PRESSURE TRANSIENT ANALYSIS USING THE PRESSURE DERIVATIVE METHOD: APPLICATION TO SOME WELLS IN THE LEYTE GEOTHERMAL POWER PROJECT

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ABSTRACT

Pressure transient data obtained from geothermal well testing has been generally analyzed using the standard techniques derived from the oil and gas industry. These tests include the usual pressure build up, drawdown, injection as well as pressure fall-off. The more defined or simpler configuration of oil and gas fields has also allowed development of a more recent detailed analysis called the pressure derivative method for a better representation of the reservoir.

The pressure derivative method presents various characteristics of a reservoir that can influence the fluid flow in the well during pressure transient tests. It tackles the different types of boundaries encountered as well as infinite-acting and dual porosity behaviors.

This paper discusses the application of the pressure derivative method to the welltest data of some of the geothermal wells in the Leyte Geothermal Power Project. The results obtained showed a more improved interpretation of well test data and better understanding of the reservoir.

1.0 INTRODUCTION

Pressure transient analysis in geothermal wells has been mostly an application of the equations and techniques derived from the petroleum industry. Pressure transient tests include build-up, drawdown, injection as well as pressure fall-off tests. The parameter calculations on permeability, storage coefficient, skin factors, etc., using type-curve matching had already been accepted used in the geothermal industry as a means of further defining and characterizing the field. Log-log, semi-log, Horner, and other plots derived from analyses of the oil and gas reservoirs are the most widely used calculation techniques in analyzing geothermal welltest responses. Most of the calculations however, can be applied only for homogeneous reservoirs of infinite extent or with infinite acting characteristics.

In reality, pressure transients in wells, may it be in geothermal or petroleum reservoirs, can be or mostly are affected by different types of boundaries. These types of boundaries create different responses on the pressure transient data, which mostly are not evident on the common techniques used. An impermeable fault boundary will give a different pressure transient response to a closed boundary system. Constant pressure boundary, dual porosity systems, etc., which are also likely to be encountered give different responses from the welltest data obtained. Because of the presence of these disturbances, it is necessary to identify the correct flow period for a valid calculation of reservoir parameters. A method developed by Bourdet et al. (1983) uses a plot called the pressure derivative plot which tackles the boundary problems that could be generated from the pressure transient behavior of the wells. This methcd has now been generally applied in the petroleum industry but not quite in the geothermal business.

Boundary responses observed from geothermal well test may come in different combinations due to the complexity of the reservoir's physical structure. A knowledge of the geological setting is, therefore, necessary in assessing and understanding the structural configuration of the field. However, even this cannot show deeper into what controls the permeability of each well, hence, individual well characteristics should be investigated to try to correlate the behavior (pressure) to the possible type of controlling mechanism encountered along the fluid flow path.

This study focuses on the application of pressure transient analysis using pressure derivative plots to identify possible types of boundaries that may control the permeability or productivity/injectivity of selected geothermal wells in the Leyte Geothermal Power Project (LGPP). The results of the pressure derivative plot also provide an initial *step* in determining other reservoir parameters (e.g. estimated distance to the boundaries encountered). The pressure derivative plot also provide an assessment of the quality and compatibility of the well test data recorded from mechanical pressure gauges (Kuster) with that of the pressure derivative calculations.

2.0 THEORETICAL BACKGROUND

The techniques used in the analysis of pressure transients employ mostly graphical presentations or different types of plots for easier handling and calculation of **well/reservoir** parameters. These generally involve plotting of the logarithm of time against pressure or against logarithm of pressure as in the semi-log (Ap against log At) and the log-log plots (log Ap against log At), respectively. This is because the solutions of the governing equations *can* be represented in logarithmic form. Other plots consider the production or injection history preceding the actual tests such as the Homer plot which uses the log $(t_p + \Delta t)/\Delta t$ against pressure. In pressure build-up tests, the variable t_p is the time from start of discharge to shut-in or start of build-up test while At is the change of time from start of build-up. Similarly, in pressure fall-off tests, t_p is the time from the start of injection to start of fall-off (shut-in) and AT is the change in time from *start* of fall-off test.

