A Review of Static Formation Temperature Test Evaluation Methods

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ABSTRACT

Five methods for estimating static formation temperatures are tested using eight different data sets. Each method differs by using linear, cylindrical or rectangular source solutions to the thermal diffusion equation. Analysis carried out using both linear and non-linear least-squares regression to correlate temperature build up and time. The calculated formation temperatures are compared with reported values of true formation temperatures and methods are evaluated. The comparison shows that the Brennand method is the lead choice of the five methods tested. This is in agreement with recommendations by Sarmiento (2011) and Horne (2016). This method is easy to implement and requires less shut-in time.

1. INTRODUCTION

The static formation temperature (SFT) of geothermal reservoirs is an important factor to know early in the exploration or production phase of development. Accurate knowledge of the reservoir SFT is required for well completion, for designing casing plans, to know the heat gradient, and to evaluate the potential heat content of a reservoir. Knowledge of the undisturbed or SFT of a geothermal reservoir is not known until wells are drilled, and bottom hole temperatures (BHT) that are recorded while drilling do not give accurate values of the SFT due to the circulation of drilling fluids. The temperature measurements made in a well are used to infer details about the reservoir as a whole, and can substantially reduce uncertainty about the heat content which can affect the viability of a project (Sarimiento, 2011). A number of factors introduced in the drilling process affect the SFT (Kutasov & Eppelbaum, 2005; Chiang & Chung, 1979; Roux, 1979), including but not limited to :

- The thermal properties of the drilling fluids.
- The thermal diffusivity of the reservoir.
- The difference between reservoir and drilling fluid temperatures
- The drilling technology used
- The amount of time drilling fluids have been circulated in a well.

The drilling process introduces fluids at a lower temperature than the formation, which reduces local temperatures that are measured during geophysical well logging. When drilling fluid circulation is stopped and the drill string removed, there will be a period of time over which recorded temperatures will increase prior to reaching equilibrium. Temperature logging requires the cessation of drilling, the removal of the drill string, and time, all of which increases the cost of completing a well. It is therefore important to take measurements and estimate the SFT in a timely manner to reduce these costs (Hyodo & Takasugi, 1995; Brennand 1984).

After drilling stops, formation temperatures may take months to reach equilibrium (Roux, 1979) and it not possible for the drilling rig to wait for that long due to the high cost of the drilling rig stand by time. Therefore, a number of analytical methods were developed to interpolate the undisturbed formation temperature of the reservoir using temperature measurements made over much shorter period. This test is known as the static formation temperature test (SFTT) and it is one of the few well tests that are carried during drilling.

In this work, we will discuss the analytical methods used to interpret the SFTT data, test these methods using published data and then evaluate and discuss these results in terms of its success, applicability, and accuracy.

2 METHOD DESCRIPTIONS

Each of the methods tested are outlined in this section, including the main formulae utilized, lists of parameters that are required, and the procedure for evaluation. The naming convention of the methods used here is given as named by authors in the original publication, as used in the literature, to illustrate the method technique. An explanation of each method along with the main formulae and the conditions imposed on them are presented below, with full derivations available in the original sources.

The selection of methods provides a range of model types and analysis methods; linear/cylindrical/rectangular models, linear or curve-fitting methods, and modelling requirements. Other methods exist that are omitted from this review, including the hyperbola method of Kabir and Signore (1997), and flow-test methods as developed by Kashikar and Arnold (1991).

2.1 Horner Method; Dowdle & Cobb (1975)

The Horner SFTT method is derived by Fertl & Timko in 1972 based on the apparent similarity between pressure and temperature diffusivity equations. However, Dowdle and Cobb (1975) note that, the two equations are not completely analogous and attempt to derive the conditions where the Horner method can be used.

The method is based on a linear source solution to the thermal diffusion equation, and assumes a reservoir of infinite radius, conductive heat flow only, and a constant linear heat source with constant heat withdrawal rate (Roux, 1979).

