Low-Cost Methodology for Monitoring and Prioritizing Gas Storage Wells/Fields for Deliverability Enhancement Potential

Final Technical Report

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NOTICE

ABSTRACT AND KEY WORDS

The reliable selection of those wells in need of some type of stimulation or remediation in a cost effective and timely manner has been the subject of many technical endeavors, particularly in the gas storage industry where deliverability maintenance is vital to the long-term stability of the business. This work set out to develop improved data collection and/or interpretation procedures for aiding in the selection of high-quality remediation candidates. Such methods were thought necessary to extract information such as the deliverability curve, permeability, true skin and non-Darcy skin from short-term, surface-measured tests. In addition, these tests should be low in cost to implement, both in absolute dollars and in relation to the financial benefits of more efficient candidate selection.

In carrying out this work, limitations of traditional candidate selection methodologies were identified as well as the drawbacks of describing deliverability using the traditional $P_{res}^2 - P_{wf}^2$ (or ΔP^2) vs. flow rate plot. Meanwhile, Forscheimer's work was brought to the forefront as a superior means of describing and characterizing natural gas deliverability. In doing so, the inertial resistance coefficient (β) was identified as a key parameter in the estimation of multi-point isochronal testing because of it's interrelation with the non-Darcy skin (D) and the non-Darcy flow (F) coefficients, which are derived from said testing.

A wide body of correlative work exists for the estimation of inertial resistance coefficients. Because it is a property of the reservoir rock, β values are easily computed in laboratories and are typically equated to core sample porosity and permeability. However, this work showed that when dealing with a producing reservoir the inception of near-well damage or stimulation could alter this characteristic coefficient.

So, a methodology first proposed by Camacho, Vasquez and Roldan was employed on a 40 well sample data set to estimate inertial resistance values for the native reservoir and the near-well skin-influenced regions. This methodology determined the permeability of each region, the total skin factor and the radius on the skin-influenced area. The results showed reasonable agreement between an average inertial resistance coefficient derived from Camacho, et al's methods with those derived from 40 multi-point isochronal tests. Additionally, between 75 and 80 percent of the non-Darcy skin coefficients directly calculated from Camacho's technique correlated to 0.8 when compared to the actual value, indicating this new methodology holds promise for the estimation of data traditionally determined only from multi-point isochronal testing.

Key Words: gas storage, candidate selection, coefficient of inertial resistance, and non-Darcy flow

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Advanced Resources International, Inc. would like to thank the Gas Technology Institute (GTI) as well as the New York State Energy Research Development Authority (NYSERDA) for finding merit in the proposal and funding this work. The use of short term, surface collected, single drawdown / buildup transient data to approximate longer term modified isochronal deliverability testing may be a significant advance in the arena of storage well stimulation candidate selection. Further, it is quite likely that the results can be transferred to non-storage, natural gas production wells, making this preliminary procedure quite useful to the natural gas industry.

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SUMMARY

The nation's gas storage facilities have been the subject of several research, development and demonstration projects in recent years. The overall objective of these projects has been to improve the performance or reduce the costs of operating the 388 underground reservoir gas storage facilities in the USA. Twenty of these facilities are located in the State of New York. None of these projects have focused on an inexpensive, reliable methodology to help select candidate wells for remediation.

Difficulty in efficient candidate well selection for remediation is a well-known problem in the oil and gas storage industry. It has only more recently been recognized as an important issue in gas storage with the advent of deregulation and greater economic pressure on individual facilities. This project took advantage of the generally large quantities of data accumulated, at great cost, by storage operators over many years of service and incorporated that with new procedures for well testing with surface data collection. Taken together, a clear understanding of a well's deliverability decline and changing damage condition over time emerged. In addition, a better understanding of the changes in well damage condition would directly translate into reduced operating costs and higher deliverability by preferentially revealing those wells with the most potential to benefit from remediation.

Traditional methods of deliverability testing for the purposes of candidate selection have been shown to not always be reliable due to inconsistent test procedures, lack of continuous data collection (pressure transient testing), and the assumption of the slope of the deliverability curve, which has been shown to change over time. As a result, "low potential" wells are frequently being remediated, whereas "high-potential" wells are being overlooked.

So, Forscheimer's work, which describes gas flow in terms of Darcy (laminar) and non-Darcy (resistive) flow, was brought to the forefront as a superior means of describing and characterizing natural gas deliverability. In doing so, the inertial resistance coefficient (β) was identified as a key parameter in the estimation of multi-point isochronal testing because of it's interrelation with the non-Darcy skin (D) and non-Darcy flow (F) coefficients, which are typically derived from multi-point isochronal testing. Insight into these coefficients readily allows an engineer to understand the flow characteristics of a given storage well and allows for an unqualified categorization as either a candidate or not a candidate for remediation or stimulation.

A wide body of correlative work exists for the estimation of inertial resistance coefficients. Because it is a property of the reservoir rock, β values are easily computed in laboratories and are typically equated to core sample porosity and permeability. However, this work showed that when dealing with a producing reservoir the inception of near-well damage or stimulation could alter this characteristic coefficient.

To meet this research need, Advanced Resources International, Inc. (ARI) explored the use of non-conventional correlations to approximate multi-point isochronal testing from short-term, surface-measured, single drawdown / buildup testing. Ultimately, a methodology first proposed by Camacho, Vasquez and Roldan was employed on a 40 well isochronal transient test data set to estimate deliverability data normally derived from multi-point isochronal testing, i.e., the characterization of the well's Darcy and non-Darcy behavior. To simulate field execution of Camacho's technique, only the first drawdown / buildup period was studied, while the results derived from the modified isochronal deliverability tests provided a means for evaluating the technique.

As a result of this work, ARI was able to obtain reasonable correlations with the expected (multi-point derived) values of inertial resistance coefficients. Subsequently, the determination of non-Darcy coefficients for about 75 percent of the wells with a confidence of approximately 80%, indicating this new methodology holds promise for the estimation of data widely thought to be available only from multi-point isochronal testing.

Based on these initial results, ARI believes that the determination of properties describing non-Darcy flow and skin can now be estimated from simple, short-term, surface-collected, single drawdown / buildup data, providing a superior means of selecting stimulation candidates in gas storage fields and quite possibly for gas production wells. To move this work forward requires:

- a further inquiry into existing inertial resistance coefficients and their approximation of values measured in the laboratory,
- research concerning the proper weighting of native reservoir and skin-influenced inertial resistance coefficient values, perhaps using neural network techniques,
- a look into whether Camacho's diagnostic derivative plot may be discarded in favor of well test-derived permeability and total skin values,
- and a field test whereby simultaneous surface and bottomhole pressure data are measured during well testing to ascertain any differences between data collection positions.

SECTION 1
INTRODUCTION

PROBLEM STATEMENT

The passing of FERC order 636 in 1992 fundamentally changed the market environment for gas storage services (FERC, 1992). This was a result of unbundling gas storage services from interstate transportation and supply contracts, requiring them to survive economically on a stand-alone basis. Since then, a considerable amount of attention has been focused on how to improve the operating efficiency of gas storage fields, the central issue being how to maintain or enhance deliverability from existing gas storage wells and fields.

Recent research in this area began in 1993 with a Gas Technology Institute (GTI), then the Gas Research Institute, sponsored a study that investigated various well deliverability enhancement techniques and their application to gas storage wells (Gas Research Institute, 1993). That work established the now well-cited benchmark that gas storage fields (and/or wells), if not "maintained" from a completion/stimulation standpoint, will on average lose over 5% of their deliverability annually. That work also identified fracturing as an enhancement technique that held considerable promise for step-change improvements in deliverability over traditional methods such as washing/blowing the wellbore, mechanical cleaning, reperforating, and acidizing.

This early GTI study led to two subsequent R&D projects. A Department of Energy (DOE) study, initiated in 1994, investigated the application of "new and novel" fracturing techniques in gas storage wells (ARI, 1999). These techniques, which included tip-screenout fracturing, fracturing with liquid carbon dioxide and proppant, extreme overbalance fracturing and high-energy gas fracturing, were specifically selected based upon the unique characteristics and requirements of gas storage wells. Results of this work confirmed the significant deliverability enhancement benefits that can be obtained, particularly using hydraulic fracturing methods. A second project, primarily sponsored by GTI, investigated the damage mechanisms that lead to deliverability decline (Yeager, 1997). The most widespread of the damage mechanisms identified included bacteria, inorganic precipitates, hydrocarbons/organic residues and production chemicals, and particulate plugging. Other mechanisms included completion/stimulation fluid effects, relative permeability effects, sanding/unconsolidation, and mechanical obstructions. The premise of this second project is that with knowledge of the particular damage mechanism at a field, an operator can utilize problem-specific remediation methods.

Following these studies, an additional phase of R&D was initiated. This R&D included several GTI-sponsored projects to develop techniques for monitoring and identifying damage mechanisms in gas storage wells as they occur. This R&D also included several DOE-sponsored projects that developed, tested and demonstrated problem-specific remediation techniques. Hence, considerable research was being conducted to understand the various damage mechanisms that contributed to deliverability decline in gas storage wells, how to monitor and identify them, and finally how to treat them.

However, there was a critical area for deliverability enhancement that remained unaddressed. That was the area of candidate well selection. Prior work by ARI on the "new and novel" fracturing project, and a separate GTI-sponsored project that developed technologies for addressing restimulating tight gas sand wells (ARI, 2002), clearly indicated the need for a robust methodology to identify the best wells for remediation and deliverability enhancement. In the restimulation project for example, an important finding was what has been termed the "85/15" rule, which states that 85% of the production enhancement potential from a field exists in 15% of the wells. Identifying those 15% is critical for a successful field enhancement program. Through ARI's experience, we believe this finding is not restricted to tight gas sand wells, but is widely applicable to the petroleum producing industry, including gas storage fields.

It was learned in the DOE "new and novel" fracturing project that the deliverability data normally collected by gas storage operators for monitoring well performance, usually short-term, single-point, surface-measured tests performed once every few years, is not always reliable for candidate selection. There are several reasons for this.

- Despite instructions to the contrary, inconsistent test procedures are frequently used and have been observed in many such datasets. Therefore, even long-term trends in such data can be misleading.
- The information these tests yield is insufficient for sound candidate selection. To elaborate, candidate wells for remediation are ideally selected with knowledge of reservoir quality (i.e., permeability-thickness) and completion efficiency (i.e., skin factor). This information usually requires the use of pressure transient analysis techniques, suggesting continuous pressure and/or flow rate data collection as a function of time. The type of data typically collected, however, is singular, for example the flow rate and flowing wellhead pressure after (say) two to four hours of flow. Additionally, pressure transient analysis assumes the collection of long-term, bottomhole data. Obviously, short-term, surface measured data is contrary to this requirement.

- The use of single point test data implies that to estimate deliverability changes over time at a set of common baseline conditions the use of an assumed slope to the deliverability curve is necessary. Unfortunately, that slope has been shown to change over time. Also important for high-deliverability gas storage wells is being able to differentiate between true skin damage and rate-dependent (non-Darcy) skin. However, both the deliverability curve and the non-Darcy skin component can only be directly obtained via multi-point testing.

The inherent drawbacks of short term, single-point, surface-measured tests for monitoring deliverability was clearly established in the "new and novel" fracturing project at several fields where concurrent long-term, multi-point, downhole-measured data was collected. The result of this process is that "low potential" wells may frequently be remediated, whereas "high-potential" wells may be overlooked. This significantly raises the cost of deliverability maintenance and enhancement. These findings have already prompted a number of major gas storage operators to rethink and modify their data collection procedures. However, an important technology gap remains between the type and amount of data required for reliable candidate identification and what gas storage operators now collect and can reasonably afford. An important need therefore exists to develop and demonstrate new methods for monitoring well performance and deliverability in an insightful yet cost effective fashion, such that wells with the most significant deliverability enhancement potential can be reliably identified and selected for remediation. Successful R&D in this area could have a significant impact on reducing the cost of deliverability maintenance (by half if the approach is only 50% successful, and by two-thirds if it is 90% successful), and could be of considerable benefit to the gas storage industry.

PROJECT OBJECTIVE

The objective of this project was to develop improved data collection and/or interpretation procedures to extract the desired information for reliable well performance monitoring and remediation candidate selection (i.e., deliverability curve, permeability, true skin, non-Darcy skin) from short-term, single-point, surface-measured tests. Such methods would be low in cost to implement, both in absolute dollar terms and in relation to the financial benefits of more efficient candidate selection. Also, these procedures should be developed such that they can maximize the value and improve the utility of the large body of historical data that operators now possess.

TECHNICAL APPROACH

From a technology development standpoint, three broad approaches were utilized to accomplish the project objectives.

- Analytical methods were developed to better interpret short-term, single-point, surface-measured test data to extract the desired well information. While some research work has been performed in this area, it has not been fully tested for practical application by the gas storage industry (Chase and Alkandari, 1993 and Chase, 1997).
- Improved data collection procedures were to be established that are consistent with the analytic methods developed. These included, for example, continuous recording of surface pressure and flow rate data over short flow and pressure buildup periods, and the correction of surface data to downhole conditions.
- In order to correlate results obtained from the new test procedures with the older historical data, and select remediation candidates using only the historical data, artificial neural networks were to be utilized. This technology had already been proved effective for predicting post-remediation, single-point deliverability data, and for selecting remediation candidates, but still suffered the inherent inaccuracies associated with using current single-point data (McVey, et al, 1994 and Mohaghegh, et al, 1999).

To calibrate the new techniques, selected wells would be tested in the field while recording both surface and bottomhole data. After calibration of the techniques and their application to a larger number of wells, candidates selected for remediation would be tested to confirm their deliverability enhancement potential. The end result of the project would then be a demonstration of how remediation candidates could be effectively selected with a minimum of expensive pressure transient testing with bottomhole gauges while making better use of the existing historical single-point tests.

