Production Logging:
Theoretical and Interpretive Elements
Second Edition
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Society of Petroleum Engineers
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For Ding.
About the Author

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Preface

In May 1990, the Society of Petroleum Engineers published my first book, SPE Monograph, Vol. 14: Production Logging—Theoretical and Interpretive Elements. Now, 31 years later, this second edition is intended to bring the monograph up to date on the subject of production logging. The changes in technology over this long period are so substantial and dramatic that approximately half of this book is new material not at all covered in the first edition.

In 1990, there were only four primary production logging tools: temperature, spinner flowmeter, fluid density, and fluid capacitance tools. These had been developed for logging vertical wells, and all interpretation methods tacitly assumed the flow would be like that observed in perfectly vertical pipes. At that time, the number of horizontal wells being drilled was in the hundreds annually, primarily being drilled in the Austin chalk trend in Texas. Of course, now a large majority of all oil and gas wells being drilled are nominally horizontal wells. The advent of horizontal wells exposed the inadequacy of traditional production logging measurements in wells in measuring multiphase flows in which significant phase separation occurs. Tools that deploy arrays of sensors to sample multiple locations in the pipe cross section are now routinely run in these challenging logging environments. This new edition contains a chapter completely devoted to production logging in nominally horizontal wells.

Of course, the other technological development that has enabled dramatically more capable production logging instruments is the evolution of electronics and computer technology. Today’s data-acquisition capabilities and the modern display of output of all production logging tools was not possible 30 years ago.

Besides the production logging tools and methodologies aimed at measuring the flow distribution in wells, I also include in this monograph logs run to directly evaluate the well completion—cement-quality logs, noise logs, and downhole video. These logs, like the more traditional production logging tools, have evolved greatly since the first edition of this book was published.

This book is intended to help the engineer or geoscientist select the best log or combination of logs to satisfy the desired well or reservoir diagnosis objectives and to be able to interpret these logs. I have also endeavored to make clear the uncertainties that exist in some of these measurements. The production logging practitioner should always understand that running a production log in a well does nothing in itself to enhance well or reservoir performance. The production log only provides information about the well and/or the reservoir, so the acquired information should have value in guiding future activities with that well or similar wells.

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First, I would like to recognize all of the students who have taken production logging courses from me, both in graduate courses taught at the University of Texas and at Texas A&M University and in the more than 100 industry short courses I have taught since the first edition of this book appeared. Many of these students, particularly those in the industry courses, shared with me and with their colleagues interesting production logs and challenging logging situations they had faced. This sharing helped me remain very interested in production logging technology and aware of the new advances continuously occurring. In fact, a number of the log examples included in this second edition derived from some of these students.

I would also like to thank Jane Eden and Shashana Pearson-Hormillosa for their efforts in editing this book. They were prompt, efficient, and very careful in their editing of this book. I also thank the Society of Petroleum Engineers for publishing this book, and hope that in the future, the Society will continue to take a leading role in publishing books for the benefit of all SPE members.

Finally, I thank my wife, Professor Ding Zhu, for her support and encouragement. I am particularly grateful that in her position as Chair of the SPE Books Committee, she asked me to undertake the writing of this second edition.
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Chapter 1

Introduction

1.1 Definition and Use of Production Logging
Production logging traditionally encompasses a number of well logging techniques run on completed injection or production wells, with the goal being to evaluate the well itself or the reservoir performance. In recent years, however, the role of production logging has expanded to include applications that start at the early stages of drilling and last throughout the life of the well. The purpose of production logs is to evaluate fluid flow inside and outside pipe or, in some cases, to evaluate the well completion directly. The most common application of production logging is the measurement of the well’s flow profile, that is, the distribution of flow into or out of the wellbore. Wade et al. (1965), referring to production wells, state that production logging is used to answer the question, “How much of what fluid is coming from where?” Casedhole formation-evaluation logs, such as pulsed-neutron logs, are sometimes regarded as production logs; for the purposes of this work, however, formation-evaluation logs will not be considered, except as they apply to measuring flow profiles. The primary logging methods that will be considered are temperature, radioactive-tracer, and spinner-flowmeter logs for single-phase flow; temperature, fluid-density, fluid-capacitance, optical gas holdup, and flowmeter logs in multiphase flow; and noise, cement evaluation, and downhole video logs as applied for well completion evaluation. The array type tools that have multiple sensors are also covered.