Log-log type curve analysis with the aid of the semi-log plot is used in the subsequent calculations. By matching the data with the type curve (e.g. Ramey curves), reservoir parameters such as permeability, storage coefficients of the wellbore, skin factor, etc., *can* be estimated. The calculated results *can* help in understanding current well behavior and aid in the prediction of future response to whatever is programmed in the well. There are several other types of graphical techniques, however, the above mentioned plots are commonly used for geothermal well test analyses by **PNOC-EDC.** In type curve matching, it is often difficult to get the best match since very little difference can be observed between the curves especially with wells having high wellbore storage and skin effects.

The pressure derivative method introduced by Bourdet et al in 1983 is a plot of the log tdp/dt against log of At. It looks at the rate of change of the pressure differential with time. With this, more spread out curves are produced out of which a better match of well test data can be obtained. This is plotted together with the conventional log-log plot (log Ap vs log At). The combined plot is called a pressure derivative plot. Various reservoir characteristics, especially boundary effects, can be distinguished from this single graph. Horne (1995) provided different boundary responses that are characterized by the following:

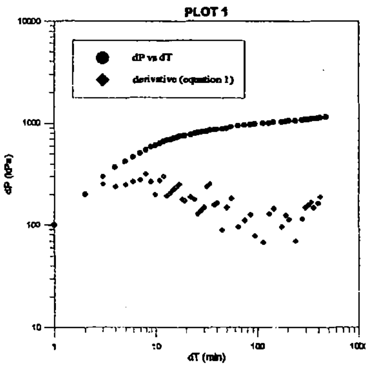
a) Infinite-acting radial flow represented by a semi-log straight line on a semi-log plot which shows as a flat region on a derivative plot
b) Storage represented by a unit slope straight line on a log-log plot which shows as a unit slope line plus a hump *on* a derivative plot. The "hump" is characteristic of a damaged well (positive skin).
c) A linear impermeable boundary represented by a semi-log straight line with a doubling of slope on a semi-log plot which shows as a second flat region on a derivative plot.
d) Dual porosity behavior represented by two parallel semi-log straight lines on a semi-log plot which shows as a minimum on a derivative plot.
e) *An* infinite conductivity fracture represented by a ½ slope line *on* a log-log plot which is the same on a derivative plot. Separation between pressure and derivative is a factor of 2.

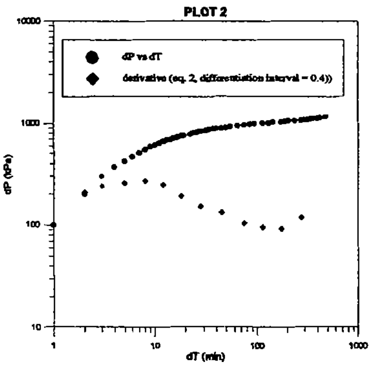
Other types of boundary responses are also presented by Horne (1995) but only the above mentioned conditions are found to be applicable to the selected wells.

3.0 DATA PROCESSING - THE CALCULATION OF PRESSURE DERIVATIVES

Calculation of pressure derivatives takes into account the change in pressure differential ΔP against the time interval or change of At. Differentiation using adjacent points of the data will produce a very noisy derivative (**equation** 1, Plot 1).

$$t(\delta p/\delta t)_i = t_i \times \frac{(t_i - t_{i-1})\Delta p_{i+1}}{(t_{i+1} - t_i)(t_{i+1} - t_{i-1})} \; t \; \frac{(t_{i+1} + t_{i-1} - 2t_i)\Delta p_1}{(t_{i+1} - t_i)(t_i - t_{i-1})} - \frac{(t_{i+1} - t_i)\Delta p_{i-1}}{(t_i - t_{i-1})(t_{i+1} - t_{i-1})} \qquad (1)$$





Home **(1995)** suggested that the best method to reduce the noise is to use a differentiation with respect to the logarithm of time considering points which are separated by **0.2-0.5** of a log cycle (equation 2, Plot **2).** The minimum interval should be considered if the derivative curve is already smooth enough for interpretation. Wider differentiation interval will tend to give a distortion of the derivative curve from the calculated values.

