Temperature
WELL LOGGING
Part 1
Heat Conduction

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THE first physical property measured in bore holes is probably temperature. As early as 1869 Lord Kelvin took temperature readings in a well 350 feet deep by using a thermocouple. Many other similar measurements were made during the following years.

Notwithstanding these early investigations, temperature data have not been used extensively as yet for the logging of formations traversed by a well. The main reason therefor is that in most instances temperature measurements cannot compete successfully with the other methods of investigation. Only in a limited number of cases, such as the location of oil and gas reservoirs in cable tool wells, the location of cement behind pipes, and a few other minor problems, are temperature measurements used at present in bore holes. It is felt, however, that this method could be more widely applied if its possibilities were better understood.

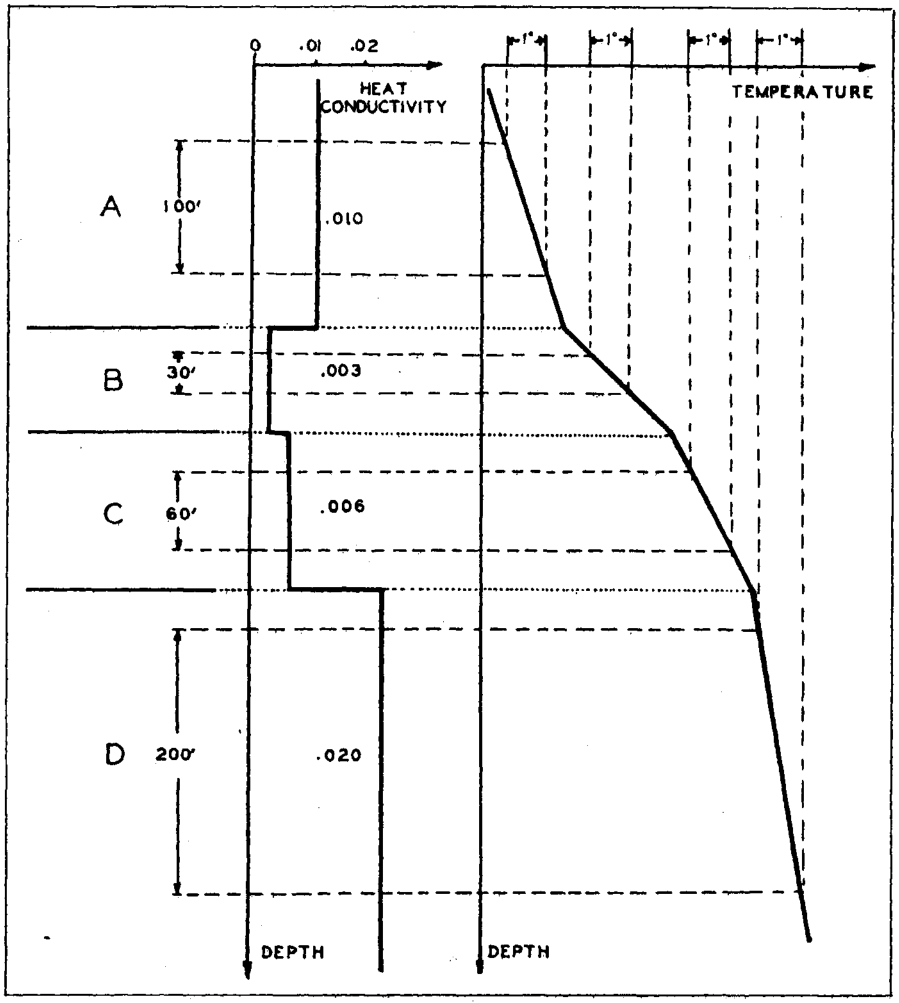

Figure 1-1. Temperature distribution in horizontal beds.

Earth Temperature

Considerable evidence indicates the presence of an extremely hot core in the center of the earth. Whether all the heat radiated by the earth's surface is coming from the core alone or part of it is produced by radioactivity disintegration has not been established with certainty. Although this question is of interest to the geologist, it need not be discussed here because the general temperature distribution in sediments is probably not much dependent upon the nature of the heat generating process.

Heat may be transferred from one point to another by the three different following mechanisms:

conduction
convection
radiation.

