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Geothermal Investigations in Permafrost Regions—The Duration of Temperature Monitoring after Wellbores Shut-In

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ABSTRACT

The most important data on the thermal regime of the Earth's interior come from temperature measurements in deep boreholes. The drilling process greatly alters the temperature field of formations surrounding the wellbore. In permafrost regions, due to thawing of the formation surrounding the wellbore during drilling, representative data can be obtained only by repeated observations over a long period of time (up to 10 years). Usually a number of temperature logs (3 - 10) are taken after the well's shut-in. Significant expenses (manpower, transportation) are required to monitor the temperature regime of deep wells. In this paper we show that in most of the cases (when the time of refreezing formations is less than the shut-in time) two temperature logs are sufficient to predict formations temperatures during shut-in, to determine the geothermal gradients, and to evaluate the thickness of the permafrost zone. Thus the cost of monitoring the temperature regime of deep wells after shut-in can be drastically reduced. A simple method to process field data (for the well sections below and above the permafrost base) is presented. Temperature logs conducted in two wells were used to demonstrate utilization of this method.

Keywords: Permafrost; Formation Temperature; Shut-In Temperature; Deep Wells; Geothermal

1. Introduction

Temperature logs are commonly used to determine the permafrost temperature and thickness. When wells are drilled through permafrost, the natural temperature field of the formations (in the vicinity of the borehole) is disturbed and the frozen rocks thaw for some distances from the borehole axis. To determine the static temperature of the formation and permafrost thickness, one must wait for some period after completion of drilling before making geothermal measurements. This is so-called restoration time, after which the difference between the temperature of the formation and that of the fluid is less than the needed measurement accuracy. The presence of permafrost has a marked effect on the time required for the near-well-bore formations to recover their static temperatures. The duration of the refreezing of the layer thawed during drilling is very dependent on the natural temperature of formation; therefore, the rocks at the bottom of the permafrost refreeze very slowly. A lengthy restoration period of up to ten years or more is required to determine the temperature and thickness of permafrost with sufficient accuracy [1-6].

Earlier we suggested a "two point method" [7] which permits one to determine the permafrost thickness from short term (in comparison with the time required for temperature restoration) downhole temperature logs. The "two point method" of predicting the permafrost thickness is based on determining the geothermal gradient in a uniform layer below the permafrost zone. Only temperature measurements for two depths are needed to determine the geothermal gradient. The position of the permafrost base is predicted by the extrapolation of the static formation temperature-depth curve to 0˚C. It should be noted that here the permafrost base is defined as the 0˚C isotherm. Precise temperature measurements [2,3] taken in 15 deep wells located in Northern Canada (Arctic Islands and Mackenzie Delta) were used to verify the proposed method. Let us assume that at the moment of time $t = t_{ep}$ the phase transitions (water-ice) in formations at a selected depth are completed, *i.e.* the thermally disturbed formation has frozen. In this case at $t > t_{ep}$ the cooling process is similar to that of temperature recovery in sections of the well below the permafrost base. It is well known [8] that the freezing of the wateroc curs in some temperature interval below 0˚C (**Figure 1**). In practice, however, the moment of time $t = t_{ep}$ cannot be determined. Only conducting long-term repetitive temperature observations in deep wells can do this. Earlier we assumed that three shut-in temperatures T_{s1}, T_{s2}, and T_{s3} are measured at a given depth (**Figure 1**). For this case we proposed a method of predicting the formation temperatures [9].

A generalized formula to process field data (for the well sections below and above the permafrost base) was developed. Temperature logs conducted in five wells were used to apply this method [9].

It is demonstrated, by using field examples, that for deep boreholes several methods of predicting the permafrost temperature and its thickness should be applied. Low temperatures (from –15˚C to –5˚C) are typical for upper sections of the well's lithological profile. In this case the refreezing period is short and the empirical formula [10] can be utilized to determine permafrost temperature and geothermal gradient) This is not the case for the lower sections of the wellbore where the surrounding formations are at high temperatures (from –3˚C to –1˚C). Here freezing time is large and only "three point" method is used.

The objective of this paper is to show that in many cases (when the time of refreezing formations is less than the shut-in time) two temperature logs are sufficient to predict formations temperatures during shut-in, to determine the geothermal gradients, and to evaluate the thickness of the permafrost zone.