The thermal diffusion equation that describes this is:

$$\frac{d^2T}{dt^2} + \left(\frac{1}{r}\right)\left(\frac{\partial T}{\partial t}\right) = \left(\frac{\rho c_p}{k}\right)\left(\frac{\partial T}{\partial t}\right) \qquad (1)$$

where T is Temperature (°C), r the well radius (m), c_p the specific heat capacity (J/kg.K), ρ the density (kg/m³), and k the thermal conductivity (W/m.K). The increase in temperature is shown to be described by equation (2):

$$T(\Delta t) = T_i - m\, log\left(\frac{t_c + \Delta t}{\Delta t}\right) \qquad (2)$$

where $T(\Delta t)$ is the temperature at shut-in time Δt (°C), T_i the SFT (°C), m the gradient per log cycle (°C), t_c the drilling fluid circulation time (hours or minutes), and Δt the time after shut-in that the temperature was recorded. The initial and boundary conditions for these equations are:

$$T = T_i, \qquad t_c = 0 \ \forall\, r$$
$$T = T_i, \qquad as\ r \to \infty \ \forall\, t$$
$$T = T_c, \qquad at\ r = r_w \ \forall\, t_c$$

The final condition above that is required for the completeness of equation (2) indicates that the temperature in the well is equal to the circulating drilling fluid temperature (T_c), which may be incorrect due to geothermal gradients that are active in the well and throughout the reservoir. It is observed that if circulation times are short then equation (2) may be sufficiently accurate for estimating the SFT (Dowdle and Cobb, 1975), i.e. when treating the temperature of fluids in the well bore as a constant, especially when there is a large recovery time (Δt) (Hyodo and Takasugi, 1995). The condition that drilling fluid circulation times are short is not always possible in the field, and many note that the Horner method yields formation temperatures that are lower than actual values (Roux, 1979; Kutasov & Eppelbaum, 2005; Brennand, 1984). Kutasov & Eppelbaum (2005) also note that for small Δt, the borehole may not be considered a linear heat source. Even with these points considered, the Horner method has gained some popularity due to its simplicity (Kabir & Signore, 1997); it can be evaluated using pen and paper in the field.

2.1.1 Requirements for evaluation

Evaluating the SFTT using the Horner method is simple when compared to other methods, and requires knowledge of only three parameters:

1. t_c, the drilling fluid circulation time
2. Δt, the elapsed shut-in time
3. $T(\Delta t)$, the temperature at time Δt

2.1.2 Procedure for evaluation

The evaluation of T_i is made as follows:

1. Temperatures are recorded at time intervals after drilling fluid circulation has ceased
2. These temperatures are then plotted against Horner time $\left[log\left(\frac{t_c + \Delta t}{\Delta t}\right)\right]$ on a semi-log plot.
3. The temperature data points that appear as linear are then chosen, and a linear fit is made.
4. The intersection of the linear fit and $log\left(\frac{t_c + \Delta t}{\Delta t}\right) = 1$ represents the SFT.

2.2 Improved Horner Method; Kutasov & Eppelbaum (2005)

Kutasov and Eppelbaum (2005) develop a method of estimating the SFT by altering the model used to derive their equations from the linear source solution of the diffusivity equation (1) to a cylindrical solution with constant heat flow. The initial conditions required to solve the thermal diffusion equation (1) are given:

$$T(t_c = 0, r) = T_i$$

$$\left(r\frac{\partial T}{\partial r}\right)_{r_w} = -\frac{q}{2\pi k}$$

$$T(t, r_{\to \infty}) \to T_i$$

Earlier work by Kutasov (2003) provides a solution under these conditions, and uses tabulated results of the integral above to find values for constants a and c in equation (3) below. The main formula derived looks very similar to equation (2) from the Horner method, hence their naming it the 'Improved Horner Method':

$$T(r_w, t_s) = T_i + m\, log(X_D) \qquad (3)$$

With the following definitions:

$$X_D =$$

$$\frac{1 + \left(c - \dfrac{1}{a + \sqrt{Gt_{cD} + t_{sD}}}\right)\sqrt{Gt_{cD} + t_{sD}}}{1 + \left(c - \dfrac{1}{a + \sqrt{t_{sD}}}\right)\sqrt{t_{sD}}} \quad (Dimensionless)$$

$$m = \frac{q}{2\pi k} \quad (°C)$$

$$t_{sD} = \frac{\alpha}{r_w^2}\Delta t \ (Dimensionless)$$

$$t_{cD} = \frac{\alpha}{r_w^2}t_c \quad (Dimensionless)$$

$$\alpha = \frac{k}{\rho c_p} \quad (m^2/time)$$

$$a = 2.7010505$$

$$c = 1.4986055$$

Where q is the heat flow rate, k the conductivity, ρ the density, and c_p the heat capacity.

