

A Novel Workflow for Using Fiber-Optic Telemetry-Enabled Coiled Tubing in Candidate Selection

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ABSTRACT

Formation damage is an undesirable operational and economic problem that can occur throughout the lifecycle of oil and gas wells due to several reasons such as using incompatible fluids during workover operations, fines migration, clay swelling, emulsions formation, and scale and organic depositions. Also, newly drilled wells sometimes do not produce optimally due to the damages caused by the drilling fluids. Therefore, addressing formation damage issues to ensure optimum recovery of hydrocarbons needs more efforts on identifying the damage mechanism and quantifying the skin factor. Skin factor is a dimensionless number that reflects the production impairment due to near-wellbore reduction of permeability. So, if this number is zero it means the well is intact, however; if this number is positive that means the well is damaged. The workflow presented in this paper focuses on the use of fiber-optic telemetry-enabled coiled tubing (FOTECT) for production enhancement in real-time by quantifying skin factor, estimating the flow potential and determining the candidate wells for matrix stimulation. This new technology can deliver pressure data in real-time during a typical unloading operation that could be further used in well test analysis for estimating key reservoir properties such as skin (S), flow capacity (Kh), drainage area (A) and initial reservoir pressure (Pi). The new technology reduces the operational time required for well test analysis compared with conventional downhole recording systems (DHR) by two-fold while enabling the performance of an acid treatment in the same run.

Moreover, in this study a workflow and user-interface software using java language were developed to execute the workflow through a two-step streamlined process:

1. Assessing the well damage through quantifying the skin value from pressure transient analysis (PTA) utilizing the downhole pressure data acquired from coiled tubing in real-time.
2. Inflow performance relationship (IPR) construction of the well using Vogel's correlation and productivity index equation under the current condition and under ideal condition (Zero skin) to assess the feasibility of a stimulation treatment.

The paper will present the application of this technique on simulated field data to show how FOTECT could be used to diagnose and treat the well in the same run. The output obtained from the developed software will be compared against the output of an industry popular well-test suite (Sapphire). Also, a case study in which this technology was used for pressure transient analysis for artificial lift design will be presented to show the applicability of this novel approach and to prove it can yield matching results with conventional techniques in a more efficient way. From the simulated data the developed software estimated the skin factor to be nine from both build-up and draw down analysis, which was later matched by Sapphire commercial Suite; moreover, it was shown that the current production rate of 792-BOPD can be increased to 1722-BOPD post a successful stimulation treatment.

Keywords: Fiber-optic telemetry-enabled coiled tubing; Flow capacity (Kh); Drainage area (A); Initial reservoir pressure (Pi); Conventional downhole recording systems (Dhr)

Abbreviations: CCL: Casing Collar Locator; Ct: Total compressibility, psia-1; CP: Centipoise; CSV: Comma separated value; CT: Coiled Tubing; DHR: Downhole recording; DST: Drill Stem Test; FOTECT: Fiber-Optic Telemetry-Enabled Coiled Tubing; ft: foot; h: Net pay thickness, ft; IARF: Infinite Acting Radial Flow; IPR: Inflow Performance Relationship; J: Productivity index, STB/D-Psi; k: Permeability, md; md: Milli-Darcy; P1 hr: Pressure at 1-hr reading on linear graph, psi; PI: Productivity index, STB/D-Psi; Pi: Initial reservoir pressure, psi; Pr: Average reservoir pressure, psia; PTA: Pressure Transient Analysis; Pwf: Flowing bottom hole pressure, psia; Qo: Oil Production rate, STB/d; Re: Drainage radius, ft; rw: Wellbore radius, ft; S Skin factor, Dimensionless; tp: Production time; hrs; UOM: Unit of Measurement; Δt : Shut-in time, hrs; β_o : Oil Formation Volume factor, STB/res, bbl; μ_o : Oil viscosity, cp; ϕ : Porosity Fraction

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INTRODUCTION

Nitters et al. [1] indicated that 60 to 70% of matrix stimulation treatments fail worldwide due to a lack of structured approach in candidate selection and treatment design. This high percentage of failure represents millions of dollars wasted due to choosing the wrong candidate and/or a bad design of the stimulation treatment. So, the motive for this study is to introduce and develop a new concept and workflow for performing candidate selection and well treatment simultaneously. This workflow will leverage the capability of the new generation of coiled tubing units of downhole pressure data transmission via fiber-optic telemetry. Acquiring such real-time pressure data will allow the operator to perform real-time pressure transient analysis (PTA), and based on the analysis results, skin factor could be calculated. In case it was concluded that formation damage is present as indicated by appositve skin factor, the same coiled tubing unit could be further used to treat the damage through a well-designed stimulation treatment in the same run saving logistical cost and time. So coiled tubing will be used for both candidate selection and remedial work simultaneously.

Conventionally During pressure transient analysis downhole parameters are commonly measured and registered using downhole memory gauges, which can only be retrieved and analyzed after the end of the well test. The main drawback of this approach is that fluid mobility (K/μ) is usually a key uncertainty before conducting the test. So, test sequence and durations cannot be planned precisely. this jeopardizes the accuracy of the test results, Since, an early-terminated test will yield incomplete set of data resulting in an inaccurate result or the need of repeating the test. And, an unnecessarily-extended test will add up extra costs associated with rig time and unnecessary flaring.

The proposed workflow overcomes the drawbacks of the downhole recording mode (DHR) by conducting dynamic and real-time pressure transient analysis. The real-time pressure data obtained from the pressure sensor deployed with the coiled tubing is the key input required for pressure transient analysis. It can be obtained with coiled tubing during a typical Nitrogen lifting operation (Drawdown analysis), or while the well is shut-in and by using an inflatable packer to minimize wellbore storage effects (Pressure build-up analysis). The main advantage over the downhole recording mode (DHR) through memory gauges is that the pressure data is monitored in real-time. So, the well test engineer can adjust the test sequence by identifying wellbore storage period, infinite acting radial flow (IARF) and reaching the boundary. Those benefits will save time and ensure accurate well test analysis [2]. Additionally, the same coiled tubing unit can be used in matrix acidizing treatment to remove skin if test results indicate the presence of formation damage After quantifying the skin factor and ensuring it is due to formation damage (i.e., no mechanical damage is present). Petroleum engineers ensure the effectiveness of the stimulation treatment by studying the inflow performance relationship (IPR) of the well. This step is done to

check the production gain value in case skin was removed. The built model performs both tasks which are pressure transient analysis and inflow performance comparison and concludes if the well is a good candidate for matrix stimulation.

LITERATURE REVIEW

Model description and approach

The workflow consists of two basic modules that integrates with each other and are used in series to conclude the final output of the software which is whether a well is candidate for matrix stimulation or not.

The petroleum engineer should confirm that the resulted skin value is only attributable to formation damage (i.e., No pseudo-skin) and the economic gain as indicated from the software justifies the expenses associated with carrying out a matrix treatment (cost-benefit analysis).

The first module is named “Pressure transient analysis” and is used to carry out the pressure transient analysis by importing the pressure data acquired from the fiber-optic telemetry-enabled coiled tubing (FOTECT) downhole pressure gauges in real-time. They are either input manually as or imported from a comma separate value (CSV) format file. The software can carry-out PTA either in build-up or drawdown mode. It is recommended in build-up analysis to add an inflatable packer to the bottom hole assembly to minimize the wellbore storage effects.

