SPE 63279

Well Testing in Ultra-High Permeability Formations

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This paper was prepared for presentation at the 2000 SPE Annual Technical Conference and Exhibition held in Dallas, Texas, 1–4 October 2000.

Abstract

Nye County, Nevada is the home of the Yucca Mountain Project, which is the proposed site for a high-level nuclear waste disposal facility. Over the last several years, Nye County has conducted an independent scientific program to evaluate the properties of the rock units around the proposed disposal site. This work has included drilling and testing several water monitor wells in clastic, valley-fill deposits. These tests indicated extraordinarily high permeability (up to 300 darcies) in some units. Well testing in reservoirs with such ultra-high permeabilities provides a unique opportunity to identify and evaluate reservoir heterogeneities. Analyses of three tests are presented.

The Nye County tests demonstrate the applicability of petroleum-industry well-test analysis methods even for ultra-high permeability reservoirs. The tests show a large number of unusual effects (ultra-high permeability, extreme wellbore storage, linear flow, radial flow, hemispherical flow, multiple layers, multiple boundaries, wide range of compressibility, atmospheric corrections for a pumping well, etc.) in just a few tests. The test data and interpretations are publicly available and constitute an important database for well test analysis education and training.

Introduction

The Yucca Mountain Project (YMP) is located near the town of Amargosa Valley, about 100 miles northwest of Las Vegas, Nevada. The U.S. Department of Energy has been studying the Yucca Mountain site for more than 15 years to determine whether it is a suitable place for disposal of high-level nuclear waste. The YMP is located in Nye County, so the Nye County Nuclear Waste Repository Project Office (NWRPO) was formed to protect the interests of the citizens of Nye County by providing independent scientific, environmental, socioeconomic, transportation, health, safety, regulatory and policy monitoring of activities and impacts related to transport, disposal and storage of nuclear waste in and through Nye County.

The largest element of Nye County's Yucca Mountain Project oversight activities is the Independent Scientific Investigations Program. Under this program, the County gathers data for independent analysis of geologic and hydrologic conditions. The Nye County Early Warning Drilling Program (EWDP) was initiated to establish a groundwater monitoring system and obtain geologic and hydrologic information outside the Yucca Mountain Project Site (**Fig. 1**).

Well tests conducted on three of the EWDP wells indicated much higher permeabilities than are normally encountered in the petroleum industry, as well as numerous other unusual effects that are seldom observed in practice.

Test Description

The EWDP wells were drilled and completed using gravel packs and slotted liners to minimize formation damage. Following completion, the wells were produced until the fluids were completely clean, and were then shut in until they were ready to test. Test data for the three wells are summarized in **Table 1**.

The tests on the EWDP wells generally consisted of a 2-day flow followed by a short buildup up of 0.25 to 3 hours. The buildup times were determined by field personnel based on how quickly the wells built up. A submersible pump rated at 6,000 bpd was used for all tests. The flow rate was determined with a turbine meter and confirmed using the time required to fill a 1.31 bbl (55 gal.) drum.

For the first well (9-SX) tested, water levels were determined using a well-sounding tape, which is a common technique in the water well industry. The water levels were recorded by hand and were then converted to pressures. For the other wells, a pressure transducer was used to record pressure every 20 seconds during the test.

Analysis

The tests were analyzed with the usual petroleum industry techniques, including log-log plots, semi-log plots, Cartesian plots, and type curve matching. Two commercially available computer-assisted well test analysis packages were used in the analyses. Both drawdown and buildup data were analyzed. Only the drawdown results are presented here, because the buildup results were essentially the same as the drawdown results.

In analyzing these tests, a number of factors were considered which differ from most oil or gas well tests. These include unconfined aquifer effects, wellbore storage effects, effective compressibility, and barriers.

Unconfined Aquifer Effects. Aquifers are commonly categorized as either confined or unconfined, depending on whether there is a sealing bed at the top of the aquifer. Aquifers that have a standing water level and no top seal are considered *unconfined*, while those with a top seal are considered *confined*. When a well in an unconfined aquifer is produced, the water level around the well drops, leading to a reduction in the net saturated thickness for flow[1,2]. This leads to an apparent skin factor because of the flow restriction near the well, and also may cause greater apparent wellbore storage.

Wellbore Storage. Conventional wellbore storage is not very important when a wellbore volume is being produced in less than 0.01 hr. In these tests, however, wellbore storage in the gravel pack can also be important, as well as storage in the drawdown of unconfined layers.