Conduction is the transfer of heat from one part of a medium to another part of the same medium without appreciable displacement of particles. Only conduction has usually to be considered in the study of the earth's crust temperature as the other processes have only a negligible effect.

Fourier's Law

There are many analogies between the flow of a liquid through a permeable medium, the flow of electricity through a conductor and the flow of heat by conduction through a solid body. In particular, the mathematical solutions of the problems involved in these three branches of physics are identical and many formulas obtained for one of them can be used for the others by simply translating each symbol into its proper analogue.

The correspondence between these three different sciences is of great significance because it frequently helps understanding the mechanism of an unfamiliar system by comparing it with a different system which is better understood. For instance, everyone is familiar with the classical method of explaining the flow of electricity in a wire by comparing it to the flow of water in a pipe.

The fundamental law of heat conduction is Fourier's law, which is analogous to D'Arcy's law in hydrodynamics, and to Ohm's law in electricity. The parallels between these laws are summarized in Table 1.

ELECTROLYTIC scale models are widely used at present for investigating the performance of petroleum reservoirs. The same method can be used also for investigating the temperature distribution in the earth's crust. How this is done is explained in this article.

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Fourier's law states that the instantaneous rate of heat flow through a section is equal to the product of the three following factors:

1. The area A of this section (taken at right angles to the direction of flow).
2. The temperature gradient dT/dx, which is the rate of change of temperature, T, with respect to the length of path, x.
3. A proportionality factor, K, known as heat conductivity (or thermal conductivity) of the medium.

Analytically expressed, Fourier's law is as follows:

$$\frac{dQ}{dt} = KA\frac{dT}{dx} \qquad (1)$$

where dQ is the amount of heat flowing in differential time dt.

In the case of the earth's crust, the heat transferred through any section is independent of time and equation (1) can therefore be rewritten:

$$\frac{dT}{dx} = \frac{C}{K} \qquad (2)$$

where C is a constant for the section considered (except at depths less than 100 feet which are the seat of diurnal and annual variations).

The value of the factor C varies from one point of the earth to another according to the geometry of the formations. In horizontal sediments, C is constant over considerable distances

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This is the first of a series of seven articles.

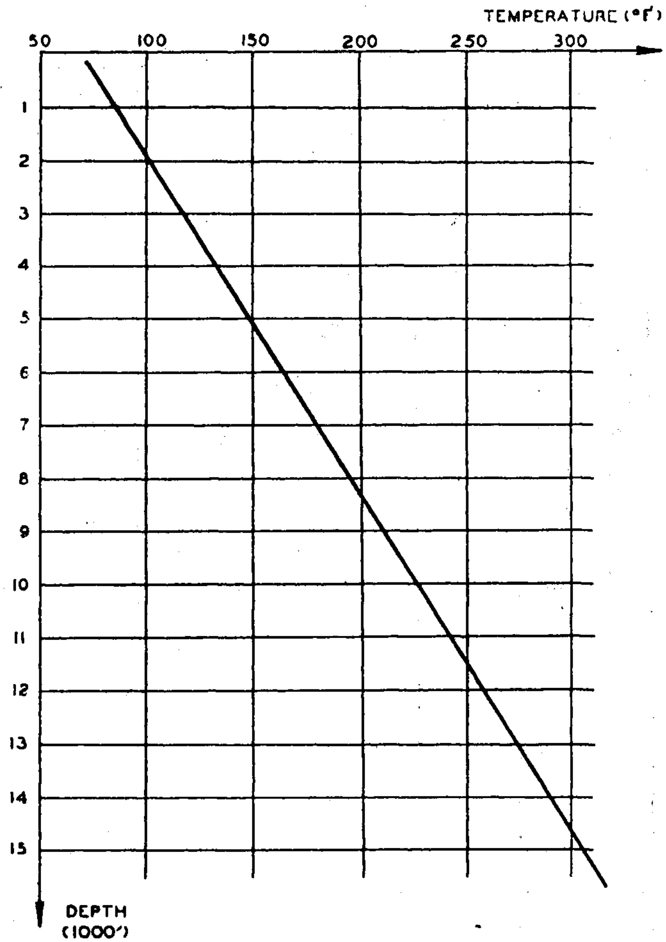

Figure 1-2. Approximate ground temperature in the Gulf Coast.

when the surface of the ground and that of the basement rock are horizontal also. Under these conditions the temperature gradient in any given bed is constant and proportional to the reciprocal of the heat conductivity of said bed, the factor of proportionality being the same for all beds.