The results obtained from the first module are used to feed the second module which is named “Treatment feasibility study” and is used to perform reservoir performance analysis. It constructs the inflow performance relationship (IPR) of the well in its current condition and under assumed ideal condition (Zero skin). The IPR is either constructed using straight-line productivity index equation or Vogel’s correlation to suit different well conditions and account for the scenario in which the flowing bottom hole pressure (P_{wf}) is below the bubble point pressure (P_b). After quantifying the skin (S) and obtaining the average permeability thickness (Kh) from module one and calculating the gain that could be achieved if the skin value is brought to zero by a stimulation treatment from module 2. The final decision maker function of the software concludes if the well is a good candidate for matrix stimulation.

Figures 1 and 2 show a flowchart describing the workflow in drawdown and build-up modes respectively.

Input data

In addition to the real-time pressure data acquired in real-time through the FOTECT, the following data will be needed to run the software [3,4]:

- a) Porosity – Fraction
- b) Wellbore Radius (r_w) – ft
- c) Reservoir height (h) – ft
- d) Oil formation volume factor β_o – res. bbl/STB
- e) Oil viscosity μ – cp
- f) Initial pressure (P_i) – psia

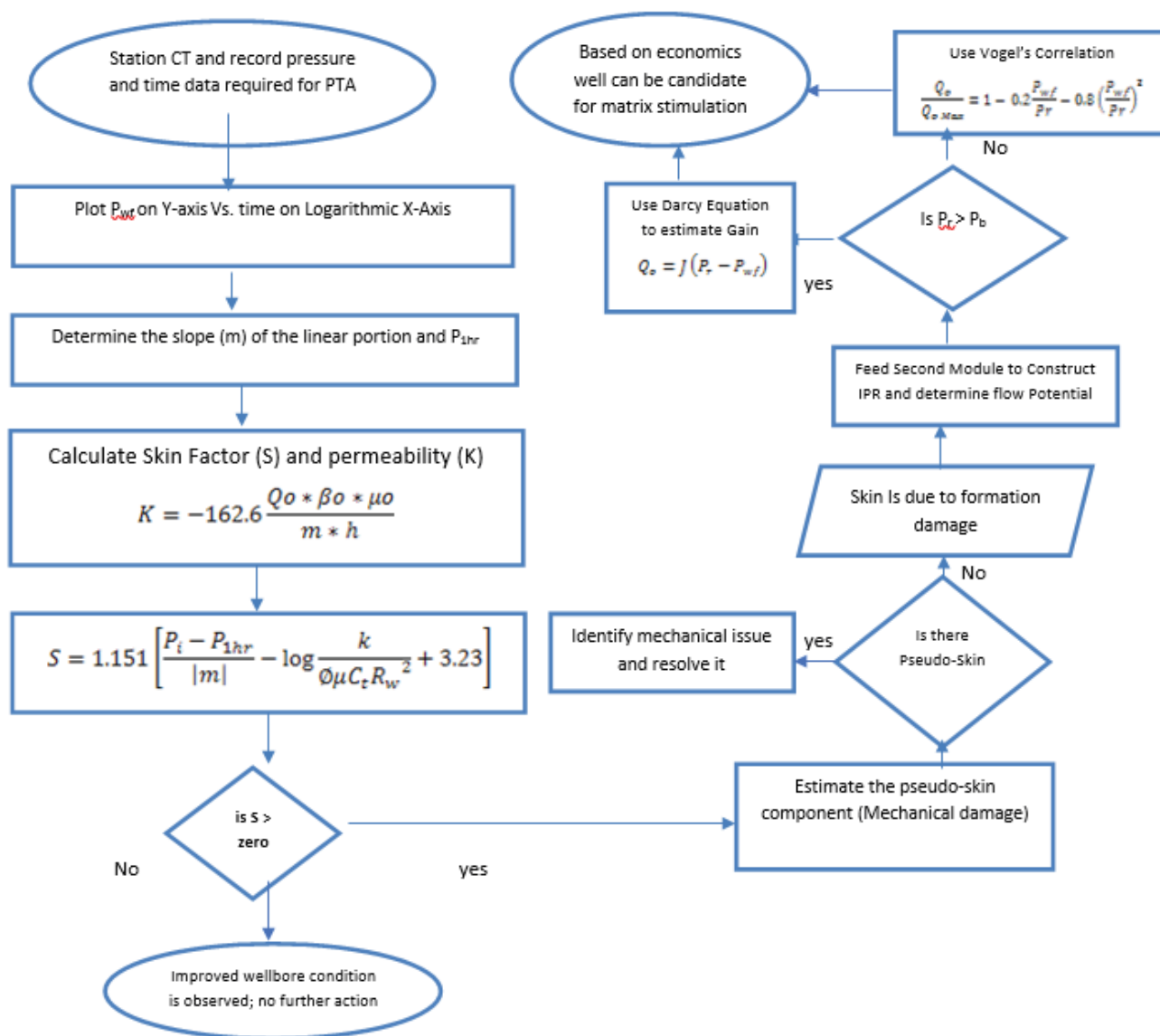


Figure 1: Candidate selection using FOTECT methodology: Drawdown mode.

g) Flow rate (Q) – STB/D

Pressure transient analysis

The model is based on the analytical solution of partial differential equation that describes the fluid flow in the reservoir as a function of time and space (diffusivity equation).

The software uses the semi-log analysis technique to calculate skin and permeability using the below equations:

For Draw Down mode:

$$K = -162.6 \frac{Q_o * \beta_o * \mu_o}{m * h} \quad (1)$$

$$s = 1.151 \left[\frac{P_i - P_{wf} at \Delta t = 0}{[m]} - \log \frac{k}{\phi_{\mu} c_t r_w^2} + 3.23 \right] \quad (2)$$

For Build-up mode:

$$K = 162.6 \frac{Q_o * \beta_o * \mu_o}{m * h} \quad (3)$$

$$s = 1.151 \left[\frac{P_i - P_{wf} at \Delta t = 0}{[m]} - \log \frac{k}{\phi_{\mu} c_t r_w^2} + 3.23 \right] \quad (4)$$

Treatment gain estimation

After skin value is obtained, it should be confirmed that no mechanical damage is present.

Table 1 shows McLeod criteria to identify pseudo skin and identify the treatable skin which is the target of this stud, and then the software uses both straight line productivity index equation and Vogel's correlation to construct the inflow performance relationship of the well under current conditions and ideal condition (zero skin). This step quantifies the production gain that could be realized if the well damage is treated through a stimulation operation.

For cases where the flowing bottom whole pressure (Pwf) is below the reservoir bubble point pressure (Pb) the straight-line productivity index equation is used to construct the IPR curves.