The planned test site was to be the Colden field, which is operated by National Fuel Gas Supply. This is the largest gas field in New York State, with 159 injection/withdrawal wells, and as such is likely to hold a considerable share of the deliverability enhancement potential in the State. Further, Nation Fuel Gas Supply operates about 75% of the gas storage wells, and over 50% of the working gas capacity in New York State, and is in an excellent position to apply the results of the project on a broad scale throughout New York State's gas storage system (American Gas Association, 1999).

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SECTION 2

DELIVERABILITY TESTING AND ITS IMPORTANCE IN CANDIDATE SELECTION

TRADITIONAL DELIVERABILITY TESTING

As previously stated, the proper identification of those oil and gas wells that would respond favorably to remedial work is a difficult task when trying to limit well downtime and overall cost. To date, the most common technique employed, specifically for high-deliverability underground natural gas storage wells, has been short-term, single-point, surface-measured tests typically performed once every few years. In some instances, these single-point deliverability results are normalized to a consistent field-wide $P_{res}^2 – P_{wf}^2$ (hereafter referred to as ? p^2) value, for use on the log of q vs. log of ? p^2 deliverability plot. In almost all cases, these procedures necessitate the assumption of an unchanging slope of the deliverability line, with respect to time. However, the slope of this deliverability line has been shown to vary not only from surface to bottomhole conditions but also as a result of well intervention or a lack thereof (ARI, 1999). As a result of this assumption, wells targeted for remediation may include candidates with little or no upside.

This dilemma is compounded by frequent use of the standard log of q vs. log of ? p^2 plot, often called the absolute open flow (AOF), deliverability plot, or C-and-n analysis (**Figure 1**). This linear AOF plot can be constructed by plotting the difference of the square of the initial and final pressures of a flow period against the respective rate for a number of constant time tests. A straight line is then fit through the data, which then characterizes a well's ability to flow a given rate (q) for any pressure difference (? p^2). The slope of this line is the inverse of the deliverability exponent, n. Often, storage operators will determine the well's maximum flowing capability, or AOF, by extrapolating this deliverability line to the well's largest expected pressure difference, which also achieves the largest flow rate. This period typically occurs when the storage reservoir is at maximum pressure and the flowing pressure is at a minimum.

However, the linear C-and-n plot is actually only a tangent to a curve better defined by Forscheimer's formulation depicted in **Figure 2**. Recognizing that Darcy's Law becomes inaccurate at high flow rates, Forscheimer was able to describe the deviation from laminar/viscous Darcy flow through the addition of a non-Darcy flow component (at the time thought to be due to turbulence). Thus, the total pressure drop at a given flow rate is the summation of these Darcy (Bq_g) and non-Darcy (Fq_g^2) pressure drop components (Slider, 1983). The general form of Forscheimer's equation (**Equation 1**) is as follows:

? $p^2 = Bq_g + Fq_g^2$ .... **Equation 1**

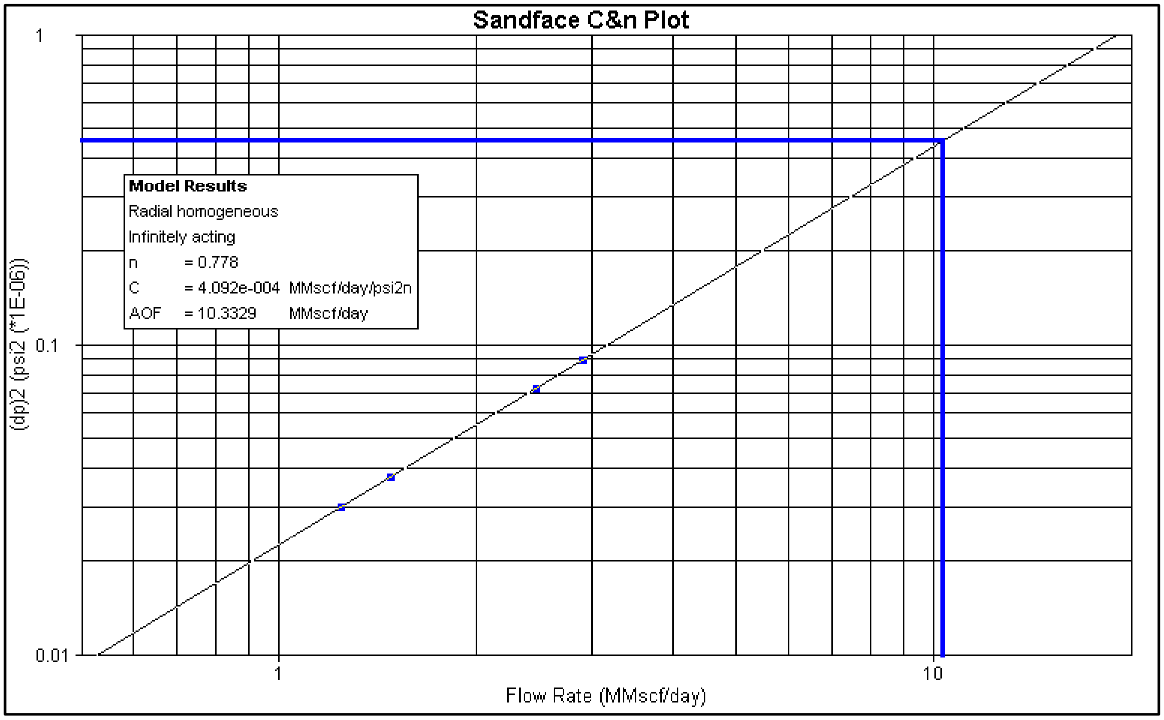

Figure 1. Example C-and-n Multi-Point Deliverability Analysis Plot.

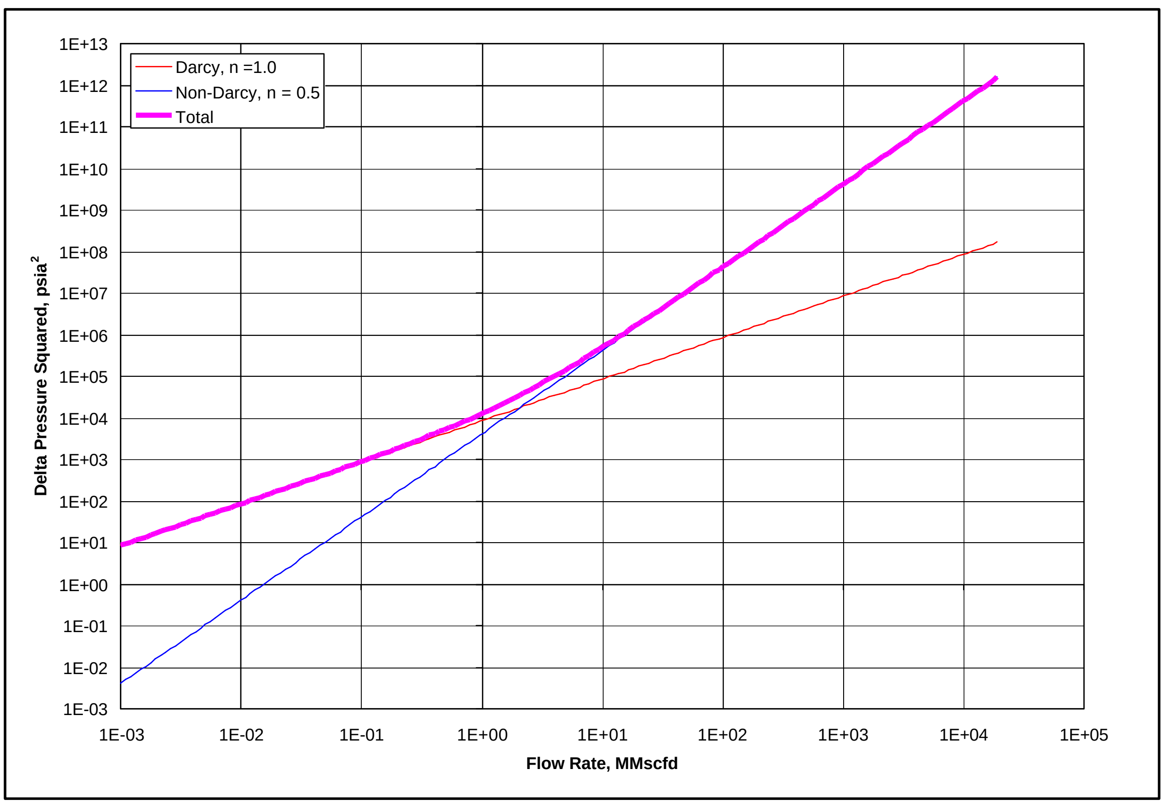

Figure 2. Deliverability Plot Showing Total Pressure Drop vs. Flowrate.

When only Darcy pressure drop is considered, the slope of the line on the C-and-n plot will be exactly 1.0, resulting in a deliverability exponent (n) of 1.0. Similarly, when only non-Darcy pressure drop is considered, the slope of the line will be 2.0, which equates to a deliverability exponent of 0.5. To demonstrate this, at low flow rates, Darcy flow conditions are dominant and the above equation reduces to ? $p^2 = Bq_g$. Solving for flow rate, the familiar form of the deliverability equation ($q_g = C$ (? $p^2)^n$) is obtained.

$q_g = 1/B$ (? $p^2)^{1.0}$... **Equation 2**

Similarly, when flow rate is high and the pressure drop is dominated by non-Darcy pressure drop, the equation reduces to ? $p^2 = Fq_g^2$. Solving for gas flow rate, the general form of the deliverability equation is again achieved.

$q_g = 1/F^{0.5}$ (? $p^2)^{0.5}$.. **Equation 3**

Therefore, the slope of the straight line through the test data on the deliverability plot will always have a slope value between 1.0 and 2.0, with its deliverability exponent ranging from 1.0 to 0.5, which is the summation of the Darcy and non-Darcy pressure drops that are present, respectively.

LAMINAR-INERTIAL-TUBUENT (LIT) ANALYSIS

As opposed to the conventional C-and-n deliverability analysis, which is only a linear approximation of the deliverability curve, the LIT-type of analysis can be employed to more rigorously characterize the collected multi-point deliverability data. The LIT analysis utilizes a pseudo-pressure (real gas potential) approach to linearize the Forscheimer equation for graphical analysis (**Equation 4**).

? $m(p) = Bq_g + Fq_g^2$ .... **Equation 4**

Compared to a C-and-n type analysis, where the results are the constant (C), the deliverability exponent (n) and an extrapolated AOF value, the LIT analysis yields the Darcy flow coefficient (B), non-Darcy flow coefficient (F) and the true AOF at maximum drawdown. **Figure 3** depicts a standard LIT analysis plot.

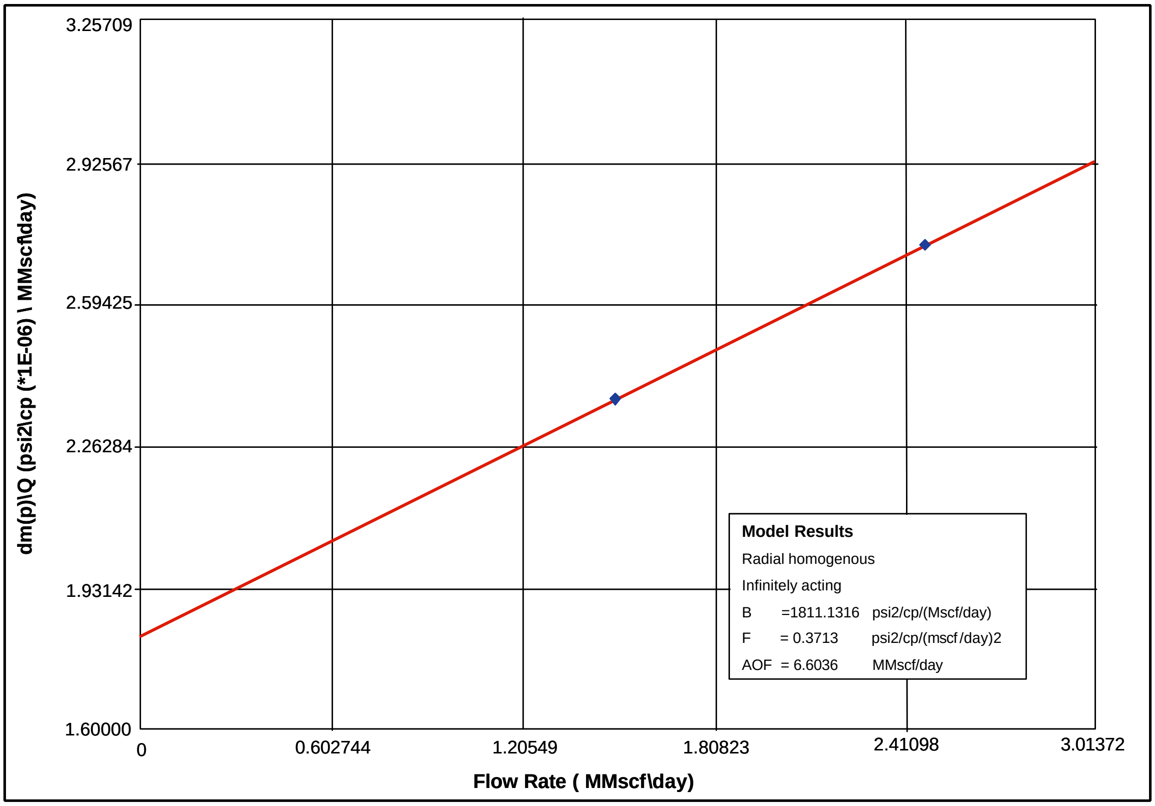

Figure 3. Sandface LIT Analysis Plot.

As a result of this analysis, an understanding of the well's total skin (true + mechanical skin) can be gained using **Equation 5,** where D is the non-Darcy skin coefficient.

$D = F\ (k\ h) / (1422\ T_f)$ .... **Equation 5**

Once the non-Darcy skin coefficient is calculated, the true skin can be determined, using **Equation 6**.