$$t(\delta p/\delta t)_i = (\delta p/\delta \ln t)_1 \qquad (2)$$

$$= \frac{\ln(t_i/t_{i-k})\Delta p_{i+j}}{\ln(t_{i+j}/t_i)\ \ln(t_{i+j}/t_{i-k})} - \frac{\ln(t_{i+j}\ t_{i-k}/t_i^2)\Delta p_i}{\ln(t_{i+j}/t_i)\ \ln(t_i/t_{i-k})} - \frac{\ln(t_{i+j}/t_i)\Delta p_{i-k}}{\ln(t_i/t_{i-k})\ \ln(t_{i+j}/t_{i-k})}$$

where $0.2 \leq \ln t_{i+j} - \ln t_i \geq 0.5$ and $0.2 \leq \ln t_i - \ln t_{i-k} \geq 0.5$

This pressure derivative calculation considers three data points. With the differentiation interval technique of smoothing the curve, problems *can* be encountered at end time of the test. The last interval would have no data following it, hence, a distortion is expected at end time or a shorter derivative curve will be obtained.

4.0 THE DATA TO BE ANALYZED

Selected wells in the Leyte Geothermal Power Project (LGPP) were considered for the application of this pressure derivative technique. The wells chosen are of different permeabilities, discharge characteristics, location with respect to production area. These could give different types of pressure transient responses and assist in looking into the applicability of such technique. Wells investigated are production wells **MG-8D, MG-19, MG-23D** and **MG-30D,** and injection well **4R-6D.** Each well's background and other characteristics are discussed for possible association with the interpretations of the pressure derivative plot. Welltest data used are derived fiom pressure fall-off tests which are incorporated in the completion test programs employed by **PNOC-EDC.** The **10** hour pressure fall-off monitoring is usually preceded by injection at relatively higher constant flow rate for around two hours. However injection at different pumprates usually started for about **12** hours (after drilling) before the *start* of constant injection. The tests investigated are all two-rate which were conducted right after drilling or as stated.

Two mechanical pressure instruments (Kuster) are lowered during the tests to ensure correct pressure data are obtained. If both instruments show the same pressure profile then the data is considered to be reliable. Since

Kuster instruments are utilized during the tests, the pressure data recorded *can* be subject to human errors when read fiom the chart records. Some of the raw data contain the Same pressure readings at certain time intervals which indicates that the change with respect to time at **this** point is very small and *cannot* be ascertained by the human eye. Only the middle point of these data are considered in the generation of the derivative plot since the same pressures will give erroneous derivative values.

As injection is likened to discharge with a negative flowrate, pressure fall-off test is conceptually the *same* as pressure build-up tests. In both build-up and fall-off tests, the pressure at late time has a tendency to be constant. This will show as a continuous downward trend in a pressure derivative plot. Hence, careful examination of the data is needed to distinguish this effect fiom other *boundary* responses. *As* in the *case* of build-up tests in a well with infinite-acting response, the effective time (Horner *or* Argawal) could be used to straighten the derivative plot (Home, **1995**). If even with the use of the effective time, the downward trend is still present, then this may be a boundary effect. In which *case,* interpretation of the plot as well as geological prognosis *can* be used to identify the type of boundary present.

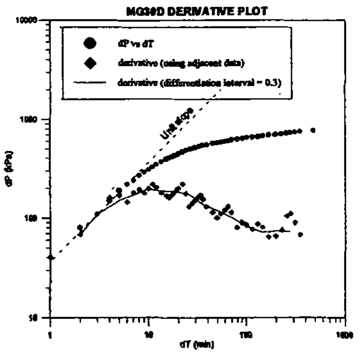
Using equation 2 above, the derivative plots were generated for the selected wells. For smoothing of the curve, **different** differentiation intervals ranging fiom 0.2 to 0.5 were used. The results were interpreted and correlated with each well's characteristics as observed during other tests (e.g. discharge, injectivity, permeability). **Interpretations** however, mainly focused *on* the use the pressure derivative plot as a diagnostic plot *on* the possible type of controlling factors *on* the wells' pressure transient response to the tests.

