Production Data Analysis — Challenges, Pitfalls, Diagnostics

Abstract

Although production analysis (PA) for reservoir characterization is approaching the popularity of pressure transient analysis (PTA), there are few consistent diagnostic methods in practice for the analysis of production data. Many of the "diagnostic" methods for production data analysis are little more than observation-based approaches — and some are essentially "rules of thumb."

In this work we provide guidelines for the analysis of production data, as well as identify common pitfalls and challenges. Although pressure transient and production data analyses have the same governing theory (and solutions), we must recognize that pressure transient data are acquired as part of a controlled "experiment," performed as a specific event [e.g., a pressure buildup (or PBU) test]. In contrast, production data are generally considered to be surveillance/monitoring data — with little control and considerable variance occurring during the acquisition of the production data.

This paper attempts to provide a "state-of-the-technology" review of current production data analysis techniques/tools — particularly tools to diagnose the reservoir model and assess the reservoir condition. This work also identifies the challenges and pitfalls of production analysis — and we try to provide guidance towards best practices and best tools. To compliment this mission, we use relevant field examples to address specific issues, and we illustrate the value and function of production data analysis for a wide range of reservoir types and properties.

Due Diligence — Literature

The literature for production analysis (PA) can be distilled into the following categories and elemental references:

- **Basic Analysis of Production Data**: The Arps work (ref. 1) was the systematic first attempt to correlate production data in the petroleum literature and is considered to be an essential starting point for analysis. Mattar and McNeil⁵ provide a coupling of material balance and pseudosteady-state flow theory which provides an analysis/interpretation methodology for production data on a per-well basis. Li and Horne⁶ provide a recent attempt to "legitimize" production analysis by providing a theoretical basis (where possible) for several of the more common production analysis relations.

Blasingame and Rushing⁴ provide a synopsis of the historical methods used for simplified production analysis and lend some theoretical support for common applications (e.g., the exponential and hyperbolic decline relations, as well as semi-analytical solutions for gas flow). Ref. 5 by Camacho and Raghavan, while not a production data analysis reference by design, provides the theoretical basis for boundary-dominated flow in solution gas-drive reservoirs — and should be considered to be an essential reference on production analysis.

- **Decline Type Curve Analysis**: The required reference for production decline curve analysis using type curves is the original work on the subject by Fetkovich.⁵ The analytical basis and "integral" plotting functions for variable-rate/variable pressure drop production data are provided by Palacio and
Blasingame⁷ (for gas wells) and Doublet and Blasingame⁸ (for oil wells).

These variable-rate/variable pressure drop methodologies were extended to fractured wells by Agarwal et al.⁹ and Araya and Ozkan¹⁰ provide important perspectives on the use of production decline type curve analysis for vertical, fractured, and horizontal wells. Recently (2004), Fuentes-C. et al.¹¹ provide extensions of the decline type curve analysis approach for a variety of cases in naturally fractured reservoirs.

- **Diagnostic Methods for Production Data Analysis:** There exists a dearth of literature on the specific topic of diagnostics with regard to production analysis. By contrast, the literature is replete with references on the diagnostic analysis of pressure transient test data. This situation exists because, as noted earlier, pressure transient test data are considered to be "high frequency/high resolution" data that can yield a unique character for a particular well/reservoir condition. Production data are viewed as "low frequency/low resolution" data — and the analysis of production data is labeled by some antagonists as the "analysis of clouds." While such a view is but a cynical, there is truth to the perception that the diagnosis of production data is much more art than science.

Mattar and Anderson¹² and Anderson and Mattar¹³ provide guidelines and examples for the diagnosis of production data with regard to model-based analysis (type curves). Kabir and Izgec¹⁴ provide guidance on the diagnosis pressure-rate data. With an emphasis on characterizing the reservoir production mechanism. Lastly, Bondar¹⁵ summarizes the modern and historical methods of analyzing water-oil-ratio (WOR) and water cut ($f_w$) data from the perspective of characterizing the reservoir drive mechanism(s) and estimating reserves.

### Expectations — Production Data Diagnosis

Using the guidelines/procedures presented in this work, a typical analyst should expect to be able to perform the following tasks using a given set of production data:

- **Assess Data Viability:** (i.e., preliminary data review) Determine whether or not a particular production data set can (or cannot) be analyzed based on the availability of:
  - Historical production data (rates and pressures).
  - Reservoir and fluid data (for quantitative analysis).
  - Well records (completion/stimulation history).

- **Check for Data Correlation:** This is the intermediate step between acquisition and analysis — a final review before the data are processed and prepared for analysis. Recommended tasks include:
  - Data correlation check ($p_i$ or $p_d$ vs. rate plot). This is an extraordinarily simple check, but data which have no correlation probably will not provide any diagnostic value (other than to serve as a sign not to proceed).
  - Rate-time and pressure-time plots — these can show features or events which should be filtered or discarded, a good example is that of well cleanup which could be (and usually is) due to poor early measurements.