Effective Compressibility. The effective compressibility of unconfined layers is orders of magnitude larger than that of confined aquifers. A typical confined aquifer with 30% porosity would have a total compressibility of about 6×10^{-6} psi^{-1}, based on typical water compressibility[3] of about 3×10^{-6} psi^{-1} and rock compressibility[4] of 3×10^{-6} psi^{-1}. The storativity of a formation is the product of the porosity, the total compressibility, and the thickness, with a unit conversion factor (0.433) to account for the density of water:

$$S = 0.433\ \phi\ c_t\ h \quad \text{……………………………………..(1)}$$

In contrast, the storativity of an unconfined aquifer depends on its *specific yield*, or the volume of moveable water present in the formation. The specific yield is given by:

$$S_y = \phi\ (1-S_{wirr}) \quad \text{………………………………………..(2)}$$

The effective compressibility that should be used for an unconfined aquifer is determined by equating the storativity equation and the specific yield equation, to find:

$$c_{t\ eff} = (1-S_{wirr})/(0.433\ h) \quad \text{….…………………………..(3)}$$

If a typical value of 20% were used for irreducible water saturation, the indicated effective compressibility for a 30 ft thick aquifer would be 0.062 psi^{-1}. The effective compressibility of an unconfined aquifer can therefore be as much as 10,000 times larger than that of a confined aquifer.

Barriers. Many aquifers are extremely permeable. The combination of low compressibility for confined aquifers, coupled with high permeability, implies that the effect of barriers in confined aquifers should be observed more frequently in aquifer tests than in oil and gas well tests. In fact, it is fairly common to observe barriers on water well tests.

Results

Well 1-S. Well 1-S was tested in Feb. 1999. Two volcanic tuff intervals 20 and 60 ft thick are present, with a 30 ft break between them. The gauge was set between the two productive intervals. The drawdown while pumping 5930 bpd was only 0.62 psi (**Fig. 2**), suggesting extremely high permeability was present.

The measured pressure data in **Fig. 2** do not follow a normal, smooth drawdown, but instead have an odd flat period followed by a more rapid pressure decline. A weather front moved in during the test, so that the barometric (atmospheric) pressure changed 0.28 psi during the test. Because the pressure change from pumping was so small, it was necessary to correct for the changes in barometric pressure during the test. Previous work[5] in other wells in the area indicated nearly 100% barometric efficiency, so a correction was made as follows:

$$P_{corrected} = P_{measured} - (P_{atm} - P_{atm@t=0}) \quad \text{…………………..(4)}$$

The adjusted pressures have a more conventional appearance (**Fig. 2**).

The log-log diagnostic plot (**Fig. 3**) has no clear wellbore storage period (unit slope). Radial flow, characterized by a flat derivative curve within the level of noise, lasts until approximately 0.75 hr. The slope of the derivative curve then increases to a positive half-slope (+0.5), indicative of linear flow, through the remainder of the flow period. The permeability indicated from the early straight line (radial flow) on the semi-log plot (**Fig. 4**) is 300 darcies, with a skin of +4.8. The type curve match required parallel barriers at a distance of 90 ft from the well.

Well 3-D. Well 3-D was also tested in Feb. 1999. A spinner survey indicated 29 feet of tuff below the bottom of the surface casing was contributing all of the production. The standing water level in the well was 138 feet above the bottom of the surface casing. Total drawdown during the test was 8.73 psi, which indicated the permeability at Well 3-D was much lower than that at Well 1-S. With the larger drawdown, no correction for barometric effects was necessary.

After a very short wellbore storage period and a classical "hump", the derivative response (**Fig. 5**) has a steady downward slope of –0.5, which is inferred to be hemispherical flow caused by partial penetration. The tuff and overlying alluvium are apparently in direct communication up to the standing water level, leading to a total thickness for flow of 167 ft. Production from the bottom 29 feet of this zone leads to hemispherical flow. The test response was therefore matched using a horizontal permeability of 13 darcies and a vertical permeability of 4 darcies. The computed partial penetration pseudo-skin was +25.

If the partial penetration effect had not been recognized and a conventional radial flow analysis was made, the computed permeability and skin for Well 3-D would have been 3.5 darcies and +2.6, respectively. If a semi-log straight line is erroneously drawn through the data after one hour (**Fig. 6**), it would lead to 4.6 darcies permeability and +4.8 skin.