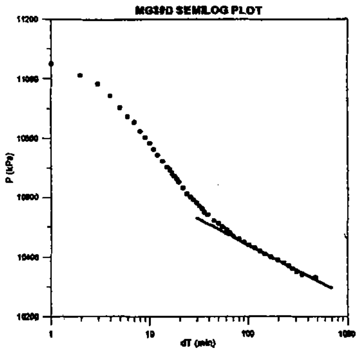
5.0 RESULTS AND INTERPRETATIONS

5.1 Well MG-30D – an example of a well with wellbore storage and skin effect

At early time, during pressure transient tests, the response seen may not be the true response of the **reservoir** but may be that of the wellbore itself. Fluid expansion or a falling liquid level in the wellbore influence the transient effects at the *start* of the test (Home, **1995**). This wellbore storage effect is characterized by a unit slope in the log-log plot. The transition time between this initial response to that of the reservoir response has been shown to be 1 ½ log cycle, hence, the 1 ½ log cycle rule. *Also,* drilling mud or cement may have created a region surrounding the wellbore which causes additional pressure *drop.* This is termed as the "skin" effect". Quantifying the skin effect will give positive values for a damaged well and negative values for undamaged or stimulated well. In the **semi-log** plot, no definite shape could characterize the two effects. However, in the pressure derivative plot, the wellbore storage influence is still reflected as a unit slope with a "hump" representing a positive skin. The amplitude of the response is dependent on the skin value. Normally, the hump feature is not seen in a stimulated well.

Well MG-30D was one of the last wells drilled in Mahanagdong *Sector* of **LGPP.** Completion and discharge test results indicated an average permeability. Because of the need to meet the power requirement with the power station commissioning date fast approaching, acidizing of the well was conducted. The post-acidizing tests yielded excellent improvement fiom an injectivity index *of* around 23 Vs-Mpa to 138 Vs-Mpa. With respect to its discharge output, the mass flowrate increased fiom 30 to 100kg/s at fully *open* condition reaching **15 MWe.**

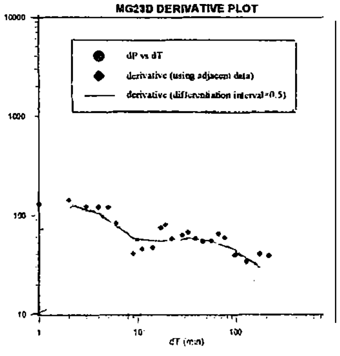


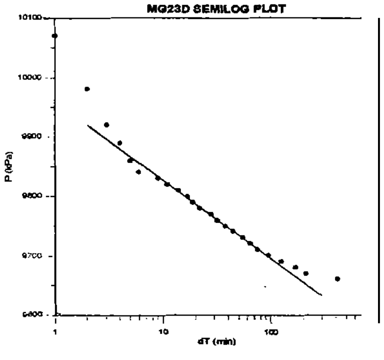


The characteristic unit slope of the wellbore storage effect can be seen in the log-log plot as well as the derivative plot in the early time of the test. About 1 ½ log cycles away, an infinite acting response reflected as horizontal line on the derivative plot can be deduced as the real reservoir response which started at about 130 minutes. The identification of the infinite acting response in the derivative plot could aid in identifying the beginning of the correct straight line slope in the semi-log plot in calculating for the reservoir parameters. In some occasions, identification of the correct straight line slope may not be very clear in a semi-log plot, hence, the derivative plot could aid in getting better or more accurate calculations. The "hump" after the unit slope is indicative of a damaged well which can be associated with the well's increase in output parameters after acidizing.

5.2 Well MG-23D – an example of a well with infinite-acting flow

Completion test results indicated a high permeability well with an injectivity index of around 114 l/s-MPa. The mass flowrate during discharge reached 181.3 kg/s with the well fully open with fluid enthalpy of 1300 kJ/kg. The power output of this well is above 20 MWe, without significant pressure drawdown or change in discharge enthalpy noted after one month discharge. This indicates that the well is supplied by a very large and permeable reservoir.



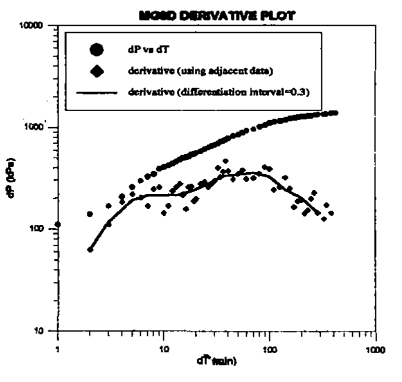


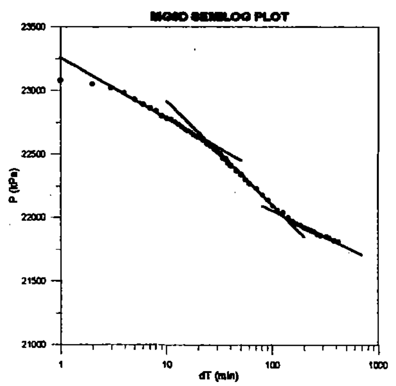
The infinite acting response is seen as the flat region starting less than ten minutes after the ***start*** of the test to about 80 minutes. However, the late time downward trend in the derivative plot is possibly due to the fall-off effect, that is, the tendency of the pressure to be constant at late time in this type of test.