2.2.1 Requirements for evaluation

To evaluate the SFTT data using the Improved Horner Method requires knowledge of the thermal properties of the formation. We note that this information many not be clearly defined at the time of drilling, and as such estimates will be required. The implementation of this method for the purposes of this review utilized an algorithm that does not explicitly require these parameters to be known, but can return their values for cross-checking. The requirements for evaluation used here are thus simplified from the original publication.

1. r_w, the well radius
2. α, the thermal diffusivity
3. t_c, the circulation time
4. Δt, the shut-in time
5. $T(\Delta t)$, the temperature at time Δt

2.2.2 Procedure for evaluation

1. Temperatures are recorded at time intervals after shut-in
2. These temperatures are then plotted against time on a semi-log plot
3. A curve is fit to the data points using equation (3)
4. The model is evaluated and the parameter T_i is the SFT

2.3 Brennand method (1984)

Brennand (1984) developed a new method for estimation of static formation temperatures. The model utilizes dimensionless variables t_{sD} and t_{cD} as in the Improved Horner method above, and introduces dimensionless temperature as:

$$\theta_D = \frac{T_i - T_{\Delta t}}{T_i - T_c}$$

Where T_c is the drilling fluid circulation temperature (°C). A number of conditions are imposed when solving the diffusion equation (1), which is then transformed into Laplace space, and linear approximations of t made to yield the final solution:

$$T(r_w, t) = T_i - m \, log\left(\frac{1}{\Delta t + p \, (t_c)}\right) \qquad (4)$$

Where $p = 0.785$ is a constant empirically derived from field test data Brennand (1984). Using the gradient over one log cycle (m), and the difference between circulation temperature and formation temperature calculated ($T_i - T_c$), one is then able to calculate the conductivity of the formation as follows:

$$m = \lambda(T_i - T_c)n \qquad (°C) \qquad (5)$$

With $\lambda = 6.28$ a constant also produced by matching data Brennand (1984), and

$$n = \frac{\rho c_p}{k} = \frac{1}{\alpha} \quad (hr/m^2) \qquad (6)$$

This provides a way of checking the viability of the estimates obtained, as one is able to back calculate and cross-reference the thermal conductivity ($n = 1/\alpha$) with evidence provided by rock cuttings, cores or other means as long at T_c is known.

Brennand (1984) noted that the method has a tendency to underestimate the SFTT due to data points lying above the linear fit at smaller Δt, skewing the results to the lower rather than higher side of temperature ranges, and that the error in the tests made in the original literature are usually $\pm 5°C$.

2.3.1 Requirements for evaluation

The knowledge of three parameters is required to evaluate the SFT, with the fourth required if one wishes to check against thermal diffusivity/conductivity. The variable T_c is not known for the data, and is thus not validated.

1. t_c, the circulation time
2. Δt, the shut-in time
3. $T(\Delta t)$, the temperature at time Δt
4. $^*T_c$, the circulation fluid temperature if known

2.3.2 Procedure for evaluation

The evaluation of T_i is made as follows:

1. Temperatures are recorded at time intervals after shut-in.
2. These temperatures are then plotted against Brennand time; $\left(\frac{1}{\Delta t + p \, (t_c)}\right)$
3. A linear fit of data points is made
4. The intersection of the linear fit and $\left(\frac{1}{\Delta t + p \, (t_c)}\right) = 0$ represents the SFTT
5. If the circulation temperature T_c is known, then using equations (5) and (6) one can theoretically calculate thermal properties to ensure/check that the results are realistic.

