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Analysis of Welltest LIR-GT-02

Updated 31 August 2014

G1107B

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Summary

Well LIR-GT-02 was production tested on 9/08/2014 by a 12 hour multi-rate test with a short build-up after each flow period, followed by a shut-in period of 12 hours. The ESP generated production rates varied between 190 and 350 m3/hr. Cumulative water produced was about 2670 m^3.
The production test was followed by a 5 hours injectivity test on 11/08/2014, the results of which are also included in this report.

Following are the main conclusions:

- The average reservoir permeability is about 1300 mD assuming that the whole net sand contributes to flow.
- The reservoir skin (S) is nearly 0. The analysed skin at the highest rate is 7, which is a rate-dependent skin caused by the flow resistance of the screens plus the vertical conduit up to the ESP.
- A single flow barrier is evaluated at a distance of about 450m from the wellbore.
- The static reservoir pressure at 2350 m tvBRT is 239 bara; at 2400 m tv 244 bara.
- The reservoir temperature is ~ 88 ºC.
- The correction for the changing temperature of the water column between the ESP and top reservoir appears to be working reasonably for the build-up data one hour after shut-in.
- The transient flow capacity (PI) after 24 hours flow at ESP depth is 23.5 m^3/hr/bar including the rate dependent skin of 7. Assuming that this skin is completely caused by the screens plus vertical flow, the PI at the outside of the screens is 40 m3/hr/bar.
- The (still increasing) transient injectivity (II) at the end of the injection test is only 10 m3/hr/bar, caused by an effective skin of 30.
- The injectivity test shows continuous decline in skin during the entire injection period. Given that a low rate-dependent skin of 4.9 was observed at the same rate during the production test, it is believed that surface lines etc. were not fully cleaned–out (grease, etc) before the injection test took place.
- Allowing for regular filter clean-outs, it is expected that the injectivity index of the well will increase further.

Resultaten van de puttest

Gegevens voor test interpretatie	Waarde	Dimensie
Naam van de put	LIR-GT-02	
Coördinaten van de put (X, Y)	**E (m) = 79090.55**	**N (m) = 443734.51**
Coordinaten mid reservoir at 2370 mtv	**E (m) = 79583**	**N (m) = 443305**
Top aquifer	2590	m (langs boorgat)
	2324	en m (TVD)
Basis aquifer	2715	m (langs boorgat)
	2418	en m (TVD)
Netto dikte Aquifer	64	m (TVD)
Netto/bruto aquifer	68	%
Gemiddelde porositeit aquifer	16.8	%
Zoutgehalte formatiewater (TDS = total dissolved	140,000.	ppm
solids)		
Maximum temperatuur geproduceerde water[1]	88	ºC
Diameter boorgat bij aquifer	8.5	Inch
Top productie-interval/filter	2531	m (langs boorgat)
	2279	en m (TVD)
Basis productie-interval/filter	2855	m (langs boorgat)
	2525	en m (TVD)
Filter + casing weerstand	6.0	bar @ 351 m3/hr
Filter + casing weerstand	3.3	bar @ 259 m3/hr
Filter + casing weerstand	1.7	bar @ 189 m3/hr
Locatie pomp	700	m (langs boorgat)
	700	en m (TVD)
Locatie meetsonde voor druk	700	m (langs boorgat)
	700	en m (TVD)
Clean up gegevens		
Pompdruk	53	bar
Debiet vs. tijd	350	m3/uur
Duur	3	uur
Meetreeksen Puttest[4]	Eind ESP druk, bar	Eind Debiet, m3/uur
Flow 0	64.9	0
Flow 1	60.4	189
Flow 2	57.6	260
Flow 3	52.55	350

[1] Deze temperatuur wordt als gemiddelde aquifer temperatuur beschouwd

Uitkomsten test interpretatie en analyse		
Permeability thickness kH	83	Dm (Darcy-meter)
Aangenomen H	64	m
Permeability k	1300	mD
Reservoir Skin S	0.3	
Totale effectieve Skin	7.2	@ 351 m3/hr
Productivity Index (P.I.) (at ESP depth)	23.5	m^3/uur/bar
Productivity Index (P.I.) (at wellbore)	40	m^3/uur/bar

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1 Introduction

Well LIR-GT-02 was production tested from 9-08-2014 05:10 to 9-08-14 17:01, followed by a shut-in period of 12 hours. ESP generated production rates varied between 190 and 350 m3/hr. Cumulative water produced was about 2670 m^3.
The pressure and temperature data were recorded only by the ESP gauge.

The ESP pressure sensor is at 700 m tvBRT. The well was produced mostly from the Delft sandstone, covered by screens from a depth of 2279 to 2525 m tvBRT (2531 – 2855 m ahBRT).

The correction formula, as determined during the LIR-GT-01 test analysis from the ESP data in combination with a downhole gauge, was used to correct the ESP pressures down to a datum depth of 2350 m tvBRT.

After the production test on 11-08-2014, 1040 m3 water was injected back into the well, using the mud pump of the drilling rig. The 5 hours of injection rates and surface (annulus) pressures have been matched with the same model as matched on the production test.