Production logging has traditionally been applied for problem-well diagnosis or reservoir surveillance (McKinley 1982). As more US fields move into secondary and tertiary recovery, the need for production logging is increasing. In these advanced stages of production, reservoir sweep efficiency is often critical; production logging is one of the few means available to ascertain the distribution of injected or produced fluids. Likewise, competent well completions are vital to efficient reservoir performance and, again, production logging is a primary method of well evaluation. As McKinley (1982) illustrates, production logging techniques are being applied even during the drilling stage in certain instances.

The prominence of horizontal wells and of multistage hydraulic fracturing has made production-logging-type measurements important for evaluating the production from such wells. While there are many other diagnostic measurements used to evaluate hydraulic fracturing, running production logging instruments designed specifically for logging horizontal wells remains a valuable diagnostic method.

Production logs, like most well tests, rely on indirect measurement to obtain desired results. For example, in a temperature log, the wellbore temperature as a function of depth is measured. The engineer then attempts to determine the injection or production intervals by applying an interpretation scheme. For this reason, log interpretation is of critical importance in production logging. Almost all production logging interpretation relies on an understanding of the fluid movements in and near the wellbore and of how these fluid movements affect the logging measurement. Thus, log interpretation will be emphasized in this book.

1.2 History of Production Logging
Production logging began with the use of temperature surveys to locate fluid entries in a wellbore (Schlumberger et al. 1937). Early workers in the field recognized that the cooling of gas as it expands caused low-temperature anomalies that located the sources of gas entries. Cool fluids were also injected to locate permeable zones on the basis of the temperature anomalies that remained after shut-in (Millikin 1941).

In the 1940s, flow rate and pressure measurements were added to temperature surveys to obtain more information about well conditions (Dale 1949; Riordan 1951). The types of fluid in the well could be identified by measuring a pressure gradient. Flow measurements gave information about the quantities of fluid produced or injected.

Further development saw the introduction of surface-recording production logging instruments. These offered the obvious advantage of providing the operator more flexibility and control during logging. With the development of reliable grease-injection lubricators, surface-recording instruments became the standard of the industry (McKinley 1982).

By the mid-1960s, other production logging instruments had been developed to gain further information about well conditions, particularly in multiphase flow. Density and capacitance (water holdup) meters were introduced to resolve complex multiphase flow behavior (Wade 1965). In addition, cement-bond logging had achieved widespread use as a completion-evaluation method (Grosman-gin et al. 1961; Riddle 1962; Pickett 1963).

With the increasing use of horizontal wells in the 1990s, it became clear that the problems of phase segregation described by Hill and Oolman (1982)—that made traditional in-line spinner flowmeters, densitometers, and capacitance logs inadequate to measure flow profiles—meant that a whole new class of production logging tools was needed. Two basic approaches were followed in developing a new class of production logging tools for horizontal wells. Either an array of sensors that could sample flow conditions at multiple positions in the wellbore (from the high side to the low side of the wellbore) or a new measurement that integrates conditions over the entire pipe cross section was needed. From the mid-1990s through the first decade of the 2000s, the development of such instruments occurred.
1.3 Scope and Objectives
This book is intended primarily as a source of information for the petroleum engineer faced with running and interpreting production logs. I have attempted to cover all the commonly applied production logs dealing with flow inside or outside of casing or with completion evaluation; casedhole formation-evaluation logs are not covered, except as applied for profile measurement.