The software calculates pre-treatment productivity index and post treatment productivity index (PI) from the output data obtained from the first step using the below equations:

$$PI \text{ (Pre-treatment)} = \frac{0.00708 k_o h}{\mu_o \beta_o \left[\ln \left(\frac{r_e}{r_w} \right) - 0.75 + St \right]} \quad (5)$$

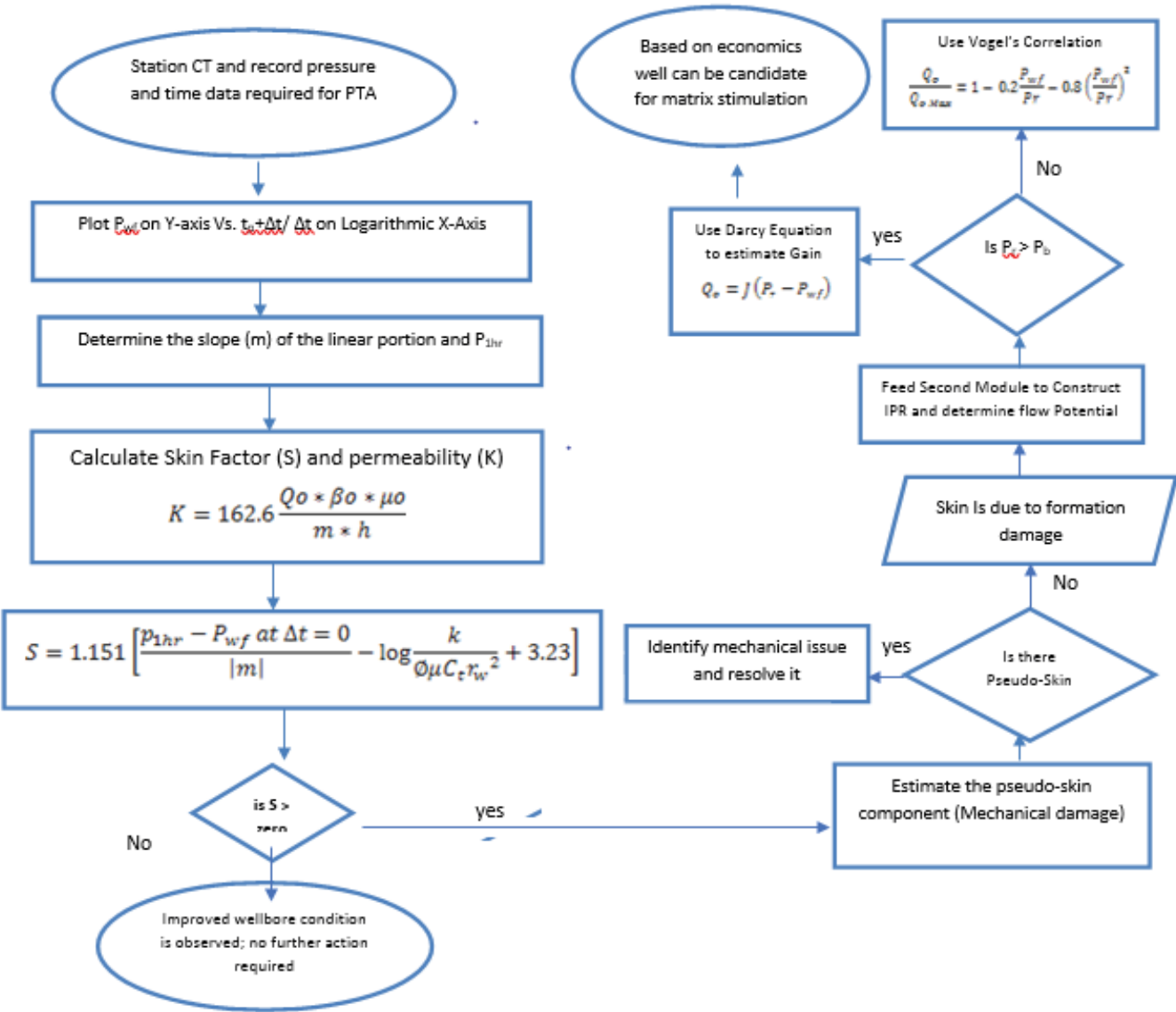


Figure 2: Candidate selection using FOTECT methodology: Pressure build-up mode.

Parameters	Value
High liquid gas ration LGR	>100 bbl/MMCF (Gas well)
High Gas oil ratio GOR	>1000 Scf/bbl (Oil well)
Three Phase Production	(Water, oil and gas)
High pressure Drawdown	(Pr-Pwf) > 1000 psi
High flow rate	Q/h > 20 BPD/ft
Production rate per perforation shot density	Q/N > 5 BPD/Perf.
Perforation shot density	< 4 SPF
Perforation Phasing	Zero degree phasing
Perforation with Small through tubing Gun	Gun diameter less than 2 inches
Reservoir pressure	>Pb; While well-bore pressure <Pb

Table 1: McLeod guidelines to distinguish damages associated to mechanical issues.

PI (Post-treatment) =
$$\frac{0.00708 \, k_0 \, h}{\mu_0 \beta_0 \left[\ln \left(\frac{r_e}{r_w} \right) - 0.75 \right]}$$

(6)

Where St in Eq. 6 is set to Zero by default (ideal condition).
Productivity ratio is then estimated which indicates the degree

of damage in the well and a very good indicator for candidate selection.

Productivity ratio =
$$\frac{\text{Pre treatment productivity index}}{\text{Post treatment productivity index}}$$

(7)

Then the oil production rate can be calculated using the basic productivity index equation eq. 8 in the current condition and ideal condition, consequently production gain could be estimated.

$$Q_o = J(P_r - P_{wf}) \quad (8)$$

The two IPR curves can be plotted on the same sheet to compare and quantify the gain that could be achieved post a successful stimulation treatment that gets skin to zero.

To account for cases in which flowing bottom hole pressure is below the reservoir fluid bubble point pressure, Vogel's correlation is used to predict the IPR using equations 9 and 10:

$$Q_o = Q_{ob} + \frac{JP_b}{1.8} \left[1 - 0.2 \frac{P_{wf}}{P_r} - 0.8 \left(\frac{P_{wf}}{P_r} \right)^2 \right] \quad (9)$$

Where:

$$Q_{ob} = J^* (P_r - P_b) \quad (10)$$

The composite IPR graph is then plotted for the pre-treatment curve and another one for the post-treatment IPR curve for the petroleum Engineer to compare and assess the production gain post a stimulation treatment.

Final output: Candidate selection advisor

The final output is a decision-making window indicating whether this well is a candidate for matrix stimulation or not based on skin value, this workflow assumes that the total skin calculated using pressure transient analysis techniques is only attributed to formation damage with zero mechanical (Pseudo-skin).

In case there's positive skin (Formation damage present) the message generated to the user from the decision-maker module of the software will be that the well is a candidate for matrix stimulation if there's no pseudo-skin and economic feasibility is assured as shown in the below Figure 3; however, if the skin value is negative the software will hint to the user that an improved well-bore condition is observed as shown in Figure 4.

Model validation

A set of simulated field data (Pressure Vs. time) for pressure build up and drawdown was used to validate the software results against commercial industry software, the output delivered from the commercial software will be compared against the output of the developed model.

This validation case proves the capability of this workflow to conclude if a well is a good candidate for matrix stimulation as an output using FOTECT that can be further used to remove the damage in the same run through a well-designed stimulation treatment saving time and cost while delivering better results than the conventional techniques for well testing (DHR).

Validation case: Well (A)

Well (A) is producing from an oil reservoir. A set of well-test simulated data for both pressure build-up and draw-down analysis is used for executing the workflow. The set of data is assumed to be obtained from the FOTECT (Pressure Vs. Time) and is presented in Table 2 along with the input parameters (reservoir properties, oil properties and production parameters) in Tables 3 and 4 required for pressure transient analysis and inflow performance relationship construction [5].

The well is diagnosed to be damaged (Positive skin of 9.4) is calculated from the pressure transient analysis module and then the well potential is calculated at (P_{wf} =zero) using this skin value and under ideal conditions using both productivity index equation and Vogel's correlation to show the improvement that could be realized post a successful damage removal operation. All results are tabulated in Table 5.

In this case the software concludes that the well is candidate for matrix stimulation in case no mechanical damage is present and if economic feasibility is assured.