2.4 Roux method (1979)

Like other methods, Roux's method aims to improve the shortcomings of the original Horner method and its underestimation of undisturbed formation temperatures. This method uses the Horner method value for T_i, though adds a correction factor aimed at increasing the consistently low SFT values that the Horner method returns. The following assumptions are made:

- Cylindrical symmetry with wellbore as the axis

- Heat flow by conduction only

- Thermal rock properties not vary with temperature

- A radially infinite reservoir

- No vertical heat flow in the formation

- The mud cake where present has no effect.

- The formation face temperature is dropped to T_c instantaneously and remains at this value throughout circulation.

- The cumulative radial heat flow at the wellbore is negligible after mud circulation has ceased.

Main equation:

$$T = T_{i(H)} + m(T_{DB})(t_{pd}) \quad (°C) \qquad (7)$$

Where

$$t_{pd} = \left(\frac{k}{\rho c_p r_w^2}\right)t_c \quad (Dimensionless) \qquad (8)$$

$$T_{DB} = 0.03 \, (\Theta^{1.678})(t_{pD}^{-0.373}) \quad (Dimensionless) \qquad (9)$$

Where Θ is the average Horner time calculated.

2.4.1 Requirements for evaluation

The correction factor that needs to be applied in order to evaluate the SFTT using the Roux method requires knowledge or estimates of the thermal properties of the formation, though Roux notes that a $\pm 50\%$ error in t_{pd} will result in an error within $10\,°F$ $(5.6\,°C)$. There are also a number of additional parameters that need to be calculated prior to evaluating by the Roux method.

1. t_c, the drilling fluid circulation time
2. Δt, the shut-in time
3. $T(\Delta t)$, the temperature at time Δt
4. t_{pd}, dimensionless time
5. m, the gradient of the linear fit of the Horner plot over one log cycle.
6. Θ, the average Horner time calculated for the linear portion of temperatures recorded and used in the calculation of $T_{i(H)}$

2.4.2 Procedure for evaluation

The evaluation of the SFTT by the Roux method begins in the same way as the Horner method, with additional steps $5 \rightarrow 8$:

5. The gradient m of the linear fit is calculated over one log cycle
6. t_{pd} is calculated using known or estimated thermal properties and equation (8).
7. T_{DB} is then calculated using equation (9)
8. The final temperature is then calculated using (7)

2.5 CFM method; Hyodo & Takasugi (1995)

Hyodo and Takasugi (1979) developed the curve-fitting method (CFM) for SFT evaluation based on Middleton's mathematical models. Middleton's model utilizes a rectangular coordinate approximation of a vertical and cylindrical heat sink to simplify the derivations. They note that this drastically simplifies the full solution, available in the original article. An illustration of models and a possible real scenario used to justify the model is given in Figure 1 below.
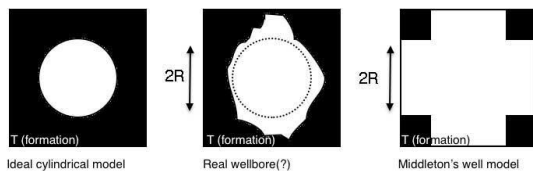
Figure 1: Well bore models (Adapted from Hyodo & Takasugi, 1995).

Main equation:

$$T(\Delta t) = T_0 + (T_i - T_0)\left(erfc\left[\frac{r_w}{\sqrt{4\alpha\Delta t}}\right]\right)^2 \qquad (10)$$

Where the original method uses the following to simplify curve-fitting / inversion to match:

$$\alpha = \frac{k}{\rho c_p} \qquad (m^2/time)$$

The thermal diffusivity α is returned by the inversion and can then be used to check how realistic the results are.

2.5.1 Requirements for evaluation

The CFM method from Hyodo and Takasugi (1995) does not require the circulation time (t_c), though requires knowledge of the initial temperature (T_0) at the time that drilling fluid circulation stopped. The algorithm used in this review did not require this parameter.