Well 9-SX. Well 9-SX was tested in Jan. 1999. A spinner pump test indicated 60% of the flow was coming from the bottom screened interval (330 to 340 ft), 20% was coming from the interval between 250 and 290 ft, and the remaining 20% was coming from the upper two zones from 90 to 120 and 140 to 160 ft depth.

Water levels for the 9-SX test were measured with a well-sounding tape and were then converted to pressure. The Cartesian plot of the pressure readings from the drawdown-buildup (**Fig. 7**) has a steep drop of 0.433 psi (1 ft) after 25 hours of flow. This drop is most likely a result of misreading or misrecording of the tape readings, so the data following that time were corrected by adding 0.433 psi.

The upper two zones in this well appear to be in communication with each other and acted like a single unconfined layer during the test, so they were combined into one layer for the analysis with a total net thickness of 70 ft and an effective compressibility of 0.026 psi^{-1}. The lower zones appear to have properties that are sufficiently similar as to allow them to also be grouped as a single confined layer with a total net thickness of 92 ft and an effective compressibility of 0.000006 psi^{-1}.

The log-log diagnostic plot for the flow period (**Fig. 8**) has a nearly flat derivative near the beginning (within the noise level of the data), which should correspond to the total permeability-thickness of the system[6]. At late times, the derivative increases with a slope of +0.5 or greater, which is inferred to be a result of two or more flow barriers channeling the flow. The best fit (**Fig. 8** and **9**) was achieved using a permeability of 39 darcies and a skin of +24 for the upper zones and 119 darcies with a skin of +29 for the lower zones. As well, two linear sealing barriers at a distance of 3200 ft from the well were used in the lower zones. It was not possible to obtain an acceptable match without at least two barriers in the lower zones. The linear barriers were not evident in the upper zones because the greater compressibility in the unconfined aquifers restricted the radius of investigation in those beds.

Discussion

The first question that arises in considering the results of these tests is whether such high permeabilities can be real. Is a range from 13 to 300 darcies really feasible? The authors believe that it is, inasmuch as these rock units are either fractured tuffs, or valley fill deposits that have fallen off the sides of the adjoining mountains and have not yet had any chance to be compacted, except for the slight overburden on them. The high production rates with minimal drawdowns correspond to productivity indices between 670 and 9600 bpd/psi, which are extremely high given the thickness of the formations.

The next factor to consider is the skin factors in Wells 1-S and 9-SX. These wells were drilled with clean fluids, and were gravel packed and produced until all sediment load in the produced water had dissipated. Why should these wells be damaged? Several possible causes exist, including flow convergence to the well, lower permeability in the gravel pack than in the formation, and inertial/turbulent flow effects. The skin effect is a measure of additional pressure drop near the wellbore. With such high permeability in the formation, a small additional pressure drop can easily occur, and the apparent skin factor is magnified because of the high formation permeability. In wells such as these, a more reliable measure of damage may be the pressure drop due to skin, which was only 0.14 psi in Well 1-S and 1.3 psi in Well 9-SX.

Barriers were identified from the test analysis of Wells 1-S and 9-SX. The linear flow observed in these wells is considered to be the result of nearby faults, or possibly non-deposition of rock units in some cases. This area has numerous faults that have been identified from surface and subsurface mapping. A subsequent high-resolution aeromagnetic survey confirmed the presence of one fault near Well 1-S and three faults near Well 9-SX, but found no faults around 3-D. The spacing of the faults at Well 1-S is inferred to be too close for resolution with the aeromagnetic survey, or possibly the faults coalesce into a single fault at the depth that the aeromagnetic survey responds to. The presence of multiple faults thousands of feet apart around Well 9-SX fits well with the aeromagnetic results. Finally, the radius of investigation for Well 3-D was much less than the other two wells, because of hemispherical flow and lower permeability, so if any well did not show faults, it should have been Well 3-D. Thus, the inferences regarding barriers form the well test analysis are considered to match the aeromagnetic results very well.

