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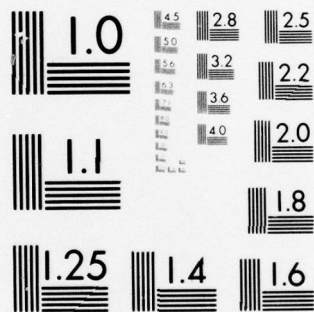
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I.M. Kutasov and V.N. Devyatkin



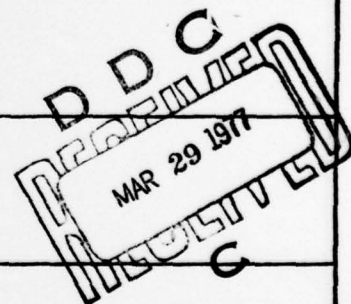
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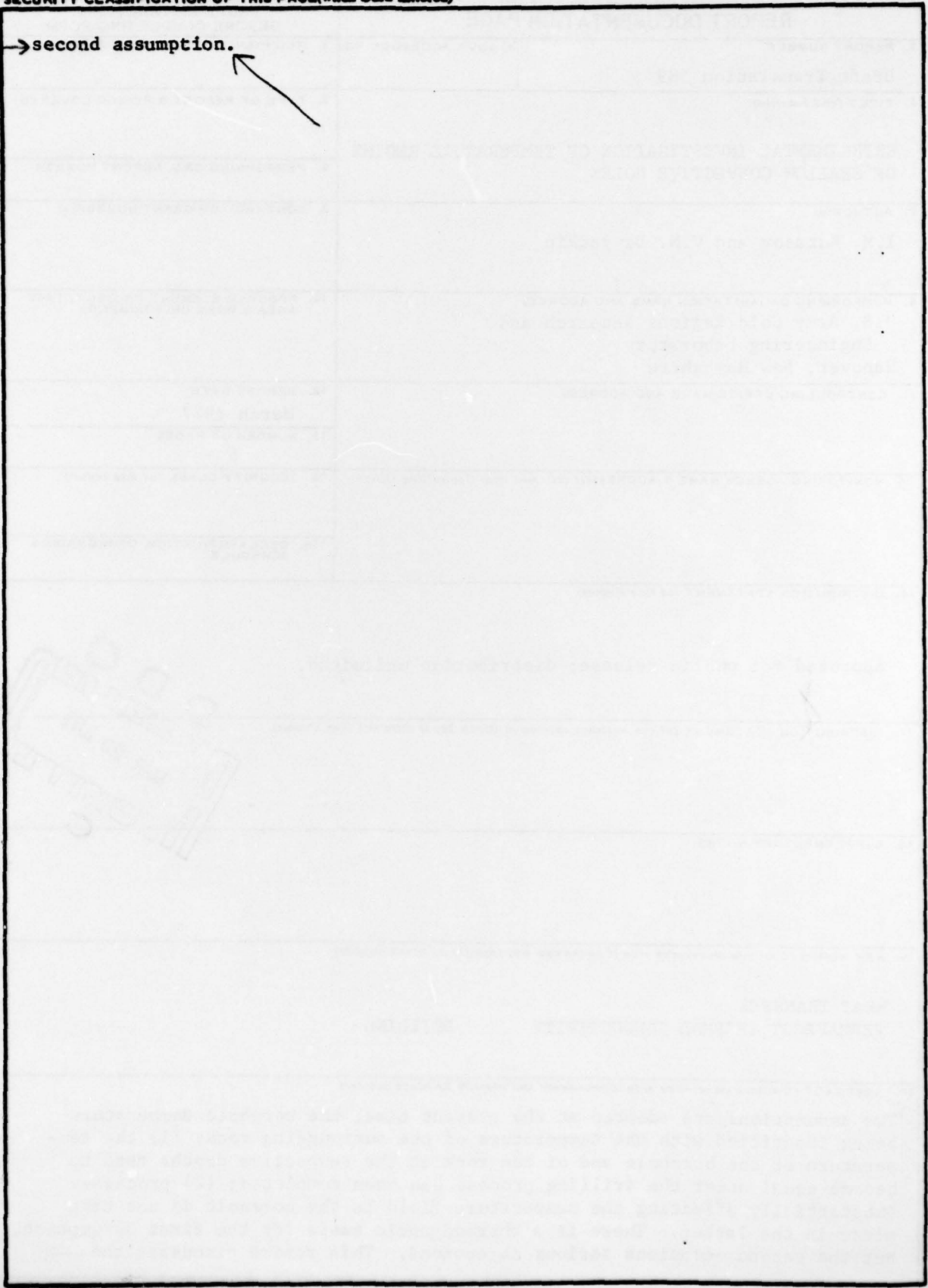
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EXPERIMENTAL STUDY OF THE THERMAL REGIME OF A SHALLOW CONVECTIVE BOREHOLE