Figure 4 shows the input window of the developed software with all the reservoir, oil and production parameters. Figure 5 shows the semi-log representation of the pressure data for drawdown and build up analysis conducted by the software and Figure 6 shows the output of module one for pressure transient analysis of permeability, skin, and radius of investigation. All results are summarized in Table 6.

While Figure 7 shows the input for the second module of the software which is used to construct the IPR curves. Figure 8 shows the software generated IPR curves using productivity index equation and Vogel's correlation under ideal and current conditions. Production rates tabulated are estimated at an assumed flowing BHP of 1,500-psi

The results of modules 1 and 2 are used to determine whether the well is candidate for matrix stimulation or not provided that

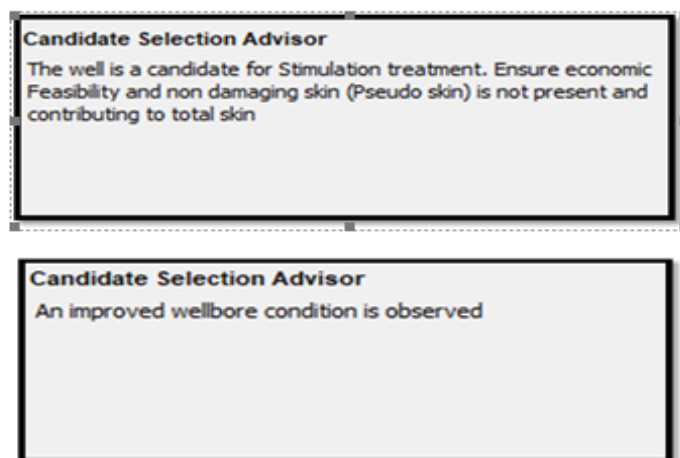


Figure 3: Candidate selection advisor output: Positive/negative skin.

Reservoir Properties	
Porosity (fraction)	0.1
Well Bore Radius (ft)	0.3
Total Compressibility (p)	3.0E-6
Reservoir Height (ft)	30.0
Oil Properties	
Oil Formation Volume (r)	1.2
Viscosity (cp)	0.8
Bubble Point Pressure (2000.0
Production Parameters	
Initial Pressure (psia)	4996.9
Flow Rate (stb/d)	1000.0
Production Time (hrs)	200.0

Figure 4: Inputs of well (A) properties (Software window).

Table 2: Simulated data used for validation example.

Time (hr)	Pressure (psia)	Liquid Rate (STB/D)	Time (hr)	Pressure (psia)	Liquid Rate (STB/D)	Time (hr)	Pressure (psia)	Liquid Rate (STB/D)
-	4,997	1000	108.03	569	1000	213.53	4,655	0
0	4,984	1000	109.53	568	1000	215.03	4,668	0
0.01	4,972	1000	111.03	566	1000	216.53	4,680	0
0.01	4,960	1000	112.53	564	1000	218.03	4,690	0
0.01	4,947	1000	114.03	563	1000	219.53	4,700	0
0.02	4,935	1000	115.53	561	1000	221.03	4,709	0
0.02	4,923	1000	117.03	560	1000	222.53	4,717	0
0.02	4,911	1000	118.53	558	1000	224.03	4,724	0
0.02	4,898	1000	120.03	557	1000	225.53	4,731	0
0.03	4,886	1000	121.53	555	1000	227.03	4,738	0
0.03	4,873	1000	123.03	554	1000	228.53	4,744	0
0.03	4,858	1000	124.53	552	1000	230.03	4,750	0
0.04	4,842	1000	126.03	551	1000	231.53	4,755	0
0.04	4,823	1000	127.53	549	1000	233.03	4,760	0
0.05	4,803	1000	129.03	548	1000	234.53	4,765	0
0.05	4,780	1000	130.53	547	1000	236.03	4,770	0
0.06	4,754	1000	132.03	545	1000	237.53	4,774	0
0.07	4,726	1000	133.53	544	1000	239.03	4,778	0
0.08	4,694	1000	135.03	543	1000	240.53	4,782	0
0.09	4,659	1000	136.53	541	1000	242.03	4,786	0
0.1	4,620	1000	138.03	540	1000	243.53	4,789	0
0.11	4,577	1000	139.53	539	1000	245.03	4,793	0
0.12	4,529	1000	141.03	537	1000	246.53	4,796	0
0.14	4,477	1000	142.53	536	1000	248.03	4,799	0
0.15	4,418	1000	144.03	535	1000	249.53	4,802	0
0.17	4,354	1000	145.53	534	1000	251.03	4,805	0
0.19	4,284	1000	147.03	532	1000	252.53	4,808	0
0.24	4,124	1000	150.03	530	1000	255.53	4,814	0
0.27	4,032	1000	151.53	529	1000	257.03	4,816	0
0.3	3,933	1000	153.03	528	1000	258.53	4,819	0
0.34	3,826	1000	154.53	526	1000	260.03	4,821	0
0.38	3,711	1000	156.03	525	1000	261.53	4,823	0
0.43	3,588	1000	157.53	524	1000	263.03	4,826	0
0.48	3,458	1000	159.03	523	1000	264.53	4,828	0
0.54	3,319	1000	160.53	522	1000	266.03	4,830	0
0.6	3,174	1000	162.03	521	1000	267.53	4,832	0
0.68	3,023	1000	163.53	520	1000	269.03	4,834	0
0.76	2,866	1000	165.03	519	1000	270.53	4,836	0
0.85	2,706	1000	166.53	518	1000	272.03	4,838	0
0.96	2,545	1000	168.03	516	1000	273.53	4,840	0
1.07	2,383	1000	169.53	515	1000	275.03	4,842	0
1.21	2,223	1000	171.03	514	1000	276.53	4,843	0
1.35	2,068	1000	172.53	513	1000	278.03	4,845	0
1.52	1,918	1000	174.03	512	1000	279.53	4,847	0
1.7	1,778	1000	175.53	511	1000	281.03	4,848	0
1.91	1,647	1000	177.03	510	1000	282.53	4,850	0
2.14	1,528	1000	178.53	509	1000	284.03	4,851	0
2.41	1,421	1000	180.03	508	1000	285.53	4,853	0
2.7	1,326	1000	181.53	507	1000	287.03	4,854	0
3.03	1,244	1000	183.03	506	1000	288.53	4,856	0
3.4	1,175	1000	184.53	505	1000	290.03	4,857	0