A final discussion topic concerns the impact of the difference in compressibility between confined and unconfined aquifers. If Well 1-S were assumed to be in a confined aquifer, the computed skin would have been +0.7 instead of +4.8, and the distance to the barriers would have been 5600 ft instead of 90 ft from the well. The skin factor difference is probably not significant, but the presence of barriers parallel barriers 5600 ft from Well 1-S cannot be reconciled with the geology of the area. There is also a problem with the long linear flow period observed. In order to account for the extended linear flow observed during the well test, the radius of investigation computation for a linear flow system[7] indicates those barriers would extend more than 113,000 ft from the well if the system is confined, or else outer boundary effects should have been observed. This is not consistent with geological analyses or the aeromagnetic survey. If the system were unconfined, the compressibility would be much higher, so the computed radius of investigation would be only 1800 ft, which *is* consistent with the aeromagnetic survey. Therefore, the best interpretation for Well 1-S is to use a very high total compressibility to account for the effects of the unconfined reservoir.

In contrast, the existence of extended linear flow in Well 9-SX is observed in a confined system around that well. Well 9-SX has lower permeability and more extensive faulting indicated on the aeromagnetic survey. Thus, the observation of extended linear flow in the pressure response of Well 9-SX is consistent with the current understanding of the geology of the area. The same barriers may be present in the unconfined layers, but are not observed in a short-term test because of the much greater compressibility in the unconfined layers than in the unconfined layers

Conclusions

1. Ultra-high permeabilities, up to 300 darcies, have been shown to occur in fractured volcanic rocks and unconsolidated, uncompressed valley fill sediments in Nevada.
2. With such high permeabilities, the effects of barometric pressure changes, partial penetration, and barriers are clearly shown on well tests.
3. The difference between confined and unconfined flow is shown to lead to differences in effective compressibility of as much as a factor of 10,000.

Nomenclature

c = compressibility, Lt2/m, psi^{-1}
h = net pay thickness, L, ft
P = pressure, m/Lt^2, psi
S = storativity, as defined in Eqn. 1
Sw = water saturation
Sy = specific yield, as defined in Eqn. 2
f = porosity

Subscripts

atm =atmospheric
atm @ t=0 =atmospheric at start of test
eff = effective
irr = irreducible
t = total

Acknowledgements

We thank Tom Buqo, Claire Muirhead and Jamie Walker of Nye County for their diligent data gathering and valuable insights on the interpretation of the tests. Copies of the test data and complete interpretation reports, as well as additional information regarding the NWRPO and the EWDP wells are available through the website www.nyecounty.com.

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TABLE 1—TEST PARAMETERS FOR EWDP WELLS

Parameter	Well 1-S	Well 3-D	Well 9-SX
Top of Test Interval, ft	160	397	90
Base of Test Interval, ft	270	426	340
Gross Test Thickness, ft	110	29	250
Net Test Thickness, ft	80	29	162
Porosity	0.30	0.30	0.30
Viscosity, cp	0.84	0.74	0.86
Wellbore Radius, ft	0.25	0.25	0.25
Temperature, °F	82	93	80
Compressibility, psi^{-1}	0.0231	0.0637	0.000006 to 0.026
Flow Time, hrs	47.75	50.50	47.75
Shut in Time, hrs	1.17	3.00	0.25
Flow rate, bpd	5930	5829	6000
Total Drawdown, psi	0.62	8.73	2.95

TABLE 2—TEST RESULTS FOR EWDP WELLS

Parameter	Well 1-S	Well 3-D	Well 9-SX
Main Flow Geometry	Linear	Hemispherical	Linear
Average Horizontal Permeability, darcies	300	13	84
Vertical Perm., darcies	--	4	--
Skin Factor	+4.8	0	+28
Pressure Drop due to Skin, psi	0.14	0.0	1.3
Partial Penetration Pseudo-Skin	--	+25	--
Distance to Barriers, ft	90	N/A	3200