- **Preliminary Diagnosis:** This task considers the following diagnostic aspects:
  - Identifying flow regimes (i.e., the reservoir model).
  - Data filtering for clarity (elimination of spurious data).
  - Data review/editing (e.g., well cleanup, recompletions).

- **Model-Based Analysis:** In some ways, this is the "easiest" part of production data analysis — analogous to well test analyses; comparison/matching with well/reservoir models, refinement, and then (if desired) — production forecasting. In this work we will simply note that the references (in particular, refs. 1-11) provide guidance with regard to historical and modern methods of production data analysis, and we encourage the reader to consult such references for the actual tasks involved in model-based analysis (and forecasting).

The emphasis of this paper is the diagnosis of production data — as such, we will avoid the details of tasks related to model-based analysis, and we instead focus on the qualitative review and quantitative diagnostics of production data.

We do note that the most substantive diagnostic tool is ultimately the reservoir model — whether provided for as "type curves" characteristic graphical solutions for a particular reservoir, or simply in the form of a simulation model which will be tuned to the data. Regardless of the form of the reservoir model (type curve or simulation module), the comparison of the production data with a consistent reservoir model is an essential task in the diagnosis of production data.

**Figs. 1 and 2** provide a schematic view (a sort of "cartoon" type curve) for common reservoir models, where evidence of transient and boundary-dominated flow periods presented. **Figs. 1** and 2 show the "equivalent" constant rate schematic — **Fig. 1** illustrates a "well test analysis" analog ([Δ$p/q$] integral-derivative functions), while **Fig. 2** is a "production decline" view of the data ([q/Δp] integral-derivative functions). For clarification, these data functions are derived from exactly the same reservoir model (in particular, the constant rate response) and are simply plotted in these formats due to historical preferences. There is no "strategic" advantage to using either format ([Δ$p/q$] or [q/Δp]) — and we encourage the user to become familiar with both formats to recognize that each format has distinct characteristic features that may provide assistance in the diagnosis procedure. For reference, the ([Δ$p/q$]) functions are often referred to as the "normalized productivity index" format, and the (q/Δp) functions are commonly referred to as the "Blasingame" format. As noted earlier, either format is satisfactory, and we encourage the user to use both formats to ensure that maximum diagnostic value is derived from the production data.

### Guidelines for Production Analysis

While no "set" of guidelines for production analysis should ever be considered absolute, we do believe that consistency is essential in the data gathering and data review process. Further, the diagnostic ("pre-analysis") phase of production analysis should never be treated as rote — it is vital that the analyst treat every analysis as independent. The analyst must use all of the data at their disposal to develop a "diagnostic" understanding of the production scenario, as well as the use these data to develop a characteristic understanding of the reservoir model.

**Fig 3** provides a graphic "guidebook" of tasks for the generic diagnosis of production data. The emphasis is in this graphic is the vigilant acquisition and "correlation" of the production history, establishing the influence of the well completion history, and providing a diagnosis of the production character (and the viability of an analysis) — before any "analysis tasks" are performed.

### Non-Graphical Diagnostics of Production Data

**Comment:** The analysis of production data to determine reservoir characteristics, completion effectiveness, and hydrocarbons-in-place has become very popular in recent years. The "modern" era of production decline type curve analysis and model-based
matching is well-documented (refs. 6-11). Production analysis continues to be validated as a reservoir characterization tool by field application — particularly with the advent of continuous measurement (surface and downhole pressure measurements, continuous surface rate and pressure measurements, etc.).

Simply put, the data makes the analysis. For competent production data (e.g., accurate, continuous rate and pressure measurements where the well completion has not been altered), we can and should expect to be able to:

- Diagnose (establish) the reservoir/well model.
- Estimate reservoir properties (e.g., $k$, $s$, $L_w$, etc.).
- Estimate the initial flow efficiency (and possibly the current flow efficiency via history matching).
- Estimate in-place fluid volumes.

Obviously all models — analytical or numerical, have assumptions and limitations — and the production analysis methods currently in use are no exception. These methods reflect idealized conditions, and accordingly, the diagnosis and results of a particular data set are subject to these assumptions and limitations. Quite often such assumptions can be justified, and meaningful interpretations and results are obtained — particularly when the data set is as complete as possible — and the data are consistent and of good quality.

As a reminder, in everyday practice, there are a significant number of production scenarios where the quality of the data is questionable, inconsistent, and sometimes just plain wrong. Experience plays a crucial role, and the current enthusiasm for production data analysis is hampered by a lack of resources which provide guidance to the analyst. Further, in the absence of such information, many analysts become self-taught, which in many regards is commendable. However, in our experience, a self-taught analyst (generally on virtually any subject, but particularly with regard to production analysis) almost always limits themselves to the domain where their knowledge was obtained.