2 Reservoir data

The porosity of the Delft sandstone has been estimated with the (exponential) GR-PHI method of TNO because no direct porosity measurements are performed for this well. The porosity is estimated at 16.8%. Net reservoir thickness of the separate sand layers behind the screens is estimated from the gamma ray log as a total of 64 m (210 ft). [1]

The wellbore radius Rw has been set to the bit size of 8.5”, or 0. 354 ft.
In view of the deviation of the well with an average angle of about 40 degrees through the Delft Sandstone, the wellbore radius was adjusted to $Rw*\sqrt{\{(1+1/\cos\alpha^2)/2\}}$ = 0.412 ft, for analysis with a vertical well model.
The reservoir temperature is estimated at 88 C, as the maximum ESP temperature is about 3 °C lower than in LIR-GT-01.
The water salinity is obtained from the observed pressure gradient at 90 ºC of 0.104135 bar/m. This has to be multiplied by 10197.16 to convert into a water density of 1061.9 kg/m3. This is consistent with a water salinity of 155 gr/ltr NaCl (14%) and a density of 1102 kg/m3 at 15 ºC.
Standard tables show for this salinity a water compressibility of 2.37E-6 psi^{-1}, and a water viscosity of 0.46 Cp.
The pore compressibility was originally assumed at 3E-6 psi^{-1}. As this low compressibility resulted in too large distances to flow barriers in LIR-GT-01, it was increased to 9.E-6 psi^{-1}, more likely for this high permeability sandstone.

[1] *The geothermal wells of Honselersdijk and De Lier have high permeability Delft Sandstones, while its porosity is modest. In other words there seems to be a discrepancy between the high permeability calculated from the well tests and the available porosity information. At PanTerra there is doubt about the porosity value of about 17%, this may be too low. Considering the high permeability, porosity values in the twenties seem more likely. Unfortunately geothermal operators do not run wireline logs from which reliable porosity values can be calculated, because such wireline logs are deemed too expensive, the result is that important information on the reservoir is lacking.*

3 Correction for water column cooling on gauge data

The pressure correction equation for water column cooling between ESP and downhole gauge data was established in well LIR-GT-01 (Ref. Report G1077A by PanTerra):

The equation is as follows: $\Delta P = CDC*L*[1061.92+0.418*\Delta T - 0.00231*\Delta T^2 + 2.545*\Delta T^{0.1}]$

Whereby : ΔP = the pressure correction,

CDC a constant [CDC= $9.8063E^{-5}$ with pressure in bar and L in meters],

L = the vertical depth difference between datum and ESP depth

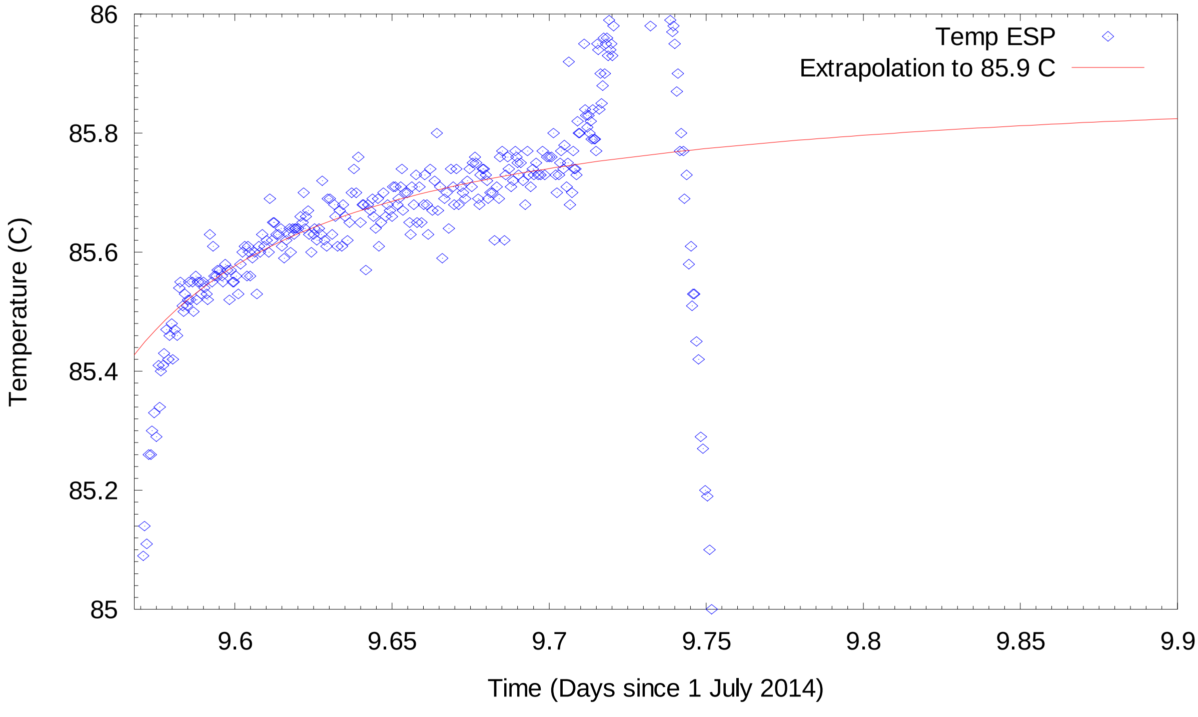
ΔT = the difference between the maximum and current ESP temperature in ºC,

Maximum temperature (reservoir temperature) was 88.0 ºC

This formula corrects the pressures from ESP depth to datum depth (difference = 1650 m.)