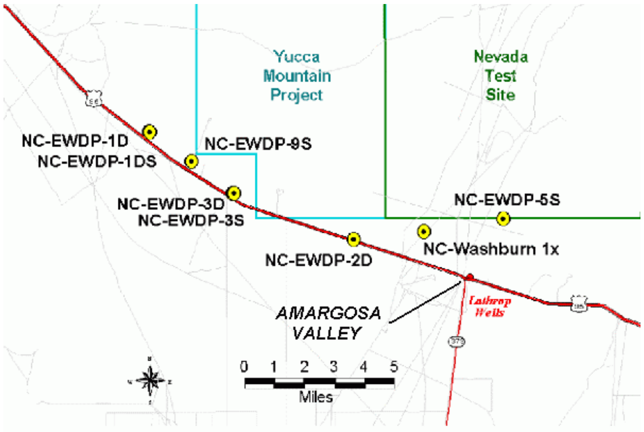

Fig. 1-Location of Yucca Mountain Project and EWDP wells

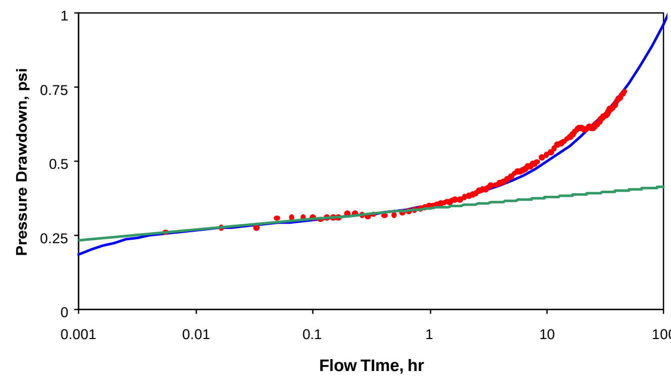

Fig. 4-Semi-log plot for Well 1-S, showing the semi-log straight line for permeability determination

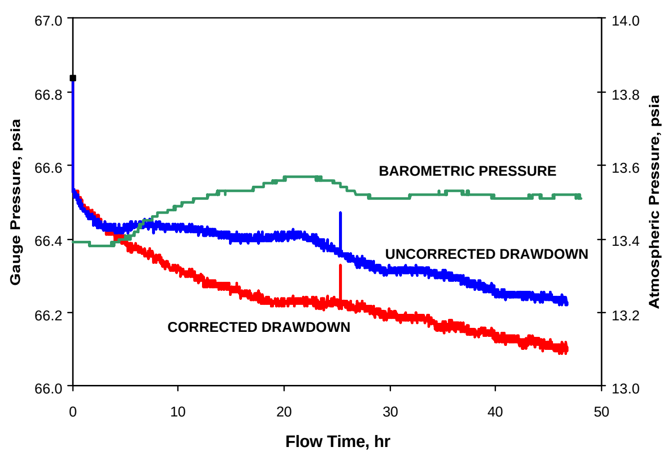

Fig. 2-Drawdown response for Well 1-S, showing the impact of barometric pressure changes

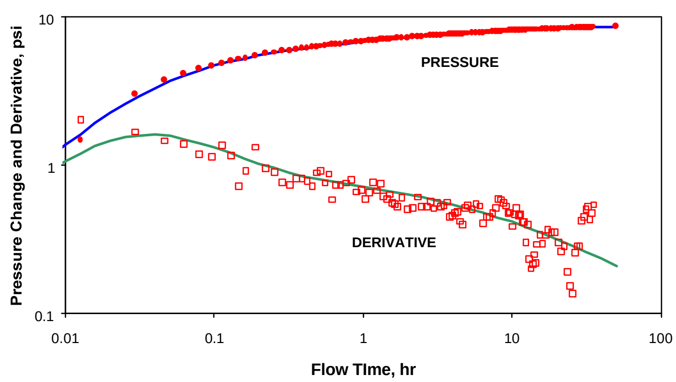

Fig. 5- Log-log plot for Well 3-D, with hemispherical flow as a negative half slope (-0.5) in the late derivative response

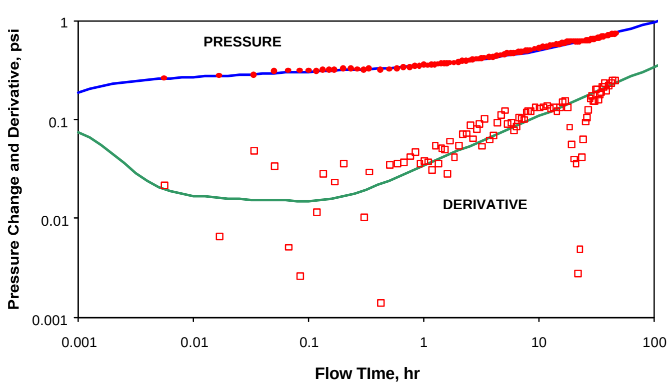

Fig. 3- Log-log Plot for Well 1-S, showing extended linear flow as +0.5 slope in the derivative curve at late times