2. Shut-In Temperatures—Permafrost Zone

In 1959 in their classical paper Lachenbruch and Brewer [10] proposed an empirical formula (Equation (1)) to predict the wellbore temperatures during shut-in.

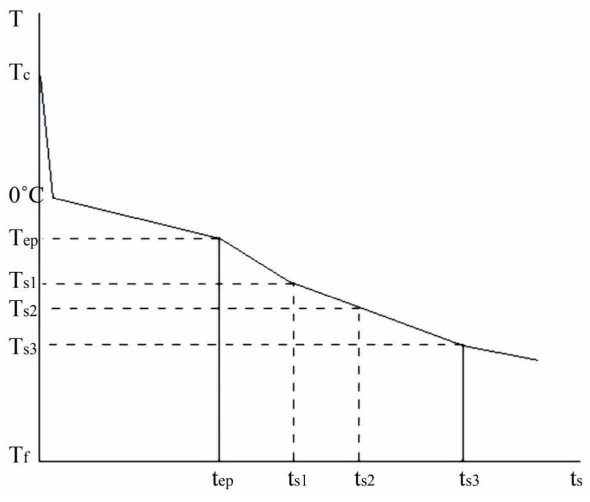

Figure 1. Shut-in temperatures at a given depth (above the permafrost base)-schematic curve.

$$T_s = B\ln\left(1+\frac{t_c}{t_s}\right)+A \qquad (1)$$

where A and B are empirical coefficients determined from field measurements.

It is a reasonable assumption that the value of t_c (the "disturbance" period) is a linear function of the depth (h):

$$t_c = t_t\left(1-\frac{h}{h_t}\right) \qquad (2)$$

Equation (1) was successfully utilized to describe the measured shut-in temperature in the Well 3, Alaska, South Barrow. The well was drilled for 63 days to a total depth of 2900 ft. Temperature measurements to a depth of 595 feet were made during a period of six years after drilling. For the depth of 595 ft the average value of T_f is 6.568˚C (9 temperature logs). The completion of freezingoc curred at temperature of about –0.6˚C and duration of the complete freezeback is approximately 20 days (**Figure 2**).

US Geological Survey conducted extensive temperature measurements in Alaska (US Geological Survey "Site" File-Alaska, Internet [11]). We selected long term temperature surveys in three wells (**Table 1**) to find out if the proposed Equation (6) (see Section 3) can be used when only two temperature logs are available. In **Table 2** the calculated values of A and B for two wells are presented. For the well Drew Point No.1 we used the values of T_s measured in the first two temperature logs (t_{s1} = 186 days t_{s2} = 547days) to determine empirical coefficients A and B. After this we calculated values of T_s for the last temperature log (t_s = 2339 days).

Similarly, for the well East Simpson #1 we used the values of T_s measured in the first two temperature logs (t_{s1} = 155 days, t_{s2} = 520 days) to obtain values of A and B. Values of T_s determined for t_s = 1947 days (the last temperature log) are also presented in **Table 2**. From for mula 1 follows that at $t_s \to \infty \quad T_s \to T_f = A$. Assuming

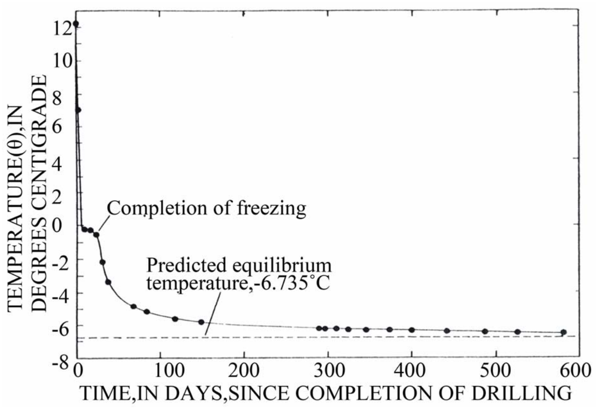

Figure 2. Cooling of South Barrow (Alaska) Well 3, 595-foot depth curve (after [10]).

Table 1. Input data and location of three wells, Alaska, (US Geological Survey “Site” File-Alaska, Internet).

