# Reservoir Dynamic Analysis

The purpose of this paper is to provide a high-level overview of Pressure Transient Analysis and of the extensions of PTA capabilities required for analysis of long-term *surveillance pressure and rate data* acquired in the course of field production operations. Surveillance data include records of well bottomhole pressure and rate data for each well in the reservoir that cover well performance over several years beginning from the start of field production. Pressure transient analysis is normally used in the context of well test analysis. Well tests are relatively short-time operations that involve individual wells. Analysis of surveillance data extends analysis problem to the scale of entire reservoir or reservoir compartment and may involve several wells.

In this high-level review we emphasize that the purpose of pressure transient analysis of well test or surveillance data is to recover from these data the reservoir and well properties that are encoded/reflected in the observed data behavior. This type of problem belongs to a class of inverse problems and is fundamentally different from forward problems dealing with prediction of future reservoir and well performance for a given reservoir model. In PTA type of analysis, we work with observed pressure and rate data and try to recover the reservoir and well properties reflected in these data. In conventional PTA analysis of well test data, we recover reservoir and well properties of the region near the well. Information content of surveillance data is richer, it may reflect reservoir properties far away from wells and possibly properties of the entire reservoir. Analysis of reservoir surveillance data requires more advanced analysis capabilities. This is not straightforward analysis functionality that is found in the existing PTA software applications used in the industry. This functionality is implemented in Convolution Explorer, the application specifically developed to handle this type of analysis problems.

Following this high-level review, we present an example of a gas well surveillance data analysis. This is a real data example of a high-rate gas well producing from reservoir compartment developed with this one well. This example demonstrates the functionality of Convolution Explorer application, the analysis workflow, and the software capabilities.

## Reservoir Appraisal

Reservoir appraisal is an integral phase of reservoir exploration. It begins after a discovery well confirms presence of hydrocarbons (oil or gas) in the geologic structure. Reservoir appraisal involves drilling so-called appraisal wells to delineate the reservoir and evaluate the reservoir volume required for sanctioning field development. Drilling large number of appraisal wells in offshore environment is cost prohibitive and exploration companies try to appraise new discoveries with small number of appraisal wells. In some situations, in order to develop better understanding of the production potential of wells in this reservoir structure the reservoir appraisal program may include well tests, special flow experiments performed on appraisal wells. Appraisal well tests are carefully planned and designed to achieve a set of objectives required for reservoir appraisal. These objectives usually include acquisition of high quality transient bottomhole pressure data. The pressure and rate acquired during a test are analyzed by the methods of *pressure transient analysis (PTA).* This allows determination of formation permeability, assessment of reservoir connectivity in the region around the well. Appraisal well tests are normally not sufficiently long to investigate the reservoir properties far away from the wells.

In offshore environment, a reservoir appraisal program may not produce sufficient understanding of reservoir properties far away from the wells, of reservoir connectivity, and the reservoir volume. However, it may provide a minimum reservoir volume estimate that is supported by the dynamic behavior observed during the test. With this level of reservoir uncertainty, an oil company may take a risk and sanction reservoir development while planning that reservoir appraisal will continue even after the reservoir is placed on production. To achieve this objective production/development wells are instrumented with downhole permanent pressure gauges that acquire pressure data during field production operations. The pressure data and especially the rate data acquired in uncontrolled environment during routine production operations often are not as good as the data obtained during well tests. Nevertheless, these data do reflect the fluid flow in the reservoir and the reservoir properties. It is possible to recover reservoir properties from such data and close the gaps still left after the reservoir appraisal stage. Convolution Explorer is the tool developed specifically for analysis of this type of dynamic data.

## What is PTA and RDA?

*Reservoir Dynamic Analysis* (RDA) is a generalization of *Pressure Transient Analysis* (PTA). Both PTA and RDA techniques deal with dynamic reservoir behavior. *Dynamic reservoir behavior* means evolution in time of the fluid flow in a reservoir. More specifically, it is evolution of the pressure field in the reservoir caused by production/injection associated with reservoir wells.

Historically, pressure transient analysis was developed and used for analysis of well tests. Well tests are limited in time duration and deal with the reservoir near-well region. Well tests normally last from several days to several weeks. These are controlled experiments where special attention is paid to data quality.