1. T_0, the temperature when drilling is stopped, $\Delta t = 0$.
2. Δt, time since drilling fluid circulation stopped
3. $T(\Delta t)$, temperature at time Δt

2.5.2 Procedure for evaluation

1. Temperatures is logged when drilling is stopped at $\Delta t = 0$
2. Temperatures are recorded at times Δt
3. Equation (10) is matched by a non-linear least-squares regression algorithm, returning unknown parameters.

3. EVALUATION

All the the methods detailed in Section 2 are now applied to published data sets from public literature, the source of which is outlined in Table 1as follows:

Table 1: SFTT data sets used in the evaluation of the different methods.

Data Set	Number of data points	Source
D1	n=5	DiPippo (2016)
D2	n=3	Roux (1979)
D3	n=3	Roux (1979)
D4	n=12	Kutasov & Eppelbaum (2005)
D5	n=14	Brennand (1984)
D6	n=10	Grant & Bixley (2011)
D7	n=3	Chang & Chiang (1979)
D8	n=9	Hyodo & Takasugi (1995)

3.1 Software

To analyse the data, each set is imported into Python and data points plotted on a semi-log or standard x-axis as required by the method, before fitting the data with the main formulae used.

Data that needs to be fit linearly is done so using the Python package scipy.stats.linregress, which calculates a linear least-

squares regression for any method or time data series. The package automatically calculates the gradient of the regression line, its intercept, and the standard error of the linear fit.

Data that need to have a curve fit uses scipy.optimize.curve_fit, in conjunction with functions that are defined as per the main equations in the method outlines above. The curve fit package uses non-linear least squares regression to fit the function to the data using defined parameters, and will return any of those in the function that are unknown. The package also attempts to return the optimum parameters to fit the function to the data set, along with errors in the fit.

In each case, the linear or curve that is calculated is extrapolated to n>100 data points inside the x-axis range that the original points defined, and the SFT is then calculated. Finally, each of the methods is then tested for robustness by varying the parameters required to evaluate the SFT, and final outcomes compared.

4. RESULTS

Each of the data is imported into Python, and scripts are written to evaluate each of the methods. The returned values are listed in individual tables for each method with calculated temperature ($°C$) and difference from reported SFT (ΔT). All of the methods produce plots for each data set. However, not all of these plots will be reported in this work.
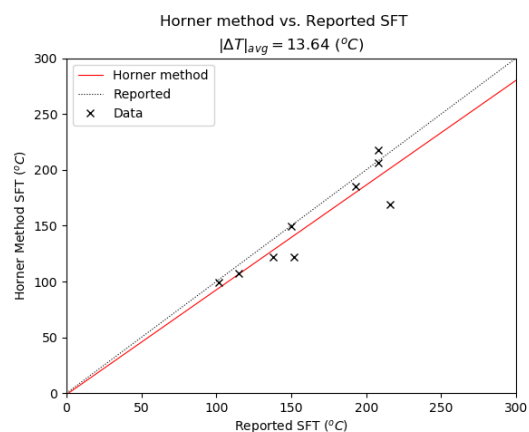
4.1 Horner method

The simplicity of the Horner method makes for speedy evaluation of SFTT for all data sets. The initial results appear in Table 2 below:

Table 2: Horner method results and the deviation from measured data.

Data	Horner ($°C$)	ΔT ($°C$)
D1	206.45	-1.55
D2	185.37	-7.41
D3	107.27	-7.73
D4	99.18	-2.28
D5	217.89	+9.89
D6	121.59	-16.41
D7	149.89	-0.09
D8	168.91	-46.99

There were no issues encountered by using this method, although the results do skew low, as has been mentioned already. A cross-plot of reported actual vs. calculated temperatures is in Figure 2 below, along with a linear fit of the calculated data points to reveal any trends. There is an average absolute difference between reported vs. calculated temperatures of $13.64°C$, which increases as a function of temperature. This indicates that the Horner Method may not only return low values, but that it may also be unsuitable for high temperature geothermal systems.