Site code	PBF	DRP	ESN
Site name	Put River N - 1	Drew Point No.1	East Simpson #1
Latitude	70°19'07"N	70°52'47.14"N	70°55'04.01"N
Longitude	148°54'35"W	153°53'59.93"W	154°37'04.75"W
Surface elevation, m	8	5	4
Casing diameter, cm	51	34	34
Hole depth, m	763	640	600
Date of drill start	02 - 09 - 70	13 - 01 - 78	19 - 02 - 79
Drilling time, days	44	60	51
Number of logs	9	6	5
Shut-in time, days	5 - 1071	186 - 2339	155 - 1947

Table 2. Calculated values of *A* and *B* for wells Drew Point #1 and East Simpson #1.

h, m	T_{s1}, ˚C	T_{s2}, ˚C	A, ˚C	T_s, ˚C	B, ˚C
			Drew Point #1		
t_{s1} = 186 days		t_{s2} = 547 days		t_s = 2339 days	
50.29	–7.373	–8.519	–9.192	–8.953	6.990
70.10	–6.925	–8.142	–8.854	–8.574	7.639
100.58	–5.892	–7.283	–8.092	–7.774	9.147
120.40	–5.309	–6.638	–7.408	–7.140	9.022
150.88	–4.466	–5.690	–6.394	–6.148	8.751
170.69	–3.951	–5.076	–5.721	–5.518	8.336
199.64	–3.247	–4.199	–4.741	–4.619	7.455
219.46	–2.698	–3.639	–4.173	–4.032	7.672
			East Simpson #1		
t_{s1} = 155 days		t_{s2} = 520 days		t_s = 1947 days	
21.34	–8.019	–9.180	–9.746	–9.601	6.268
42.67	–7.501	–8.817	–9.456	–9.245	7.332
60.96	–7.145	–8.486	–9.135	–8.917	7.683
79.25	–6.699	–7.999	–8.626	–8.437	7.669
100.58	–6.107	–7.427	–8.060	–7.866	8.069
124.97	–5.538	–6.736	–7.308	–7.155	7.644
149.35	–4.935	–6.063	–6.598	–6.474	7.532
173.74	–4.487	–5.499	–5.977	–5.905	7.092
201.17	–3.538	–4.526	–4.989	–4.980	7.338
225.55	–2.775	–3.963	–4.517	–4.308	9.328
249.94	–2.433	–3.275	–3.666	–3.702	7.019

that at values of t_s = 2339 days and t_s = 1947 days the values of T_s are close to the undisturbed temperature of formations, we can see from **Table 2** that values of T_s and A are in good agreement. In **Tables 3** and **4** we compare the calculated and measured shut-in temperature. The agreement between the values T_{eq} and T_s is very good. US Geological Survey has obtained unique data for the well Put River N - 1 (**Table 5**). Indeed, during two month of well's shut-in five temperature logs were taken. For the well Put River N - 1 we used values of t_{s1} = 34 days and t_{s2} = 66 days to estimate the empirical coefficients A and B.

In **Table 6** we compare the calculated and measured shut-in temperatures for the well Put River N - 1. In this case the difference between the calculated and measured temperatures is significant (**Table 6**). We can conclude that the shut-in times (34 and 66 days) are comparable with the formation freezeback period (**Table 5**). For this case we can use the suggested earlier a three-point method [9] for predicting the formation temperatures (**Table 7**). Here an additional temperature log (t_s = 48 days) was used. From **Table 7** follows that the agreement between calculated and measured temperatures is very good.

3. Temperature Gradient and Estimation of the Permafrost Thickness

In the permafrost areas the rate of heat flow at the frozen-unfrozen interface serves as the main criterion of the steadiness or non-steadiness of the thermal regime.

Let us assume that q_t and q_f are the heat flow density at the phase boundary in the unfrozen and frozen zone, respectively.

$$q_f = \lambda_f G_f$$

$$q_u = \lambda_t G_t$$

where λ is the thermal conductivity of geological formations.

