anything else. Some guidelines for data collection are presented in Table 1. The X's in Table 1 denote the appropriate times for data collection. It is particularly important early in the flow period to monitor not only the nature of the produced fluids with samples, but also to periodically check the concentration of hydrogen sulfide either with length of stabil tubes or by titration.

Data quality control does not end with calibration. Constant vigilance is required throughout the test to be sure that all of the equipment is functioning properly. It may even be desirable to change orifice plates and calibrate flow meters against the test tanks while performing the test to ensure accurate measurements.

One of the most time consuming jobs of the test engineer is sampling. While monitoring the test, collecting data, and ensuring data quality, the engineer must find time to collect quality samples. With the aid of the production plot, he must first decide if operation is sufficiently stable to permit the use of pressurized separator samples. After three to five hours in which separator rates have varied less than ten percent, pressurized separator samples should be obtained. If separator operations are not sufficiently stable, bottom-hole samples may be required.

Before the flow period is complete, the test engineer should be confident that all of the data and samples needed to meet the objectives of the test have been obtained. Wherever possible, the test engineer should not be constrained by previous design. Rather, the successful achievement of the test objectives should govern how long the test lasts. Once the well is shut-in, the test engineer should begin monitoring bottom-hole pressures, if available, and attempting to analyze the pressure buildup data.

DATA ANALYSIS

The only way to be sure the test objectives have been met is to analyze the data. As a result, preliminary on-site evaluation can be one of the most important aspects of a test. Often an evaluation of the data will reveal gaps in the data or questions which can only be answered at the well site. To facilitate rapid data analysis, a systematic approach is important. The following approach is a guide to on-site analysis and should not be considered as the answer to all analysis problems.

The preferred systematic approach, referred to as the Unified Method of Analysis, utilizes the semilog plot shown in Figure 6 as the primary diagnostic and analysis tool. This plot, a Horner plot, is expected to be a straight line when radial flow is dominant. The use of this plot to evaluate formation properties depends upon the correct selection of the straight line characteristic of formation properties.

To assist in the correct selection, the Horner plot should be divided into three time regions. The Early Time Region data are dominated by near wellbore phenomena such as damage and wellbore storage. The Middle Time Region is a straight line characteristic of bulk formation properties. The Late Time Region reflects reservoir heterogeneities.

The first step in any analysis should be to find the end of the Early Time Region. Two guidelines are useful here. First, the radius of investigation,

$$r_i = \sqrt{4nt}$$

should be greater than 50 ft to ensure that near wellbore damage or flow perturbations are not important. Second, the rate of afterflow or afterproduction due to wellbore storage should be less than one percent of the flow rate prior to shut-in. Whichever of these occurs at the later shut-in time should be used as the end of the Early Time Region.
Our experience has shown that material balance calculations in the wellbore represent the most reliable technique for determining the rate of afterflow. The afterflow rate, \( q_{af} \), depends on the rate of change of bottom-hole pressure, \( \frac{dp}{dt} \), and the wellbore storage coefficient, \( a \).

\[
q_{af} = \frac{\alpha}{B} \frac{dp}{dt}
\]

(2)

The wellbore storage coefficient, \( a \), is the product of the wellbore volume, \( V_{wb} \), and the average compressibility of wellbore fluids, \( C_{wb} \).

Once the Early Time Region has been chosen, the Middle Time Region straight line can be used to evaluate the formation properties. The slope of the straight line is inversely proportional to the permeability-thickness product. The permeability-thickness is determined from the slope with the following equation:

\[
k_h = 162.6 \frac{Q_{cu}}{m}
\]

(3)

As shown in Figure 6, it is also useful to extrapolate the Middle Time Region line to infinite shut-in \((t_b \to t/d\to 1)\) to obtain \( p^* \).

When material balance calculations indicate a significant duration of afterflow, the data from the Early Time Region may be analyzed by log-log type-curves matching techniques. Comparison of the results of type-curve matching to the results of the Horner analysis will hopefully establish the consistency of the data. In general, type-curve matching is less reliable than the primary Horner analysis because of the similarity of the curves to be matched. When all of the data are dominated by afterflow, Early Time Region analysis will give the only estimate of formation properties.

The definition of the Late Rate Region is poorer than that of the other regions. The Late Time Region begins at the first noticeable deviation from the Middle Time Region straight line. The Late Time Region will have a shape characteristic of reservoir boundaries or heterogeneities encountered during the test. When delineating the Middle and Late Time Regions, care must be exercised. When the reservoir heterogeneities are close to the well, it is possible that only the Early and Late Time Regions exist.