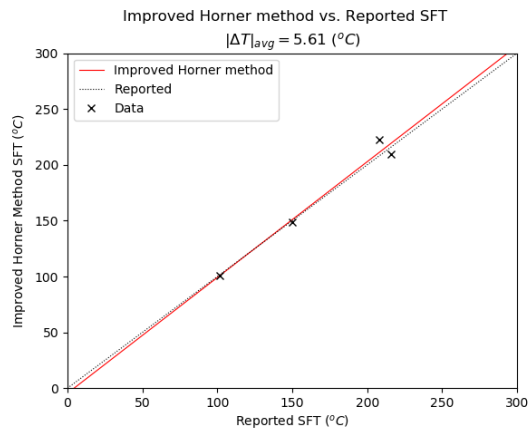**Figure 2: Cross-plot of Horner method vs reported temperatures.**

4.2 Improved Horner Method

The Improved Horner method by Kutasov and Eppelbaum (2005) is one of the curve-fitting methods used in this review, and did not initially work for all data sets using the scipy.optimize.curve_fit package. This is may be due to the lack of data points in sets D2 and D3 (both with n = 3), though for set D7 with the same number of measurements yielded a result that is very close to the reported temperature. For the method to function with D1 an unrealistic estimate of thermal parameters obtained later via the CFM method was required,

Table 3: Improved Horner Method results and the deviation from measured data.

Data	Improved Horner ($°C$)	ΔT ($°C$)
D1	222.49	14.49
D2	-	-
D3	-	-
D4	101.08	-0.38
D5	-	-
D6	-	-
D7	148.76	-1.22
D8	205	-10.89

The cross-plot below shows very little diversion from the reported values, with an average absolute difference between reported vs. calculated temperatures of $5.61°C$, however as mentioned above an unlikely parameter estimate was required in order for the method to work with data set D1. There is also very little data used in the linear regression analysis, which may assist in decreasing the reported difference.

Figure 3: Cross-plot of Improved Horner method vs. reported temperatures.

4.3 Brennand method

In the development of the method, Brennand (1984) noted that the results tend to be on the lower side of the real temperatures. For the values obtained in this test there are also over estimates. There is one anomalous value for D8, which is considerably lower than the reported SFT.

Table 4: Brennand method results and the deviation from measured data.

Data	Brennand (°C)	ΔT (°C)
D1	208.29	0.29
D2	201.28	8.50
D3	110.47	-4.53
D4	100.54	-0.92
D5	206.72	-1.28
D6	146.11	8.11
D7	167.29	17.31
D8	172.95	-42.95

The Brennand method reveals only minor differences from reported temperatures, with an average absolute difference between reported vs. calculated temperatures of $9.98°C$, and an even distribution above and below the line of reported temperatures with the exception of D8 data set:
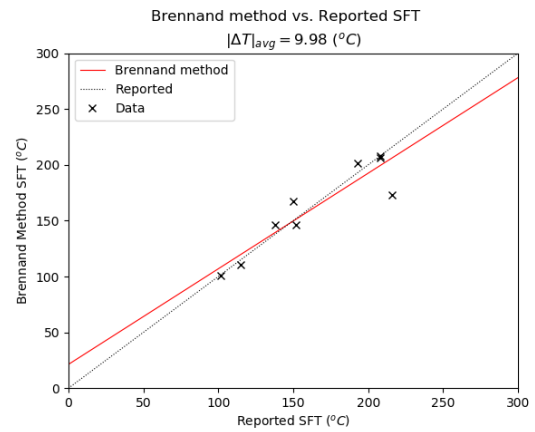
Figure 4.1: Cross-plot of Brennand method vs. reported temperatures