3.81	1,116	1000	186.03	504	1000	291.53	4,859	0
4.28	1,066	1000	187.53	503	1000	293.03	4,860	0
4.8	1,025	1000	189.03	502	1000	294.53	4,861	0
5.39	991	1000	190.53	501	1000	296.03	4,863	0
6.04	962	1000	192.03	501	1000	297.53	4,864	0
6.78	938	1000	193.53	500	1000	299.03	4,865	0
7.61	916	1000	195.03	499	1000	300.53	4,866	0
8.54	897	1000	196.53	498	1000	302.03	4,868	0
9.58	879	1000	198.03	497	1000	303.53	4,869	0
10.75	862	1000	199.53	496	1000	305.03	4,870	0
12.06	846	1000	199.77	496	1000	306.53	4,871	0
13.53	830	1000	200	496	1000	308.03	4,872	0
15.03	816	1000	200	508	0	309.53	4,873	0
18.03	792	1000	200.01	533	0	312.53	4,875	0
19.53	782	1000	200.01	545	0	314.03	4,876	0
21.03	772	1000	200.01	558	0	315.53	4,877	0
22.53	763	1000	200.02	570	0	317.03	4,878	0
24.03	755	1000	200.02	582	0	318.53	4,879	0
25.53	747	1000	200.02	594	0	320.03	4,880	0
27.03	740	1000	200.03	606	0	321.53	4,881	0
28.53	733	1000	200.03	620	0	323.03	4,882	0
30.03	726	1000	200.03	634	0	324.53	4,883	0
31.53	720	1000	200.04	651	0	326.03	4,884	0
33.03	714	1000	200.04	669	0	327.53	4,885	0
34.53	709	1000	200.05	690	0	329.03	4,886	0
36.03	703	1000	200.05	713	0	330.53	4,886	0
37.53	698	1000	200.06	738	0	332.03	4,887	0
39.03	693	1000	200.07	767	0	333.53	4,888	0
40.53	689	1000	200.08	798	0	335.03	4,889	0
42.03	684	1000	200.09	833	0	336.53	4,890	0
43.53	680	1000	200.1	872	0	338.03	4,890	0
45.03	676	1000	200.11	916	0	339.53	4,891	0
46.53	672	1000	200.12	963	0	341.03	4,892	0
48.03	668	1000	200.14	1,016	0	342.53	4,893	0
49.53	664	1000	200.15	1,074	0	344.03	4,893	0
51.03	660	1000	200.17	1,138	0	345.53	4,894	0
52.53	657	1000	200.19	1,208	0	347.03	4,895	0
54.03	653	1000	200.21	1,285	0	348.53	4,896	0
55.53	650	1000	200.24	1,369	0	350.03	4,896	0
57.03	647	1000	200.27	1,460	0	351.53	4,897	0
58.53	643	1000	200.3	1,559	0	353.03	4,898	0
60.03	640	1000	200.34	1,666	0	354.53	4,898	0
61.53	637	1000	200.38	1,781	0	356.03	4,899	0
63.03	634	1000	200.43	1,904	0	357.53	4,900	0
64.53	632	1000	200.48	2,035	0	359.03	4,900	0
66.03	629	1000	200.54	2,173	0	360.53	4,901	0
67.53	626	1000	200.6	2,318	0	362.03	4,901	0
69.03	623	1000	200.68	2,470	0	363.53	4,902	0
70.53	621	1000	200.76	2,626	0	365.03	4,903	0
72.03	618	1000	200.85	2,786	0	366.53	4,903	0
75.03	613	1000	201.07	3,109	0	369.53	4,904	0
76.53	611	1000	201.21	3,269	0	371.03	4,905	0
78.03	608	1000	201.35	3,424	0	372.53	4,906	0

79.53	606	1000	201.52	3,573	0	374.03	4,906	0
81.03	604	1000	201.7	3,714	0	375.53	4,907	0
82.53	602	1000	201.91	3,845	0	377.03	4,907	0
84.03	600	1000	202.14	3,964	0	378.53	4,908	0
85.53	597	1000	202.41	4,071	0	380.03	4,908	0
87.03	595	1000	202.7	4,165	0	381.53	4,909	0
88.53	593	1000	203.03	4,246	0	383.03	4,909	0
90.03	591	1000	203.4	4,316	0	384.53	4,910	0
91.53	589	1000	203.81	4,375	0	386.03	4,910	0
93.03	587	1000	204.28	4,424	0	387.53	4,911	0
94.53	585	1000	204.8	4,464	0	389.03	4,911	0
96.03	583	1000	205.39	4,498	0	390.53	4,912	0
97.53	582	1000	206.04	4,527	0	392.03	4,912	0
99.03	580	1000	206.78	4,551	0	393.53	4,913	0
100.53	578	1000	207.61	4,572	0	395.03	4,913	0
102.03	576	1000	208.54	4,591	0	396.53	4,914	0
103.53	574	1000	209.58	4,608	0	398.03	4,914	0
105.03	573	1000	210.75	4,624	0	399.53	4,915	0
106.53	571	1000	212.06	4,640	0	400	4,915	0

Table 3: Assumed reservoir parameters for validation example.

Reservoir parameters	Value
Porosity (Φ)	0.1
Wellbore Radius (r_w) - ft	0.3
Total Compressibility (C_t) - Psia-1	3.00E-06
Reservoir Height (h) - ft	30

Table 4: Assumed oil properties for validation example.

Oil properties	Value
Oil Formation Volume Factor (β_o) - Res bbl/STB	1.2
Viscosity (μ_o) - cp	0.8
Bubble point Pressure (P_b) - psia	2000

Table 5: Assumed production parameters for validation example.

Production parameters	Value
Initial pressure (P_i) - psia	4997
Flow rate (Q_o) - STB/D	1000
Production time (t_p) - hrs	200

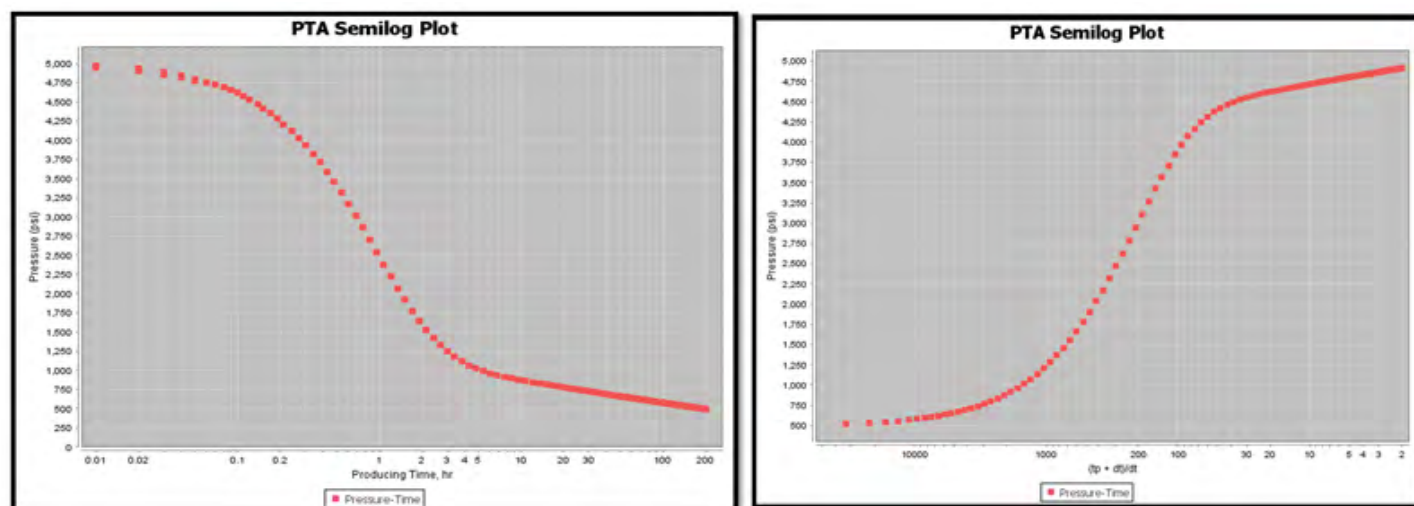


Figure 5: Semi-log plot of simulated data for drawdown/build up analysis.

Pressure Transient Analysis		Pressure Transient Analysis	
Method	Draw Down	Method	Build Up
Linear Points	95	Linear Points	88
End of Transient Time (t)	199.52	End of Transient Time (t)	199.53
Pressure 1 Hour (psi)	1131.41	Pressure 1 Hour (psi)	4358.06
Slope	276.35	Slope	277.97
Drainage Radius (ft)	1177.0	Drainage Radius (ft)	1177.0
Permeability (md)	18.82	Permeability (md)	18.71
Skin	9.52	Skin	9.42

Figure 6: Software output for drawdown/build up analysis.