For example, an analyst who may be very proficient at analyzing the performance of tight gas wells may be unprepared for cases of horizontal oil wells. Why elaborate so with regard to experience? Quite simply, because the analyst is their own worst enemy when it comes to production data analysis/interpretation. The expectation that a particular data set can, and will, at all costs be analyzed has led to cases of very poor analysis (even by the authors of this work). This is especially true in cases of inconsistent, uncorrelated data. An "experienced" analyst will know the tricks of the trade (particularly the software) and will, almost by definition, achieve an analysis that appears perfect. A novice analyst will often not consider the physics of the process (or data quality issues) and will exhaustively try to obtain an analysis/interpretation. And because of the robustness of the solutions and the ease of use of commercial software, an exhaustive approach will eventually yield an analysis/interpretation — where the results may have little or no relation to the actual properties of the system.

Experience is a valuable tool — but not a foolproof one. All analysts are encouraged to use a deliberate and consistent set of procedures — one that ensures that experience will not triumph over reason. Consider that most of the work performed by an airline pilot consists of pre-flight and post-flight checks — flying is relatively easy (and enjoyable) by comparison. The same can be said for production analysis — all of the tedious work is in the problem set-up and the post-mortem check — the analysis/interpretation portion is arguably the least tedious part of the production analysis sequence.

In summary, a prudent analyst will always be skeptical with regard to production data (especially the pressure data and, to a lesser degree, the well completion history) — and said analyst will always recheck the reservoir and fluid data as these are required input data. There is no guarantee that such efforts will keep the analyst clear of a bad analysis/interpretation, but these efforts will greatly reduce erroneous analyses.

Obviously our comments with regard to production analysis apply equally to pressure transient analysis — but, in the case of pressure transient analysis, the focus is on a controlled, small-scale event which typically contains a very large set of high-precision measurements (i.e., the pressure data). Due to the event scale and the quantity/quality of the measurements, the analysis and interpretation of pressure transient data is almost easy by comparison to the process for production data.

**Common Challenges/Pitfalls:** There is no closed set that can accurately encompass all of the challenges and pitfalls that one might encounter in production data analysis. However, there are certainly some issues which are worse, or at least more prevalent, than others. A sample of the more common challenges/pitfalls which occur in the analysis/interpretation of production data are:

<table>
<thead>
<tr>
<th>Issue</th>
<th>Influence/Severity</th>
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<tbody>
<tr>
<td><strong>Pressure:</strong></td>
<td></td>
</tr>
<tr>
<td>— No pressure measurement(s)</td>
<td>High</td>
</tr>
<tr>
<td>— Incorrect initial pressure estimate</td>
<td>High</td>
</tr>
<tr>
<td>— Poor $p_f \rightarrow p_{st}$ conversion (models)</td>
<td>Moderate</td>
</tr>
<tr>
<td>— Liquid loading: effect on $p_{st} \rightarrow p_{st}$ conversion</td>
<td>Moderate</td>
</tr>
<tr>
<td>— Incorrect location of pressure measurement</td>
<td>Very High</td>
</tr>
<tr>
<td><strong>Flowrate:</strong></td>
<td></td>
</tr>
<tr>
<td>— Rate allocations (potential for errors)</td>
<td>Moderate</td>
</tr>
<tr>
<td>— Liquid loading: effect on gas flowrate</td>
<td></td>
</tr>
<tr>
<td><strong>Well Completion:</strong></td>
<td></td>
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<tr>
<td>— Zone changes: new/old perforations</td>
<td>Very High</td>
</tr>
<tr>
<td>— Changes in the wellbore tubulars</td>
<td>High</td>
</tr>
<tr>
<td>— Changes in surface equipment</td>
<td>Mod./High</td>
</tr>
<tr>
<td>— Stimulation: hydraulic fracturing</td>
<td>High</td>
</tr>
<tr>
<td>— Stimulation: acidizing, etc.</td>
<td>Moderate</td>
</tr>
<tr>
<td><strong>General:</strong></td>
<td></td>
</tr>
<tr>
<td>— Reservoir properties ($\phi$, $h$, $r$, $c_f$, $c_p$, etc.)</td>
<td>Moderate</td>
</tr>
<tr>
<td>— Oil properties: $B_o$, $R_o$, $\mu_o$, $c_o$, etc.</td>
<td>Moderate</td>
</tr>
<tr>
<td>— Gas properties: $\gamma_f$, $T$, $z$ (or $B_g$), $\mu_g$, $c_g$, etc.</td>
<td>Moderate</td>
</tr>
<tr>
<td>— Poor time-pressure-rate synchronization</td>
<td>Mod./High</td>
</tr>
<tr>
<td>— Poor time-pressure-rate correlation</td>
<td>Very High</td>
</tr>
</tbody>
</table>

Understanding these issues is critical — if a production analysis sequence is to be conducted, these issues must be recognized if not addressed.