$s'_{TOTAL} = (q_g D) + s'_{TRUE}$ .... **Equation 6**

In the above equation, the skin factor (total) determined during the well test analysis and the flow rate associated with that analysis are used in conjunction with the non-Darcy flow coefficient to determine the true skin, which is the skin of the well under static conditions. Once true skin is known, **Equation 6** can then be used to calculate the total skin at any flow rate.

BRIDGING THE GAP BETWEEN SINGLE- AND MULTI-POINT TESTING

It is easy to see that when multi-point deliverability testing can be conducted, a wealth of information can be readily attained, including permeability, reservoir pressure, total skin, true skin, Darcy and non-Darcy flow coefficients, the non-Darcy flow coefficient as well as an understanding of the well's current deliverability capabilities (exponent, AOF). With this information at hand, the field engineer can readily assess whether or not remedial action would benefit a given well. Nonetheless, the process of collecting this information on even an infrequent basis can prove time consuming and costly.

What is typically available, due to the low cost nature of collecting the information, may be only a single-point deliverability test. From this data the engineer may be able to ascertain permeability, total skin, reservoir pressure, ? p^2 and test flow rate. To complete the analysis, the operator would then most likely, at a minimum, assume the deliverability exponent (n) to enable the deliverability value to be estimated at a pre-determined ? p^2 value. Then, a comparison is made against historical deliverability values to judge apparent decline. In the absence of multi-point deliverability data, there is no information available for estimating the non-Darcy flow (F) or non-Darcy skin coefficients (D), which could significantly improve the candidate selection process by adding insight into the well's rate dependent and true skin.

Continuing along this vein, if we re-write the Forscheimer equation in its quadratic form (**Equation 7**) and also its explicit form (**Equation 8**), we can compare it to its generalized form in **Equation 1**.

$$dp/dr = \mu v/k + \boldsymbol{ß}\, ? v^2 \text{ .... } \textbf{Equation 7}$$

$$?\, p^2 = \frac{1.424 \mu z T_f \ln(r_1/r_2)\, q_g}{kh} + \frac{3.161(10^{-12})\boldsymbol{ß}\, ? z T_f (1/r_2 - 1/r_1) q_g^2}{h^2} \text{ .... } \textbf{Equation 8}$$

As previously noted, the first term in each equation represents the pressure drop due to Darcy flow while the second term represents the pressure drop due to non-Darcy flow, respectively. Within the non-Darcy pressure drop term, a key analysis parameter has been highlighted in each of the above equations. This term is the coefficient of inertial resistance (ß). This coefficient has the dimension of length [L^{-1}] and has been related to the porosity, permeability, tortuosity, specific surface area, pore and grain size distribution, as well as the surface roughness of a given porous medium (Noman, et al, 1985). As a result, ß is related to the porous medium's structure and unrelated to its fluid properties.

Since ß is characteristic of reservoir structure, it can be derived in the laboratory using fairly straightforward core testing methodologies (Noman, et al, 1985). Perhaps the earliest such study was that of Katz in 1959 (Katz, et al, 1959). In this work, inertial resistance coefficients were determined from a number of dolomite, limestone and sandstone test samples. The results were plotted against sample permeability, with lines of constant porosity overlain (**Figure 4**).

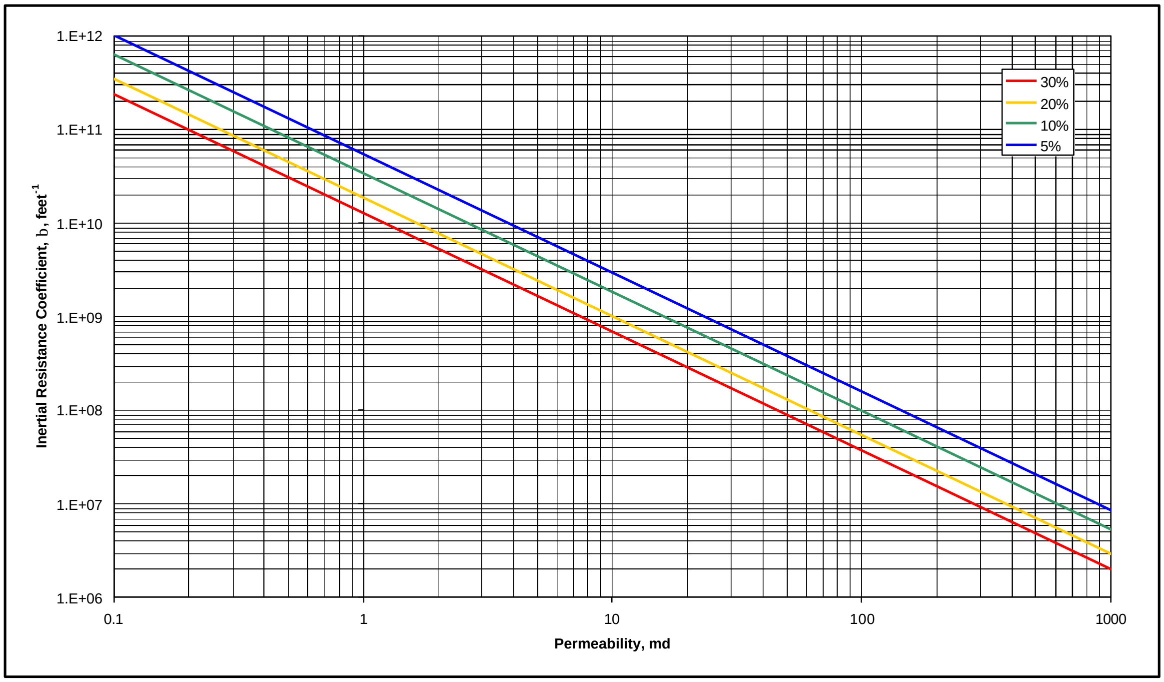

Figure 4. ß vs. Permeability for Variable Porosity Values (After Katz, et al, 1959).

A relationship such as this could be a very powerful tool for estimating the components of skin and therefore selecting appropriate remedial candidates. To show this, we can re-write the non-Darcy pressure drop expression in **Equation 8** in terms of the non-Darcy flow coefficient, generating the following (assuming the radius of investigation is sufficiently large):

$F = ß \bullet 3.161(10^{-12})?zT_f / h^2 r_w$ .... **Equation 9**

Once F is known, we can determine the non-Darcy skin coefficient using **Equation 5**. So, it could be possible to use single-point deliverability test data to approximate a multi-point deliverability test when a correlation, such as Katz, et al, is used to estimate the porous medium's inertial resistance coefficient.

Drawing upon the very large dataset of well tests available from ARI's "new and novel" project (ARI, 1999), ARI was able to calculate inertial resistance coefficients (depicted as *PTA*) for each of the pre-stimulation well tests. These values were then plotted against the determined permeability values (**Figure 5**). Using **Figure 4**, inertial resistance coefficients, based on Katz, et al, were derived for each well's permeability and porosity value and then plotted as a line on the chart (depicted as *Katz*). Although the Katz correlation passed through the "cloud" of values between 1 and 100 md, the correlation very much under-predicted coefficient values for the higher permeability wells. So, a superior correlation for estimating the coefficient would be required to fully utilize this technique.

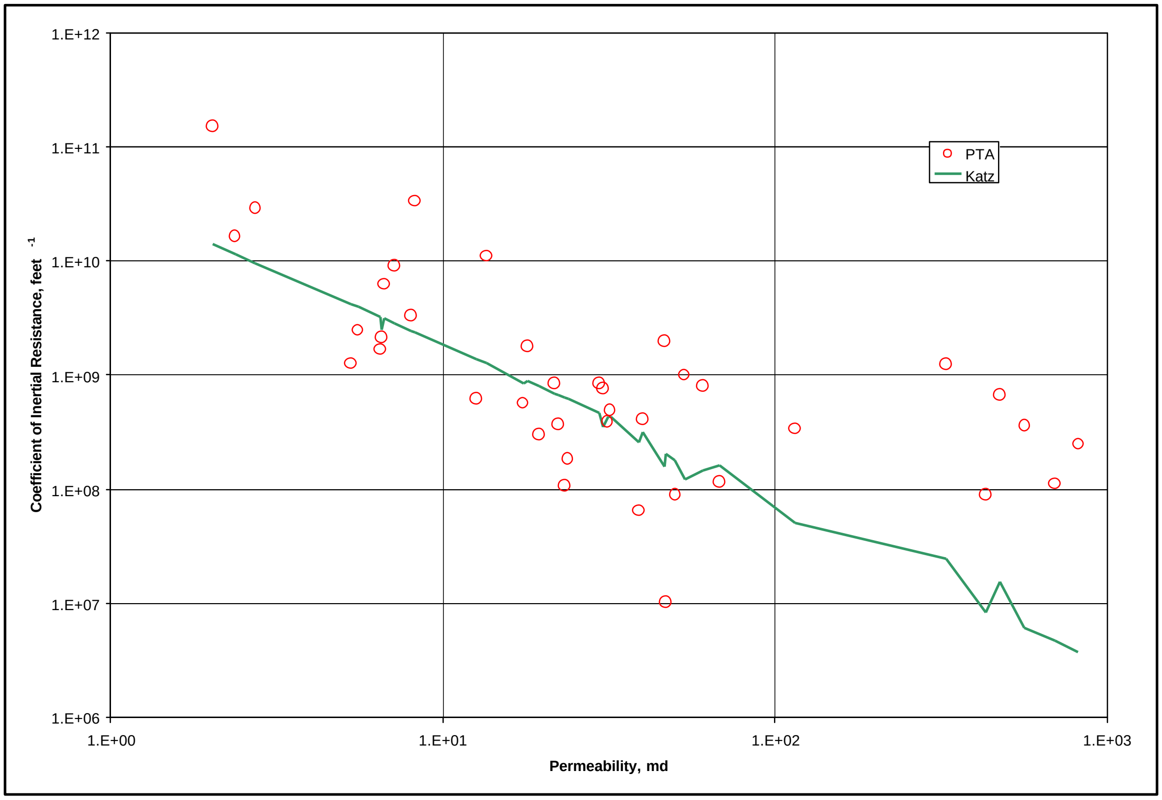

Figure 5. Multi-Point Deliverability Test-Derived b **Values with Katz, et al Fit.**

In the search for a better inertial resistance coefficient relation to permeability and/or porosity a literature review was conducted to review the available relationships. **Appendix A** contains the abridged results. For each formula, a similar plot to **Figure 5** was constructed to ascertain the fit of the given correlation with the multi-point deliverability well test derived data. Overall, Geertsma's (Geertsma, 1974) equation best fit both the low, albeit not as well as Katz, and high permeability dataset (**Figure 6**). This equation is shown in **Equation 10**.

ß = 48511 / ($F^{5.5}$ $k^{0.5}$) .... **Equation 10**

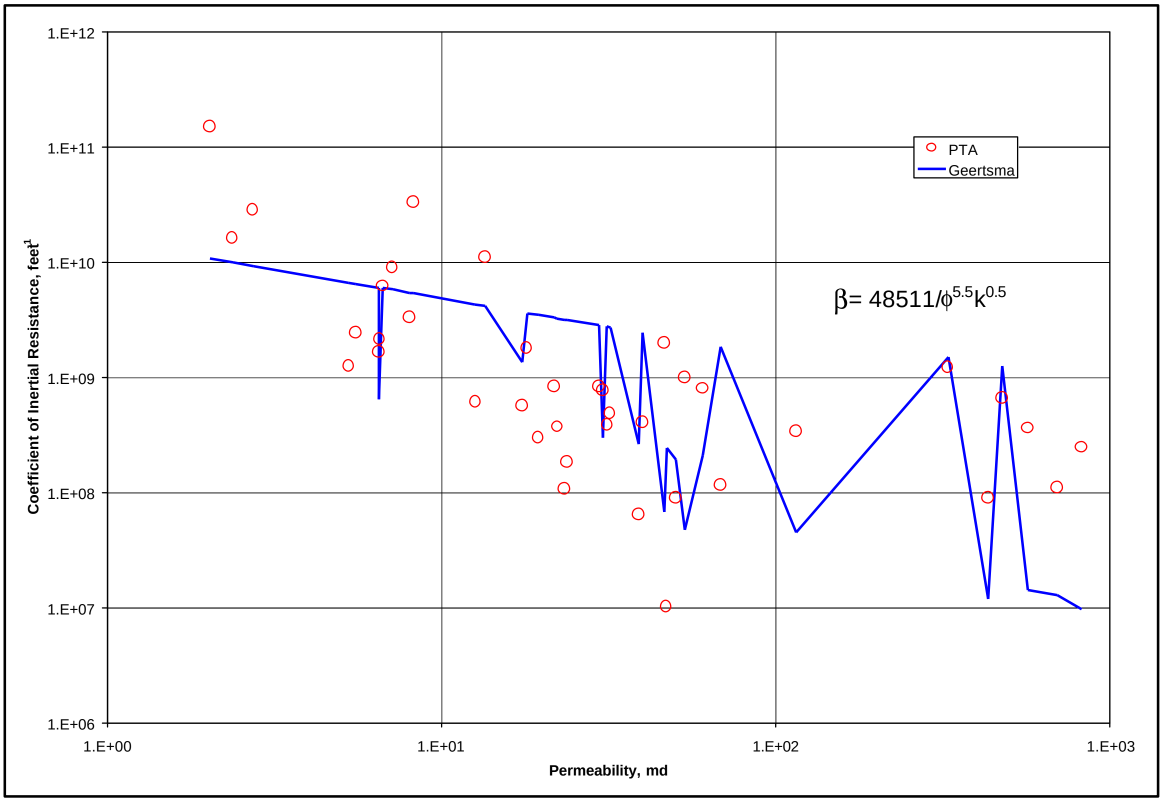

Figure 6. Multi-Point Deliverability Test-Derived b Values with Geertsma Fit.