Table 6: Summary of outputs of sapphire and well-master for PTA and IPR.

Parameters	Workflow		
	Developed software	Sapphire	Absolute error
Pressure transient analysis (Drawdown)			
Skin Factor	9.53	9.89	2.70%
Permeability - md	18.82	19.2	1.90%
Pressure transient analysis (Build-up)			
Skin Factor	9.42	9.8	3.80%
Permeability - md	18.71	19.2	2.50%
Inflow performance relationship (Pre-treatment)			
Well Potential - Darcy Eq. STB/D	1220	1217	0.20%
Well Potential - Vogel's correlation STB/D	986	986	0%
Inflow performance relationship (Post-treatment)			
Well Potential - Darcy Eq. STB/D	2743	2740	0.10%
Well Potential - Vogel's correlation STB/D	2220	2220	0%

Treatment Feasibility (Productivity Index Equation)	
Post Treatment Skin (Ideal)	0.0
Pre Treatment PI (stb/d*psi)	0.23
Post Treatment PI (stb/d*psi)	0.5
Productivity Ratio	0.46
Average Reservoir Pressure (psia)	5000.0
Flowing Bottom Hole Pressure (psia)	1500.0
Pre Treatment Flow Rate (stb/d)	822.22
Post Treatment Flow Rate (stb/d)	1761.3

Figure 7: Inputs for treatment feasibility section.

economic feasibility is assured and no mechanical damage present and the output for this example is shown in Figure 9.

Figures 10-13 Shows the execution steps using the Sapphire Ecrin module for pressure transient analysis and IPR curves using straight-line productivity index equation and Vogel's correlation.

A tabulated summary of the results comparison between the developed software and the commercial software is given in Table 6 and visually presented in Figures 14 and 15.

RESULTS AND DISCUSSION

A field application is discussed to prove the viability of this technology on performing pressure transient analysis and to show its advantages over conventional techniques (DHR on memory gauges)

The technology was tried in one well in shushufindi field in Ecuador [6,7], the main objective of the operation was to evaluate the well and perform pressure transient analysis for artificial lift design. Historically pressure data required for well test analysis was acquired by deploying memory gauges into the production tubing; however, some challenges were faced during well testing operations that encouraged the operator to try the fiber-optic telemetry enabled coiled tubing (FOETCT) for well testing [8]. Those problems were:

1. Ineffective closure caused by debris found in ball's seat when using conventional shut-in method with memory gauges and standing valves.
2. Long test times due to wellbore storage effects and uncertainty about data completeness during well testing.

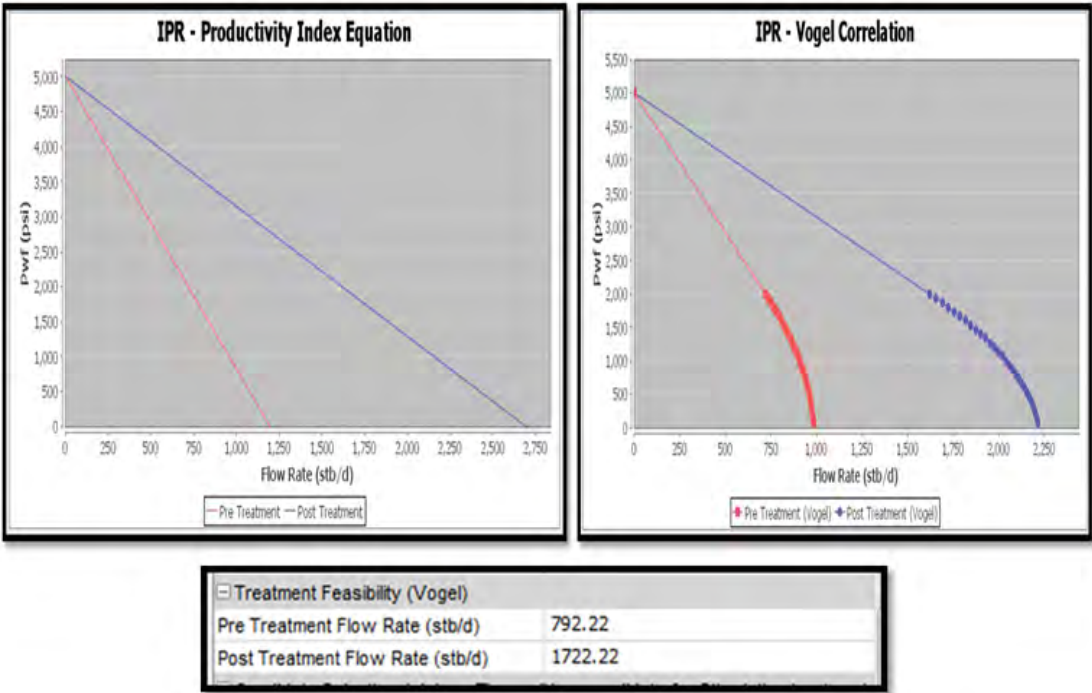


Figure 8: Software generated IPRs (Vogel and straight-line).

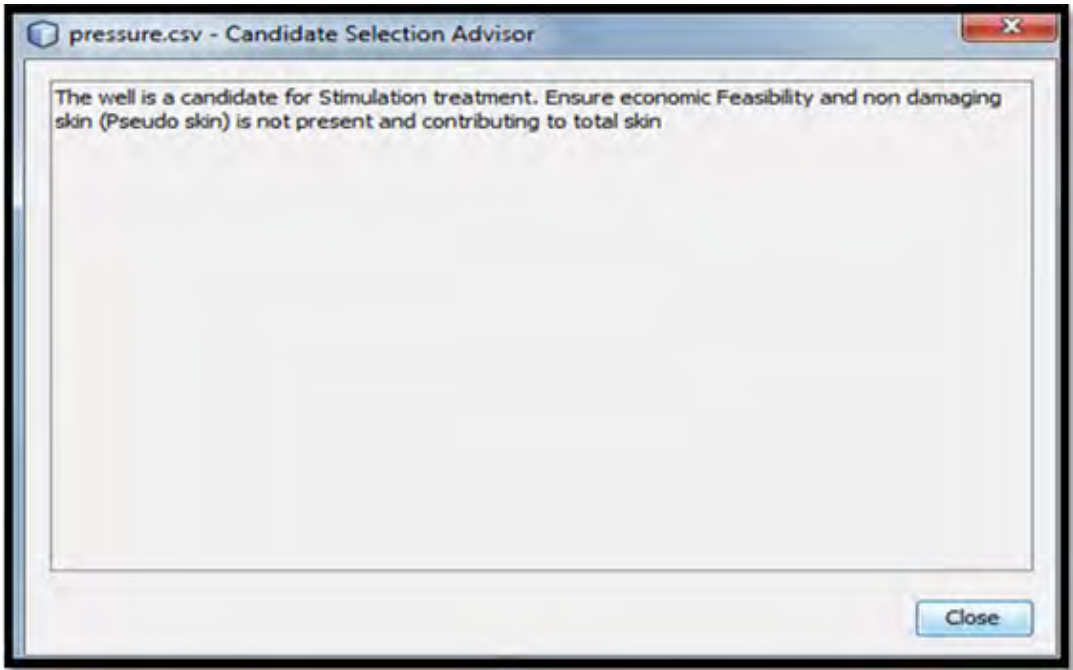


Figure 9: Candidate selection advisor results.