We can separate the analysis of production data into two separate initiatives — the estimation of reservoir properties from transient flow data and the estimation of reservoir volume from boundary-dominated flow data. Perhaps the most important issue for the estimation of reservoir properties is to acknowledge that legacy production data (i.e., data which are 20+ years old) may contain neither the quality, nor the frequency sufficient to produce competent estimates of reservoir properties. In short, it
is necessary to have accurate and frequent estimates of rate and pressure data. The expectation that low quality/low frequency data can yield highly accurate results is simply unrealistic.

An important issue, albeit one that, at present, is not easily resolved is the issue of the oil compressibility \( c_i \) and its influence on the calculation of oil-in-place \( N \). The black oil material balance equation for pressures above the bubblepoint pressure \( (i.e., p > p_b) \) is given as:

\[
\bar{p} = p_i - \frac{1}{Nc_t} \frac{B_p}{B_{oi}} N_p
\]

Where the total compressibility \( c_t \) is defined as:

\[
c_t = c_o S_o + c_g S_g + c_w S_w + c_f
\]

The issue is the total compressibility term \( c_t \). We assume that \( c_i \) is constant in our treatment of the liquid (oil) problem — but obviously, \( c_i \) is function of pressure and saturation. As with the gas case \([\text{where the gas problem is formulated in terms of pseudo-variables (Palacio and Blasingame\textsuperscript{3})}], \) we should formulate the oil case in a similar manner. The theory is straightforward \([\text{Camacho and Raghavan}\textsuperscript{5}], \) but the implementation of the oil problem in terms of oil pseudo-variables requires knowledge of average reservoir pressure and oil saturation. These variables can only be known (or predicted) if the oil-in-place \( N \) (as well as other variables) is known. This issue remains the major challenge for the slightly compressible liquid (oil) case.

**Simple Diagnostics for Time-Pressure-Rate Data:** In this section we discuss simple diagnostics for time-pressure-rate (TPR) data. This discussion is designed to serve as a practical "checklist," performed to ensure the viability of particular data set. The most important issue reverts to the previous discussion of common challenges/pitfalls — the quality/quality of TPR data.

At times, a simple visual scrutiny of the reported production data \( \text{(flowing pressure, flowrate and time)} \) may reveal obvious or potential inconsistencies — or provide insight for interpretation. The following points are proposed as diagnostics for time-pressure-rate (TPR) data:

- If the flowrate suddenly increases or decreases, then the flowing pressure should decrease or increase (respectively). If that does not happen, then the flowrate and pressure data are inconsistent or uncorrelated — it is that simple. This observation must be investigated — either the flowrate or the pressure is wrong — or both.
- Possible explanations include:
  - A well completion change, flow is taking a different path.
  - The flowing pressure is measured at the wrong location.
  - Liquid loading.
  - Artificial lift corrupts the pressure measurement.

- If the tubing and casing pressure profiles diverge, possible causes include:
  - Liquid load-up.
  - A leak in the tubulars.

- Pressure/rate issues:
  - Pressures are averaged over a measurement period \( \text{(e.g., pressure is measured every minute, but averaged to a single sample per day). Rate averaging is generally acceptable, but pressure averaging is not meaningful.} \)
  - Flowrate prorating/allocation may honor the field or manifold volume, but may not represent the performance of an individual well — particularly for disruptions \( \text{(shut-ins, short-time rate changes, etc.)}. \)
  - A high-level of scatter in production rates and flowing pressures can indicate unstable flow in the wellbore and/or unstable operating conditions.
  - Flowrate measurements/estimated with large-duration step changes tend to indicate infrequent (and probably inaccurate) measurements. This type of flowrate data diminishes the quality of calculated bottomhole pressures — even if the surface pressure measurements are of high quality.
  - Flowing pressure measurements with large-duration step changes indicate infrequent measurements. If this is the case then the pressure should be compared to the flowrate data to ensure that the pressure data are competent.

**Deconvolution as a Diagnostic Tool for Production Data Analysis**

**Theory:** By definition, deconvolution provides the equivalent constant rate or constant pressure response of a reservoir system affected by variable-rate/pressure production. Such a response should greatly improve the interpretation of the reservoir model \( \text{(provided (obviously) that the deconvolution does not bias the deconvolved pressure signal).} \) In this work we only propose that deconvolution be considered as a diagnostic for evaluating the character and quality of production data.