The maximum expected future water temperature at the ESP depth of 85.9 ºC is obtained by extrapolation of the recorded temperature during the 3.6 hours long flow period at the highest rate of 350 m3/hr (ref. Fig A)

De Lier GT02 ESP Temperature increase at 350 m3/hr Fig A



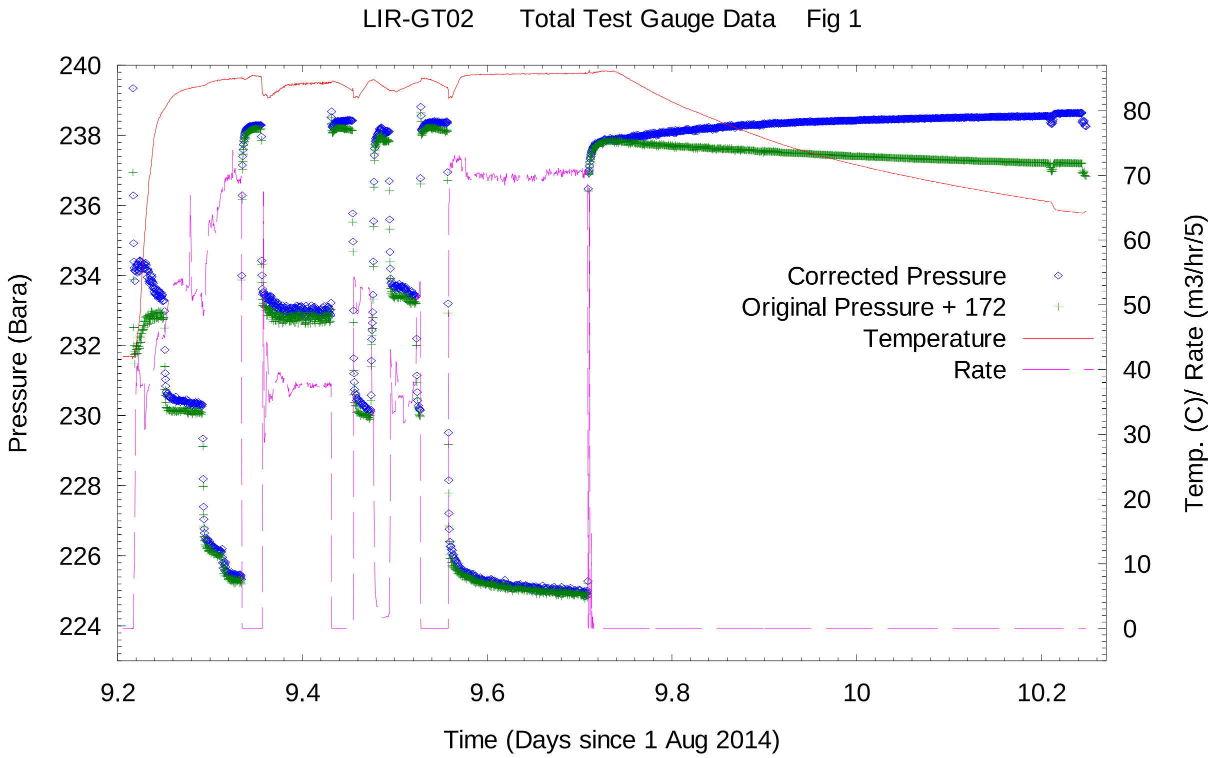
4 Pressure recordings

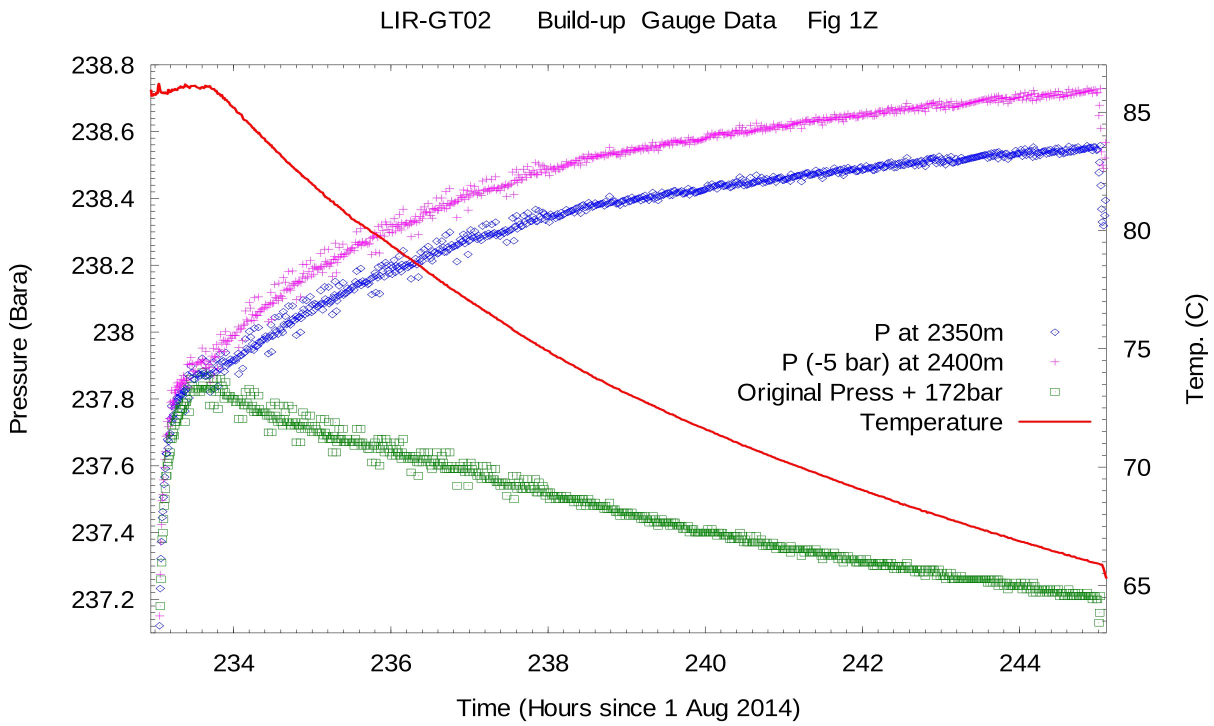
Fig-1 shows the original and the corrected ESP data (with 172 bar added to the original values for plotting in same figure), plus the rates.