OTHER TECHNIQUES WITH MERIT

In addition to approximating the coefficient of inertial resistance using correlations, literature has shown that there are four other techniques available that may have merit. They are:

- Dimensionless IPR curves (Chase and Alkandari, 1993),
- Simultaneous rate and pressure measurement from a single drawdown/buildup (Nashawi, et al, 1998),
- Computer-aided well test analysis history matching of a single drawdown/buildup test,
- Determination of inertial effects from a single drawdown/buildup test (Camacho-V, et al, 1993).

Chase and Alkandari were able to develop dimensionless IPR curves for the determination of AOF for both fractured and unfractured wells, requiring only pressure buildup or drawdown data. The analysis of the data would provide the engineer with knowledge of the total skin (true + rate dependent skin), reservoir pressure and the permeability of the reservoir. Using the dimensionless IPR curves, the analyst could ascertain not only the current AOF with a good degree of certainty, but also determine what the AOF would be if a remedial treatment (skin improvement) was enacted on a well. The solution process, however, relied on the use of the C-and-n type of deliverability analysis and provided little insight into the non-Darcy components of the skin term, which could result in a stimulated well behaving as if where damaged under the significant flow rates.

Nashawi, et al's technique, while extremely rigorous, required simultaneous downhole rate and pressure measurement during the drawdown/buildup test, including the after flow portion of the test. While the technique did provide insight into the rate dependent skin factor, the overall cost of conducting such a study would most likely be greater than traditional multi-point deliverability testing.

On the other hand, a type of history matching could be conducted on drawdown/buildup data using computer-aided well testing software. Following the permeability and skin analysis of the well test data, the analyst could conduct a trial-and-error approach to estimate the non-Darcy skin coefficient. **Figure 7** depicts a left-to-right analysis methodology whereby the initial analysis yielding permeability and skin factor is on the left. The engineer would first estimate the true skin factor and using **Equation 6** and solve for the non-Darcy skin coefficient based on the total skin factor derived from the initial analysis. The true skin would be varied and the non-Darcy skin coefficient solved for until a superior match of the derivative data is achieved (analysis on the right). While this type of analysis can be accomplished readily, the results, much like simulation history matching, are not unique.

Finally, Camacho, et al presented a graphical means of identifying the presence of non-Darcy flow, which is a plot of the pressure derivative vs. the inverse of the square root of time (**Figure 8**). Analyzing non-Darcy flow as variable permeability as well as deviation from laminar flow, the authors were able to fit a straight line through the pseudo-radial flow period. From this straight line, the ordinate to the origin (y-intercept) was used to calculate reservoir's permeability value. Subsequent calculations include Reynolds number, the inertial resistance of the skin (improved or damaged) zone, and inertial resistance of the reservoir body. Because of its potential synergy with computer-aided well test analysis, this particular method may hold promise for determining non-Darcy flow characteristics from a single drawdown/buildup test.

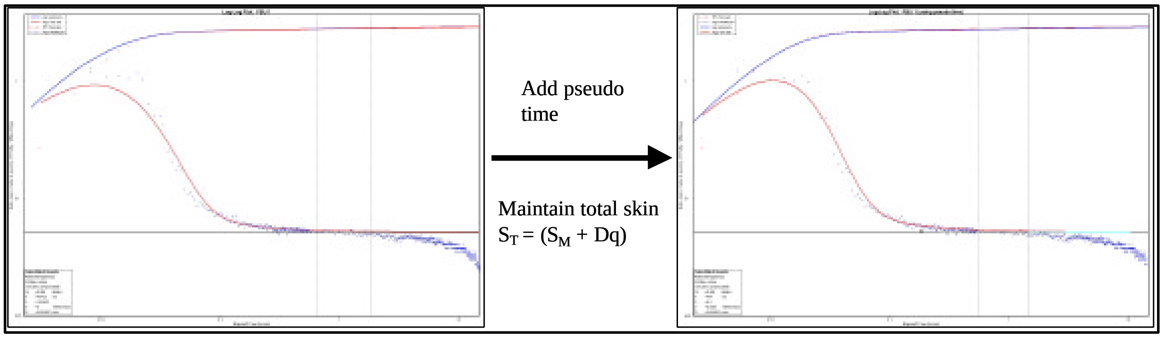

Figure 7. Trial-and-Error Method Determination of non-Darcy Flow Characteristics.

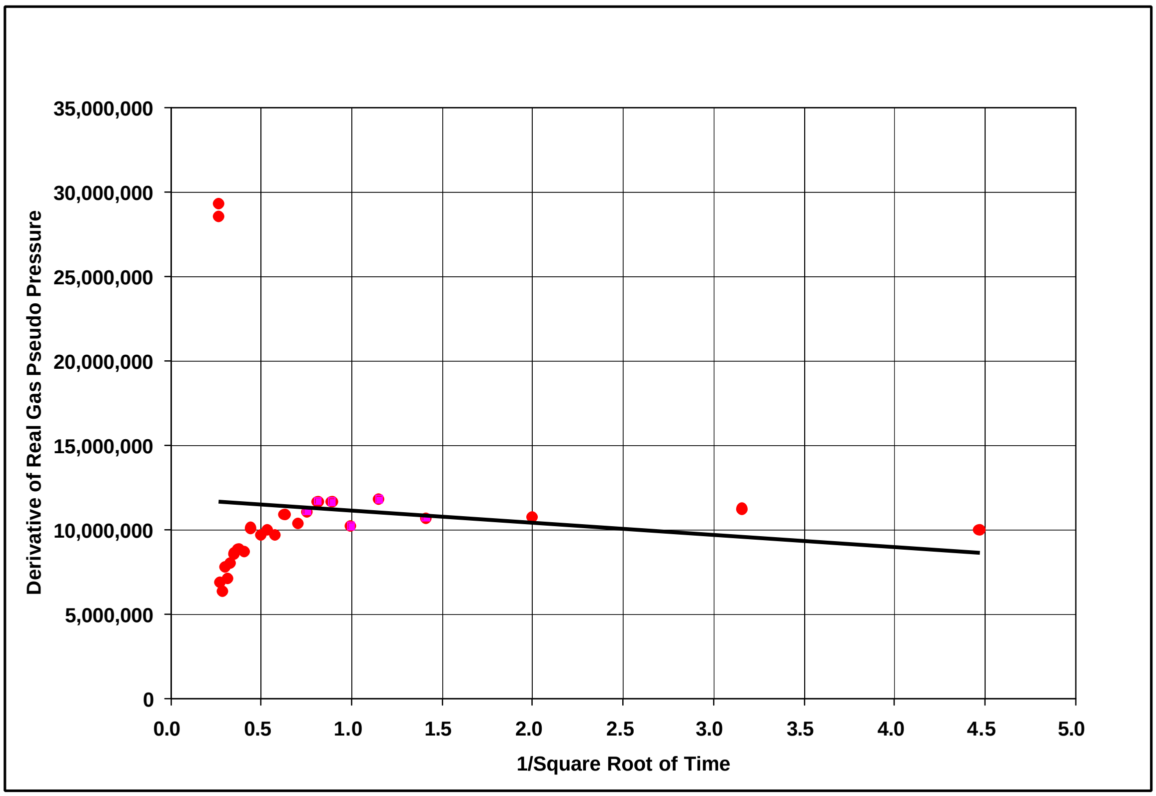

Figure 8. Diagnostic Plot for the Determination of Inertial Flow Characteristics.

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NOMENCLATURE

B	= Darcy flow coefficient, $psia^2$/Mscfd
D	= non-Darcy skin coefficient, 1/Mscfd
F	= non-Darcy flow coefficient, $psia^2$/Mscfd
h	= thickness, ft
k	= permeability, md
q_g	= gas flow rate, Mscfd
r	= radius, ft
s'_{TOTAL}	= skin at any flow rate, dimensionless
s'_{TRUE}	= non-mechanical skin, dimensionless
T_f	= formation temperature, ^oR
v	= velocity, ft/s
z	= z-factor, dimensionless

ß	= coefficient of inertial resistance, ft^{-1}
?	= gas gravity, dimensionless
F	= porosity, fraction
?	= density, lb/ft^3
µ	= viscosity, cp
? p^2	= difference of squared initial and final pressures, $psia^2$
? m(p)	= difference of squared initial and final pseudo-pressure, $psia^2/cp$

SECTION 3

APPROXIMATION OF NON-DARCY FLOW CHARACTERISTICS FROM A SINGLE DRAWDOWN-BUILDUP TRANSIENT TEST

WELL STIMULATION AND TIME CONSIDERATIONS

As was shown in the previous chapter, the Katz (Katz, et al, 1959) formulation was able to approximate inertial resistance coefficient values from 1 to 100 md reasonably well, while the Geertsma (Geertsma, 1974) equation was better in covering the entire permeability range. Therefore, one could readily ascertain an approximate value of the coefficient of inertial resistance and carry forward with the necessary calculations to estimate those properties traditionally derived from multi-point deliverability testing, such as the non-Darcy skin coefficient.

However, what has been learned as a result of ARI's previous work stimulating gas storage wells (ARI, 1999) is that true skin and the non-Darcy skin coefficient vary from pre-stimulation through post-stimulation multi-point deliverability testing. Further, anniversary testing one and two years after post-frac testing revealed that skin parameters continued to change. Thus, because the inertial resistance coefficient can be calculated directly from the non-Darcy skin coefficient, inertial resistance must be varying with these parameters as well.

To show this behavior, **Figure 9** depicts the non-Darcy skin (D) and inertial resistance coefficients (Beta) plotted against their respective true skin values for a series of multi-point deliverability tests conducted on a typical Stark-Summit storage well. A review of **Figure 9** shows that while the true skin was relatively constant from the pre- to the post-frac test, both the non-Darcy and inertial resistance coefficients increased. This is due to the introduction of water into a system that had been cycling "dry" gas for a period of years, essentially reducing the near-well, water saturation to zero. The highly negative pre-frac skin factor is due to a previous hydraulic fracturing stimulation conducted in prior years.

The following year, both coefficients are significantly lower, as is the true skin value, due to full fracture cleanup. The second anniversary test (2-years after the stimulation) exhibits declining inertial resistance and non-Darcy skin coefficients, as well. The variability of these coefficients with time and the introduction of stimulation show that both Katz's and Geertsma's correlations will not be able to adequately describe inertial resistance over time using only permeability and porosity as a basis. Therefore, any correlation employed to deduce inertial resistance must be able to consider stimulation, or skin, as well as permeability and porosity.

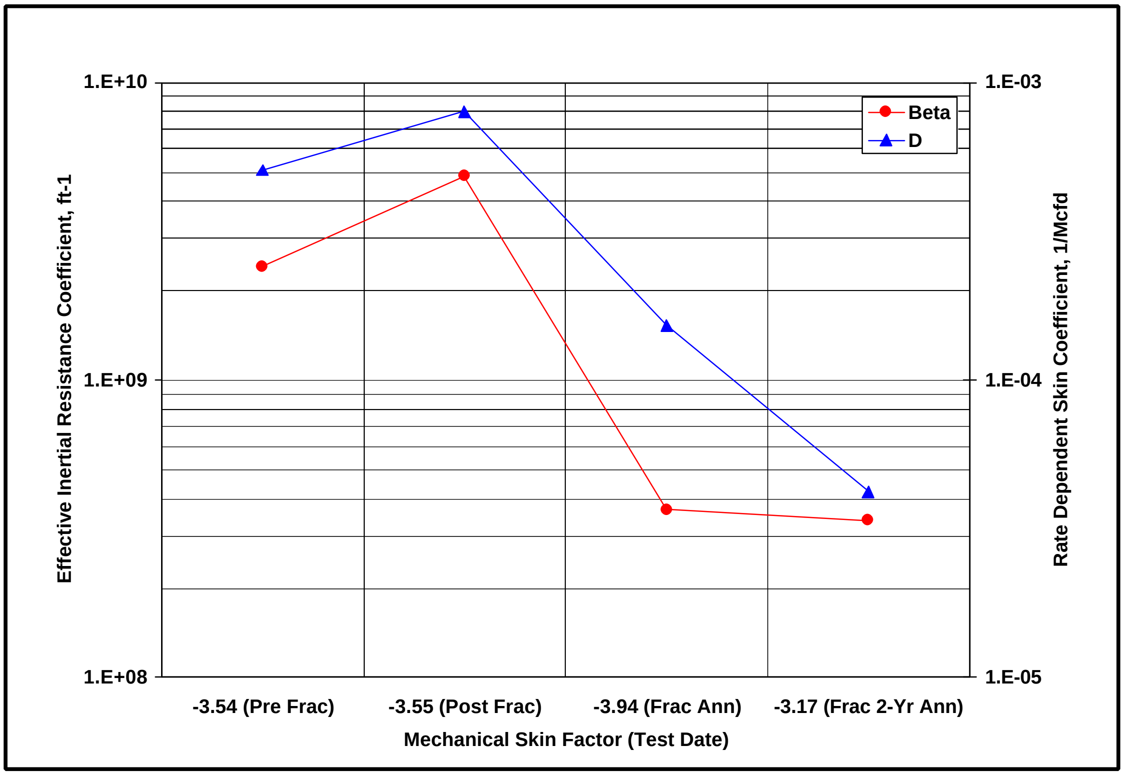

Figure 9. Changing Inertial Resistance (Beta) and Non-Darcy Skin (D) Coefficients as a Result of Stimulation and Time.

Since inertial resistance is a property that can typically be studied in the laboratory, a wealth of literature is available that considers laboratory-derived values for permeability, porosity and saturation (see **Appendix A**). Unfortunately, it is clear that even the incorporation of gas or water saturation into the analysis would not adequately determine inertial resistance coefficients following fracture stimulation or other remedial well activities, even though the understanding of the impact of re-introduced water may be helpful when dealing with gas storage wells. So, Camacho, et al's (1993) work was revisited to ascertain its ability to handle the variability of a parameter such as the coefficient of inertial resistance.