It is clear that the condition $q_f = q_u$ corresponds to a steady regime, the condition $q_f > q_u$ corresponds to a regime of freezing and the condition $q_f < q_u$ corresponds to a thawing regime. In addition, the change in the heat flow density at the permafrost base (frozen-unfrozen interface) is also an indicator of the climate change in the past [1]. When interpreted with the heat conduction theory, these sources can provide important information of patterns of contemporary climate change. For example, precision measurements in oil wells in the Alaskan Arctic indicate a widespread warming (2˚C - 4˚C) at the permafrost surface during the 20th century [6]. Thus to estimate values of q_u and q_f, it is necessary to determine the geothermal gradient and formation conductivity in the frozen and unfrozen sections of the wellbore. Unfortunately at present no methods are available for *in-situ* determination of formation conductivity. Samples of rocks are usually used to estimate formation thermal conductivity. Experimental studies show that $\lambda_f > \lambda_u$. For a given formation the $\lambda_f > \lambda_u$ ratio is mainly a function of total water content [12]. The duration of the refreezing of the layer thawed during drilling is very dependent on the natural temperature of formation; therefore, the rocks at the bottom of the permafrost refreeze very slowly. In practice the position of the permafrost base (h_p) is estimated by extrapolation. Let us examine the restoration of the natural temperature field by the example of the Bakhynay borehole 1-R [1]. The borehole was drilled for 23 months (1956 - 1958) to a depth of 2824 m. Nine temperature logs were performed over a shut-in period of 10 years, but the difference between the temperature of formations and that in the borehole was still greater than the measurement accuracy (0.03˚C - 0.05˚C). After a shut-in period of 1.5 years the thickness of permafrost was estimated as 470 m instead of 650 m. The restoration of the temperature regime was accompanied by formation of practically zero temperature gradient intervals (**Figure 3**). Therefore, if the shut-in time is insufficient, one may incorrectly attribute the zero temperature gradient intervals to some geological-geographical factors, an example of which in this case is the warming effect of the Lena River (the drilling site is the bank of the river). Below we present several examples of determination of the temperature gradients and evaluation of the permafrost thickness. For each section of the well we used a linear regression program to calculate the coefficients in the following Equation

$$T_s = a + gh \tag{3}$$

As can be seen for the section 21.34 - 249.94 m at t_s = 520 days (**Table 8**) practically g = G (0.0267˚C/m). Similarly, for section 451.10 - 600.46 m at t_s = 520 days the values g and G are very close (0.0408 and 0.0415˚C/m). Finally, the position of the permafrost base (h_p) is estimated by extrapolation by using Equation (3) for T_s = 0˚C.

Therefore:

$$0 = a + gh,\ h_p = -\frac{a}{g} \tag{4}$$

As can be seen the values of h_p calculated for both sections of the well are in a good agreement (**Table 8**). In **Table 9** we present an example of data processing for two wells. As can be seen shut-in times of 155 days and 186 days do not enable to estimate the permafrost thickness with a sufficient accuracy. Earlier we developed "two temperature logs method" for determination the undisturbed formation temperatures.

The working formulas are [13, page 171]:

$$T_f = T_{s2} - \gamma\left(T_{s1} - T_{s2}\right) \tag{5}$$

Table 3. Comparison of measured and observed shut-in temperatures, well East Simpson #1.

h, m	A, ˚C	B, ˚C	T_{eq}, ˚C	T_s, ˚C	T_{eq}, ˚C	T_s, ˚C	T_{eq}, ˚C	T_s, ˚C
			at t_s = 865 days		at t_s = 1608 days		at t_s = 1947 days	
21.34	–9.746	6.268	–9.399	9.344	9.557		–9.590	–9.601
42.67	–9.456	7.332	–9.065	–9.060	–9.243	–9.222	–9.280	–9.245
60.96	–9.135	7.683	–8.738	–8.742	–8.919	–8.903	–8.956	–8.917
79.25	–8.626	7.669	–8.243	–8.274	–8.418	–8.440	–8.454	–8.437
100.58	–8.060	8.069	–7.673	–7.692	–7.850		–7.886	–7.866
124.97	–7.308	7.644	–6.959	–6.987	–7.118		–7.151	–7.155
149.35	–6.598	7.532	–6.272	–6.303	–6.421		–6.451	–6.474
173.74	–5.977	7.092	–5.686	–5.734	–5.819		–5.846	–5.905
201.17	–4.989	7.338	–4.707	–4.799	–4.836	–4.940	–4.862	–4.980
225.55	–4.517	9.328	–4.180	–4.137	–4.334	–4.285	–4.366	–4.308
249.94	–3.666	7.019	–3.429	–3.524	–3.537	–3.684	–3.560	–3.702
274.32	–3.066	4.944	–2.910	–3.023	–2.982	–3.126	–2.996	–3.161
301.75	–2.113	5.660	–1.950	–2.085	–2.024		–2.040	–2.247

Table 4. Comparison of measured and observed shut-in temperatures, well Drew Point #1.