The completion and discharge analyses of the well indicated a very high permeability well. ***An*** infinite acting response is more or less expected in the type and length of test employed. The stabilization of pressure at late time especially in high permeability well will be observed at relatively early time than low permeability well as the pressure will tend to stabilize earlier. This can be detected as a downward trend in the pressure derivative plot. In this case, the injection time may not be long enough to have encountered boundaries, hence, none can be expected in the fall-off test; none are seen. The infinite acting response can be seen as a straight line in a semi-log plot.

5.3 Well MG-8D – an example of a well with a sealing/leaky fault boundary

This well is located at the western boundary of Mahanagdong sector of LGPP. Almost no permeability was encountered during drilling. The low permeability of the well was confirmed during the early part of the completion tests. Pumping at 16 BPM, the wellhead pressure (WHP) reached a high value of around 5.2 MPag. The well developed a WHP of almost 10 MPag due to CO_2 after shutting the well for 15 days. The well was bled to zero but after 2-3 days WHP rose back to near 10 MPag. The well was opened for discharge without stimulation, but the discharge did not sustain and ceased after 17 hours. Pressure drawdown of about 14 MPa at the bottom was measured after the test. Acidizing and hydraulic fracturing jobs were conducted to enhance the permeability of the well but post stimulation surveys and discharge tests yielded no improvement.





Early time portion of the plot shows no sign of a “hump”. This is **because** the data analyzed were after acidizing which means the well is already stimulated and not damaged.

The part containing two flat regions can be related to a model with an impermeable fault boundary. The late time response showed a downward trend after the second flat region which may be the effect of the tendency of the pressure to be constant. However, with the length of the test and its seemingly impermeable behavior during pumping, it is a possible that this might be an effect of a leaky fault. The permeability might be so small that the initial response looked like an impermeable boundary. The third stabilization is not obvious (there’s a slight trace of infinite acting behavior or a third horizontal line in the derivative plot) as it might have been masked by the fall-off effect or the tendency of the pressures to be constant at late time.

The diagnosis fiom the derivative plot can explain the well discharge characteristics. The discharge lasts less than a day due to the massive pressure drawdown encountered, which could indicate that the mass recharge is slow. The pressure after shutting the well for 2-3 days was almost 10 MPag. This is an indication that the source is at a high pressure but is controlled by an almost impermeable matrix which is of a leaky fault type (see illustration). During the discharge, depletion of the fluids near the wellbore occurs because the discharged mass flowate is higher than the recharge. The fluid as it turns two-phase tends to be depleted. The surrounding permeability might be associated with a small storage volume which could be depleted in less than a day at the rate of discharge and can be refilled in 2-3 days by the source of recharge.

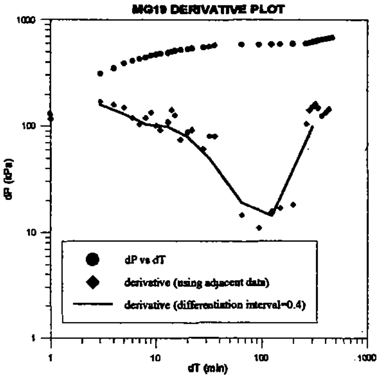
This “leaky fault” behavior can be seen as two parallel straight lines in a semi-log plot just like a dual-porosity system, but an increase in slope during the transition period is observed. The transition period in this case can be seen as a doubling in slope which is a characteristic of an impermeable fault boundary but as pointed out it might be just because of very low permeability.