by I. M. Kutasov, V. N. Devyatkin

Two assumptions are adopted at the present time, the borehole temperature being identified with the temperature of the surrounding rock: (1) the temperature of the borehole and of the rock at the respective depths tend to become equal after the drilling process has been completed; (2) processes substantially affecting the temperature field in the borehole do not take place in the latter. There is a thermodynamic basis for the first assumption, but the second occasions serious objections.

Processes such as evaporation and condensation of moisture and convective movement of air (liquid) take place in a borehole, which from the thermophysical viewpoint is a foreign body in the mass of rock, and in the region of the cryolithozone favorable conditions exist for sublimation of ice from the walls of the hole and its subsequent crystallization in certain areas.

All these processes involve considerable transfer of heat and matter. The need for studying the phenomena taking place in a borehole has been noted by many Soviet scientists. A. N. Tikhonov (1939), in analyzing the data obtained in six years in the Skovorodino borehole, arrived at the important conclusion that the temperature deviations observed in boreholes may not always be ascribed to errors of the heat measuring instruments. He expresses the opinion that it is necessary to modify the methods of geothermal measurement. S. A. Kraskovskiy (1939) is even more specific: "In order for the data of geothermal measurements to acquire the accuracy they have hitherto lacked, not only must we have fully adapted equipment and carefully developed methods; we must conduct special experiments organized in a number of boreholes definitively to determine all the factors which may modify the temperature distribution in the borehole in one direction or another. This applies primarily to convection flows. If their influence is strong enough, special measures must be developed to eliminate them or suitable corrections must be introduced."

A major contribution to the theory of convective heat exchange in a cylindrical cavity has been made by G. A. Ostroumov (1952). He has obtained the solution of a system of differential equations describing free thermal convection for the case of a vertical tube, on the assumption that the vectors of the flux particle velocities are parallel to the axis of the tube and that the vertical temperature gradient is constant.

It is to be noted at the same time that no experimental research has as yet been conducted which demonstrates that free thermal convective plays an appreciable role in formation of the thermal regime in a borehole.

This article presents certain results of annual observations of the thermal regime of four shallow boreholes drilled in a stratum characterized by annual temperature fluctuations. Since this rock stratum is characterized by high temperature gradient values, the convective process should be the most pronounced in such boreholes.

Study of the thermal regime of boreholes drilled in a stratum characterized by annual temperature fluctuations is important in itself, since geothermal measurements within the limits of this stratum are conducted on a large scale in practical work.

Four boreholes up to 20 m deep were drilled for prolonged observation of the temperature regime. Boreholes No 1, 2, and 3 were situated at a distance of 2.5 m from borehole No 4. All the boreholes are under identical geological and geographic conditions and are outfitted as follows: No 1 open and empty, No 2 covered and empty, No 3 filled with transformer oil, and No 4 filled with soil.

Boreholes No 1, 2, and 4 have metal casings with an internal diameter of 6 cm to a depth of 2 m. Borehole No 3 is cased to the bottom with a casing having an internal diameter of 4 cm. The casing is plugged at the face.

The thermophysical characteristics of the rock through which the boreholes pass are shown in Table 1 (data of N. S. Ivanov).

The mouth of each hole is shielded by a wooden duct against entry of rain and snow. Strings with MMT-4 thermistors are installed in the holes at depths of 0, 1, 2, 3, 7.5, 12.5, 15, 17.5, and 20 m for temperature measurement. The thermistors were coated with several layers of nitro-cellulose varnish and wrapped in rubber and insulating tape. The upper two meters of the strings were sheathed in rubber hosing to improve the water-proofing. Then the strings were boiled in a mixture of tar and transformer oil at a temperature of 70-80° C.