h, m	A, ˚C	B, ˚C	T_{eq}, ˚C	T_s, ˚C	T_{eq}, ˚C	T_s, ˚C	T_{eq}, ˚C	T_s, ˚C
			at t_s = 907 days		at t_s = 1259 days		at t_s = 2339 days	
50.29	–9.192	6.990	–8.778	–8.726	–8.892	–8.736	–9.029	–8.953
70.10	–8.854	7.639	–8.417	–8.355	–8.537	–8.292	–8.681	–8.574
100.58	–8.092	9.147	–7.596	–7.470	–7.732	–7.607	–7.896	–7.774
120.40	–7.408	9.022	–6.936	–6.852	–7.066	–6.953	–7.222	–7.140
150.88	–6.394	8.751	–5.962	–5.856	–6.081	–5.961	–6.224	–6.148
170.69	–5.721	8.336	–5.326	–5.233	–5.435	–5.335	–5.566	–5.518
199.64	–4.741	7.455	–4.409	–4.342	–4.500	–4.441	–4.611	–4.619
219.46	–4.173	7.672	–3.847	–3.760	–3.936	–3.860	–4.045	–4.032
243.84	–3.336	5.148	–3.129	–3.043	–3.186	–2.991	–3.255	–3.304

Table 5. Measured shut-in temperatures, well Put River N-1.

h, m	Shut-in time, days					
	5	22	34	48	66	1071
30.48	–0.400	–2.686	–4.793	–6.252	–7.040	–9.167
45.72	–0.300	–2.093	–4.507	–6.012	–6.910	–9.052
60.96	–0.250	–2.941	–4.911	–6.148	–6.950	–8.957
91.44	–0.300	–1.633	–4.101	–5.646	–6.590	–8.771
121.92	–0.210	–0.882	–2.565	–4.781	–6.060	–8.520
152.40	–0.030	–0.976	–1.852	–3.173	–4.760	–8.124
182.88	0.020	–0.757	–1.217	–2.506		–7.619
213.36	0.200	–0.490	–0.805	–1.528		–7.144
243.84	0.380	–0.433	–0.608	–0.950	–2.660	–6.602
274.32	0.640	–0.418	–0.555	–0.823		–6.029
304.80	0.740	–0.379	–0.506	–0.682	–1.150	–5.462
335.28	0.910	–0.325	–0.451	–0.577		–4.935
365.76	1.040	–0.322	–0.452	–0.579	–0.800	–4.454
396.24	1.230	–0.354	–0.505	–0.644	–0.860	–4.039
426.72	1.220	–0.280	–0.415	–0.517	–0.630	–3.453
457.20	1.890	–0.326	–0.395	–0.497		–2.961
487.68	1.480	–0.305	–0.398	–0.476		–2.493
518.16	1.520	–0.264	–0.309	–0.389		–2.006
548.64	1.880	–0.171	–0.316	–0.382		–1.418
579.12	2.540	–0.010	–0.236	–0.309	–360	–0.778
609.60	2.600	3.491	1.918	1.212	0.710	–0.195
640.08	6.830	5.275	4.047	3.254	2.640	0.761
670.56	9.350	5.948	4.749	4.002		1.664
701.04	9.910	7.251	6.022	5.256	4.650	2.885

Table 6. Comparison of measured and observed shut-in temperatures, well Put River N-1.

h, m	A, ˚C	B, ˚C	T_{eq}, ˚C	T_s, ˚C	T_{eq}, ˚C	T_s, ˚C	T_{eq}, ˚C	T_s, ˚C
			at t_s = 117 days		at t_s = 163 days		at t_s = 1071 days	
30.48	–10.728	6.703	–8.407	–7.970	–8.985	–8.716	–10.432	–9.167
45.72	–10.824	7.265	–8.366	–7.900	–8.979	–8.428	–10.511	–9.052
60.96	–10.246	6.251	–8.180	–7.860	–8.698	–8.263	–9.984	–8.957
91.44	–9.262	5.303	–7.595	–7.620	–8.015	–7.965	–9.052	–8.771
121.92	–10.486	8.121	–8.065	–7.250	–8.678	–7.624	–10.184	–8.520
152.40	–9.235	9.832	–6.467	–6.510	–7.172	–7.026	–8.892	–8.124

Table 7. Observed (T^*) and calculated (T) shut-in temperatures (˚C) at three depths of the Put River N-1 well, Alaska; t_{s1} = 34, t_{s2} = 48, and t_{s3} = 66 days (after [9]).