DETERMINATION OF A SKIN-INFLUENCED b

Highlighted in the last portion of **Section 2**, the Camacho, et al methodology is a graphical means of determining the presence of non-Darcy flow, much like pressure transient analysis. Examining the problem as one of variable permeability as well as one of deviation from laminar flow, the authors were able to use Oliver's (Oliver, 1990) proposed solution to the transient non-laminar flow problem. Since Camacho, et al's technical work contains the derivation of the solution for this problem, only the practical application shall be explored further in this report. A step-by-step process is outlined in **Table 1**.

Table 1. Process Outline for Determining Multi-Point Isochronal Deliverability Values from Single Buildup / Drawdown Tests.

Step	Process
	Well testing
1	Conduct well test
2	Determine permeability and total skin from well test
	Camacho's Technique
3	Construct pressure derviative vs. inverse sq. rt of time
4	Determine y-intercept (ordinate)
5	Calculate permeabiltiy using **Equation 11**
6	Calculate N_{RE} (skin approximation) using **Equation 12**
7	Calculate β (native reservoir) using **Equation 10**
8	Calculate β_s (skin-influenced zone) using **Equation 13**
9	Calculate k_s (skin-influenced zone) using **Equation 14**
10	Estimate r_s (skin-influenced zone) using **Equation 15**
11	Average β and β_s for effective inertial resistance value
	Forscheimer's Correlations
12	Calculate F using **Equation 9***
13	Calculate D using **Equation 5***
14	Estimate s'_{TRUE} using **Equation 6**

*** Steps 12 and 13 may be combined by substituting Equation 9 into equation 5**

Following the construction of a plot of the pressure derivative vs. the inverse of the square root of time for a drawdown or buildup period, a semi-log, best-fit line can be placed through what could best be described as the pseudo-radial flow region. This region, in standard well test analysis, is where permeability and skin can be determined with confidence. From the best-fit line, the y-intercept (or ordinate) can be determined and is used to directly compute reservoir permeability and the Reynolds number, which is roughly equivalent to the total skin value (**Figure 10**). Further formulations employ the use of Geertsma's correlations for the determination of inertial resistance coefficients in the skin-influenced (positively or negatively) and native reservoir regions as well as the calculation of the permeability and radius of the skin-influenced zone.

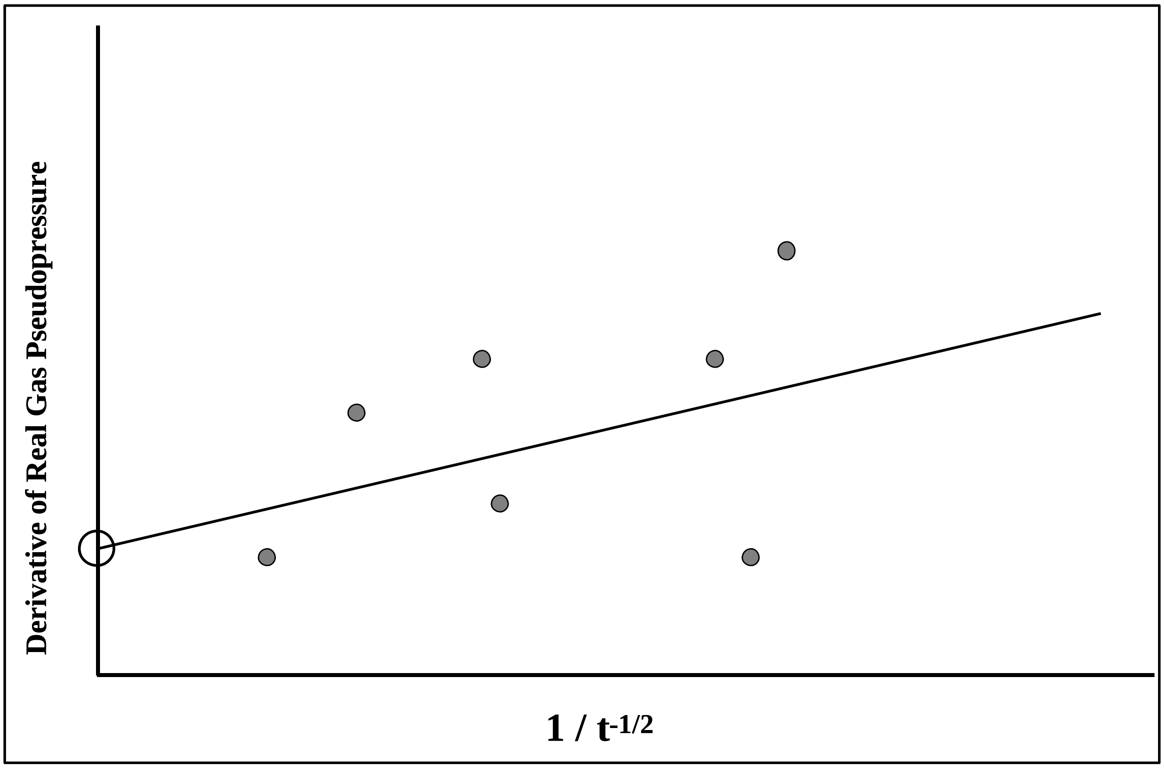

Figure 10. Idealized Example for the Determination of the Y-Intercept Using Camacho et al's Graphical Methodology.

Following the determination of the y-intercept from the best-fit line on the plot of the pressure derivative vs. the inverse of the square root of time, the first step is then to determine the permeability of the reservoir (**Equation 11**).

$$k = (1637\ q_g\ T_f) / (\text{Ordinate} * h) \qquad \textbf{Equation 11}$$

Then, the Reynolds number (skin approximation) can be calculated using **Equation 12**.

$$N_{RE} = \frac{1.151\{(?m(p)_{1,hr}/\text{Ordinate}) - \log[2.637E\text{-}4\ k/(F\ c_{gi}\ \mu_{gi}\ r_w^2)]\}}{1 + \{1.151\ \text{sqrt}(2\pi)\ \log[2.637E\text{-}4\ k/(F\ c_{gi}\ \mu_{gi}\ r_w^2)]\}/\{\text{sqrt}[(2.637E\text{-}4\ k\ t_{max}/(F\ c_{gi}\ \mu_{gi}\ r_w^2)]\}} \qquad \textbf{Equation 12}$$

Once reservoir permeability and skin factor (N_{RE}) have been determined, the inertial resistance coefficients for the skin-influenced ($ß_s$) and reservoir (ß) can be determined using **Equations 10 and 13**.

$$ß = 48511 / (F^{5.5}\ k^{0.5}) \qquad \textbf{Equation 10}$$

$$ß_s = (N_{RE}\ \mu_{gi}\ h\ r_w) / (2.22E\text{-}15\ k\ ?\ q_g) \qquad \textbf{Equation 13}$$

The permeability of the skin-influenced zone can then be determined by reversing Geertsma's equation and solving for permeability (**Equation 14**), while the radius of the damaged or improved area can be estimated by equating the left and side of **Equation 15** to the right hand side and varying the skin-influenced radius (r_s).

$k_s = (ß_s F^{5.5} / 48511)^2$ .... **Equation 14**

$(k/k_s - 1) \ln(r_s/r_w) = s'_{TRUE} - (2.22E\text{-}15k?q_g) / (\mu h) [ß_s(1/r_w - 1/r_s) + ß /r_s]$.......... **Equation 15**

Thus, the implementation of this technique is able to yield permeability and inertial resistance coefficients for both the near-well, skin-influenced region as well as the native reservoir rock. Additionally, the Reynolds number can be determined, which equates to skin factor, as well as the radius of the skin-influenced zone. However, at this time, the meaning and weight one should apply to one or the other calculated values of inertial resistance, for comparative purposes with well test data, is unclear.

What is clear is that the near-well ($ß_s$) values of inertial resistance are significant, but whether they should be weighted evenly or more heavily than those values derived for the reservoir body (ß) remains to be determined. For the time being, the inertial resistance values have been averaged to determine a singular coefficient value for comparison with well test data set.

EXAMPLE

To test Camacho, et al's methods, ARI conducted a detailed review of nearly 40 well tests conducted during the five year, new and novel stimulation technologies for gas storage wells study, with 17 pre-stimulation test and 23 post-stimulation or anniversary test reviewed. For this example, Stark-Summit storage well 2130 was chosen.

The Stark-Summit storage field is located in Stark and Summit counties, Ohio. The field contains 630 injection/withdrawal wells and has a working gas capacity of approximately 56 Bcf. Almost all of the wells have been hydraulically fractured to improve deliverability, and some have been fractured repeatedly to help maintain their performance.

The 2130 well test was prior to novel stimulation and very well behaved from a pressure transient analysis standpoint. **Figure 11** depicts the diagnostic log-log plot with the pressure derivative from the well test. Although the test exhibited single-fault boundary dominated behavior at late time, permeability and total skin have been determined to be 12.6 md and –3.64, respectively, which correctly depicted its pre-existing stimulation. Other relevant parameters for test are shown in **Table 2**.

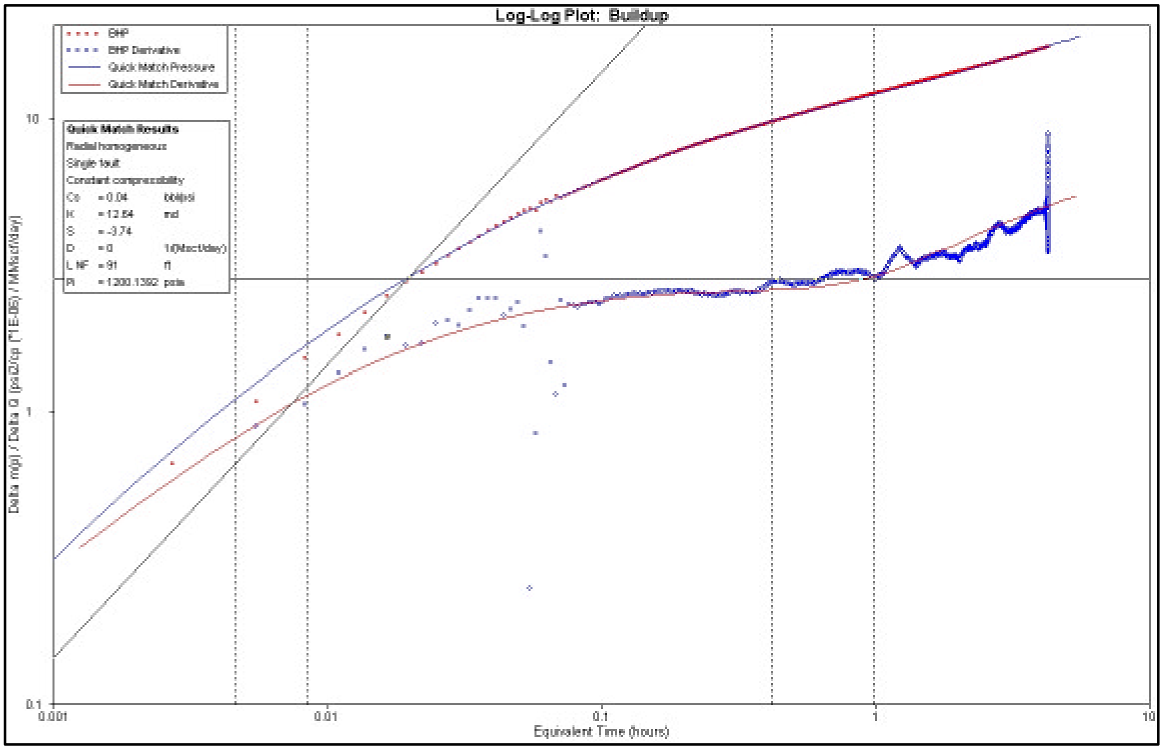

Figure 11. Stark Summit 2130 Pre-Stimulation Buildup Test Analysis.

Table 2. SS 2130 Pre-Stimulation Test Properties.

Reservoir Properties		**Pressure-Test Properties**	
11.00	Thickness, ft	4.00	Duration, hours
0.25	Well radius, ft	1,160	Initial pressure, psia
0.10	Porosity, fraction	1,006	Final pressure, psia
0.60	Gas gravity	1,922	Flow Rate, Mscfd
554.00	Formation temperature, ^{o}R	12.64	Permeability, md
0.013	Avg. viscosity, cp	(3.74)	Total skin factor
0.855	Avg. z-factor	(4.49)	True skin factor
6.77E-04	Total compressibility, psi^{-1}	0.00029	D, 1/Mscfd
		6.2E+08	β, ft^{-1}

To move forward with the analysis, the original bottomhole pressure records from the first drawdown / buildup period for the pre-stimulation transient test were delimited to create a representative, albeit smaller, data stream to work with. This data was loaded into a spreadsheet program, which calculated all gas PVT properties as well as gas pseudo-pressure, and the analysis plots were automatically created.

To ensure a reasonable amount of data was maintained, a Horner plot was created and analyzed within the program. **Figure 12** depicts the Horner plot analysis, showing the semi-log straight line. Determined permeability and skin factor from this analysis provided a good check as permeability and total skin were determined to be 12.5 md and –3.7 as compared to the more rigorous well test analysis values of 12.6 md and –3.7, respectively.