Table 1				
Soil	Layer limits	Temperature, °C	Moisture content per unit weight, w, fractions of unit	Coefficient of thermal conductivity, kcal/m·h·deg.
Loam	1.0-1.5	10.0	0.187	0.60
		0.0	0.189	0.60
		-14.0	0.201	0.59
	2.00-2.25	2.0	0.021	0.47
		0.0	0.025	0.47
		- 7.0	0.018	0.35
Sand	3.0-4.0	-2.5	0.256	1.40
	4.0-5.0	-2.5	0.259	1.40
	5.0-7.5	-2.5	0.219	1.40
	7.5-10.0	-2.5	0.244	1.40
	10.0-12.5	-2.5	0.228	1.40
	12.5-15.0	-2.5	0.264	1.40
	15.0-17.5	-2.0	0.262	1.40
	17.5-19.0	-2.0	0.211	1.40

The average diameter of the string insulated in this manner was 12 mm. The sand filling hole No 4 had a moisture content of 4% and an initial temperature of 1.1°, and the transformer oil filling hole No 3 had an initial temperature of -20.4°. Systematic observation of reestablishment of the thermal regime indicated that the temperatures in holes No 4 and 3 were stabilized in 2 and 1.5 days respectively.

The thermistor resistances were measured with an MVL-47 direct-current bridge with a GMP and GPZ-2 galvanometer. The bridge supply voltage was 1.3-1.5 v. The MVL-47 bridge has an accuracy rating of 0.05. In our case, with a thermistor temperature coefficient of $\alpha = 3-4\%$, it ensured a measurement accuracy of $\Delta T_m = 0.012-0.015^\circ$. The total resistance of the leads did not exceed 7 ohms, this yielding an absolute error of $\Delta T_{pr} = 0.02^\circ$ (rated thermistor resistance $R = 10,000$ ohms). The error caused by heating of the thermistors by the measuring current amounted on the average to $\Delta T_h = 0.01^\circ$. The thermistor graduation error equalled approximately $\Delta T_{gr} = 0.02^\circ$. The error caused by longitudinal displacement of the string can be obtained from the following relation:

$$\Delta T_1 = 0.02 \cdot A,$$

where 0.02 is the possible error of adjustment of the thermistors in depth, m;

A is the mean value of the vertical temperature gradient.

For the depth interval from 0 to 1 m the value of A reaches 10 deg/m. In this instance $\Delta T_1 \approx 0.2^\circ$. This error may be disregarded for greater depths. Thus the total absolute error is

$$\Delta T = \Delta T_m + \Delta T_{pr} + \Delta T_{gr} + \Delta T_h + \Delta T_l$$

$$\Delta T \approx 0.08 - 0.1^\circ \text{ for } h > 1.$$

$$\Delta T \approx 0.3 \text{ for } h < 1.$$

The observations were made daily at 0800 hours. Since the daily temperature fluctuations at the various depths (with the exception of $h = 1$ m) are small in comparison to the absolute measurement error, the variations in the temperatures at the respective depths were found rather than the absolute temperatures.

The error in determination of the temperature variation obviously can be found only by use of a sensitive bridge, since $\Delta T_{pr} + \Delta T_h + \Delta T_{gr} + \Delta T_l$ is virtually constant. Consequently, in our case the error equals $0.012-0.015^\circ$.

The first observation (31 July 1959) was processed with an accuracy of 0.1° , and the increments with a "relative" accuracy of $0.1-0.2^\circ$ (variation error).

We will give an example of the processing. Say that five thermistor resistance values have been obtained for a specific time interval at a depth of 20 m in borehole No 4.

Measurement number	1	2	3	4	5
Measured thermistor resistance, ohm	8349	8360	8395	8406	8509
Resistance variation, ohm	0	-11	-46	-57	-160
Temperature variation, $^\circ\text{C}$	0	0.04	0.16	0.20	0.57
Temperature, $^\circ\text{C}$	1.0	0.96	0.84	0.80	0.43

The temperature variations were determined in this manner down to a depth of 17.5 m. The resistance of the thermistors installed at a depth of 20 m did not vary in the course of a year.