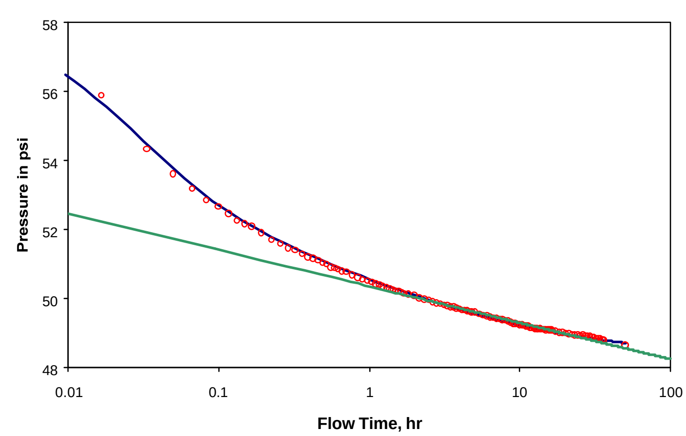

Fig. 6- Semi-log plot for Well 3-D. showing an erroneous semi-log straight line that should not be used for permeability determination

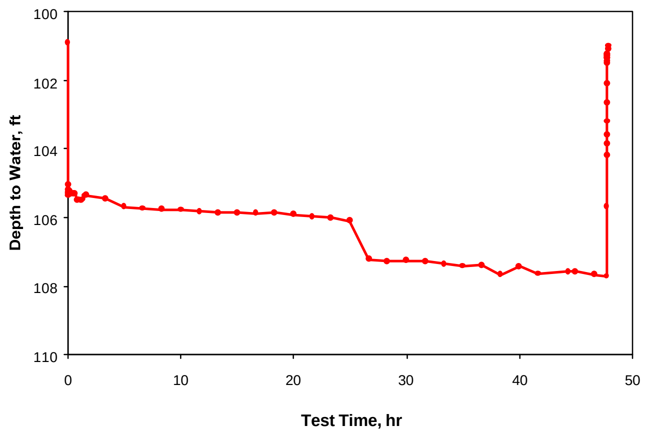

Fig. 7-Test response of Well 9-SX with anomalous 0.433 psi (1 ft) drop after 25 hr of flow

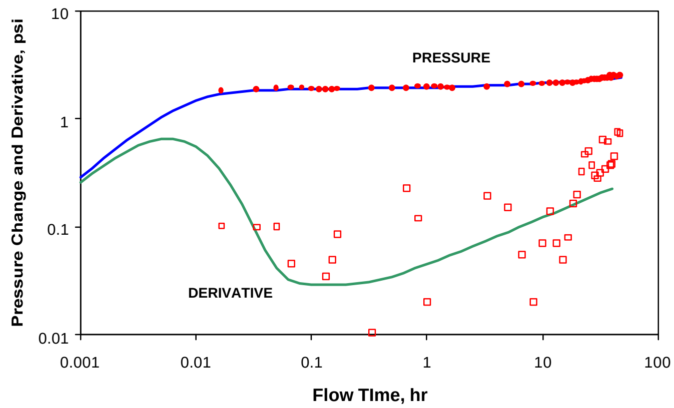

Fig. 8 - Log-log Plot for Well 9-SX, showing extended linear flow as +0.5 slope in the derivative curve at late times

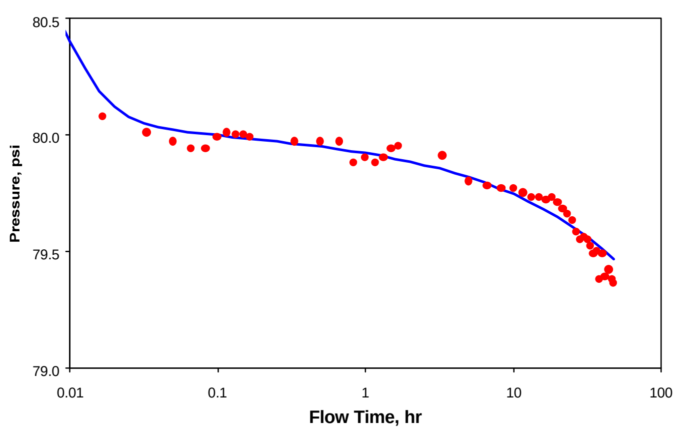

Fig. 9- Semi-log plot for Well 9-SX with type curve match for 2-layer model with sealing faults in the deeper layer