3. Operational issues related to slickline running of memory gauges.

To overcome the above challenges, a fiber-optic telemetry-enabled coiled tubing intervention was deployed to perform PTA in real-time. In this operation the down hole real-time pressure gauge will run in conjunction with an inflatable packer to minimize wellbore storage effects.

It was reported that the real-time monitoring of the downhole parameters with pressure and temperature sensors provided a positive confirmation of well inflow, reducing risk associated with running memory gauges. Additionally, it presented a safer way for artificial lift design to avoid non-productive time associated with

waiting-on-equipment and extended rig operation [9].

The operational outline of the coiled tubing intervention was executed according to the below steps:

1. Drawdown testing was mainly conducted using N₂ Lifting as a well kick-off method.
2. A mechanical tubing packer (Mechanical-set) and a double flapper check valve were used in the bottomhole assembly (BHA) to allow for downhole shut-in and prevent reservoir fluids from entering the CT workstring.
3. Real-time CCL measurement allowed for accurate placement of the BHA during well test analysis.

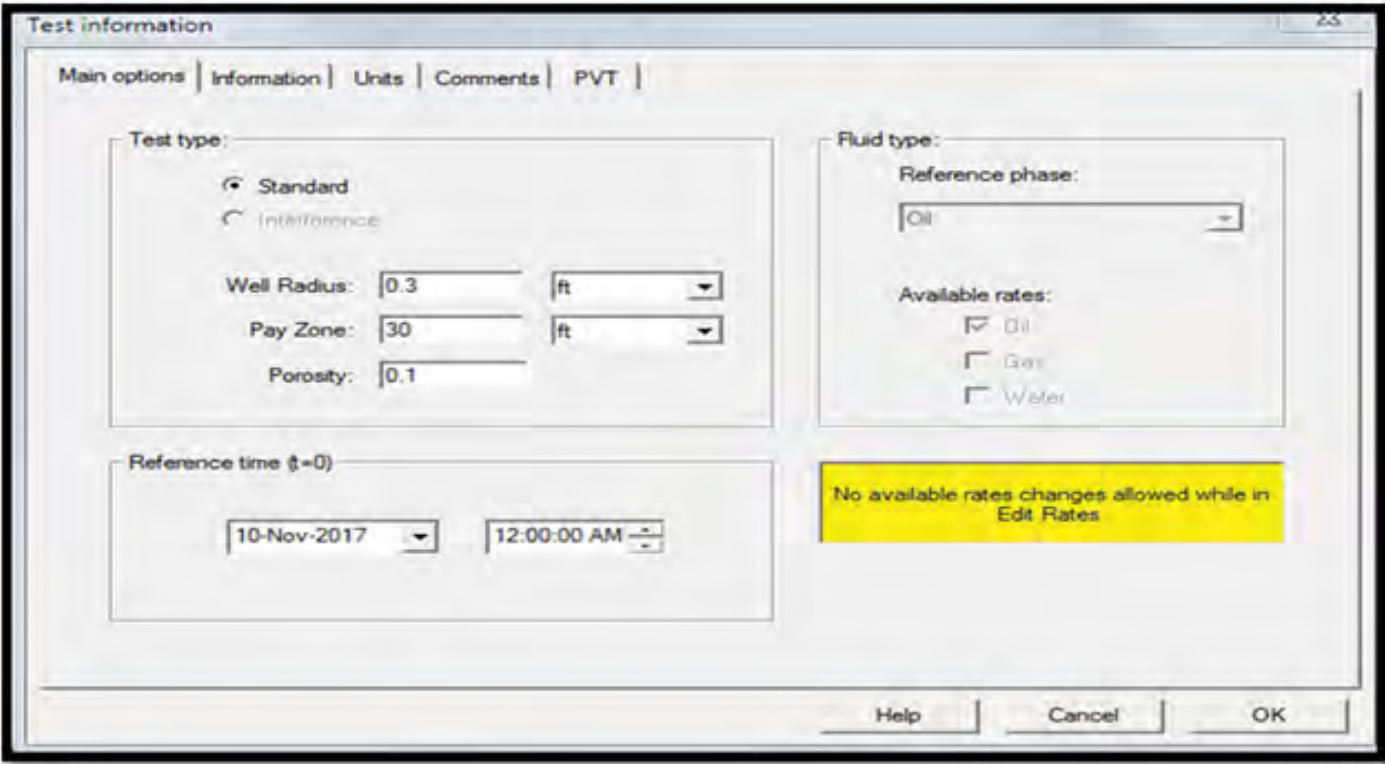


Figure 10: Input window for sapphire for PTA. Courtesy of Kappa.

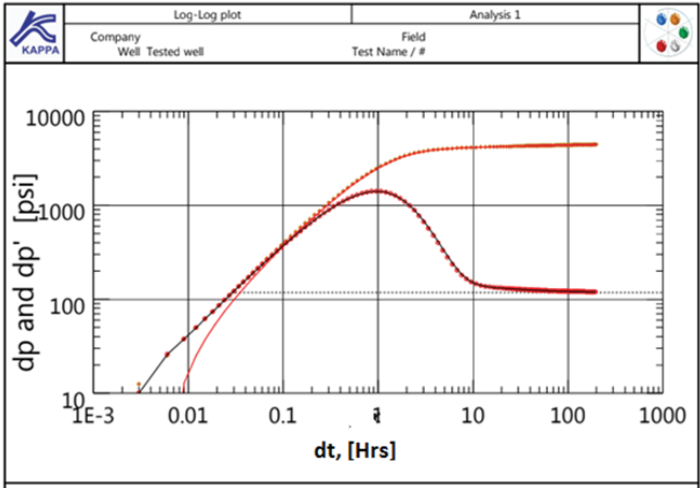


Figure 11: Type curve matching using sapphire.

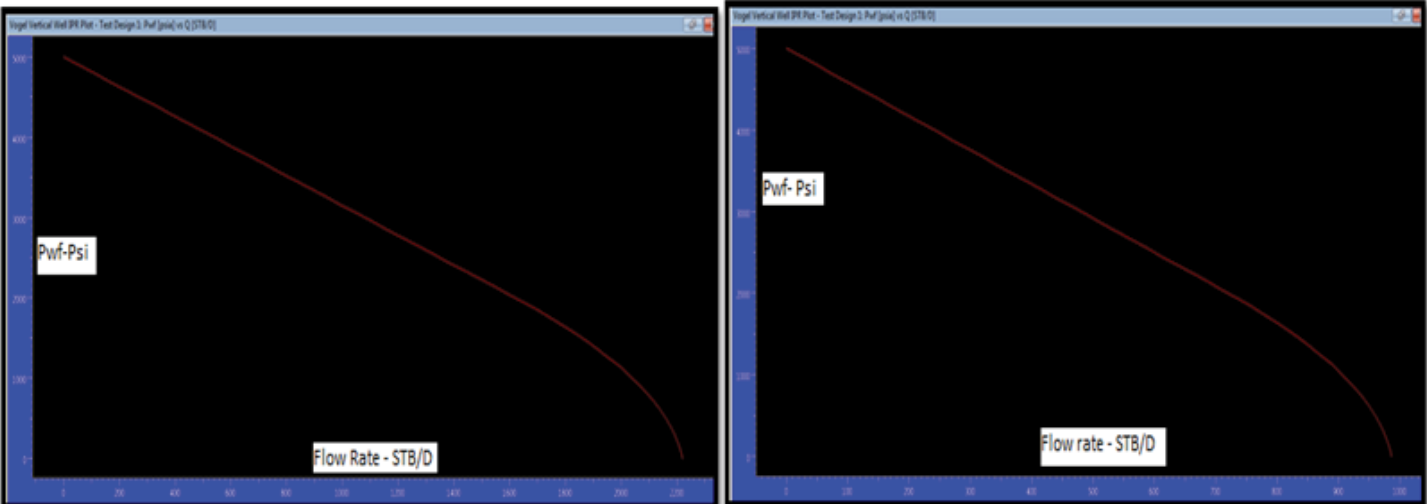


Figure 12: Sapphire Vogel IPR (Ideal case-left - Damaged case-right).