In general, deconvolution techniques are applied to well test data \( \text{[see recent work by von Schroeter et al and Levitan, (refs 16-19)]}. \) On the other hand, although there are no "theoretical" limitations for the application of deconvolution methods to production data — and there are few recent attempts \( \text{(refs. 21-23)} \) to deconvolve the long-term production data for a given well \( \text{(i.e., the full rate and pressure history).} \)

The main issue for the consideration of deconvolution of production data is the typical poor quality of these data. Therefore, the applicability of deconvolution for the analysis of production data is not realistic for these lower quality rate/pressure data — but deconvolution may provide significant diagnostic value for production data.

For orientation, the convolution integral is given as:

\[
p_{wf}(t) = p_i - \int_0^t q(t-\tau)\Delta p_{fu}^{\prime}(\tau)\,d\tau
\]

Eq. 3 is valid when the reservoir flow equations are linear \( \text{[i.e., there are no non-linearities present (e.g., gas flow, multiphase flow, kfp, etc.).} \) Eq. 3 is not applicable for real gas flow in the given form, but this issue can be overcome by using the appropriate pseudopressure and pseudotime transforms. Eq. 3 also becomes invalid in a physical sense if the reservoir model changes during the production sequence. Examples of scenarios where Eq. 3 may not be valid include:

- Well completion changes \( \text{(tubulars)/wellbore flow path changes)} \)
- Liquid loading \( \text{(multiphase flow/liquid invasion)} \)
- Water production \( \text{(multiphase flow/liquid invasion)} \)
- Hydraulic fracturing \( \text{(flow path/reservoir model changes)} \)
- Zone changes \( \text{(flow path/reservoir model changes)} \)

The factors given above \( \text{(and others)} \) result in inconsistencies — primarily in the measured pressure data, but also in the flowrate data. Further, \( \text{(as noted in other sections of this paper)} \) incorrect estimates of the initial reservoir pressure and/or the wrong loca-
tion of the pressure measurements can also cause yield significant inconsistencies. In such cases, we can not solve for the constant rate pressure response function in Eq. 3 \[ \Delta p_s(t) \].

In the context of production data analysis, deconvolution will be used only as a diagnostic method to identify inconsistencies in the pressure data. For example, if we consider a case where the input pressure data are inconsistent — then Eq. 3 is invalid, and (any) deconvolution will be (by definition) unsuccessful. A comparison plot of the raw (measured) pressure data with the pressure history reconstructed by deconvolution will establish if Eq. 3 is satisfied (or not).

For this work we use the "B-spline deconvolution method" by Ilk et al. to identify the inconsistencies in the pressure data. We note that this method does not allow for the estimation of rates — we then assume that given rates are essentially correct (as a comment, this assumption generally holds for production analysis where rates are frequently measured). Nevertheless, if the "history match" plot exhibits major variations, it is understood that the data are inconsistent (i.e., the data do not satisfy Eq. 3), regardless of whether the measured flowrates or pressures are incorrect.

In summary, we propose deconvolution as a diagnostic tool to compare the measured well pressures with the well pressures which are "reconstructed" as a product of the deconvolution. The only purpose of this task is to identify inconsistencies in the pressure data (directly), as well as possible inconsistencies in the rate data (indirectly).

**Diagnostic Plots for Production Analysis**

**Philosophy:** The concept of a diagnostic plot implies that a certain feature or behavior will emerge from a given data profile. A simple example could be a plot which confirms that the data shown are "good" by observing that a certain character exists — or that the data are "bad" because a certain feature does not exist, or that the observed profile deviates significantly from expectations. We suggest that a diagnostic plot for production data should:

- Highlight that there is something wrong with the production data. (e.g., an expected or relevant reservoir signal cannot be extracted, or a potentially misleading reservoir signal would be extracted if analysis were to proceed)
- Identify the cause(s) of (mis)behavior(s) from the data plot. This process is more qualitative than analytical, but that is the nature of a diagnostic plot.
- Verify the correlation (or lack thereof) between a flowrate and flowing pressure data set.

**Proposed Diagnostic Plots:** The diagnostic plots for production analysis considered in this work include:

<table>
<thead>
<tr>
<th>Proposed Diagnostic Plots</th>
<th>[gas variables]</th>
<th>Plot Code</th>
<th>Value in Practice</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>History and Data Correlation:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>—log((q/\Delta p)) vs. log((N/\Delta p)) [ \Delta m(p), q_s, G_s ]</td>
<td>7</td>
<td>Good</td>
<td></td>
</tr>
<tr>
<td>—log(1/(q)) vs. log((N/\Delta p)) [ q_s, G_s ]</td>
<td>8</td>
<td>Very Good</td>
<td></td>
</tr>
<tr>
<td>—((p_{\text{ref}})) mean and ((p_{\text{ref}})) decon vs. (t)</td>
<td>9</td>
<td>Good</td>
<td></td>
</tr>
</tbody>
</table>

* Auxiliary Diagnostics:
- \[ \log(q/\Delta p) \] vs. \[ \log(N/\Delta p) \] \[ \Delta m(p), q_s, G_s \] — Requires pseudopressure and pseudotime transformations for deconvolution.