Throughout the monograph, guidelines are presented to aid in the selection of proper logging techniques for obtaining the desired data. With each logging method, the theory of the measurement is presented in sufficient detail to allow the engineer to appreciate the accuracy and limitations of the log and to understand interpretation procedures. General operational procedures are reviewed, primarily to point out the steps that must be followed to obtain high-quality logs. Log interpretation methods are then detailed, with examples for illustration. Throughout the monograph, I have tried to demonstrate the utility of a properly run and interpreted production log, while pointing out the limitations inherent in many of the measurements.

1.4 Applications of Production Logging
Production logging can be a powerful tool for evaluating the performance of a well or reservoir, but also can be a waste of time and resources when applied poorly or in inappropriate circumstances. An understanding of the capabilities and limitations of the various production logging measurements available and of the types of problems that can be addressed with production logs is essential to the efficient use of these services.

Reservoir performance monitoring, well completion evaluation, and planning and evaluation of well completions and workovers are the most common applications of production logging (Wade 1965; McKinley 1982; Petevello 1975; Curtis 1967; Cucanower and Morris 1966; Stratton et al. 1970; Jones 1967; Connolly 1965). Production logs are sometimes run as part of a regular reservoir surveillance program; they are used more commonly to diagnose a problem implied by a well’s performance. Surface conditions or a comparison of a well’s behavior with that of nearby wells often suggests problems that can be pinpointed with production logs.

Production logs can be useful diagnostic tools from the time a well is being drilled until its abandonment. The rest of this section first describes applications of production logging during drilling operations, followed by the more common applications during a well’s production or injection stage. Uses of production logs in conjunction with well completion or workover operations are then described.

1.4.1 Production Logging Applications During Drilling. Although production logs traditionally have been thought of for use in completed injection or production wells, they can also be applied as a well is being drilled or completed. From the start of drilling operations, production logs can be used to locate lost-circulation zones or to find underground blowouts or the source of kicks. Production logs run during drilling must be run in the drillpipe, so logs that respond to flow behind pipe, temperature, and noise logs, are the most commonly applied during drilling.

1.4.2 Applications of Production Logs During Subsequent Production or Injection. The primary applications of production logging are problem-well diagnosis and reservoir surveillance throughout the producing (or injecting) life of a well. This section describes the common uses of production logs during this phase of a well’s life. The section is divided into single-phase and multiphase flow applications, because the well problems or logging objectives and the logging procedures applied often differ for these two types of flow.

Deciding whether the flow consists of a single phase or multiple phases in the region of the well to be logged is not as trivial a problem as it may seem. Most production logging measurements are made below the tubing, in the region of the reservoir zones producing or receiving fluids. Most injection wells—water or gas—will be single-phase, though exceptions can exist, particularly when steam or CO2 is injected. In production wells, the downhole flow conditions may be single-phase, but are more likely to be two- or three-phase. Examples of single-phase production wells would be an oil well producing no water with a bottomhole pressure (BHP) above the bubblepoint pressure of the crude oil, or a dry gas well. Even in these cases, the flow conditions oppose the producing formations may be multiphase because water may be present in the wellbore even though there is no net production of water at the surface. In general, single-phase flow conditions are rare in producing wells, so the complications of multiphase flow should usually be considered when logging in production wells.

Single-Phase Flow Applications—Injection Wells. Because single-phase flow conditions are most commonly encountered in injection wells, this section describes the uses of production logs in injection wells, though it should be remembered that these same techniques can be applied in the occasional production well that is producing a single phase. Production logs are used in injection wells to monitor reservoir behavior and to evaluate problems observed with the individual injection well or the reservoir. Among the problems that may arise are abnormally low or high injectivity, abnormal pressure or fluid level in the annulus, and low productivity or high water production in offset producers. To evaluate such problems, production logs are run to measure the amount of flow to each reservoir interval, to check for interval isolation, to locate high-permeability zones, and to find leaks in the well equipment. Stratton et al. (1970) concisely summarize these applications of production logs:

“The injection wells are generally receiving water as part of a secondary recovery, a pressure maintenance, or sometimes simply a disposal system. The injection medium may also be liquid hydrocarbons, gas (including air), or a combination of liquid and gas such as saturated steam. Whatever the injection fluid, the main purpose of the production log is generally to determine the injectivity profile, that is, to quantitatively assign volumes or percentages of fluid to each of the intervals taking significant amounts of fluid. While the profile is being obtained, it is often important to check also for casing failures, packer leaks, faulty cement jobs and interzonal migration.”