Reservoir dynamic analysis, however, deals with data on much longer time scale that reflect the reservoir properties on the scale of entire reservoir. Difference between RDA and PTA techniques is not just limited to different time scales of analyzed data. Longer time scale of data requires RDA to deal carefully with some physical effects that are not so dominant/significant in analysis of well test data. Among these effects are pressure interference between wells and variation of fluid properties with pressure as reservoir depletes in the course of production over long period of time.

A reservoir may have a number of wells. Dynamic reservoir behavior is reflected in the records of pressure and rate data as functions of time of all reservoir wells. This is what we observe during field operations and what constitutes observed reservoir behavior. Another term often used for these data is *Surveillance Data*. Surveillance pressure data are normally recorded by permanent downhole pressure gauges routinely used now in most offshore and many onshore reservoir developments. Well rate data may be measured by individual flow meters installed on wells or obtained by back allocation of grouped well production to individual wells using surveillance well pressure data. Surveillance pressure data may cover reservoir behavior beginning from field startup through several years of field production and possibly through the entire reservoir production life.

Another point to note is that both PTA and RDA techniques deal with inverse problem of data analysis. The word *Analysis* present in the above two terms means interpretation of dynamic data in terms of respective reservoir and well properties. This type of problem when we attempt to define/determine the characteristics of a system from the system's observed behavior belongs to a class of inverse problems. The problem of surveillance data analysis is, therefore, an ***inverse*** problem. Inverse problems are inherently non-unique. In case of oil or gas reservoirs, the same observed reservoir behavior may be produced by different reservoir systems. Hence, we should not expect that analysis of observed pressure and rate data will lead to unique reservoir and well characterization. Despite this inherent non-uniqueness of analysis problem, it is still possible to develop reasonably good and accurate understanding of the reservoir and its properties sufficient for efficient reservoir development and production.

## Information Content of Dynamic Reservoir Data

Fluid flow in a reservoir is a diffusive process governed by diffusivity equation. Rock and fluid properties are present in the coefficients in this governing diffusivity equation. Rock properties, for example permeability, may vary across the reservoir. Since this permeability function is present in the governing equation, one may expect that every small detail present in this permeability distribution across the reservoir (permeability heterogeneity) will have effect on the pressure at the wellbore. This, however, is not the case due to diffusive nature of the fluid flow problem in the reservoir. Not every small detail in reservoir properties that may actually exist in the reservoir (or imagined and included in the reservoir description/model built by the user) will affect the pressure at the well. As a result, dynamic reservoir pressure data recorded by downhole pressure gauges located in wellbores do not contain information about small-scale reservoir heterogeneities. The only rock characteristics that are reflected in the dynamic reservoir behavior are:

1. average permeability,
2. large-scale rock property heterogeneities,
3. large-scale flow barriers (faults),
4. large-scale characteristics of external reservoir boundaries
5. the total reservoir volume (in case of closed reservoir behavior).

This leads us to conclusion that only some of the reservoir characteristics listed above could potentially be recovered in the course of dynamic reservoir analysis.

## Fundamental Concepts of Pressure Transient Analysis

Methods and techniques of Pressure Transient Analysis (PTA) were developed over several decades beginning from 1930s. Early on, it was recognized that evolution of bottomhole pressure behavior in wells in response to a change of the well rate is somehow related to fluid flow in the reservoir in the region close to the well. Fluid withdrawal from the reservoir by a well creates a pressure sink area around the well that grows areally with time as long as the well continues to flow. After the well is closed, the pressure sink starts to heal because fluid continues to flow towards the well even after the well is shut in. Every change of well rate creates a pressure disturbance/ pressure signal that evolves in time and expands through the reservoir formation around the well. This pressure signal is not a wave-type signal. It is a diffusive signal that spreads out away from well. It is sometimes called as pressure transient. The pressure field in the reservoir created by a succession of well rate changes (variable rate production) is a result of superposition of these pressure signals.

This fluid flow in porous media is analogous to other diffusive physical phenomena, for example heat conductivity. Heat conductivity theory has been already developed by the time when reservoir engineering as a discipline became to take shape by mid 1900s. As a result, early developments in the area of pressure transient analysis were influenced to large extent by theoretical advancements in heat conductivity theory.

The notion that the pressure signals produced by well rate changes superpose to form the pressure field in the reservoir is characteristic of not just flow in porous media but of any physical phenomena governed by linear differential equations. The fluid flow in the reservoir consistent with superposition is physically much simpler, it is easier to understand and this helps tremendously with the inverse problem of observed dynamic behavior analysis.