These candidate plots have been proposed historically, from theory, and from practice as diagnostic plots for production data.

We provide example application of each plot as an attempt to demonstrate the functional performance of a particular plot for diagnostic use in practice. While goal is to provide a broad spectrum of diagnostics, we also realize that not all of the proposed plots will provide diagnostic insight for every case. This is the rationale and the purpose of the examples that have been selected — i.e., to provide insight on the interpretation of the diagnostic plots, but also to establish when these plots do not work.

**Diagnostic Plots — Case 1:** In this example we consider the case of liquid loading in a gas well. The diagnosis plots are shown in Figs. 4.01 to 4.09 (using the "plot codes" given above). The characteristic behavior in this case is that of the erratic pressure and rate behavior shown in Figs. 4.01 and 4.04 — this behavior confirms the liquid loading phenomenon.

An apparent mis-match of the data is seen in the \( p_{\text{off}} \) vs. \( q_s \) plot (Fig. 4.03), but this behavior is more or less resolved in the "material balance time" plots — Figs. 4.05 and 4.06. Fortunately, the data are confirmed by the material balance time plots, and (to a lesser degree) by the material balance and reciprocal rate plots (Figs. 4.07 and 4.08, respectively).

Lastly, the comparison of measured pressures and those pressures computed from deconvolution show only fair agreement (Fig. 4.09). We note that the purpose of Fig. 4.09 is data validation — not analysis. If significant data mis-match were to exist in Fig. 4.09 then we would conclude that these production data are not correlated, or possibly corrupted.

**Diagnostic Plots — Case 2:** This case represents perhaps the most common change in the reservoir model — well stimulation. In this case the well is hydraulically fractured after approximately 100 days of production. The diagnostic plots for this case are shown in Figs. 5.01 to 5.09 — where we note that the "mis-match" of a change in the reservoir model is evident in virtually all plots.

The issue of well stimulation (or recombination) is not trivial — as these are common practices, we must be prepared to accept that production and reservoir engineering principles clash on such issues. The best recommendation we can provide is to perform well stimulation very early in the completion history, essentially at or near initial production. This will minimize the impact of the "change" in the reservoir model.

Particular to this case, we find the "model change" caused by hydraulic fracturing is strongly evident in the "history" plots (Figs. 5.01 and 5.04), as well as the \( p_{\text{off}} \) vs. \( q_s \) "correlation" plot (Fig. 5.03). The influence of model change is clearly evident in the material balance plots (Figs. 5.05 and 5.06) (note the discontinuities in the data functions), as well as in the material balance and reciprocal rate plots (Figs. 5.07 and 5.08, respectively), where we note 2 distinct data trends. Lastly, we note an obvious discontinuity in the deconvolved and measured pressures in Fig.
Diagnostic Plots — Case 3a and 3b: This is a single data case that is split into two diagnostic cases — the first case is the presentation of the diagnostic plots based on an incorrect estimate of the initial reservoir pressure \( (p_i) \) and the second case is the same diagnostic performed using the correct estimate of \( p_i \). We present these "cases" separately, then we contrast our interpretations of the diagnostic plots.

In Case 3a (the incorrect \( p_i \) case) we present our usual suite of diagnostic plots in Figs. 6.01 to 6.09. At first glance, the history plots appear normal (Figs. 6.01-6.04) — and should, as these plots are independent of the initial reservoir pressure estimate. The "reciprocal rate" plot (Fig. 6.08) is also unaffected by the \( p_i \) estimate.

The "material balance time" plots (Figs. 6.05 and 6.06) and the "material balance" plot (Fig. 6.07) for this case all confirm that "something" is wrong with this data set. However, assessing "what" is wrong is complicated, the material balance time plots are clearly distorted — and the material balance plot has no character. These behaviors are consistent with "bad" production data — however; the history plots (Figs. 6.01, 6.02, and 6.04) all appear "normal."

We must consider what factor(s) would yield poor material balance behavior — but leave all of the other diagnostic data functions to appear normal. It may seem obvious that, in this case, by the process of elimination, the most probable culprit is the estimate of the initial reservoir pressure \( (p_i) \). The deconvolution comparison (Fig. 6.09) confirms that something is wrong (we would expect much better correlation of the measured and reconstructed pressure histories). While the "deconvolution" diagnostic does not confirm absolutely that the error lies in the pressure(s), but in conjunction with the other diagnostics, deconvolution does strongly suggest that the issue lies with the pressure data.

Case 3b (the correct \( p_i \) case) is presented in Figs. 7.01 to 7.09 — and as noted in Case 3a, we note that the history plots (Figs. 7.01 to 7.04) as well as the reciprocal rate plot (Fig. 7.08) are identical in this case, as these diagnostic functions are not dependent upon the \( p_i \) estimate. In contrast, the material balance time plots (Figs. 7.05 and 7.06) and the material balance plot (Fig. 7.07) each appear to present results which are much more consistent with accurate production data.