With the anomalous D8 removed, the linear regression of all data points is a very close match to the reported temperatures, with a reduced average absolute difference of $4.22°C$:
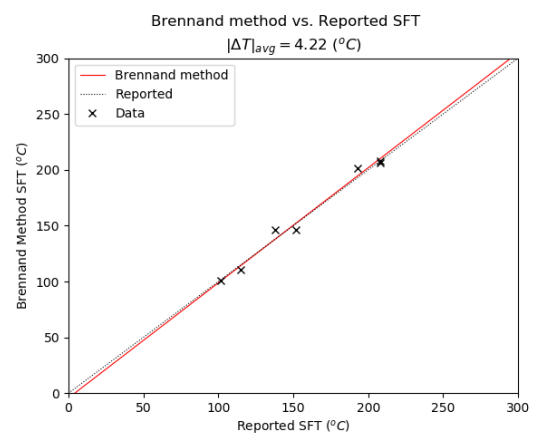
Figure 4.2: Cross-plot of Brennand method with D8 removed vs. reported temperatures.
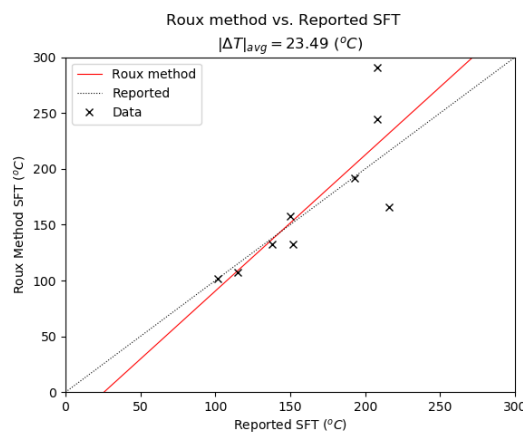
4.4 Roux method

The Roux Method calculates the Horner temperature ($T_{i(H)}$), then adds a correction that is calculated using the gradient of the linear fit from the original calculations. There are some results that are $\pm10°C$ of the reported temperatures, though others that are calculated at more than $30°C$, and up to $80°C$ above the reported values (Table 5).

Table 5: Roux method results and the deviation from measured data.

Data	Roux (°C)	ΔT (°C)
D1	290.43	82.42
D2	191.88	-0.90
D3	110.52	-4.48
D4	101.57	0.11
D5	244.45	36.45
D6	132.08	-5.92
D7	157.85	7.87
D8	165.64	-50.26

The cross-plot below displays a deviation from the reported temperatures, especially as these increase beyond $200°C$, with an average absolute difference between reported vs. calculated temperatures of $23.49°C$.

Figure 5: Cross-plot of Roux method vs. reported temperatures

As this method requires knowledge, or estimates of thermal diffusivity, the script that was then altered to change the thermal properties as provided by Roux in the original paper for D2 and D3. The thermal properties as provided in Equation (8) are varied by 100% in order to see the effect as follows:

$$t_{pD} = 2 \times \left(\frac{k}{\rho c_p r_w^2} \right) t_c$$

With the following results given in Table 6:

Table 6: The effect of changing the rock thermal properties using Roux method.

Roux data	New (°C)	Old (°C)	ΔT (°C)
D2	190.40	191.88	-1.44
D3	109.78	110.52	-0.74

The result is very minimal, with variation less than $2°C$ for

both data, indicating that the thermal properties may not need to be known accurately for a fair estimate of SFT.
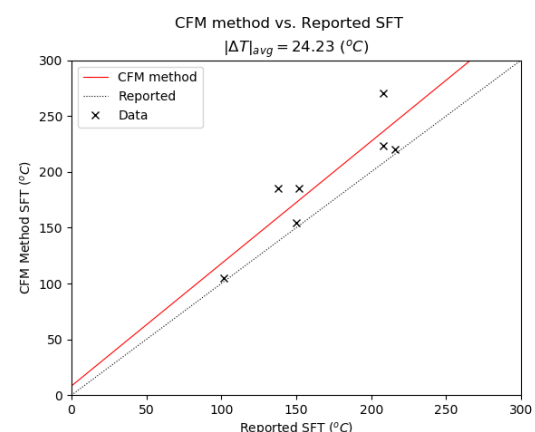
4.5 CFM method

The CFM method of Hyodo and Takasugi (1995) fits the error function to the data, and approaches both the circulation and formation temperatures asymptotically. This illustrates a realistic temperature build up without the use of one-sided semi-log plots, and from $\Delta T = 0$ to $\Delta T = \infty$. The use of scipy.optimize.curve_fit in the processing of data does not require an accurate value for T_0, though in some instances the results are much higher than the reported value. It is also noted that the method failed to produce results for D2 and D3, possibly due to the lack of data points in each set.