Superposition principle works for physical phenomena governed by linear equations. In the case of fluid flow in porous media, this requirement for superposition to be valid translates into a requirement of single-phase flow in the reservoir and the requirement that fluid and rock properties do not to depend on pressure. These are very restrictive requirements and, in this sense, PTA is not a general analysis technique. It is limited to single-phase flow conditions in the reservoir.

The problem of analysis deals with interpretation of observed pressure transient behavior in terms of reservoir and well properties. Specifically, it tries to identify some features or trends present in dynamic data and translate them into respective reservoir and well characteristics or properties. The techniques for revealing such features in the data are based on application of appropriately devised variable transforms applied to the data. An example of such transform is the *superposition time* transform. When applied to pressure data during a flow period it transforms the pressure vs. time function into the pressure vs. superposition time function and reveals a straight-line trend during a time interval within the flow period. This linear trend is associated with radial flow geometry in the vicinity of the well. The slope of this trend is related to the permeability-thickness characteristic of the formation. This is just one example of how transient behavior translates into respective reservoir and well properties. PTA methods include a number of other variable transform and techniques that relate transient pressure behavior to the reservoir and well characteristic. This pressure transient analysis methodology is based on the use of superposition principle. When using these analysis techniques, we implicitly assume that the observed pressure data we analyze are consistent with superposition. Superposition principle is at the heart of PTA and the pressure transient analysis is in a way "synonymous" to superposition. The point is that we do know how to analyze the data that are consistent with principle of superposition and we are mostly lost if observed data are inconsistent with superposition.

The assumption that analyzed data are consistent with superposition is justified in the case of short-term well test type data – it is unlikely that during a short well test the character of transient behavior of well-reservoir system could change. However, in the case of long-term surveillance data it is not so obvious to assume that observed data are consistent with superposition. We should be more careful in this case. It is necessary to investigate/explore the data and determine if the data or at least some portions of the data are indeed consistent with superposition. Only these data can and should be used in the analysis.

The analysis approach implemented in Convolution Explorer application provides a way to explore the data and determine the parts of the data that are consistent with superposition. Please note that this data exploration/assessment is not limited to simple form of superposition integral. It could be a much more general multi-well superposition, or a form of superposition for gas reservoirs that involves special material balance pseudo-time transform. This ability of the application to evaluate the data and assess its consistency with superposition is why the application is named Convolution Explorer (C*onvolution* is another word for S*uperposition*).

In the last three decades, significant progress has been made in development of numerical simulators for solving non-linear multi-phase flow problems in reservoirs. Note that this is an area of reservoir simulation that deals with forward problem of predicting future reservoir behavior given a reservoir model which is based on assumed reservoir description and reservoir properties. Reservoir simulators are sufficiently effective in solving this forward problem. The hope was that it will be possible to rig up these numerical simulation tools to address inverse analysis problem for reconstruction of sufficiently unique reservoir description supported by the observed dynamic data. A lot of promises have been made, new terms have been invented (like "numerical well testing", "multi-phase numerical well test analysis") but looking back we can see that these promises were not realized and the problem of reservoir dynamic analysis did not make much progress towards multi-phase flow conditions in the reservoir. In other words, PTA and RDA analysis techniques are effectively still restricted to single-phase flow conditions in the reservoir and to linear flow problem formulation. Nevertheless, we have made significant progress in how to efficiently and reliably recover the reservoir information from observed dynamic behavior, the reservoir information that is indeed encoded in the data. This is exactly the purpose of Convolution Explorer analysis tool.

## Analysis Requirements That Distinguish RDA from PTA

At the time of reservoir appraisal, well tests are normally performed on one well at a time while other wells (if any) are closed. If an observation (closed) well detects a pressure signal from a well that is being tested this interference signal is directly recorded by the observation well pressure gauge. Appraisal well testing does not require any special analysis techniques for identification of interference pressure signals between wells. Situation is fundamentally different in the case of RDA when several wells may produce at the same time and affect the pressure at its own locations and at the locations of other producing wells. Reservoir dynamic analysis, therefore, requires special analysis capabilities for reconstructing interference pressure signals between wells. Hence, the reservoir dynamic analysis problem is fundamentally a multi-well analysis problem.