In geology, the reciprocal gradient is frequently used instead of the gradient. The reciprocal gradient is the vertical distance between two points having a temperature difference of one degree. Evidently, in parallel media the reciprocal gradient in a bed is proportional to the heat conductivity of said bed.

It is customary to consider only vertical gradients, such as those which are determined by taking temperature measurements in bore holes. This will be done also in this work, unless specified otherwise.

Horizontal Beds

It is obvious from the foregoing discussion that, in an alternation of horizontal uniform sediments, the isogeotherms — or surfaces of equal temperature— are parallel horizontal planes. Furthermore, in any given uniform bed these planes are equidistant. Their distance is proportional to the bed conductivity.

If the geologic section comprises four beds, A, B, C, D, for example, whose heat conductivities are 0.010, 0.003, 0.006 and 0.020, respectively, the vertical temperature distribution in the ground is as shown by the graph to the right of Figure 1-1. If there is, for instance, a temperature change of one degree over a vertical distance of 100 feet in bed A, the same temperature change will be observed over distances of 30 feet, 60 feet, and 200 feet in beds B, C, and D, respectively.

In any uniform horizontal formation the temperature T at a given point is given by the following formula:

$$T = T_o + bd \qquad (3)$$

where T_o is the mean temperature of the ground close to the surface, b the temperature gradient in the formation, and d the depth of the point of observation. This formula is valid at any point below 100 feet provided the surface of the ground and the basement rock are reasonably horizontal.

In practice, a formation is never uniform. Equation (3) can nevertheless be used to estimate the temperature at a given depth provided the average value of the temperature gradient is used for b. In the Gulf Coast, for instance, when the sediments consist of an alternation of almost horizontal shales and sands the following formula can be used far from intrusions:

$$T = 70 + \frac{d}{64}$$

(T in degrees Fahrenheit and d in feet). The resulting temperature graph in terms of depths is shown on Figure 1-2.

TABLE 1

Parallels Between Heat Conduction, Hydrodynamics and Electrodynamics

Heat Conduction	Hydrodynamics	Electrodynamics
Heat flow per unit time: $(F = \frac{dQ}{dt})$	Fluid output or input per unit time: $(F = \frac{dQ}{dt})$	Current intensity: $(I = \frac{dQ}{dt})$
Heat conductivity (K)	Permeability (K)	Electrical conductivity (C)
Temperature (T)	Pressure (P)	Potential (V)
Temperature gradient (dT)	Pressure gradient (dP)	Potential gradient (dV)
Fourier's law: $F = K\frac{A}{dx}dT$	D'Arcy's law: $F = K\frac{A}{dx}dP$	Ohm's law: $I = C\frac{A}{dx}dV$

A = Path cross section. dx = Path length.

Heat Conductivity

It has been seen above that the temperature in the ground is controlled primarily by the heat conductivity of the formations. To understand how the temperature is distributed it is therefore advisable to have some knowledge of the thermal properties of the materials found in the ground.

The heat conductivity of a material depends upon the following factors:

conductivity of the solid particles,

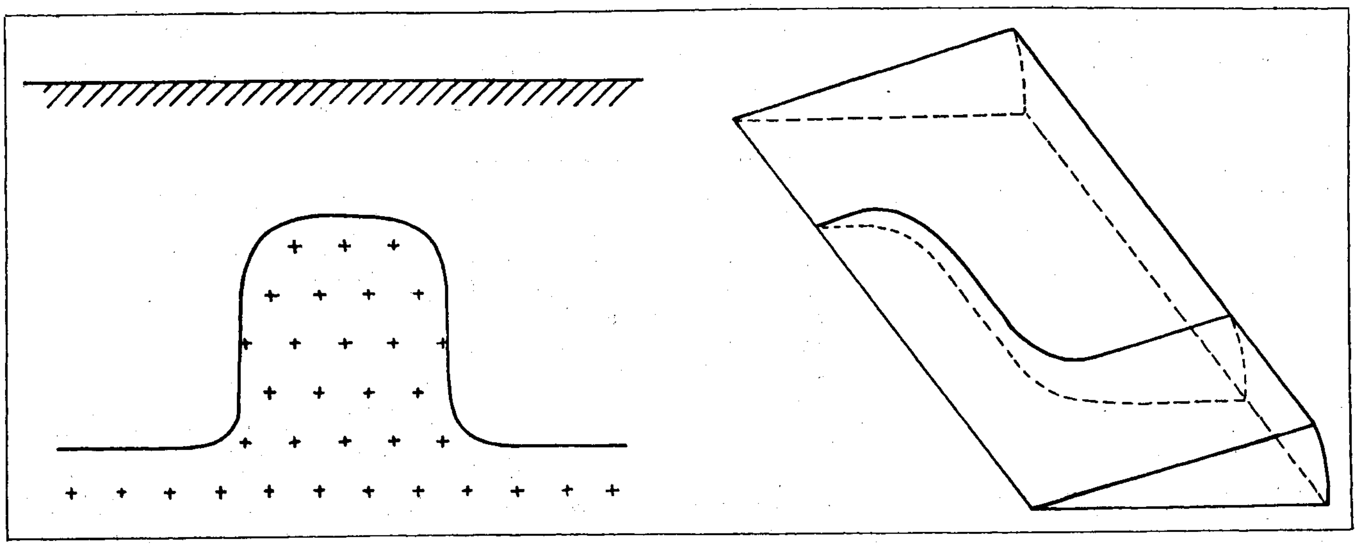

Figure 1-3. Salt dome (left) and its model (right).

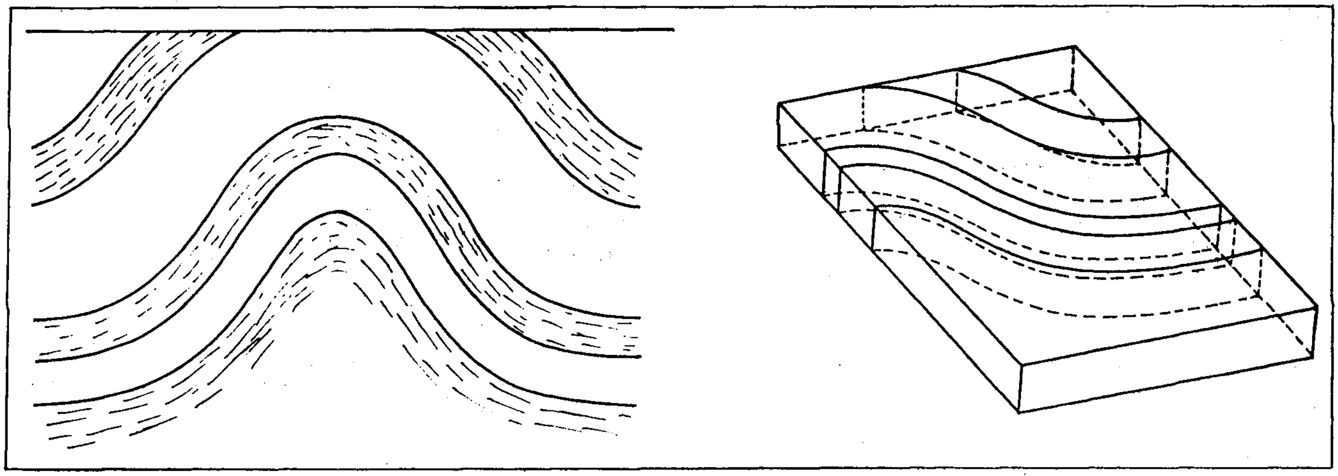

Figure 1-4. Anticline (left) and its model (right).

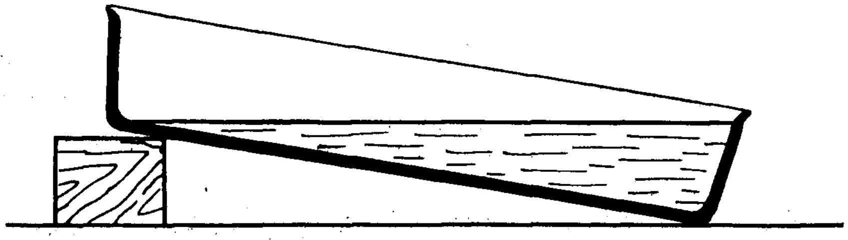

Figure 1-5. Tray for salt-dome investigations.