In particular, we provide no fixed procedure to establish the correct initial reservoir pressure \( (p_i) \) estimate, but we believe that \( p_i \) can be varied to assess the influence of this parameter on the "material balance" functions. Lastly, the deconvolution plot (Fig. 7.09) exhibits a near-perfect match of the measured and reconstructed pressures — which confirms the influence of \( p_i \).

In the absence of say, rate errors, we can conclude that this case is affected by an incorrect estimate of the initial reservoir pressure \( (p_i) \). We can also suggest that Case 3b represents the power of diagnostics — while we can not establish "exactly" the cause of the poor performance of the plots given for Case 3a, we can conclude that Case 3b, via the correct estimate of the initial reservoir pressure, provides a much better representation of the production data — in a diagnostic sense.

Diagnostic Plots — Case 4: This is a case of "where things went right" — the flowrate and pressure data are measured on a daily basis, and appear to be both representative and accurate. The plots for this case are presented in Figs. 8.01 to 8.09 — and, as a general observation, we note excellent performance of all diagnostic plots for this case.

The "history" plots (Figs. 8.01 and 8.04) show good correlation of the rate and pressure data, and the "correlation" plot \( (p_{wf}, q_{wf}) \) (Fig. 8.03) confirms the boundary-dominated flow behavior in this case — as well as the transients associated with scheduled and unscheduled well shut-ins. The material balance time plots (Figs. 8.05 and 8.06) also confirm a very good correlation of data for this case — we note the distinct trends for all of the data functions — the reservoir model (fractured well in a closed reservoir system) is easily interpreted from these plots.

The "material balance" and "reciprocal rate" plots (Figs. 8.07 and 8.08) also confirm the excellent correlation of the data functions for this case. Perhaps obvious, but the "deconvolution" comparison is also excellent for this case, the measured and computed pressure data function agree uniquely as shown in Fig. 8.09.

As a closure comment, the diagnostic plots confirm the quality, relevance, and accuracy of the production data provided for this case, and we advocate vigilance in data acquisition as was given in this case. We noted earlier in this work that in production analysis "the data define the analysis" — this is particularly true for cases such as this where the data are accurate and well-correlated.

Summary and Conclusions

Summary: This paper presents a comprehensive and systematic approach for the diagnosis of production data to be used for analysis and forecasting of production performance. The most relevant mechanism for the diagnostic analysis of production data analysis is a sequence of raw and enhanced data plots.

For orientation, we have categorized the various diagnostic plots into the following categories:

- History and Data Correlation: (refs. 1,14,15) These plots are limited to certain types of theories (e.g., constant \( p_{wf} \), boundary-dominated flow, etc.). The primary value of these plots is the simplicity of the base theory upon which they are based — i.e., the plots tend to be error-tolerant and useful for establishing correlation of the rate and pressure data.
- Reservoir Diagnostics: (refs. 7-9) This consists of a series of log-log plots which have strong theoretical ties — i.e., to boundary-dominated flow and material balance. These plots tend to be error-tolerant, or perhaps even "error-ignorant" (it is very difficult to completely disrupt these data plots). The fundamental purpose of these plots is the determination of the reservoir model.
- Auxiliary Diagnostics: (refs. 2,15,20-21) The "auxiliary" diagnostic plots (Plots 7 and 8) are used to assess reserves and Plot 9 is the "deconvolution" plot used to assess the relative accuracy of the pressure data. These plots are designed to be complimentary — i.e., to provide additional diagnostic value. We note that numerous other plots were considered in this category, but were not included due to inconsistent performance and/or limited applicability.
Conclusions: The following conclusions are derived from this work:

1. Diagnostic plots are indispensable in the characteristic evaluation and analysis of production data. The analysis of production data is uniquely tied to the quantity and quality of data — diagnostic plots assist in assessing the quality and character of the production data.

2. The well history is an essential element of the analysis/interpretation process and must always be taken into account — particularly for cases of recompletions, well stimulation, and/or major workovers.

3. A “mis-match” in a particular diagnostic plot may not be a sign of eminent failure in an analysis/interpretation sequence — but any/all “mis-matches” should be thoroughly investigated. In virtually every case, a mis-match can be traced to an unknown/unreported event in the well completion history, so (again) vigilance is warranted in the well completion review.

Recommendations/Comment: We believe that the area of diagnostics for data analysis is a somewhat overlooked area of reservoir engineering and we strongly advocate efforts to diagnose characteristic features (and failures) using data plots. As for the specific area of production data analysis, we believe that the following efforts are warranted:

1. Vigilance in data acquisition — particularly for pressure data.
2. Periodic reviews of data, including the possibility of well testing to evaluate the present condition of the well.
3. Continued efforts in developing data diagnostic plots — particularly plots/mechanisms to assess the correlation of flowrate and pressure data.