Systematic observation for a period of one year indicated that convective heat exchange plays a significant role in formation of the thermal regime of the test boreholes (Figures 1, 2).

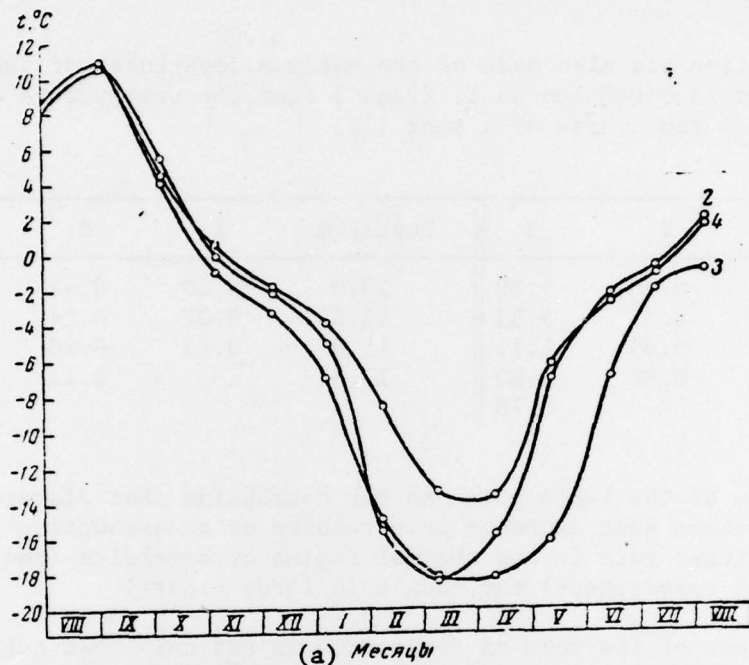


Figure 1. Graphs of variation in temperatures at a depth of 1 m in boreholes No 2, 3, 4.

Key: (a) Month

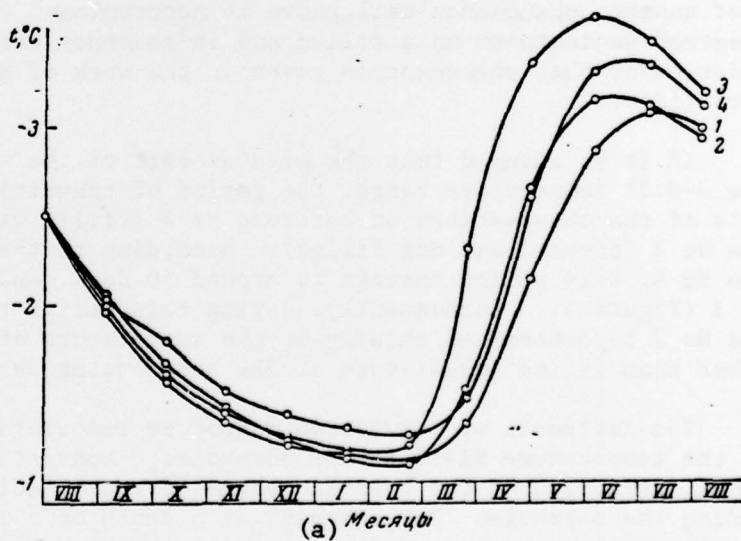


Figure 2. Graphs of variation in temperatures at a depth of 5 m in boreholes No 1, 2, 3, 4.

Key: (a) Month

Calculation was also made of the maximum departures of the temperatures measured in boreholes No 1, 2 and 3 from the temperature of the undisturbed mass in the course of a year ($^{\circ}\text{C}$).

Depth, m	1	2	3	Depth, m	1	2	3
1.0	-	6.90	9.80	10.0	0.20	0.42	0.64
2.0	0.55	2.35	5.33	12.5	0.07	0.18	0.21
3.0	0.65	0.69	1.19	15.0	0.15	0.20	0.22
5.0	0.47	0.24	0.83	17.5	-	0.11	0.04
7.5	-	-	0.75				

The data of the table point to the conclusion that disregard of the role of convective heat exchange in boreholes or an assumption that it plays an insignificant role in the thermal regime of boreholes (the viewpoint of the majority of researchers) may result in large errors.