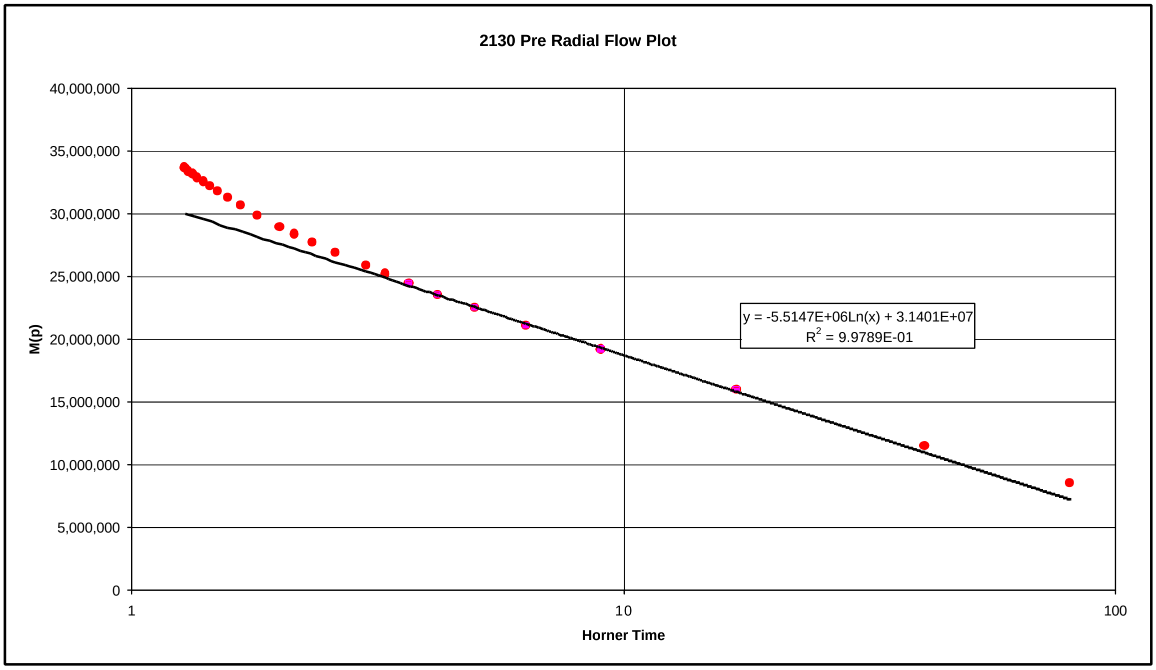

Figure 12. Horner Analysis of Stark Summit 2130 for Data Integrity.

For the Camacho, et al derivative analysis, the semi-log straight line was fit through the pseudo-radial flow region determined from the Horner plot, obtaining the y-intercept value of 1.19E+7, (**Figure 13**) which was input along with the properties in **Table 2** to determine a permeability value of 13.3 md using **Equation 11**. Following through the process outlined earlier in **Equations 10 through 15**, the following parameters were determined. Additionally, the non-Darcy coefficient (D) was computed using $ß_{avg}$ as an input to **Equation 9** and substituting the determined non-Darcy Flow coefficient (F) value into **Equation 5**.

- k = 13.3 md
- N_{RE} = - 2.91
- $ß_s$ = -3.18E+9 ft^{-1}
- ß = 4.20E+9 ft^{-1}
- $ß_{avg}$ = 5.14E+8 ft^{-1}
- k_s = 23.32 md
- r_s = 3.92 ft
- D = 2.4E-4 1/Mscfd

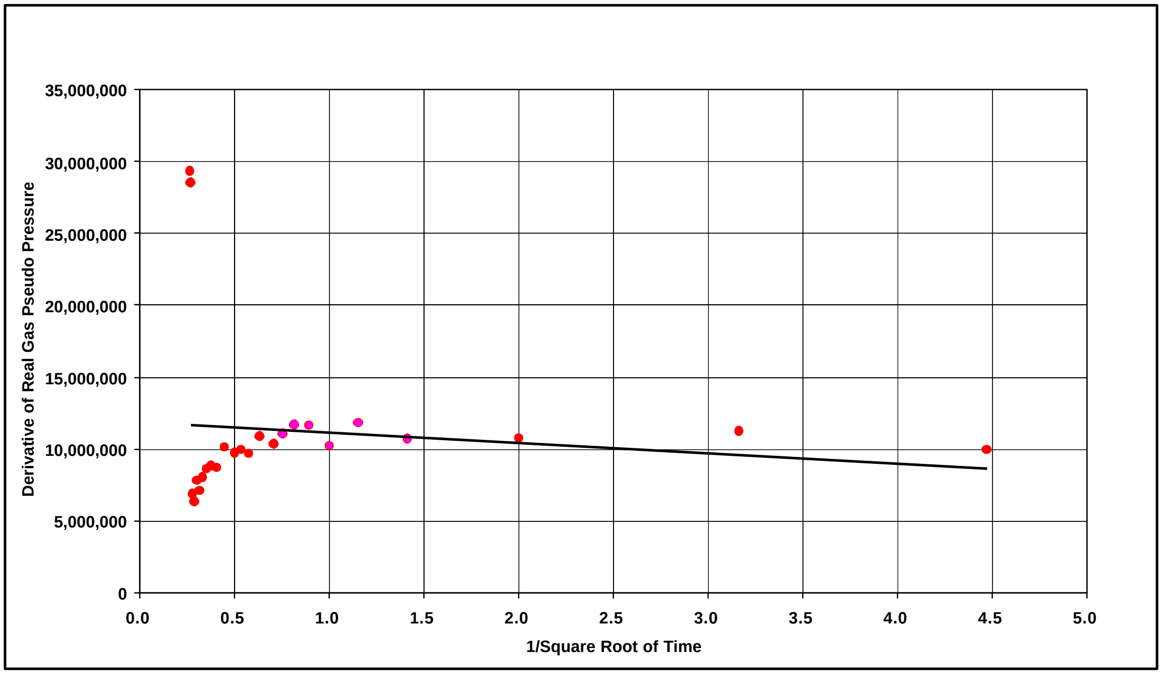

Figure 13. Semi-log Fit of the Camacho, et al Derivative Plot.

From the above results, a couple of items warrant further discussion. First, the determined permeability and Reynolds number (skin approximation) values reasonably approach those derived from well test analysis. This suggests that in later applications of this methodology, the creation of a derivative plot and the determination of a y-intercept value can be waived, allowing the inertial resistance coefficients to be calculated using well test determined permeability and skin values in lieu of using **Equations 11 and 12**. Further computations could then be carried out using **Equations 10 and 13 to 15**.

Next, the determination of a negative value for the skin-influenced coefficient of inertial resistance is not well understood at this time. However, Jones offered insight into the reasons why such values may be determined (Jones, 1987) as he suspected that negative resistance coefficients were due to variations in permeability during testing – stress dependent permeability, for example. Nearly half of the remaining analyses also generated negative inertial coefficient values for the skin-influenced region. However the majority of these negative instances were eliminated during the averaging process. Thus, a look at how to better "average" the skin-influenced inertial resistance coefficient with the native reservoir inertial resistance coefficient to replicate well test performance may improve this behavior.

Lastly, the permeability of the skin-influenced zone is greater than that of the reservoir body. However, because of the negative skin factor, or negative Reynolds number, the skin-influenced zone has been enhanced. Thus, the overall permeability of the roughly 3.9 feet (r_s) of reservoir about the well should have an effective permeability greater than the remaining unstimulated reservoir body.

ALL RESULTS

All results for these analyses are contained in **Appendix B**. Therein, a table depicts the general reservoir properties, pressure transient analysis results, Katz and Geertsma correlation values as well as the determined inertial resistance values from the Camacho, et al methodology, including a computation of the non-Darcy flow coefficient based on Camacho results.

Several plots have also been generated for the purposes of comparing the multi-point deliverability test with the estimates derived from the Camacho, et al methodology. **Figures 14, 16 and 17** depict comparisons between the inertial resistance coefficient, the non-Darcy flow coefficient and the true skin for well tests and Camacho's technique. For the inertial resistance coefficients (**Figure 14**), those positive values have been plotted against the well test-derived results and compare reasonably well. Many are very close and all are within one log cycle of the "actual" result.

From the average Camacho inertial resistance estimates, a computation for the non-Darcy skin coefficient (D) can be carried out using **Equations 9 and 5**. **Figure 15** depicts a comparative plot, which enables a quick review of the agreement between well test and estimate of the non-Darcy skin coefficient. For those points that agree, the point should plot along the 45 degree line. While there is generally good agreement between the estimates and the actual well test values, the well test values tend to be greater. This suggests that on the whole, the average inertial resistance coefficients are under-predicting the actual values determined from the well tests. Also, all data is plotted, so those wells with negative average inertial resistance coefficients using the Camacho technique, resulted in negative non-Darcy skin coefficients.

A closer review of the 40-point data set depicted in Figure 15, reveals that if 9 outlying high and low values are removed, a trend line, which is similar to the 45 degree line, can be fit through the data (**Figure 16**). The correlation coefficient for this data set is 0.8, indicating a good correlation exists between the two data sets, demonstrating that non-Darcy flow characteristics can be reasonably ascertained from single drawdown and buildup tests. Should this trend line be redrawn such that the correlation passed exactly over the 45 degree line, the correlation coefficient would be reduced but would not change significantly.

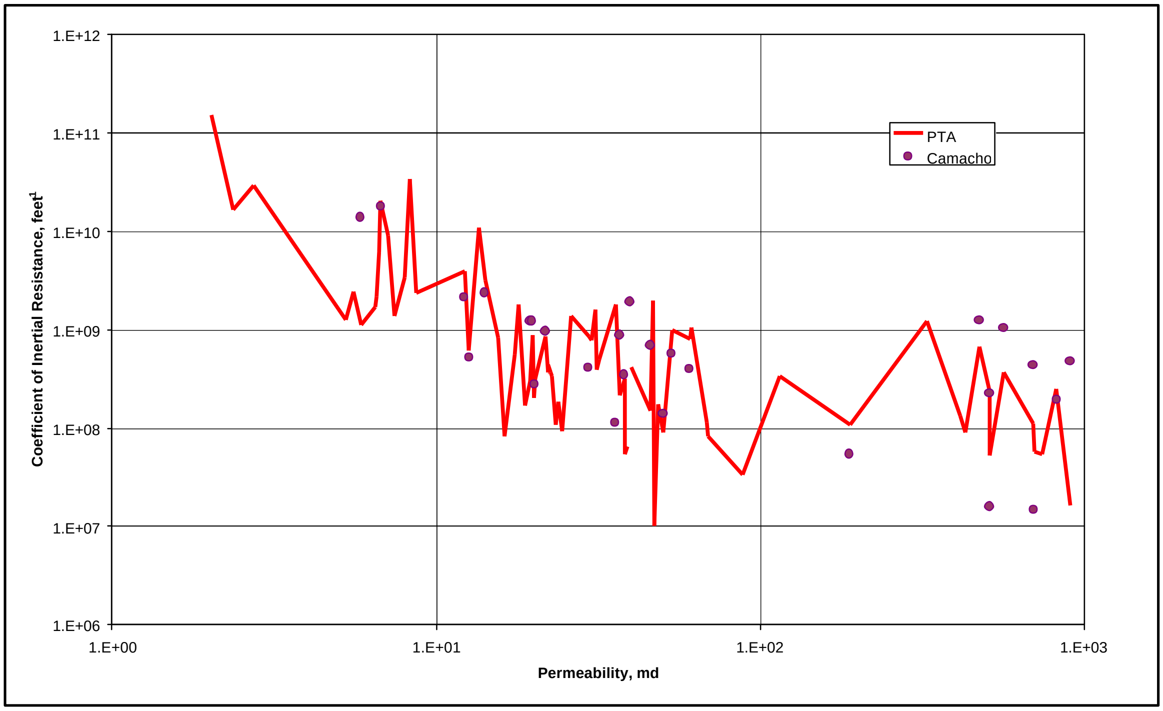

Figure 14. Comparison of Camacho and Well Test Derived b Values.

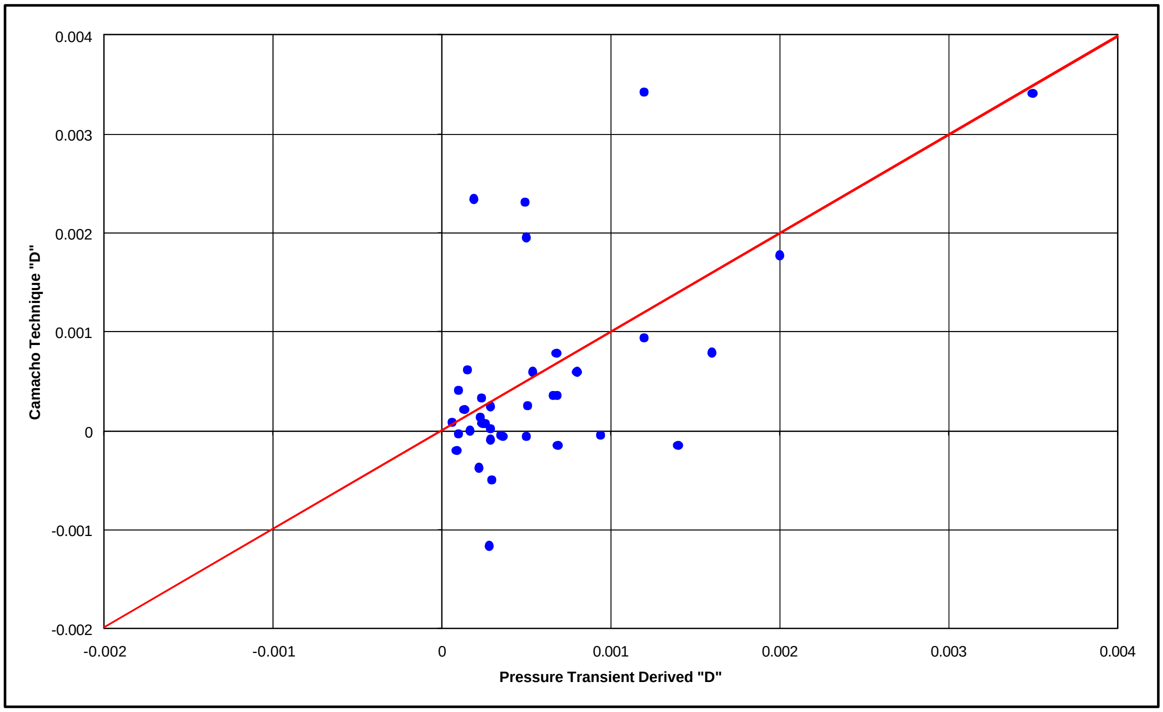

Figure 15. Comparison of Camacho and Well Test Derived D Values.