The gauge data during the main build-up are enlarged in Fig-1Z: This clearly demonstrates the effect of the latent motor heat on the gauge temperature (and thus on the correction for the water column weight) for the first hour after shut-in. These pressures have thus to be ignored during the analysis.

This period with increasing temperature is longer than in the LIR-GT-01 test as the motor was using more power at a higher flow rate. The uncorrected pressure show at the same time the water-hammer effect, as the kinetic energy of the water flow is converted into potential energy (pressure) at shut-in.

In order to test if the poor match with the early shut-in pressures could be improved by extrapolating to the same 2400m datum level as in LIR-GT-01, the purple points in Fig-1Z are corrected to 2400 m, using also a maximum T in the correction formula of 86.35 ºC.





5 Analysis method

The analysis is carried out by the match of the most appropriate analytical well/reservoir model with the total test history. In this way, no approximations have to be used, as for the model response the flow equations are solved with great precision for the reported flow rates. It should be noted that each pressure point measured in a well depends on the total previous rate history of that well, both in the real reservoir as in the analytical model. Analysis of only one rate period can thus give only an approximation of the real reservoir/well parameters.

As no model for a deviated well is available, a vertical well model has been used, based on the assumption that the flow in the reservoir at some distance from the well will be horizontal, as the vertical permeability is normally lower than the horizontal one in sandstone. The matched-model response for short times can be expected to deviate somewhat from the observed pressures. But these early build-up pressures are also expected to be influenced by cold water, falling down from the annulus above the pump, by water hammer and by the latent motor heat.

6 Analysis of corrected pressure data

The pressures of the ESP gauge, corrected for the water column temperature, have been analysed as presented in figures 2 and 3.

The early build-up pressures were ignored, as they are influenced by the latent heat of the pump motor, increasing the temperature around the pump after shut-in. This effect results in a wrong correction for the water column temperature variation.
The later (one hour after shut-in) build-up pressures could be matched assuming a single layer reservoir with one flow barrier at a distance of about 450 m. This distance may indicate that the minor fault to the south-west is a real flow barrier (Fig. 6).
The permeability is some 1300 mD, based also on the match with the final flow period. The skin at the highest rate of 350 m3/hr is +7.2, but is mainly a rate-dependent skin of 0.02 hr/m3, plus a fixed skin of 0.3. This is based on a match of the lowest flow period at 189 m3/hr, resulting in a total skin of 4.
This rate-dependent skin is due to a combination of flow resistance at the screens and the vertical flow conduit up to the ESP.

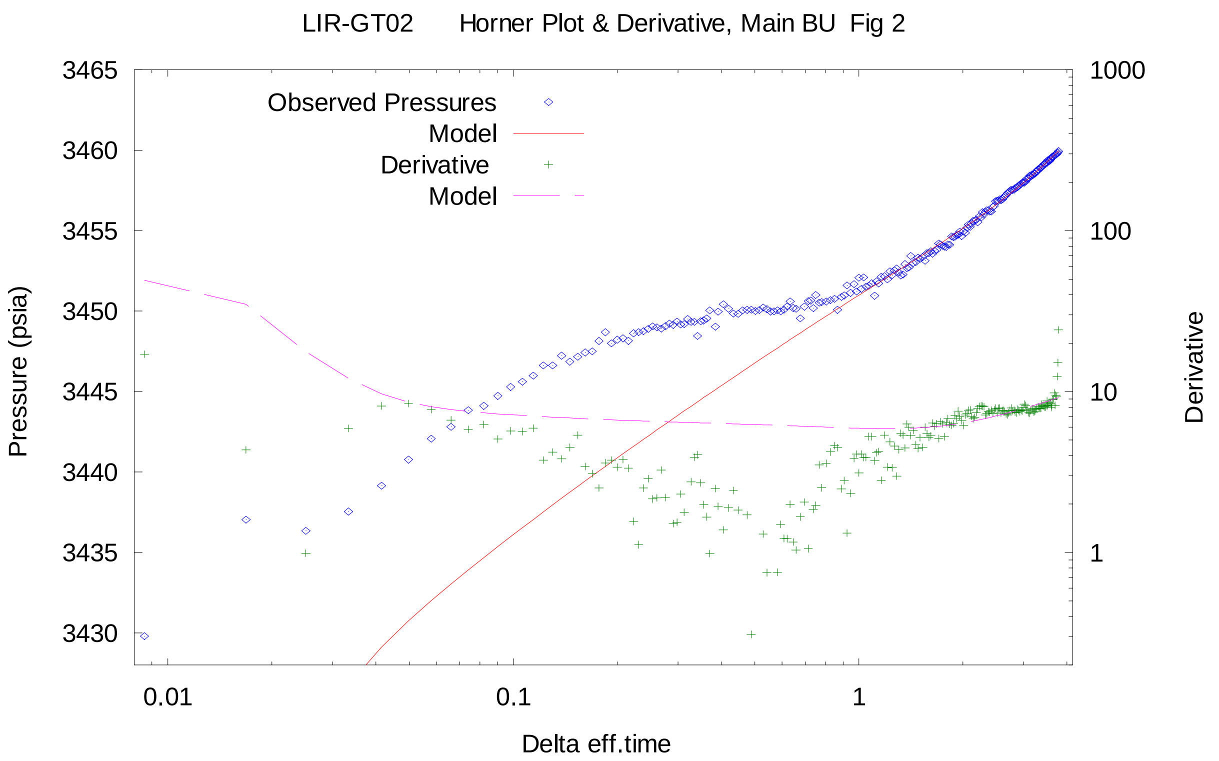
Fig 2 represents the Horner plot plus derivative of the main build-up.
The model does not match the earlier short shut-in periods, as is shown in the linear-time plot of the whole test match, Fig 3.
It is not fully understood why this mismatch is so much worse than observed in the short shut-in periods of the LIR-GT-01 production (see Fig.GT01-6 at page 11).