The effect of the role of convection is not only that temperatures at corresponding depths do not equal each other in different boreholes, but also that the vertical temperature distribution is qualitatively different. The role of convection is particularly striking in the wholly different course of another phenomenon well known in geocryology, the time lag of the "zero degree" geoisotherm in a filled and in an empty but covered borehole. A description of this phenomena is given in the work of M. I. Sumgin and coworkers (1940).

If it is assumed that the greater part of the water passes to ice over the $0-0.2^{\circ}$ temperature range, the period of transition will vary on the basis of the observations of borehole No 4 (filled with soil) and of borehole No 2 (covered but not filled). According to the observations of borehole No 4, this period amounts to around 50 days, and 20 days in borehole No 2 (Figure 3). Consequently, during this period the temperature in borehole No 2 is determined chiefly by the temperature of the convective air rather than by the temperature of the surrounding stratum of rock.

The influence of convection cannot be restricted merely to distortion of the temperature field in the boreholes. Convective heat exchange also caused disruption of the thermal regime of the immediate stratum of rock surrounding the borehole. For example, at a depth of 1 m the transformer oil greatly chilled the surrounding stratum of rock over the winter period, so that the transition to positive temperatures was made more slowly than in the other boreholes (see Figure 1). The most significant departure from the temperature of the undisturbed rock stratum (on the basis of borehole No 4) is observed in borehole No 3. This latter circumstance is readily understood when one remembers the large convective parameter value of the transformer oil. As a matter of fact, the occurrence of convection and its intensity depend on the value of the Rayleigh number (Ostroumov, 1952):

$$Ra = kAR^4,$$

where $k = \frac{g\beta}{\nu a}$ is the convective parameter, $m^{-3} \cdot \text{deg}^{-1}$;

$$g = 9.8 \text{ m/sec}^2;$$

β is the coefficient of volumetric expansion, $1/\text{deg}$;

ν is the coefficient of kinematic viscosity, m^2/sec ;

a is the coefficient of temperature conductivity, m^2/hour ;

A is the vertical temperature gradient, deg/m ;

R is the radius, m .

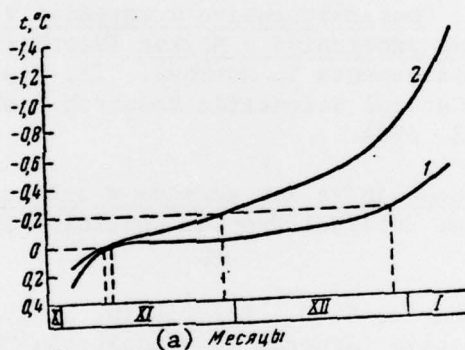


Figure 3. Time lag of "zero degree" geoisotherm in boreholes at a depth of 1 m. 1. filled; 2. covered but not filled.

Key: (a) months

Calculation yields the values of $k_{oil} = 11.7 \cdot 10^8 m^{-3} \cdot \text{deg}^{-1}$ and $k_{air} = 1.41 \times 10^8 m^{-3} \cdot \text{deg}^{-1}$ for transformer oil and air respectively. Hence an effort should be made to carry out the following in outfitting thermal boreholes.

1. The substances filling the hole should have the smallest possible convective parameter value. Other conditions being equal, a larger temperature gradient $A > A_c$ will be required in this case in order for convection to occur;

$$A_c = \frac{Ra_c}{kR^4}.$$

The Ra values have been determined in the work by G. A. Ostroumov (1952). The liquid is stationary when $Ra < Ra_c$. Air, which has a relatively low k value, is a highly suitable filler. It should be noted that as the temperature is lowered the values of the convective values of industrial oils decrease sharply owing to the high values of the coefficient of kinematic viscosity.

2. The boreholes employed for observation should if possible have small diameters, since the Ra value is heavily dependent on the radius of the hole. Thus, for example, doubling of the radius of a borehole is equivalent (in the sense of possibility of occurrence of convection) to 16-fold increase in the temperature gradient.

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