Nomenclature

Variables:

- $B_o$ = Oil formation volume factor, RB/STB
- $c_f$ = Formation compressibility, psi$^{-1}$
- $c_g$ = Gas compressibility, psi$^{-1}$
- $c_o$ = Oil compressibility, psi$^{-1}$
- $c_t$ = Total compressibility, psi$^{-1}$
- $c_w$ = Water compressibility, psi$^{-1}$
- $D_t$ = Decline constant, 1/D
- $\phi$ = Effective porosity, fraction
- $\gamma_t$ = Reservoir gas specific gravity (air = 1)
- $G$ = Original gas-in-place, MSCF
- $G_p$ = Cumulative gas production, MSCF
- $h$ = Net pay thickness, ft
- $N$ = Original oil-in-place, STB
- $N_p$ = Cumulative oil production, STB
- $q$ = Oil production rate, STBD
- $q_g$ = Gas production rate, MSCFD
- $m(p)$ = Pseudopressure, psia$^2$/cp
- $\Delta m(p)$ = Pseudopressure drop [$m(p)-m(p_{ref})$], psia$^2$/cp
- $p_i$ = Initial reservoir pressure, psia
- $p_f$ = Flowing surface pressure, psia
- $p_{ref}$ = Flowing bottomhole pressure, psia
- $\bar{p}$ = Average reservoir pressure, psia
- $\Delta p$ = Pressure drop ($p_i-p_f$), psi
- $\Delta p_{m}$ = Deconvolution pressure drop, psi
- $r_w$ = Wellbore radius, ft
- $R_o$ = Solution gas-oil-ratio, scf/RB
- $S_g$ = Gas saturation, fraction
- $S_o$ = Oil saturation, fraction
- $S_w$ = Water saturation, fraction
- $t$ = Time, days
- $t_{p}$ = (gas) Pseudotime, days
- $t_{mab}$ = $[N_i/q]$ (oil) Material balance time, days

Pseudofunctions:

$$m(p) = \frac{1}{2}\int P_{base}^{p} \frac{p}{\mu z} dp$$

$$t_a = \mu c_g^2 g_i \int_{0}^{t} \frac{1}{\mu (p) c_g (p)} dt$$

$$t_{mab, gas} = \frac{\mu c_g^2 g_i}{q(t)} \int_{0}^{t} p(t) q(t) dt$$

SI Metric Conversion Factors

- $cp \times 1.0$ E-03 = Pa⋅s
- $ft \times 3.048$ E-01 = m
- $md \times 9.869$ 233 E-04 = μm$^2$
- $psi \times 6.894$ 757 E+00 = kPa
- $bbl \times 1.589$ 873 E-01 = m$^3$

*Conversion factor is exact.

References

Analytical/Semi-Analytical Production Analysis of Data


Decline Type Curve Analysis


Diagnostic Methods for Production Data Analysis:

Deconvolution:
Figure 1 — Schematic/diagnostic plot for production data analysis (rate-normalized pressure drop integral-derivative function — material balance time format). This format provides a "well test" equivalent behavior, *increasing* pressure functions with time.

Figure 2 — Schematic/diagnostic plot for production data analysis (pressure drop-normalized rate integral-derivative function — material balance time format). This format provides a "decline type curve" equivalent behavior, *decreasing* rate functions with time.
Guidelines for Production Analysis

- **REVIEW** production data for consistency (allocations, accuracy, etc.)
- **REVIEW** well history — particularly recompletions/stimulations.
- **GATHER** reservoir (well and petrophysical) data and PVT (fluid) data.
- **PERFORM** diagnostic analysis of production data.
  - **REVIEW** data history and check data correlation (rate/pressure data).
  - **PERFORM** simplified analysis of production data.
  - **ESTABLISH** reservoir model using diagnostic plots.

- **PERFORM** model-based analysis/forecast of production data.
Figure 5.01 — Logarithmic flowrate and Cartesian pressure versus production time (Case 2).

Figure 5.02 — Logarithmic flowrate and cumulative gas production versus production time (Case 2).

Figure 5.03 — Flowing bottomhole pressures versus gas flowrate (Case 2).

Figure 5.04 — Logarithmic flowrate and Cartesian pressure versus cumulative production (Case 2).

Figure 5.05 — Normalized productivity index versus gas material balance time function (Case 2).

Figure 5.06 — Productivity index versus gas material balance time function ("Blastingame" plot) (Case 2).

Figure 5.07 — Productivity index versus pressure drop normalized cumulative gas production (Case 2).

Figure 5.08 — Reciprocal of gas flowrate versus gas material balance time function (Case 2).

Figure 5.09 — Base and reconstructed wellbore flowing pressures versus time (Case 2).