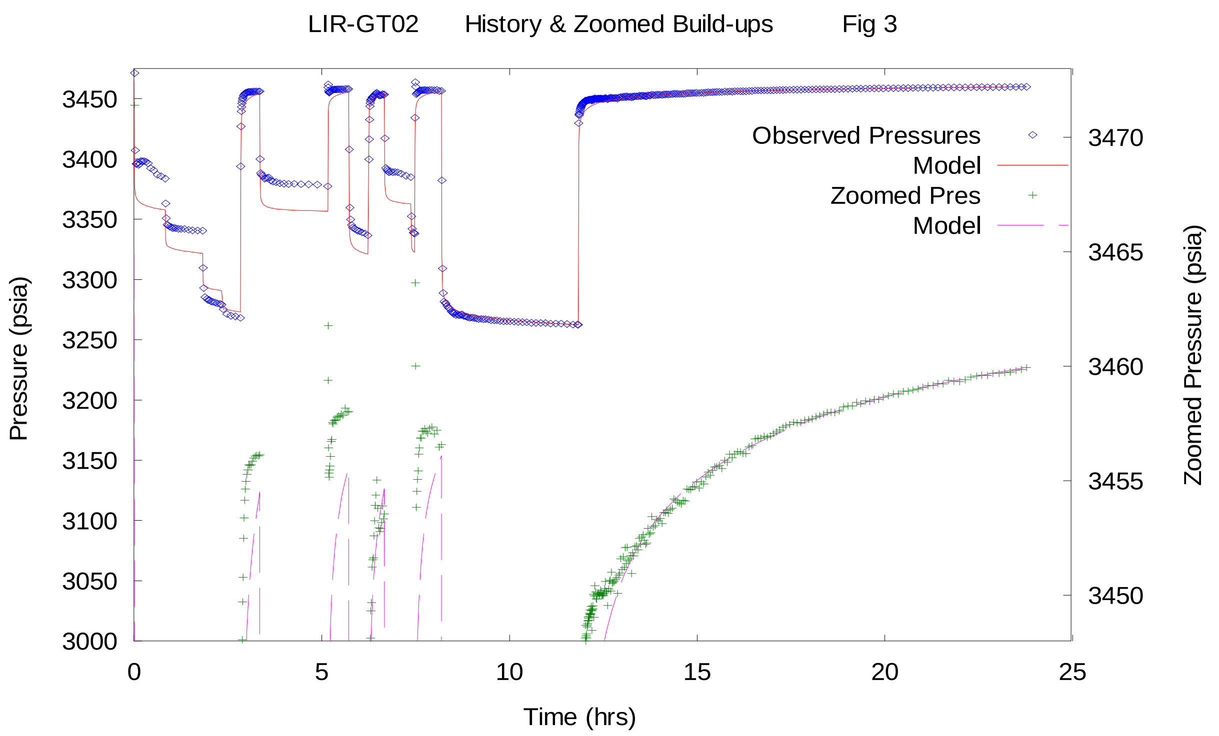
The pressures corrected to 2400 m with a lower Tmax of 86.35 C (see Fig 1Z above) did improve the match of the earlier build-ups slightly, but did hardly change the analysis results, except of course for the static reservoir pressure, Pi, to 3539 psia (244 bar at 2400 m).
The static reservoir pressure at 2350 mtv is 3465 psia (239 bara).