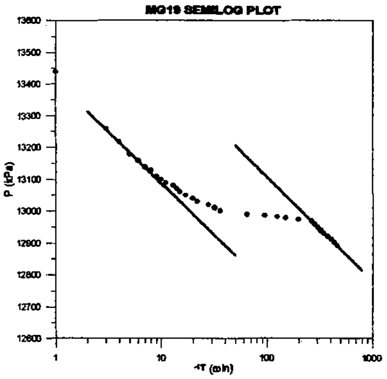
5.4 Well MG-19 – an example of a well with dual porosity behavior

Geothermal reservoirs are quite complex. and naturally fractured rocks mostly control the permeability. Because of the nature of these rocks, a dual porosity behavior is often encountered in the geothermal wells. In this model, the reservoir is seen to be of two distinct media. The fissures, which are of low storativity but high permeability and the matrix, with high storativity but with low permeability.

The initial response or at early time of the test, the fissures’ influence is detected and then the matrix which flows to the well through the fissures is seen last. The transition between the two is an inflection in the pressure response which can be observed in the derivative plot as a minimum value (“Valley”). The overall response would be of a homogeneous medium with the total storativity but with the permeability of the fissures. In a semi-log plot this can be seen as two parallel straight lines.

Based on the results of the completion tests, well MG-19 is of average permeability with the discharge output of about 10 MWe. It is located along the outflow path but not at the margins of the field. Its pressure response to the fill-off tests conducted can be classified into a reservoir model which is of the dual porosity type.





The derivative plot shows a distinct minimum value on the derivative curve. This can be related to the transition zone between the primary and secondary media. The depth of the transition valley is a function of the storativity ratio between the two media (Bourdet et al 1983).

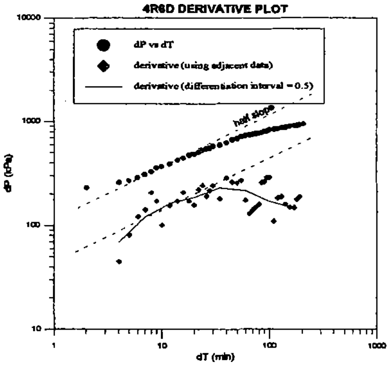
The derivative values show a flattening of end data which was not shown by the curve fit. This can be explained by the limitation of the differentiation interval technique where it tends to give a shorter curve as the data tends to " run out" at the last interval. The semi-log plot shows two parallel straight lines, as expected for dual porosity behavior.

5.5 Well 4R6D – an example of a well with an infinite conductivity fracture

Geothermal wells often encounter fractures during drilling especially directional drilling. Since permeability of these fractures is usually higher than the surrounding formation, influences on the pressure responses are significant.

Highly conductive or infinite conductivity fractures are characterized by a linear response at early time of the test. This can be seen as a straight line with ½ slope in a log-log plot. Likewise, in a pressure derivative plot, the ½ slope still exists with the derivative values half that of the pressure values or are separated by a fictor of 2.

Drilled in Upper Mahiao sector of LGPP for utilization as a injection well, 4R-6D completion test results yielded parameters which are that of a moderate permeability well with an injection capacity of about 30 kg/s.



Data during the first two minutes may be affected by the unstable second flowate (two-rate PFO test). Though the pressure derivative plot shows quite a lot of scatter, there exists a ½ slope straight line which can also be seen in the log-log plot. The derivative values are half that of the pressure values which is indicative of an infinite conductivity fiacture characteristic.

After the half-slope, an infinite acting response is evident. End time distortion might be because of the last interval problem as data tends to "run out". Test might also be too short to identify the end time effect.

6.0 CONCLUSIONS

Analysis of the pressure transient responses using the pressure derivative method has been shown to be applicable to geothermal wells. Though scatter in the pressure derivative values are evident, nevertheless, smoothing of the curve gives quite good agreement with established types of effects whether infinite-acting, dual porosity or with boundary effects. Pressures during fall-off tests tends to stabilize early especially in high permeability wells. This can be seen as a downward trend in the pressure derivative plot at late time of the test. In addition, the method of differentiation interval may sometimes obscure the real boundary effects as it can give problems at end time as data tend to "run out". Therefore, the end time region of the derivative plot needs to be interpreted with care. Two rate PFO test has tendency to give a noisy or scattered pressure derivative plots as slight changes in flowate may cause significant effects on the pressure responses.

A more in-depth study can also be undertaken to further investigate the applicability of the pressure derivative technique not only in the diagnosis for the boundary effects but also of the corresponding reservoir parameter calculations. Currently available softwares could be utilized to get more suitable fits for the plots.

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