t_s, days	45.72 m		60.96 m		91.44 m	
	T	T^*	T	T^*	T	T^*
91	–7.546	–7.511	–7.525	–7.497	–7.258	–7.227
117	–7.921	–7.900	–7.867	–7.860	–7.651	–7.620
163	–8.294	–8.428	–8.207	–8.263	–8.040	–7.965
1071	–9.098	–9.052	–8.946	–8.957	–8.875	–8.771

Table 8. The estimated values of permafrost thickness for two sections, East Simpson #1.

t_s, days	G, ˚C /m	B, ˚C	h_z, m
	Section 21.34 - 249.94 m		
155	0.02501	–8.6303	345.1
520	0.02660	–9.9999	375.9
865	0.02658	–10.236	385.1
1608	0.02750	–10.519	382.1
1947	0.02673	– 10.437	390.5
	Section 451.10 - 600.46 m		
155	0.04008	–13.674	341.2
520	0.04078	–14.492	355.4
865	0.04109	–15.035	365.9
1608	0.04105	–15.139	368.8
1947	0.04150	–15.432	371.8

Table 9. An example of data processing for two wells.

h, m	T_s, ˚C	T_{scal}, ˚C	T_s, ˚C	T_{scal}, ˚C
East Simpson #1 t_s = 155d h_z = 340.4 m			East Simpson #1 t_s = 520d h_z = 368.2 m	
451.1	4.490	4.414	3.906	3.867
475.5	5.348	5.387	4.857	4.883
499.9	6.288	6.359	5.855	5.898
524.3	7.291	7.332	6.915	6.914
551.7	8.509	8.425	8.101	8.056
573.0	9.268	9.276	8.930	8.945
R_{aver} = 0.99%, a_o = –13.573˚C, g = 0.03987˚C/m			R_{aver} = 0.60%, a_o = –14.918˚C, g = 0.04164˚C/m	
Drew Point No. 1, Well 555 t_s = 186d, h_z = 266.2 m			Drew Point No.1 t_s = 547d, h_z = 290.3 m	
400.2	4.740	4.67	3.981	3.925
450.2	6.417	6.408	5.746	5.711
500.2	8.064	8.149	7.381	7.497
550.2	9.829	9.891	9.232	9.284
600.2	11.586	11.632	11.091	11.070
638.9	13.093	12.981	12.510	12.453
R_{aver} = 0.90%, a_o = –9.2752˚C, g = 0.03484˚C/m			R_{aver} = 0.95%, a_o = –10.376˚C, g = 0.03574˚C/m	

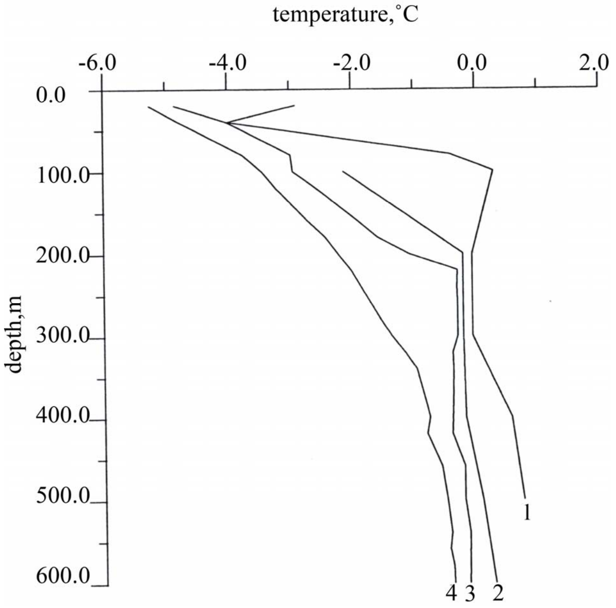

Figure 3. Restoration of temperature profile in the Bakhynay borehole 1-R (after [1]). Temperature surveys 1, 2, 3, and 4 were conducted at shut-in times of 0.4, 1.5, 3.4 and 10.4 years, respectively.

where

$$\gamma = \frac{Ei\left(-D/n_2\right) + \ln n_2 - D_1}{Ei\left(-D/n_2\right) - Ei\left(-D/n_1\right) + \ln \dfrac{n_2}{n_1}}$$

$$n_1 = \frac{t_{s1}}{t_c},\ n_2 = \frac{t_{s2}}{t_c}$$

$$D = 1.1925,\ D_1 = 0.7532$$

In **Table 10** we present results of estimation of the formation temperature for two wells. And, finally, we use a linear regression program to determine the geothermal gradient (**Table 11**).

$$Tf = a + Gh \qquad (6)$$

The position of the permafrost base (h_p) is estimated by extrapolation

$$0 = a + Gh_p,\ hp = -\frac{a}{G}$$

Comparing the results of calculation h_p (**Table 9** at t_s = 520 days and t_s = 547 days) with that (**Table 11**) we can see the agreement between calculated values of h_p is good.