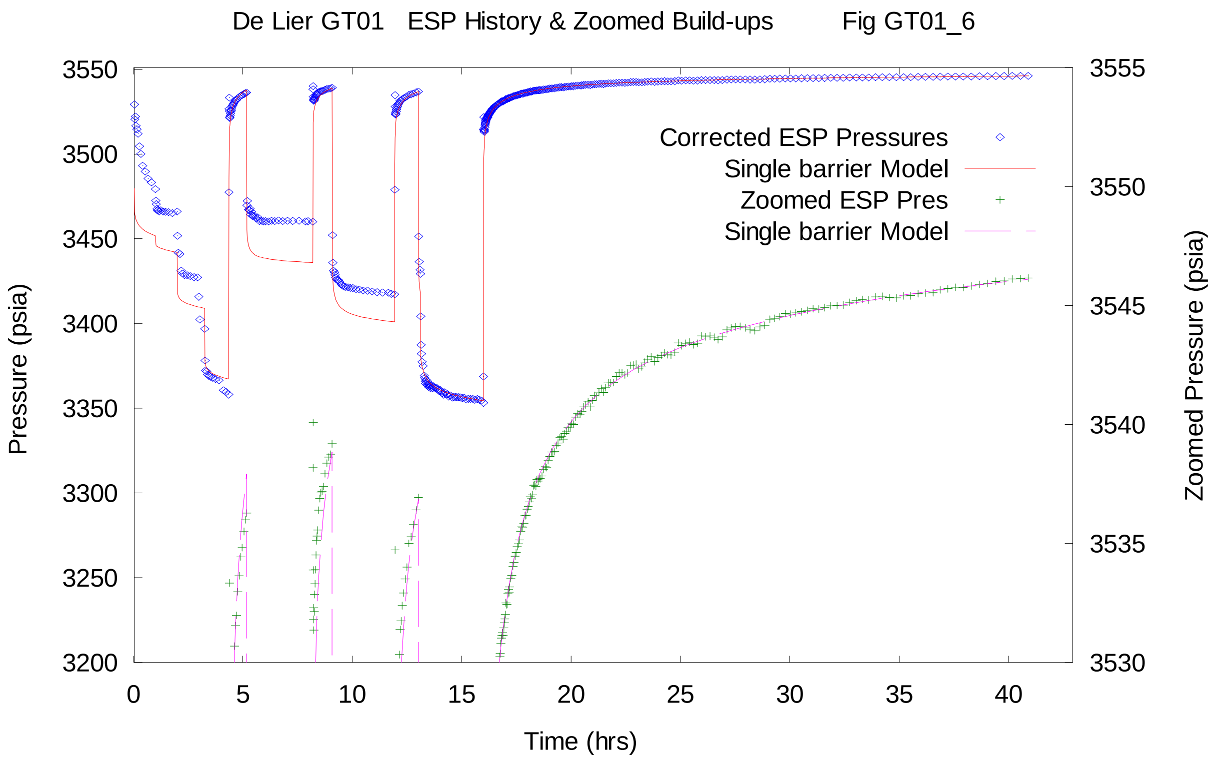
The transient productivity index (PI) after 24 hours is 245 b/d/psi (23.5 m3/hr/bar) at ESP level, therefore including the rate dependent skin of 7.2. The reservoir PI without this rate dependent skin is nearly twice as high at 40 m3/hr/bar. This is the PI at the reservoir/wellbore interface, but only if the rate dependent skin is indeed completely caused by the screens plus the vertical flow.
It should be noted that both values are transient, still declining, PI's.

The rate dependent skin is equivalent with a pressure drop of 1.7 bar at 189 m3/hr, 3.3 bar at 259 m3/hr and 6.0 bar at 351 m3/hr.

The free water level at the end of the build-up period is calculated at 95 m tvBRT, based on the static ESP pressure of about 64.9 bar, the ESP depth of 700 mtvBRT, an assumed average temperature of 30 ºC of the water column above the ESP and a water density of 1094 [95 = 700 – 64.9/(1.094*0.098067)].







7 Conclusions and Recommendations

The equation to correct ESP pressures for the changing weight of the water column down to the reservoir seems to work reasonably well for the build-up data more than one hour after shut-in. During the first hour, the ESP temperature is too high, caused by the latent motor heat which increases the temperature after shut-in. This apparently affects also the short build-ups. Why this effect is much worse than during the test of LIR-GT-01 is not clear.

The distance to the flow barrier of about 450 m may indicate that the minor fault to the south-west is a real flow barrier, see figure 6 below.

The match of all flow periods in Fig 3 shows that there is no clean-up during the production test, as then the first flow periods would have shown pressures below the matched model response. As they are above the model response there seems to be a rate dependent skin, probably caused by the screens plus vertical flow conduit in this high-permeability reservoir.

The early ESP pressures after shut-in for the main build-up are indeed poorly matched. It would be better if the temperature sensor could be about 20 meters below the pump.

The match of the final flow period was used to confirm the reservoir permeability. From the build-up alone, the permeability is concluded to range between 1000 to 1300 mD.
The short build-ups in between the flow rates could not be matched, probably due to the wrong ESP temperature just after shut-in. They did not contribute anything to the test analysis. In fact, this time could have better been used for a longer maximum rate period, which has still been rather short at 3.6 hours. The short build-up after the clean-up however, can provide useful information about boundaries, but should be 2 hours in view of the motor heat distortion during the first hour. The presence of at least

one extra short flow period at a lower rate (e.g. 40% of the maximum) is useful to determine the presence of a rate dependent skin.

For the next test a test scheme is proposed of 3 hours clean-up (2 hours of increasing motor power ending with 1 hour at maximum rate), 2 hours build-up, 2 hours at 40%, 2 hours at 70% and 6 hours at highest rate, followed by 12 hours build-up (if only the ESP pressures are taken; with a downhole gauge the build-up should be 24 hours). The highest test rate should be selected on the basis of the total storage capacity for the produced water. The maximum clean-up rate should be the real maximum.
The final test rate should be as long as possible and at a constant rate, as it may be the best period for analysis if only the ESP pressures/temperatures are available due to the nearly constant temperature and the high reservoir transmissibility (hardly any decline in flow rate during a fixed pump frequency period).

8 Injection Test

After the production test, water was injected back into the reservoir with the mud pump, measuring the injection rate and pressure, see Fig 4.
The injection pressure went to a maximum of about 57 bar (annulus pressure) during the initial rate increase. During further injection at this pressure the injectivity improved continuously.

For water with a salinity of 155 gr/ltr, the density at 30 ºC is 1094 kg/m3. With a cold water column of 2350 m, a constant Δp of 1.094 * 2350 * 0.098067 = 252 bar had to be added to the surface pressures.
At the start of the injection, the temperature in the well is on average some 60 ºC with an average water density of 1080, resulting in a Δp of 249 bar. The extra 3 bar can thus not explain the increasing injectivity, see figure 5.