Measurement of Flow Profiles. The fundamental information sought with a production log in an injection well is the flow profile, the amount of fluid being injected into each interval. The injection profile obtained with a production log is typically displayed as shown in Fig. 1.1, with the percent of total injection rate plotted vs. depth in the right track and a bar graph of the percent of total flow rate entering certain discrete intervals presented in the left track. Flow profiles are measured in injection wells with temperature, radioactive-tracer, and spinner-flowmeter logs. A temperature log will yield a qualitative indication of the formation injection intervals, while the spinner-flowmeter or radioactive-tracer logs more precisely define the amount of flow exiting the wellbore.
The formation injection intervals and the fluid exit locations may not be contiguous; if channeling is occurring, they will not be. Thus, a combination of logs is often necessary to determine the profile of injection into the formation.

*Determination of Interval Isolation.* The flow profile shows where fluids leave the wellbore, but there is no guarantee that fluids are entering the formation at these same locations, because they may move through channels behind the casing and enter zones other than those intended. The capability of the well completion to isolate the injection zones from other formations is crucial to proper reservoir management and is thus an important property to be evaluated with production logs. Cement-bond or ultrasonic-pulse-echo logs indicate the possibility of channeling by measuring the mechanical properties of the cement behind the casing. To identify channeling positively, a production log that can respond to flow behind the casing is needed. Among the logs that will serve this purpose are temperature, radioactive-tracer, and noise logs.

*Reasons for Anomalous Rate Changes.* A change in rate and/or wellhead pressure often indicates a serious well or reservoir problem. Abnormally low injectivity or a marked drop in injection rate can result from formation damage around the wellbore, plugged perforations, restrictions in the casing or tubing, or scaling. An unusually high injection rate may be caused by leaks in the casing, tubing, or packer; by channeling to other zones; or by fracturing of the reservoir. Some of these problems can be clearly identified with production logs and application of techniques used for flow profiling or measuring interval isolation, while others may require additional well tests to confirm the cause of the abnormal behavior. For example, a pressure-transient test can measure a well’s skin factor, a measure of restricted or enhanced flow around the wellbore; a flow profile obtained with production logs can indicate the very nature of the damaged or stimulated regions near the wellbore.

The cause of a rate change in a well is often easier to diagnose if production logs have been run periodically throughout the life of the well. For example, the flow profile in a water injection well may change gradually throughout the life of the well. For example, the flow profile in a water injection well may change gradually throughout the life of the well as the saturation distribution changes in the different reservoir layers. Occasional logs would show this as being a natural progression in a waterflood. Without knowledge of this gradual change, a profile obtained several years after the start of injection might appear sufficiently different from the initial profile to lead an engineer to conclude that channeling had developed, or some other dramatic change had taken place.

*Multiphase Flow Applications—Production Wells.* At the downhole conditions where production logging measurements are made, the presence of more than one phase is likely in production wells, regardless of the surface production conditions. In oil production wells, water production is common, and if the BHP is below the bubblepoint pressure, free gas will be present in the wellbore. A gas well may have water or condensate present in the wellbore even when there is no liquid production at the surface. Thus, in any production well, the possibility of multiphase flow must be considered in planning a production logging job or in interpreting production logs.