4. Onset of Formations Freezeback

To plan the schedule of conducting temperature logs is important approximately to estimate the onset of the formations freezeback. Earlier we introduced term "safety period"-the length of the shut-in period during which water-base mud remains free from freezing in permafrost areas [14]. From physical considerations it is clear that the "safety period" (t_{sp}) can be determine from the condition $T_s(t_{sp})$ = 0˚C (**Figure 2**). Thus, the time $t_s = t_{sp}$ can be considered as the onset of the formations freezeback. The magnitude of the "safety period" depends mainly on the duration of the thermal disturbance (drilling time) and on the static temperature of permafrost. Precise temperature measurements (61 logs) conducted by the Geothermal Service of Canada in 32 deep shut-in wells in Northern Canada [2-5] were used to estimate the values of t_{sp} [14]. The total drilling time (t_t) for these wells ranged from 4 to 404 days, the total vertical depth (h_t) ranged from 1356 m to 4704 m), and the depth of permafrost (h_p) ranged from 74 m to 726 m. The range of formations temperatures was –0.5˚C > T_f > –4.6˚C.

We have found that the duration of the "safety period" t_{sp} for a given depth can be approximated with sufficient accuracy as a function of two independent variables: time of thermal disturbance at the given depth (drilling time) and permafrost static temperature (T_f). A regression analysis computer program was used to process field data. It was revealed that the following empirical formula could be used to estimate the safety shut-in period:

$$t_{sp} = 6.12 t_c^{0.817} \left(-T_f\right)^{-1.5} \qquad (7)$$

where t_c is the thermal disturbance time (in days) at a given depth and temperature is inoc.

The value t_d is: $t_d = t_t - t_h$, where t_h is the period of time needed to reach the given depth. The values of t_h can be determined from drilling records. The value t_d can be also estimated from Equation (2). Please note that in our paper [14] a safety factor of 2 was introduced in Equation (7). When planning to conduct a temperature log the condition $t_s >> t_{sp}$ should be satisfied. We conducted calculations of t_{sp} for the section 335.3 - 548.6 m, well Put River N - 1 (**Table 12**). From **Table 12** follows that for the temperature logs with t_s = 5 days and t_s = 22 days the condition $t_s >> t_{sp}$ is not satisfied. As a result these temperature logs cannot be used for determination formation temperatures and estimation of the permafrost thickness. It should be remembered that in Equation (7), time is in days and temperature inoc.

5. Conclusion

It is shown that for large shut-in times the empirical Lachenbruch-Brewer formula can be used with good accuracy to estimate the shut-in temperatures. Only two temperature logs are needed to calculate the coefficients in the Lachenbruch-Brewer formula. Thus two temperature logs enable to predict formations temperatures, to determine the geothermal gradients, and to evaluate the thickness of

Table 9. An example of data processing for two wells.

h, m	T_s, ˚C	T_{scal}, ˚C	T_s, ˚C	T_{scal}, ˚C
	East Simpson #1 $t_s = 155d$, $h_z = 340.4$ m		East Simpson #1 $t_s = 520d$, $h_z = 368.2$ m	
451.1	4.490	4.414	3.906	3.867
475.5	5.348	5.387	4.857	4.883
499.9	6.288	6.359	5.855	5.898
524.3	7.291	7.332	6.915	6.914
551.7	8.509	8.425	8.101	8.056
573.0	9.268	9.276	8.930	8.945
	$R_{aver} = 0.99\%$., $a_o = -13.573$˚C, $g = 0.03987$˚C/m		$R_{aver} = 0.60\%$, $a_o = -14.918$˚C, $g = 0.04164$˚C/m	
	Drew Point No.1, Well 555 $t_s = 186$d, $h_z = 266.2$ m		Drew Point No. 1 $t_s = 547$d, $h_z = 290.3$ m	
400.2	4.740	4.67	3.981	3.925
450.2	6.417	6.408	5.746	5.711
500.2	8.064	8.149	7.381	7.497
550.2	9.829	9.891	9.232	9.284
600.2	11.586	11.632	11.091	11.070
638.9	13.093	12.981	12.510	12.453
	$R_{aver} = 0.90\%$, $a_o = -9.2752$˚C, $g = 0.03484$˚C/m		$R_{aver} = 0.95\%$, $a_o = -10.376$˚C, $g = 0.03574$˚C/m	