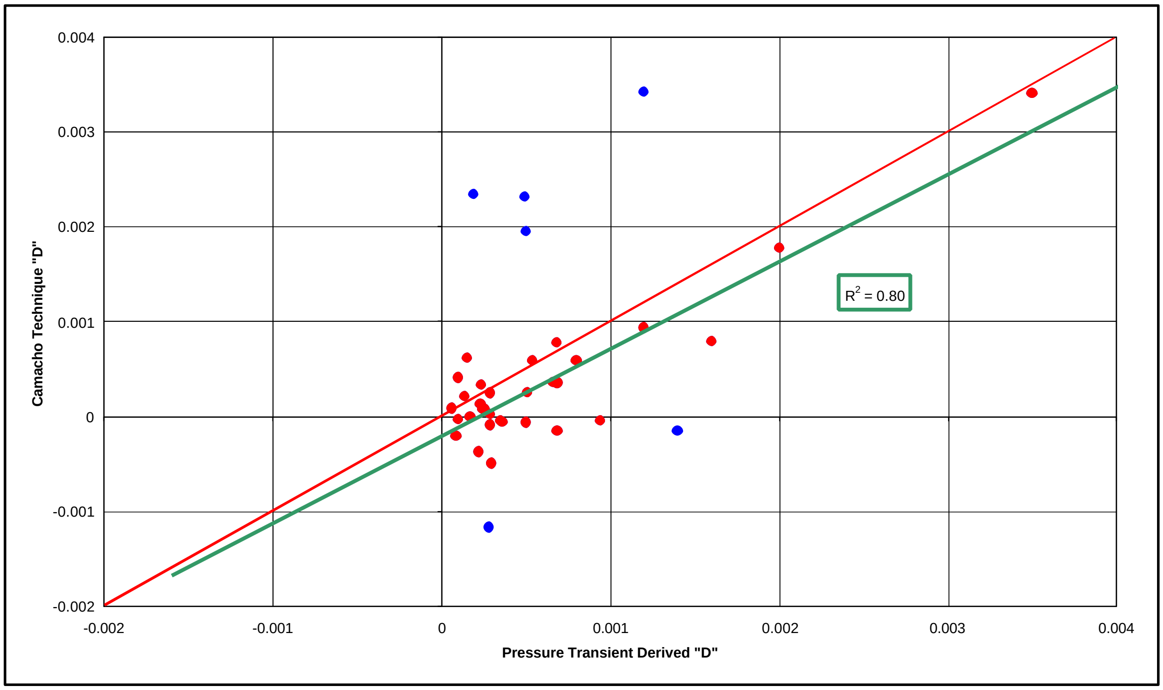

Figure 16. Comparison of Camacho and Well Test Derived D Values with Fit of Significant Data.

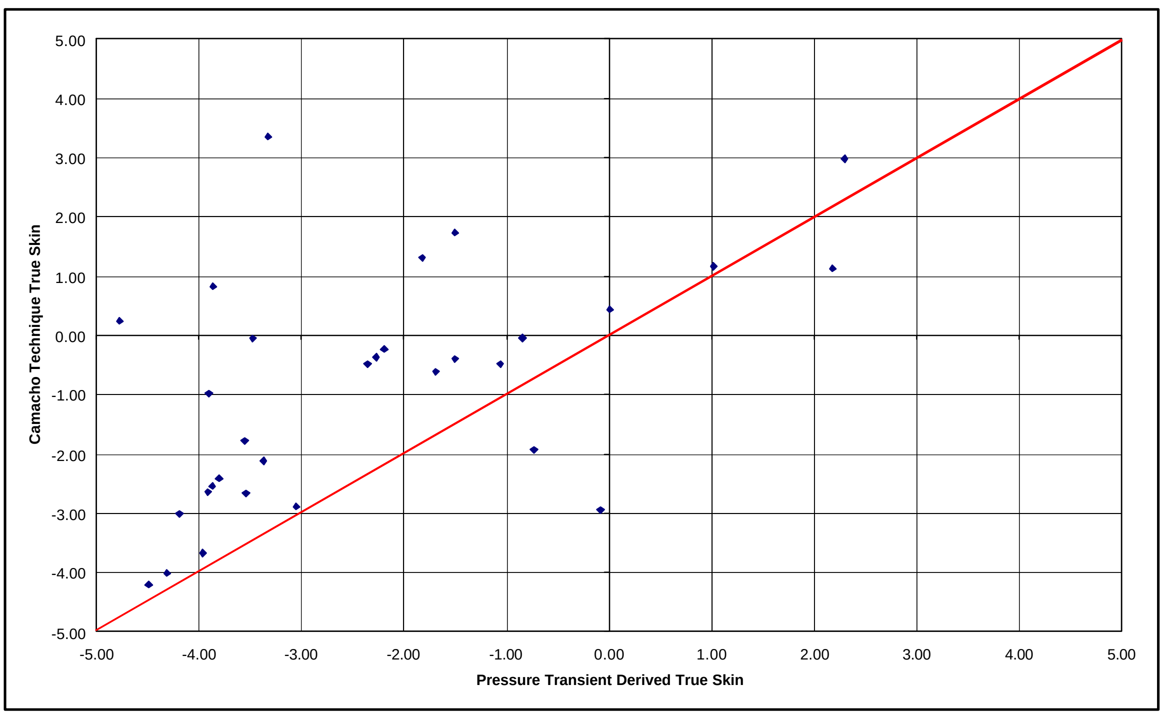

Figure 17. Comparison of Camacho and Well Test Derived s'_{TRUE} Values.

Once the non-Darcy skin coefficients have been estimated, we have all the inputs necessary to determine true skin values for comparison to the well test data. Using **Equation 6**, and solving for true skin, the results have been displayed on the comparison plot in **Figure 17**. As a result of the Camacho technique determining lower, on average, inertial resistance and subsequently non-Darcy skin coefficients, the resultant is more "positive" true skin values as compared to the well test data.

FUTURE WORK

For further refinement of the Camacho technique, an exploration of using neural networks to determine the proper ratio of $ß_s$ and ß for comparative purposes with well test data is warranted. Neural networks can be an extraordinary tool for non-linear problem solving and would be well equipped for determining the relationships between the permeability and inertial resistance coefficient values for the reservoir body and skin-influenced zone as well as the radius of the skin-influenced zone for the determination of a representative inertial resistance coefficient for reservoir. This value could then be equated to multi-point derived coefficients.

Another key consideration in the use of Camacho, et al's methodology is the reliance on Geertsma's correlation (see **Equations 14 and 15**). While this correlation did provide reasonable coverage of a wide range of permeability values (**Figure 6**), its implementation for comparison to well test data, particularly in instances where stimulation has been employed, raises the question of its accuracy. For characterizing the reservoir body, which is neutrally stimulated, there may be a superior correlation available for use in its place.

Once refinement of Camacho, et al's original work was completed. It would seem logical to then carry forth the analysis as an additional step during well test analysis. Since the well test will generate superior values for permeability and total skin, these parameters can be equated to Camacho's values for permeability and Reynolds number, eliminating the need for the generation of the diagnostic derivative plot. Further, the knowledge of permeability and Reynolds number would then be sufficient to allow the determination of the remaining variables – inertial resistance coefficients of the reservoir body and the skin-influenced zone as well as the skin-influenced radius and permeability. A possible simplified procedure using this methodology is outlined in **Table 3**.

Table 3. Modified Process Outline.

Step	Process
	Well testing
1	Conduct well test
2	Determine permeability and total skin from well test
	Camacho's Technique
~~3~~	~~Construct pressure derviative vs. inverse sq. rt of time~~
~~4~~	~~Determine y-intercept (ordinate)~~
~~5~~	~~Calculate permeabiltiy using **Equation 11**~~
6	Calculate N_{RE} (skin approximation) using **Equation 12**
7	Calculate β (native reservoir) using **Equation 10**
8	Calculate β_s (skin-influenced zone) using **Equation 13**
9	Calculate k_s (skin-influenced zone) using **Equation 14**
10	Estimate r_s (skin-influenced zone) using **Equation 15**
11	Average β and β_s for effective inertial resistance value
	Forscheimer's Correlations
12	Calculate F using **Equation 9***
13	Calculate D using **Equation 5***
14	Estimate s'_{TRUE} using **Equation 6**

So with the use of short-term, surface-measured, pressure transient data generated during a single drawdown / buildup test, an engineer could easily determine reservoir permeability, pressure, and total skin using traditional well test analysis techniques. With the inclusion of the core of Camacho's methodology and enhanced with the aforementioned working points, the analyst could carry forward discerning inertial resistance coefficients for both the skin-influenced and native reservoir body. Using the proper weighting factor for these coefficients would then provide the representative value for the computation of the non-Darcy flow and skin characteristics. With knowledge of these values, the engineer could then determine the need of a given well for stimulation from a single-point test, meeting the original goals of this work.

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NOMENCLATURE

c_g = gas compressibility, $psia^{-1}$

h = thickness, ft

k = permeability, md

q_g = gas flow rate, Mscfd

r = radius, ft

N_{RE} = Reynolds number, dimensionless

t = time, days

T_f = formation temperature, ^oR

ß = coefficient of inertial resistance, ft^{-1}

? = gas gravity, dimensionless

F = porosity, fraction

π = pi, dimensionless

μ_g = viscosity, cp

? m(p) = difference of squared initial and final pseudo-pressure, $psia^2/cp$

OTHER SUBSCRIPTS

1,hr	= value at one hour of elapsed test time
i	= initial
max	= maximum duration
s	= skin-influenced zone
w	= wellbore

SECTION 4
CONCLUSIONS

CONCLUSIONS

Based on the initial results outlined in this report and highlighted below, ARI believes that the determination of properties describing non-Darcy flow and skin can now be estimated from simple, short-term, surface-collected, single drawdown / buildup data, providing a superior means of selecting stimulation candidates in gas storage fields and quite possibly for gas production wells.

- Deliverability data normally collected by gas storage operators for monitoring well performance, usually short-term, single-point, surface-measured tests performed once every few years, is not always reliable for candidate selection. Reasons for this include the potential for inconsistent test procedures, lack of continuous data collection (pressure transient testing), and the assumption of the slope of the deliverability curve, which has been shown to change over time. As a result, "low potential" wells are frequently being remediated, whereas "high-potential" wells are being overlooked.
- C-and-n deliverability plots are merely a tangent of a deliverability curve better described through Forscheimer's equation and analyzed using Laminar-Inertial-Turbulence (LIT) analysis techniques.
- Several laboratory-derived correlations exist for determining the coefficient of inertial resistance for a particular reservoir, with an understanding of at least the porosity and the permeability of the producing formation. With an estimate of this coefficient, it has been shown that multi-point deliverability tests can be approximated with only a single drawdown / buildup transient test, saving significant operational time and monies.
- It has been demonstrated that the non-Darcy flow characteristics for a given reservoir vary with not only time, but also with remediation. As a result, the inertial resistance coefficient is variable and must be estimated with an understanding of the skin factor.
- A methodology proposed by Camacho, Vasquez and Roldan has been implemented to estimate the inertial resistance coefficient for a given reservoir via buildup transient data. This technique incorporates a diagnostic plot of pressure derivative plotted against the inverse of the square root of time. Values determined from this analysis are permeability and inertial resistance coefficients of the reservoir body and the skin-influenced zone. Additionally, Reynolds number, an approximation for skin factor, and the radius of the skin-influenced zone can be determined.
- Permeability variations with pressure (stress-dependent permeability) have been reported to generate negative inertial resistance coefficients.

- Because of its similarity with pressure transient testing and analysis, it is envisioned that the Camacho, et al technique could be carried out as an additional step in the well test solution process. To do so, one would simply equate the permeability and total skin values from the well test to the permeability and Reynolds number of Camacho's technique and carry forth with the remaining computations.
- The use of neural network analysis techniques may hold promise for determining the proper ratio of Camacho-derived $ß_s$ and ß values for comparison to well test data, thereby improving the simple averaging methodology employed in this report.
- Camacho's reliance on Geertsma's correlation can be further explored to improve the determination of inertial resistance coefficients. There may be a superior relationship available for neutrally stimulated (for the undamaged reservoir body) formations.
- Through the use of Camacho's technique, Advanced Resources International, Inc. was able to reasonably approximate non-Darcy flow characteristics typically derived from multi-point deliverability testing from single drawdown / buildup transient tests. Although technique refinement is warranted, this procedure may hold merit as both a time and cost saving methodology for the determination of superior remediation candidates.