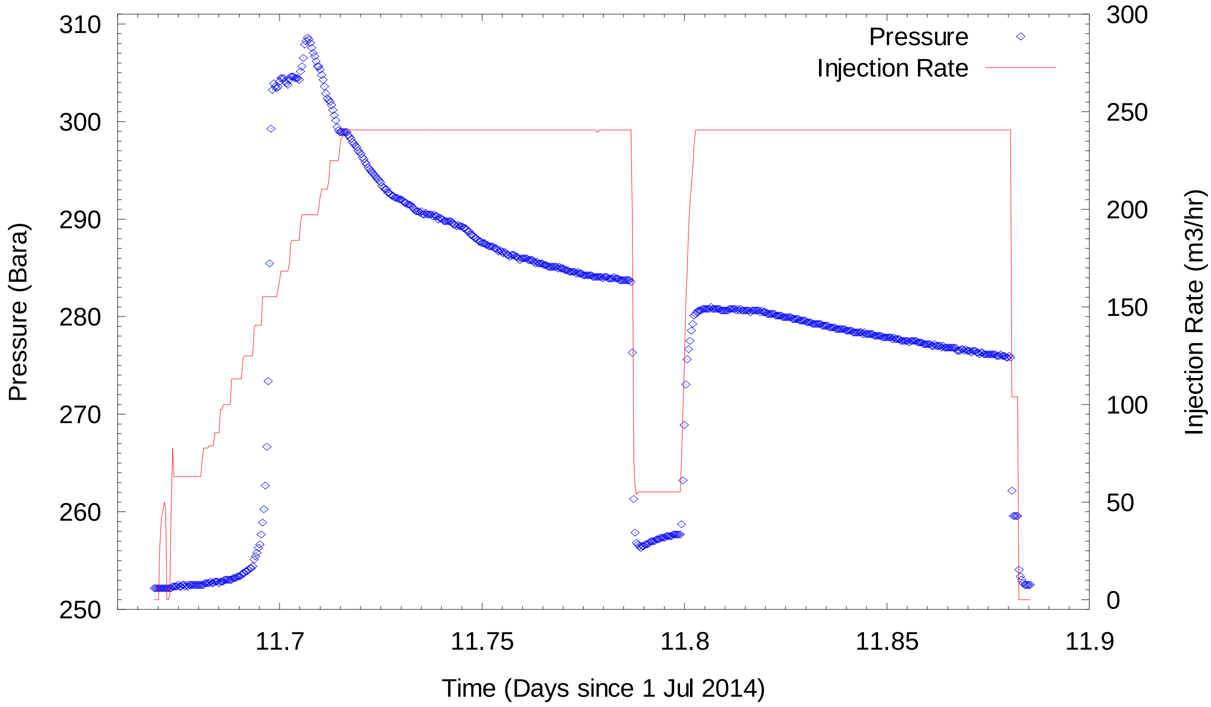
Fig 5 presents the match of the same model as matched on the production test, only matching on skin, wellbore storage and static reservoir pressure (Pi).
The final skin at 240.7 m^3/hr was 30, indicating that the screens were still partially plugged, resulting in an injectivity index (II) of only 10 bar/hr/bar. The matched Pi is 252 bara, 13 bar higher than the Pi of the production test, similar as in LIR-GT-01.

Matching the model on the first pressure at the same injection rate of 240.7 m^3/hr resulted in a skin of 66 and an II of only 5 m^3/hr/bar.

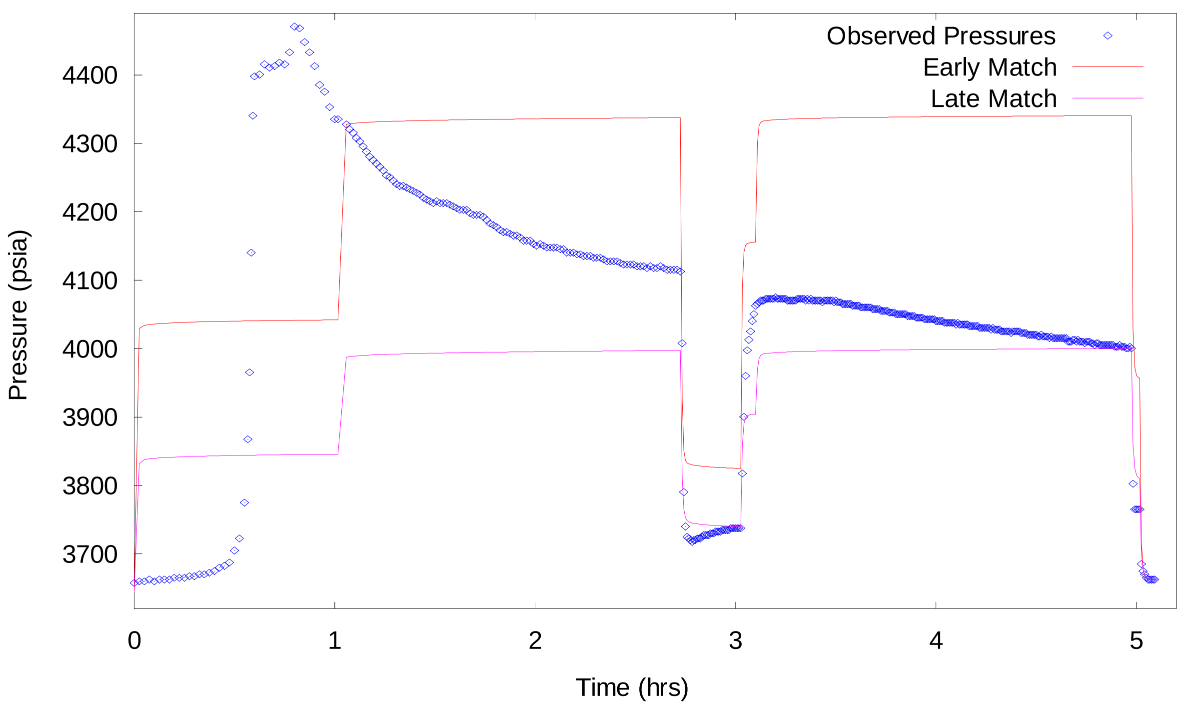
Part of the total skin is the rate-dependent skin of the vertical conduit. At 240.7 m^3/hr the rate dependent skin during the production test was 4.9.
This included the flow conduit from ESP to reservoir.
The extra 700 m down to the ESP level (120 m tubing and 580 m casing) will make this rate dependent skin at surface as measured during the injection test somewhat higher, say 7.0, with a reservoir skin of 0.
The reservoir skin at the end of the injection is thus about 23.