As we discussed earlier, PTA analysis techniques are applicable only to single-phase flow problems when fluid and rock properties are not dependent on pressure. This second requirement is satisfied in oil reservoirs. This is not the case, however, for gas reservoirs where gas properties depend on pressure. Even in this case the pressure changes induced in the reservoir during a short well test are relatively small and do not have significant effect on pressure behavior. Linear approximation of fluid flow problem that assumes constant gas properties generally works well even for gas problems.

There are, however, some special variable transforms sometimes used in PTA that account for variation of fluid properties with pressure and linearize the fluid flow problem formulation. One of such transforms is called *pseudo-pressure* transform. This transform accounts for variation of gas density and viscosity with pressure. When formulated in terms of pseudo-pressure instead of pressure the governing flow equation becomes linear and standard PTA analysis techniques can be used in this case. Application of this variable transform is reasonably straightforward and it is implemented in most of PTA analysis software programs.

In contrast to well tests, pressure changes in the reservoir resulting from long term production become very large and cannot be ignored. For RDA problems, in addition to pseudo-pressure transform that takes care of gas density and gas viscosity we have to account for variation of gas compressibility with pressure. This is achieved by using special form of pseudo-time transform called *material balance pseudo-time.* In this approach we replace regular time by appropriately defined pseudo-time variable so that material balance in the reservoir is correctly preserved. Strictly speaking, this transform does not linearize the flow problem exactly. However, it is a practical way to approximate the flow problem as a linear problem and account for variation of gas compressibility as the reservoir depletes in the course of production. This approach was validated (SPE-134261) by comparison with numerical flow simulations and was shown to work well.

While multi-well character of RDA problems and the need to account for fluid property variation with pressure are distinguishing characteristics of RDA vs. PTA, there is another requirement that differentiates RDA problems. This is a need to integrate in the analysis the long-term well pressure trends that develop in the course of field production. It is these pressure trends that reflect the reservoir properties far away from the wells, connectivity across the field, reservoir boundaries and the reservoir volume. There is a special analysis technique that has been gradually introduced into PTA practice over the last two decades. This technique is called *Pressure-Rate Deconvolution*. Pressure-rate deconvolution presents a path for such long-term pressure trend integration. Deconvolution analysis approach attempts to convert observed variable-rate well pressure and rate data into a pressure function/behavior that would be observed if the well produce at constant rate during entire well test sequence. This another much simpler form of well test data easily reveals the reservoir characteristics and properties that we try to recover from the original well test data.

There are several automatic deconvolution algorithms that are developed and implemented in PTA software applications used in the industry. Success of these automatic algorithms depends on quality of well test data and on whether these data are consistent with superposition. If the data that are fed into the algorithm are not consistent with superposition, the algorithm will fail. These new developments in PTA analysis techniques when used for well test analysis produced mixed type of response in the industry. There are well tests where automatic pressure-rate deconvolution worked reasonably well, and there are well tests where this approach failed miserably. Everything depends on the data used in the analysis. This attempt to bring deconvolution analysis approach for use in the industry leads to the following conclusion: automatic deconvolution approach is not sufficiently robust for use in routine well test analysis. It does not mean that the deconvolution analysis approach is wrong. It just means that the *implementation* of deconvolution in the form of *automatic regression algorithm* is not sufficiently robust. Application of automatic pressure-rate deconvolution for RDA problems is even more problematic because the quality of pressure and rate data acquired in the course of routine production operations is expected to be even worse.

Convolution Explorer does use the pressure-rate deconvolution approach for long-term pressure trend integration. However, Convolution Explorer does not rely on automatic deconvolution algorithms. Instead, it implements pressure-rate deconvolution analysis approach in a robust way when the user himself performs deconvolution by using special interactive functionality implemented in the application. The entire process is under complete control of the user. This approach does require some level of expertise from user in pressure transient behavior. However, a user easily develops necessary knowledge and expertise while doing the analysis. While doing constant-rate response reconstruction, the user develops intimate insights into the pressure behavior reflected in the data and whether the data or what parts of the data are consistent with superposition and what parts are not.

## Next Installment

In the next installment of this paper, we present a reservoir dynamic analysis example of surveillance data that cover five years of production by a dry gas well. The purpose of this presentation is to demonstrate application of the analysis technology implemented in Convolution Explorer application, the entire workflow process, the thought process of a person doing analysis, and the specific capabilities available in this software application.