Unfortunately, analysis of Late Time Region buildup behavior is not unique. Even the simplest observed behavior may have several plausible explanations. However, the comparison of the initial pressure, \( p_i \), to the extrapolated pressure, \( p^* \), does provide useful information. When \( p^* \) is greater than \( p_i \), some form of pressure support is indicated and when \( p^* \) is less than \( p_i \), nearby reservoir heterogeneities may curtail long-term productivity. Also, even though only limited fluid is removed, it is important to check the ultimate buildup pressure against the initial pressure to be sure no permanent pressure drop has occurred.

Even though most tests can be completely analyzed by this simple unified approach, this technique is not intended to answer all questions. The purpose behind this rapid field analysis of all of the data is to ensure that all of the test objectives are met. This technique ensures that all of the data are available and can be analyzed. In addition, rapid analysis can help identify the rare test which needs to be rerun due to indicated depletion. Quickly rerunning a test can save many questions and many dollars on a limited prospect.

FIELD EXAMPLE

To demonstrate the principles discussed in this paper, we have chosen a well tested by the authors. The objectives, as stated earlier, were to determine the formation fluid, measure productivity, measure the reservoir temperature and pressure, obtain fluid samples, obtain reservoir description, and estimate completion efficiency. To meet the objectives, a dual-flow-dual-shut-in test was run. This test was conducted from a drillship anchored in 300 feet of water.

The bottom-hole completion chosen for this test is shown in Figure 7. The well was tested through 3 1/2-inch tubing and the bottom-hole assembly consisted of a mule shoe, seal assembly, locator sub, and annulus pressure operated safety valve. Three pressure gauges, one surface recording strain gauge and two mechanical gauges, were used in this well to monitor the bottom-hole pressure. Not shown in this figure are the chosen well control equipment, the subsea test tree, subsea lubricator, and the control head. The surface test equipment shown schematically in Figure 8 was chosen to accommodate a maximum of 5000 B/D of oil production.

The test consisted of a five minute initial flow period, a sixty-nine minute initial shut-in period, a twelve hour major flow period, and an eighteen hour major shut-in period. The production history for this test is presented as a production plot in Figure 9. The results from this test are summarized in Table 2. The reservoir description is based on the Horner plot shown in Figure 10.

As shown in Table 2, all of the test objectives in this test were easily met by careful planning and documentation. The test was constructed to meet the objectives and the test was not terminated until the objectives had been accomplished.

CONCLUSIONS

Proper exploration well tests are relatively simple to run, provided precautions are taken. Carefully select and specify your test objectives. Select a Test Engineer and make him responsible for test design, test supervision, data collection, documentation, and analysis. Only by systematically setting and following the test objectives can you hope to have consistently successful evaluations of exploration wells with minimum effort and expense.
NOMENCLATURE

- $B$: Formation volume factor (RB/STB)
- $C_{WB}$: Compressibility of wellbore fluids (1/psi)
- $m$: Slope of the Horner plot (psi)
- $p$: Pressure (psi)
- $p_i$: Initial reservoir pressure (psi)
- $p^*$: Pressure obtained when the Middle Time Region is extrapolated (psi)
- $p_w$: Bottom-hole pressure (psi)
- $\bar{p}$: Average reservoir pressure (psi)
- $t$: Time (hrs)
- $t_h$: Horner time (hrs)
- $\Delta t$: Time after shut-in (hrs)
- $q$: Flow rate (STB/D)
- $q_{af}$: Afterflow rate (STB/D)
- $r_i$: Radius of investigation (ft)
- $\alpha$: Wellbore storage coefficient (RB/psi)
- $n$: Hydraulic diffusivity (ft$^2$/hr)
- $\mu$: Viscosity (cp)
- $\phi$: Porosity

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REFERENCES

### TABLE 1 - DATA AND SAMPLE COLLECTION GUIDELINES

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### TABLE 2 - SUMMARY OF RESULTS - FIELD EXAMPLE

- **Produced Fluid**: Oil (37.5° API at 60° F)
- **Flow Rate**: 2755 STB/D
- **Gas-Oil Ratio**: 1590 SSCF/STB
- **Initial Pressure**: 5634 at 10903 ft
- **Reservoir Temperature**: 292° F
- **Permeability-Thickness**: 4300 md-ft
- **Flow Efficiency**: 24%
- **Length of Test**: 11.72 HR

2 sets of pressurized separator samples obtained
No hydrogen sulfide detected during this test
Fig. 1—Dual-flow/dual-shut-in test.

Fig. 2—Bottomhole equipment schematic for surface shut-in.

Fig. 3—Bottomhole equipment schematic for bottomhole shut-in.

Fig. 4—Surface test equipment schematic.

Fig. 5—Example production plot.
UNIFIED METHOD OF ANALYSIS

Fig. 6—Unified method of analysis.

Fig. 7—Example well bottomhole equipment schematic.

Fig. 8—Example well surface test equipment.

Fig. 9—Example well production plot.

Fig. 10—Example well semilog plot.