As in a single-phase well, the fundamental information most commonly sought with a production log is the flow profile, but in the multiphase case, the locations and rates of the entries of each phase are needed. Fig. 1.2 shows a flow profile for a well producing oil and water. The water production rate and the total production rate are plotted vs. depth, with the oil rate shown as the difference.
between the two curves. To define the flow profile of more than one phase, a log or logs that can identify the amount of each phase present in the wellbore and logs that measure total flow rate must be run (Carlson and Johnston 1983). Using traditional production logging tools, fluid density or capacitance logs are generally used with some type of flow-metric technique, such as a spinner, flow-meter, a flow-concentrating-flowmeter, or a radioactive-tracer log. The results of these combinations of logs are interpreted by making assumptions about the nature of the multiphase flow to yield the flow rate of each phase at different depth positions in the well, as discussed in Chapters 7 and 8. Including a temperature log as one of the production logs run in a multiphase well is always a good practice. For example, when flowmeters and fluid-identification logs are inaccurate because of the complex flow regime, a temperature log will often yield at least a qualitative measure of the flow profile.

Increasingly, array production logging tools that make multiple measurements of fluid velocity and phase holdups at multiple locations in the wellbore are being used to obtain better measurements of complex multiphase flows. These instruments and the interpretation of array tool logs are discussed in Chapters 7 and 8.

Production logs in multiphase-flow wells are often aimed at the same problems as in single-phase wells, such as testing for interval isolation or determining the reason for anomalous rate changes. In addition, an anomalous rate of production of a particular phase is often the problem being investigated with a production log in a multiphase well. Excessive water or gas production is usually the difficulty addressed and can be caused by channeling, preferential flow through high-permeability zones in the reservoir, or coning.

We will illustrate these conditions using excessive water production as the example.

Preferential flow of water through high-permeability zones (Fig. 1.3) is an extremely pervasive problem that can sometimes be pinpointed with production logs. The preferential high-permeability pathway through the reservoir may not be as simple as the layered structure shown in Fig. 1.3, but no matter its precise path, it will exist in many reservoirs. Excessive water production may result from injected water in a waterflood or from water encroaching from an aquifer. An accurate flow profile of the production well will identify the location of the high-permeability zone or zones contributing the high water production. Because the measurement and interpretation of logs in the multiphase flow in production wells are generally less accurate than those in a single-phase flow, water distribution in the reservoir is often monitored by measuring injection well profiles and assuming continuity of the reservoir layers between injectors and producers in waterflood operations (Yoelin et al. 1970).

Water or gas coning, illustrated in Fig. 1.4, is another possible source of excessive water production. Water coning results when a well is completed near a water/oil contact and sufficient vertical permeability exists for water to migrate upward to the wellbore as the pressure is drawn down around the well. Discussions of water or gas coning are presented by Frick and Taylor (1962) and Timmerman (1982). Coning is a difficult phenomenon to identify conclusively with production logs. Consider a well experiencing water coning. A flow profile will indicate water production from the lower part of an interval. This water could result from channeling from below the perforated zone, flow through a high-permeability zone located in the lower part of the interval, or coning. A log responding to flow outside the casing, such as a noise log, might be able to eliminate channeling as the water source. Distinguishing between coning and flow through a high-permeability layer will be difficult with production logs alone. Other well tests, such as pressure-transient tests, or information from cores about the permeability distribution in the reservoir (including vertical permeability) will be needed to identify coning clearly. Another possible approach is to measure the flow profile at several different total production rates because coning is sensitive to the pressure drawdown of the well. An increasing water production rate as total production is increased and, in particular, the water production expanding upward as total rate increases would indicate coning.

Channeling between the casing and the formation caused by poor cement conditions (Fig. 1.5) is sometimes the cause of high water-production rates. Logs that respond to flow behind casing—including temperature, radioactive-tracer, and noise logs—are the best means of identifying channeling.

1.4.3 Applications of Production Logs with Well Completions and Workovers. Production logs can often play a key role in planning and evaluating well completions and workover operations. Among the well operations that can benefit from production logging are cement squeezing, perforating, acidizing, fracturing, and water-shutoff or profile-modification treatments.

Information provided by production logs is often essential to the proper planning of a well workover. For example, before conducting a cement squeeze operation aimed at eliminating channeling, the channel should be located with a cement-quality, temperature, radioactive-tracer,