Table 10. Calculated formation temperatures by "Two temperature logs method".

h, m	T_{s1}, ˚C	T_{s2}, ˚C	T_f, ˚C
		Well East Simpson #1	
	$t_{s1} = 155$ days		$t_{s2} = 520$ days
451.10	4.490	3.906	3.653
475.49	5.348	4.857	4.645
499.87	6.288	5.855	5.669
524.26	7.291	6.915	6.754
551.69	8.509	8.101	7.928
573.03	9.268	8.930	8.788
		Drew Point No.1	
	$t_{s1} = 186$ days		$t_{s2} = 547$ days
400.20	4.740	3.981	3.576
450.19	6.417	5.746	5.391
500.16	8.064	7.381	7.023
550.17	9.829	9.232	8.921
600.15	11.586	11.091	10.837
638.86	13.093	12.510	12.303

Table 11. Determination of the geothermal gradient, $\boldsymbol{R = \frac{T_{fcal} - T_f}{T_f} \cdot 100\%}$.

h, m	T_f, ˚C	T_{fcal}, ˚C	R,%
Well East Simpson #1 R_{aver} = 0.43%, h_z =365.6 m $T_f = a_o + Gh$ G = 0.04245˚C /m, a_o = –15.518˚C			
451.10	3.6530	3.6301	0.63
475.49	4.6450	4.6653	–0.44
499.87	5.6690	5.7002	–0.55
524.26	6.7540	6.7355	0.27
551.69	7.9280	7.8998	0.36
573.03	8.7880	8.8056	–0.20
Drew Point No. 1 R_{aver} = 1.23%, h_z = 304.0 m G = 0.03652˚C/m, a_o = –11.103˚C			
400.20	3.5760	3.5131	1.76
450.19	5.3910	5.3388	0.97
500.16	7.0230	7.1638	–2.00
550.17	8.9210	8.9903	–0.78
600.15	10.8370	10.8156	0.20
638.86	12.3030	12.2293	0.60

Table 12. The values of t_{sp} for the section 335.3 - 548.6 m, well Put River N-1.

h, m	t_d, days	T_f, ˚C	t_{sp}, days	t_s = 5 days T_s, ˚C	t_s = 22 days T_s, ˚C
335.3	24.7	–4.93	7.7	.910	–.325
365.8	22.9	–4.45	8.4	1.040	–.322
396.2	21.1	–4.04	9.1	1.230	–.354
426.7	19.4	–3.45	10.8	1.220	–.280
457.2	17.6	–2.96	12.5	1.890	–.326
487.7	15.9	–2.49	14.9	1.480	–.305
518.2	14.1	–2.01	18.7	1.520	–.264
548.6	12.4	–1.42	28.3	1.880	–.171

the permafrost zone. As a result the cost of monitoring the temperature regime of deep wells after shut-in can be drastically reduced. For short shut times (comparable with the time of complete freezeback) we suggest to utilize the "Three point method" [9]. The approximate evaluation of the onset of formations freezeback will assist in planning the schedule of conducting temperature logs.

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Nomenclature

A, B	empirical coefficients (Equation (1));
a	parameter (Equations (3) and (6));
G	geothermal gradient;
g	temperature gradient;
h_t	total well depth;
h	depth;
h_p	depth to base of ice-bounded permafrost;
T_{eq}	shut-in temperature predicted by Lachenbruch-Brewer formula;
T_f	formation temperature;
T_s	shut-in temperature;
t	time;
t_c	time of "thermal disturbance" at a given depth;
t_t	otal drilling time;
t_s	shut-in time;
t_{ep}	time of the thawed formation refreezing;
t_{sp}	onset of the formation freezeback.

Greek Symbols

λ	thermal conductivity of formations.

Subscripts

u	unfrozen;
f	frozen.