Part of this reservoir skin of 23 is the expanding cold-water bank around the wellbore, probably already reducing the Injectivity Index by some 10% after a few hours injection of cold water.

LIR GT02 Injection Gauge Data Fig 04



LIR GT02 Matched Injection History Fig 5



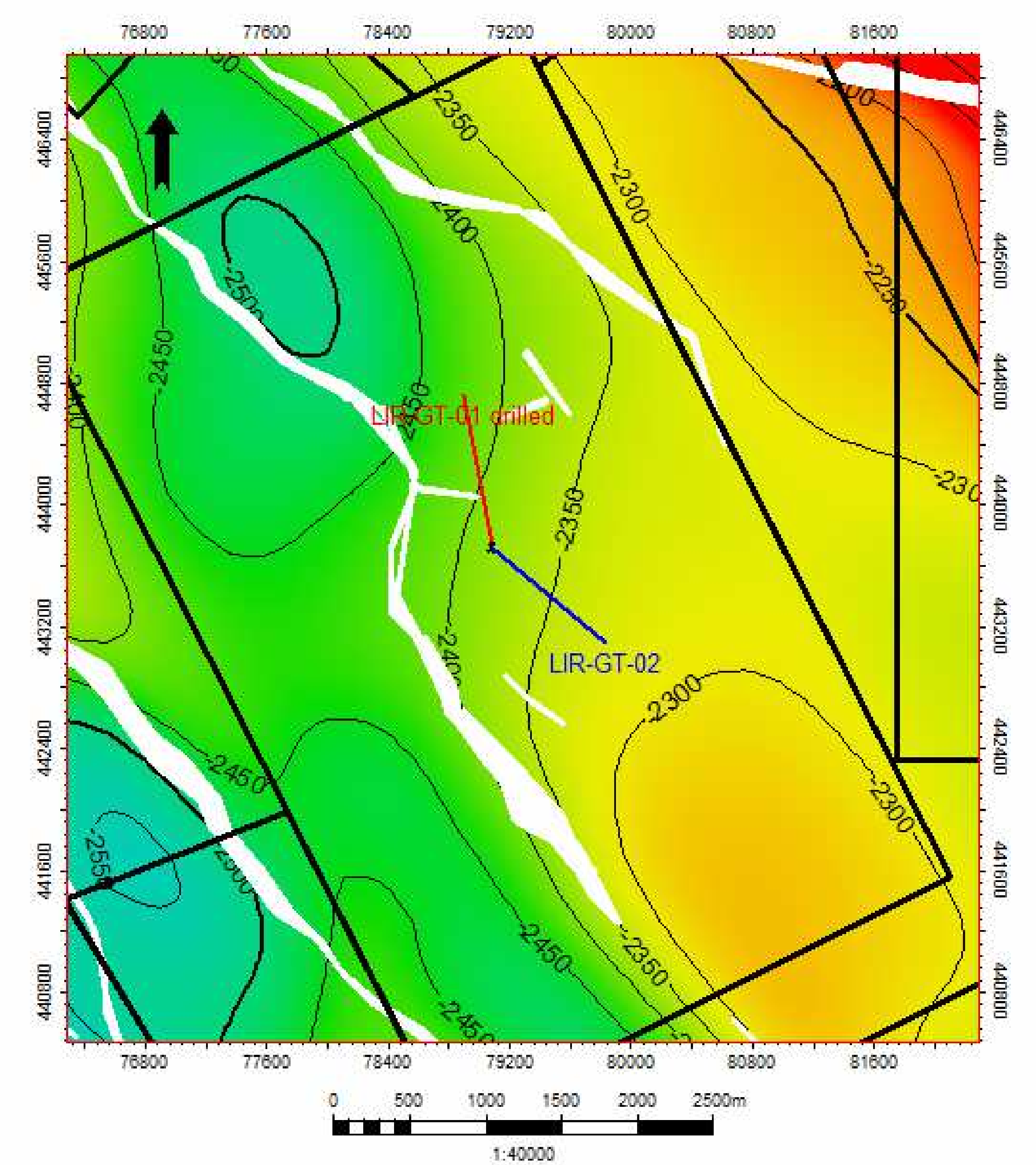


Fig. 6 – Top Structure map with well trajectories of LIR-GT-01 (drilled) and LIR-GT-02 (planned)

9 Well completion scheme

Wellschematic LIR-GT-02_14082014.pdf