APPENDIX A

ABRIDGED NON-DARCY FLOW LITERATURE REVIEW RESULTS

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APPENDIX B

WELL DATA AND ANALYSIS RESULTS TABLE

					Pressure Transient Testing Results						b Correlations		Camacho Technique		
Field	Well	Test	Net Pay ft	Porosity	Rate Mscfd	Perm md	Total Skin	True Skin	D 1/(mcf/d)	b PTA	Geertsma	Katz	bs	bavg (G)	D (G) 1/(mcf/d)
Chippewa	1861	Pre-Frac	10.0	0.100	800	68.3	-3.95	-4.19	0.0003	1.2E+08	1.9E+09	1.6E+08	-3.0E+09	-4.8E+08	(0.0012)
Chippewa	1861	Post-Frac	10.0	0.100	1,222	69.3	-0.67	-0.87	0.0002	8.1E+07	1.8E+09	1.6E+08			
Chippewa	1874	Pre-Frac	22.0	0.100	1,183	22.2	-3.34	-3.46	0.0002	3.7E+08	3.3E+09	6.7E+08			
Chippewa	1874	Anniversary	22.0	0.100	2,404	18.8	-3.70	-3.94	0.0001	1.7E+08	3.5E+09	8.3E+08			
Chippewa	2080	Pre-Frac	31.0	0.100	1,330	13.5	-1.49	-3.59	0.0017	1.1E+10	4.2E+09	1.3E+09			
Chippewa	2093	Pre-Frac	12.0	0.100	833	31.3	-3.16	-5.06	0.0004	3.9E+08	2.7E+09	4.3E+08			
Chippewa	2096	Pre-Frac	12.0	0.100	725	8.3	1.43	-4.30	0.0094	3.3E+10	5.3E+09	2.4E+09			
Chippewa	2391	Pre-Frac	28.0	0.100	710	6.7	-1.50	-2.33	0.0006	6.2E+09	5.9E+09	3.1E+09			
Chippewa	2400	Pre-Frac	28.0	0.100	2,302	23.3	-2.76	-2.89	0.0000	1.1E+08	3.2E+09	6.3E+08			
Chippewa	2405	Pre-Frac	29.0	0.100	844	2.7	-3.32	-4.82	0.0012	2.9E+10	9.3E+09	9.6E+09			
Chippewa	2417	Pre-Frac	36.0	0.100	2,308	23.8	-2.90	-2.98	0.0001	1.8E+08	3.1E+09	6.2E+08			
Chippewa	2417	Anniversary	36.0	0.100	2,441	22.2	-3.00	-3.47	0.0001	4.3E+08	3.3E+09	6.7E+08			
Chippewa	2481	Pre-Frac	68.0	0.100	1,663	5.3	-4.56	-4.45	0.0000	1.3E+09	6.7E+09	4.2E+09			
Chippewa	2557	Post-Frac	24.0	0.100	6,494	22.1	-3.58	-4.22	0.0001	3.7E+08	3.3E+09	6.8E+08			
Chippewa	2557	Anniversary	24.0	0.100	1,698	20.2	-4.22	-4.41	0.0001	3.2E+08	3.4E+09	7.6E+08			
Chippewa	2557	2-Yr Anniversary	24.0	0.100	4,800	22.8	-3.62	-4.55	0.0001	3.3E+08	3.2E+09	6.5E+08			
Chippewa	2645	Pre-Frac	53.0	0.100	3,144	6.5	-4.45	-4.48	0.0001	1.7E+09	6.0E+09	3.2E+09			
Cooks Mills	C 12	Pre-Frac	14.0	0.150	4,500	38.9	-3.34	-3.80	0.0001	6.4E+07	2.6E+08	2.6E+08	-5.6E+08	-1.5E+08	(0.0002)
Cooks Mills	C 12	Post-Frac	14.0	0.150	1,640	48.3	0.00	-3.86	0.0003	1.8E+08	2.4E+08	1.9E+08	-8.3E+08	-3.0E+08	(0.0005)
Cooks Mills	C 12	Anniversary	14.0	0.150	5,721	88.3	0.02	-4.77	0.0001	3.3E+07	1.8E+08	9.0E+07	-1.9E+08	-1.3E+07	(0.0000)
Cooks Mills	C 14	Pre-Frac	18.0	0.150	3,122	60.6	-3.50	0.12	0.0016	8.0E+08	2.1E+08	1.5E+08	5.4E+08	3.9E+08	0.0008
Cooks Mills	D 15	Pre-Frac	20.0	0.150	3,344	30.3	-1.50	-3.90	0.0007	7.6E+08	3.0E+08	3.5E+08	-6.5E+08	-1.7E+08	(0.0002)
Cooks Mills	DF 1	Pre-Frac	20.0	0.155	1,189	50.1	-2.70	-0.08	0.0001	9.0E+07	1.9E+08	1.8E+08	4.7E+07	1.4E+08	0.0002
Donegal	4019	Anniversary	9.0	0.150	3,050	38.1	2.96	1.02	0.0005	3.2E+08	2.7E+08	2.6E+08	4.2E+08	3.5E+08	0.0006
Donegal	4037	Anniversary	7.0	0.150	381	16.3	-1.71	-1.70	0.0001	8.1E+07	4.1E+08	7.7E+08			
Donegal	4037	2-Yr Anniversary	7.0	0.150	900	22.6	-0.53	-0.68	0.0004	3.7E+08	3.5E+08	5.1E+08			
Donegal	4053	Pre-Frac	6.0	0.150	902	47.0	-0.40	-0.47	0.0000	1.0E+07	2.4E+08	2.0E+08			
Donegal	4053	Post-Frac	6.0	0.150	911	39.6	7.81	8.73	(0.0016)	-5.5E+08	2.6E+08	2.5E+08	3.6E+09	1.9E+09	0.0055
Donegal	4053	Anniversary	6.0	0.150	855	45.9	0.04	-0.73	0.0005	1.5E+08	2.4E+08	2.1E+08	1.2E+09	6.9E+08	0.0023
Donegal	4110	Pre-Frac	15.0	0.150	1,800	6.5	-0.52	-1.23	0.0004	2.2E+09	6.5E+08	2.5E+09			
Donegal	4110	Post-Frac	15.0	0.150	466	5.9	2.22	2.18	0.0002	1.1E+09	6.8E+08	2.8E+09	2.7E+10	1.4E+10	0.0023
Donegal	4110	2-Yr Anniversary	15.0	0.150	1,373	7.5	-0.37	-0.87	0.0003	1.4E+09	6.0E+08	2.1E+09			
Galbraith	2960	Anniversary	15.0	0.200	2,915	510.3	20.70	9.40	0.0035	2.3E+08	1.5E+07	6.9E+06	4.4E+08	2.3E+08	0.0034
Galbraith	4886	Anniversary	13.0	0.200	2,370	188.5	0.78	-0.84	0.0007	1.1E+08	2.5E+07	2.5E+07	8.5E+07	5.4E+07	0.0003
Galbraith	4936	Post-Frac	17.0	0.200	1,440	26.1	-0.30	-2.19	0.0009	1.4E+09	6.6E+07	3.0E+08	-2.1E+08	-7.1E+07	(0.0000)
Galbraith	4936	Anniversary	17.0	0.200	730	31.1	-0.73	-1.69	0.0014	1.6E+09	6.1E+07	2.4E+08	-4.1E+08	-1.7E+08	(0.0002)
Huntsman	8	Pre-Frac	42.0	0.212	15,100	431.2	2.64	-3.32	0.0003	9.0E+07	1.2E+07	8.2E+06	-3.6E+07	-1.2E+07	(0.0000)
Huntsman	8	Post-Frac	42.0	0.212	16,357	511.0	2.50	-1.82	0.0002	5.2E+07	1.1E+07	6.6E+06	2.0E+07	1.6E+07	0.0001
Huntsman	8	Anniversary	42.0	0.212	3,826	415.0	-0.62	-2.27	0.0005	1.3E+08	1.2E+07	8.7E+06	-4.8E+07	-1.8E+07	(0.0001)
Huntsman	21	Pre-Frac	64.0	0.207	3,196	819.7	5.95	2.30	0.0012	2.5E+08	9.8E+06	3.7E+06	3.7E+08	1.9E+08	0.0009
Huntsman	23	Pre-Frac	71.0	0.189	1,641	46.5	-0.58	-1.06	0.0004	2.0E+09	6.8E+07	1.6E+08	-7.1E+08	-3.2E+08	(0.0001)
Huntsman	23	Post-Frac	71.0	0.189	10,731	35.7	0.14	-3.47	0.0003	1.8E+09	7.7E+07	2.2E+08	1.5E+08	1.1E+08	0.0000
Huntsman	23	Anniversary	71.0	0.189	4,079	61.3	-0.88	-2.36	0.0003	1.0E+09	5.9E+07	1.1E+08	-7.4E+08	-3.4E+08	(0.0001)
Huntsman	25	Pre-Frac	68.0	0.188	4,222	114.7	-0.41	-1.50	0.0002	3.4E+08	4.4E+07	5.1E+07	-5.1E+07	-4.9E+06	(0.0000)
Huntsman	43	Pre-Frac	64.0	0.199	3,546	53.4	0.90	0.01	0.0002	9.9E+08	4.8E+07	1.2E+08	1.1E+09	5.7E+08	0.0001
Huntsman	44	Pre-Frac	51.0	0.200	6,645	565.0	45.11	38.51	0.0012	3.6E+08	1.4E+07	6.1E+06	2.0E+09	1.0E+09	0.0034
Huntsman	45	Pre-Frac	50.0	0.200	6,670	695.0	22.13	18.35	0.0005	1.1E+08	1.3E+07	4.7E+06	8.5E+08	4.3E+08	0.0019
Huntsman	45	Post-Frac	50.0	0.200	13,803	700.0	2.65	-1.50	0.0003	5.7E+07	1.3E+07	4.6E+06	1.7E+07	1.5E+07	0.0001
Huntsman	45	Anniversary	50.0	0.200	13,071	739.0	2.74	-1.50	0.0003	5.4E+07	1.2E+07	4.3E+06			
Oakford	17	Pre-Frac	18.0	0.090	1,460	327.0	39.00	23.91	0.0099	1.2E+09	1.5E+09	2.5E+07			
Oakford	17	Anniversary	18.0	0.090	6,580	905.0	11.50	2.17	0.0004	1.7E+07	9.1E+08	6.8E+06	3.3E+07	4.8E+08	0.0107
Oakford	55	Pre-Frac	25.0	0.090	5,060	474.8	41.40	11.84	0.0056	6.6E+08	1.3E+09	1.5E+07	1.2E+09	1.2E+09	0.0104
Overisel	282	Pre-Frac	50.0	0.120	670	17.5	-3.12	-3.31	0.0001	5.6E+08	1.3E+09	8.3E+08			

					Pressure Transient Testing Results						β Correlations		Camacho Technique		
Field	Well	Test	Net Pay ft	Porosity	Rate Mscfd	Perm md	Total Skin	True Skin	D 1/(mcf/d)	β PTA	Geertsma	Katz	βs	βavg (G)	D (G) 1/(mcf/d)
S-Summit	1187	Pre-Frac	11.0	0.100	1,888	21.7	-2.55	-4.31	0.0007	8.4E+08	3.3E+09	6.9E+08	-1.4E+09	9.6E+08	0.0008
S-Summit	1551	Pre-Frac	47.0	0.100	485	2.0	-0.04	-1.47	0.0029	1.5E+11	1.1E+10	1.4E+10			
S-Summit	1656	Pre-Frac	24.0	0.100	4,573	19.5	-3.63	-4.02	0.0001	3.0E+08	3.5E+09	7.9E+08	-4.9E+08	1.2E+09	0.0004
S-Summit	1656	Post-Frac	24.0	0.100	1,680	6.8	0.43	-3.87	0.0020	2.0E+10	5.9E+09	3.1E+09	3.4E+10	1.8E+10	0.0018
S-Summit	1656	Anniversary	24.0	0.100	2,210	20.1	-3.49	-3.96	0.0001	2.0E+08	3.4E+09	7.6E+08	-2.3E+09	2.8E+08	0.0001
S-Summit	1656	2-Yr Anniversary	46.0	0.100	8,386	15.5	-3.15	-4.03	0.0001	8.3E+08	3.9E+09	1.1E+09			
S-Summit	1885	Pre-Frac	26.0	0.100	5,046	31.9	-2.98	-4.28	0.0002	4.9E+08	2.7E+09	4.2E+08			
S-Summit	1885	Post-Frac	26.0	0.100	3,643	12.2	-0.83	-3.37	0.0007	4.0E+09	4.4E+09	1.4E+09	3.7E+08	2.1E+09	0.0004
S-Summit	1885	Anniversary	26.0	0.100	3,000	19.8	-1.90	-3.05	0.0002	8.6E+08	3.4E+09	7.8E+08	-4.9E+08	1.2E+09	0.0003
S-Summit	1885	2-Yr Anniversary	26.0	0.100	3,335	24.4	-3.06	-3.22	0.0000	9.1E+07	3.1E+09	6.0E+08			
S-Summit	2130	Pre-Frac	11.0	0.100	1,922	12.6	-3.74	-4.49	0.0003	6.2E+08	4.3E+09	1.4E+09	-3.2E+09	5.1E+08	0.0002
S-Summit	2186	Pre-Frac	20.0	0.100	1,900	40.0	-4.26	-4.69	0.0002	4.1E+08	2.4E+09	3.2E+08			
S-Summit	2207	Pre-Frac	26.0	0.100	3,864	8.0	-3.44	-3.78	0.0004	3.3E+09	5.4E+09	2.4E+09			
S-Summit	2467	Pre-Frac	59.0	0.100	6,190	5.6	-3.21	-3.79	0.0001	2.5E+09	6.5E+09	3.9E+09			
S-Summit	2471	Pre-Frac	20.0	0.100	1,317	29.5	-2.34	-3.54	0.0005	8.4E+08	2.8E+09	4.7E+08	-1.9E+09	4.1E+08	0.0002
S-Summit	2471	Post-Frac	20.0	0.100	3,401	14.1	0.23	-3.55	0.0008	3.2E+09	4.1E+09	1.2E+09	7.0E+08	2.4E+09	0.0006
S-Summit	2471	Anniversary	20.0	0.100	4,227	36.8	-2.87	-3.94	0.0002	2.2E+08	2.5E+09	3.5E+08	-4.6E+08	8.7E+08	0.0006
S-Summit	2471	2-Yr Anniversary	20.0	0.100	3,410	38.4	-2.87	-3.17	0.0000	5.4E+07	2.5E+09	3.4E+08			
S-Summit	2480	Pre-Frac	16.0	0.100	531	18.0	-3.77	-4.11	0.0007	1.8E+09	3.6E+09	8.8E+08			
S-Summit	2571	Pre-Frac	35.0	0.100	3,389	7.1	-2.43	-4.96	0.0008	9.1E+09	5.7E+09	2.8E+09			
S-Summit	2571	Anniversary	35.0	0.100	1,890	8.7	-3.36	-3.91	0.0002	2.3E+09	5.2E+09	2.2E+09	-1.3E+10	-4.0E+09	(0.0004)
S-Summit	2918	Pre-Frac	37.0	0.100	687	2.4	-2.04	-2.35	0.0004	1.6E+10	1.0E+10	1.2E+10			