Table 7: CFM method results and the deviation from measured data.

Data	CFM (°C)	ΔT (°C)
D1	223.18	15.18
D2	-	-
D3	-	-
D4	105.05	3.59
D5	270.24	62.24
D6	185.00	47.00
D7	154.71	4.73
D8	219.78	3.88

We see a diversion from the reported temperatures in the cross-plot below, noting that all values are above those reported. The average absolute difference between reported vs. calculated temperatures is $24.23°C$, increasing with reported temperatures.

Figure 6: Cross-plot of CFM method vs. reported temperatures

As the starting temperatures were not known for most sets of data, these were estimated at a value below the first temperature recording, though this value did not have any effect on the calculated values. The method returns a values of for the thermal diffusivity $\alpha = \frac{k}{\rho c_p}$ that can be checked to

validate the calculations. Kashikir and Arnold (1991) noted that the typical values for α for a well radius of $r_w = 0.10795\ m$ are within the range $[0.003163, 0.004661]\ m^2/hr$. When these values are calculated for the data, this range matches results for only three of the five sets that the method was successful with (D2, D3, & D7). As mentioned in section 4.2, the value for D1 was not physically plausible at $\alpha = 0.000278\ m^2/hr$, though this value was required in order for the Improved Horner method to work for that set.

4.6 Effect of variation of t_c on results

To further test the robustness of these methods, the circulation time t_c was varied by ±20% to see the effect. This is has on each of the data sets that requires t_c as input and had success in the original calculations for all eight sets of data, with the results in Table 8 below:

Table 8: Testing the effect of varying the circulation time t_c by ±20%.

Method	t_c +20% ΔT_{avg} (°C)	ΔT_{avg} (%)	t_c −20% ΔT_{avg} (°C)	ΔT_{avg} (%)
Horner	-1.55	-1.09	1.42	0.99
Brennand	-5.03	-3.30	4.91	3.23
Roux	-2.78	-1.47	2.88	1.55

Table 8 show that the variation in t_c produces only minor changes to the final temperatures calculated, with the maximum average change of $5.03°C$ or -3.3% for the Brennand method. This indicates that when using these three methods, that estimates within twenty percent of actual circulation time will achieve values for T_i within $5°C$ of the calculated predictions.

5 DISCUSSION

The method used to evaluate the SFTT data of an unproven reservoir or for new formations needs to be practical, quick, easy to implement, and accurate. This review has tested five methods using eight data sets and found that not all the methods tested meet these criteria.

The method that best meets these criteria is the Brennand (1984) method. The method requires only three parameters to calculate the SFT, and a linear fit can be made of all data points without the need to pick linear data in a semi-log plot. The recovery time (Δt) required to produce these results were as low as 11.82 hours, making the method very fast and cost efficient. The temperatures calculated using this method produced an average absolute difference of $9.98°C$ from the reported SFT of all data sets. With one anomalous result removed this decreased to $4.22°C$, though the reason for the anomaly remains unclear.

Other methods consistently over estimated (CFM) or under estimated (Horner) the SFT, or diverged as reported temperature increased. The linear methods of Horner and Brennand (1984) prove to be the easier to applied, although the curve-fitting methods can readily be implement with free and open-source programming languages such as Python as done in this work.

The Improved Horner method of Kutasov and Eppelbaum (2005) is one of the curve-fitting methods that shows promise, with an average absolute difference between calculated and reported SFT of $5.61°C$. However, it requires knowledge of multiple parameters that are not always readily available in the field. The Python script used for this method does not need all of these parameters, but the method was initially successful for only three of the eight data sets.

6 CONCLUSION

This review of static formation temperature testing methods has revealed that the Brennand (1984) method is the lead choice of the five tested methods. This is in agreement with recommendations by Sarmiento (2011) and Horn (2016). It is easy to calculate in the field by hand, or by computer, and requires little shut-in time.

By using Python to test the methods, the need for some parameters that are called for in original publications is not required, though further development of the script could be more successful and reveal more information with greater statistical analysis.

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