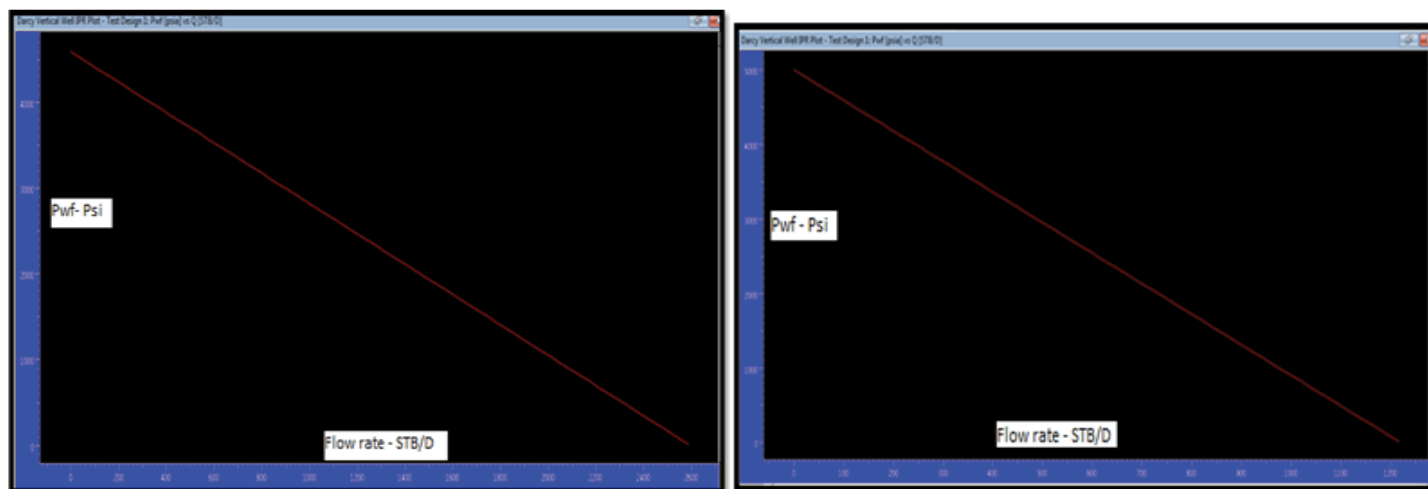


Figure 13: Saphire Darcy law IPR (Ideal case-left – damaged case-right).

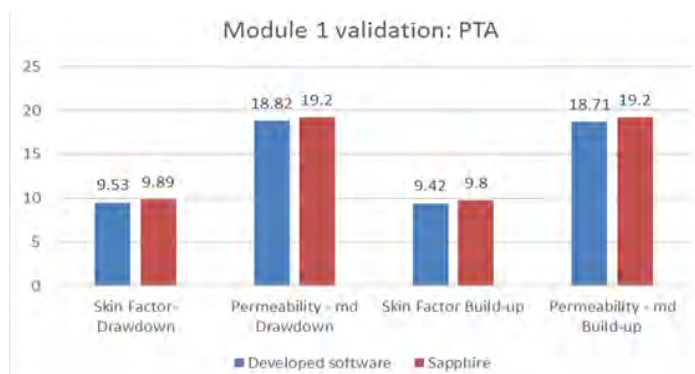


Figure 14: Comparison between developed software and Sapphire output for PTA.

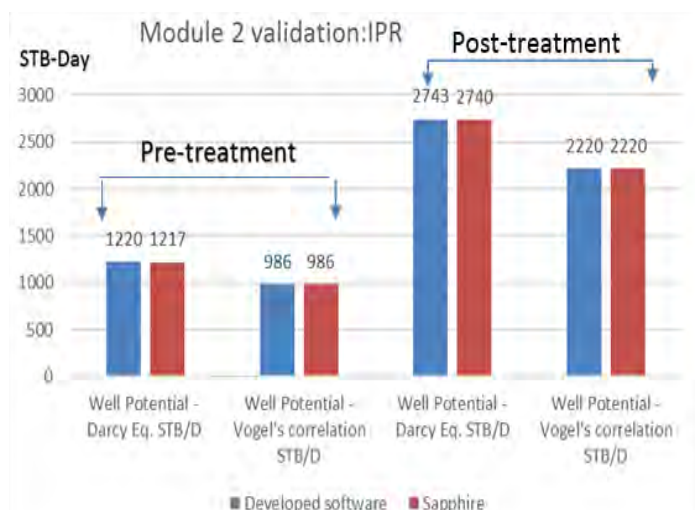


Figure 15: Comparison between developed software and Sapphire output for IPR.

CONCLUSION

Formation damage is one of the prominent reasons why oil and gas wells are not operating to their full capacity. Failure rate is also so high in executing stimulation jobs due to lack of following a structured approach in candidate selection and damage identification. Well test analysis is one of the key petroleum engineering aspects for quantifying damage and identifying candidates for stimulation; however, the conventional methods (DHR) used for PTA are ineffective and time consuming due to the risks associated with running memory gauges into completion nipples and the inability to read and optimize the test in real-time since all the data is being recorded downhole. Moreover, in case a well damage is identified, extra time will be needed to mobilize CT equipment for well stimulation.

This study tried to overcome all those hurdles by designing a new workflow that enables petroleum engineers to diagnose and treat the problem in the same run. This workflow relies mainly on pressure transient analysis (PTA) as a key technique for candidate selection through skin quantifications and inflow performance relationship analysis (IPR). The added values of the new workflow could be summarized in the below points:

1. The workflow avoided the drawbacks of conventional downhole recording (DHR) techniques for pressure data acquisition. As they frequently render inaccurate results or cause additional operational costs. So, the workflow relies on pressure data obtained by fiber-optic telemetry-enabled coiled tubing (FOTECT) as a communication medium for real-time well test analysis.
2. This workflow aims at adding a value of maximizing recovery levels using a streamlined study. This study combines the benefits of real-time well test analysis while leveraging the capability of the coiled tubing as a pumping medium to do perform stimulation job. So, diagnosis and remedial will be done with coiled tubing.
3. This new approach will save rig time due to optimized well test timing sequence. Also, save logistical time required to mobilize coiled tubing unit for remedial operation after identifying formation damage by combining both in the same run.

4. A surface acquisition system was used to receive the downhole measurements and allow well test engineers to perform well test interpretation in real-time
5. In summary, the use of this technology in shushufindi field in Ecuador [7] proved to provide matching results with conventional techniques. The well test analysis was made in less time due to real-time monitoring and the use of mechanical-packer that minimized wellbore storage effects. The ability to perform multiple applications in the same intervention, stimulation or logging for example greatly enhances the economics of the intervention operation.

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