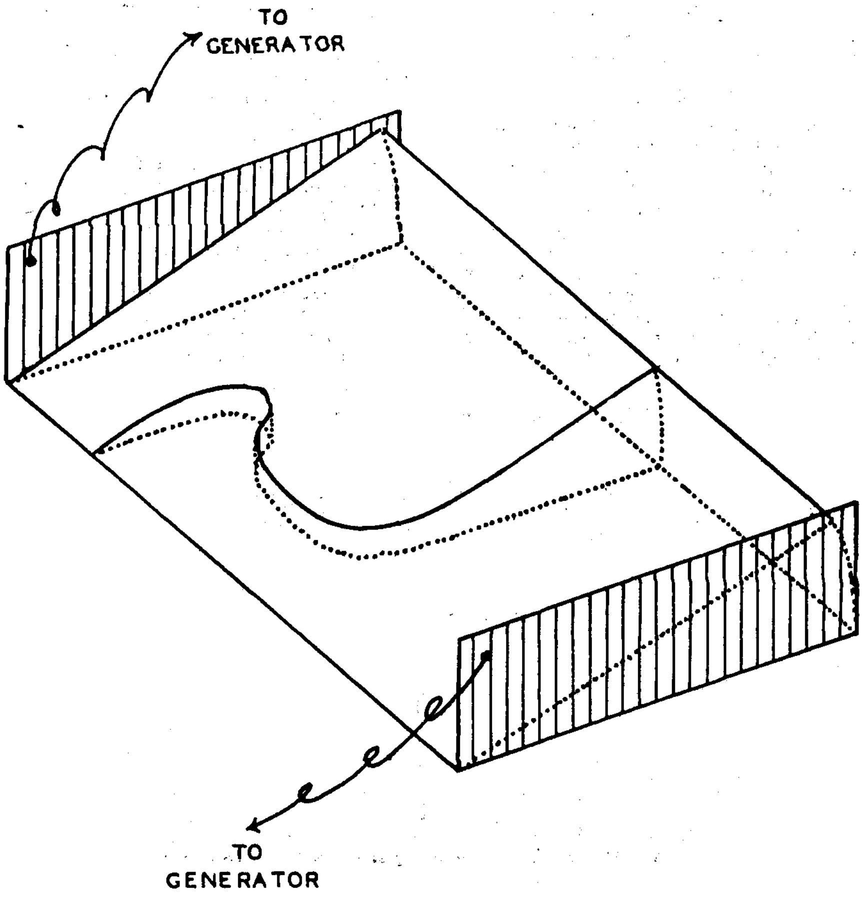

Figure 1-6. Flat electrodes simulating horizontal ground and horizontal basement rock.

geometry of the solid particles,
conductivity of the fluids comprised between the solid particles.

The heat conductivity of quartz is greater than that of calcite, while the latter is greater than that of the usual silicates.

In heterogeneous substances the heat conductivity increases with compactness. For instance, igneous and metamorphic rocks are usually better conductors than sediments.

The nature of the fluids present in the pores is also an important factor. If the material is dry and very porous the heat conductivity is considerably less than if the pores contain water (sediments). This is due to the fact that air is a much poorer heat conductor than water. Oil and natural gas are also poor conductors; therefore, the heat conductivity of petroleum-bearing reservoirs should be smaller than that of the same reservoirs when they contain only water. Unfortunately, the difference is rather small, as will be explained later.

Approximate conductivity of common substances and sediments is given in Table 2. The data for sediments are not always reliable because a few are based on values obtained from samples not entirely saturated with water (outcrops). More accurate conductivity values can be obtained when temperature data are available from wells which are in thermal equilibrium. This procedure gives excellent relative conductivity values for sediments which are reasonably horizontal and far from salt or igneous intrusions. Approximate absolute values can be obtained by using the following formula:

$$K = \frac{1}{2} G_R \times 10^{-4}$$

where K is the heat conductivity (C.G.S. units), and G_R the reciprocal gradient (vertical distance, in feet, for a temperature change of one degree Fahrenheit). This formula gives an average conductivity of 0.004 in nonconsolidated formations and of 0.006 in older formations.

Sands usually have a significantly greater heat conductivity than shales, possibly because of the rather high conductivity of quartz. For instance, in a well in thermal equilibrium located near the Dickinson oil field (Galveston County, Texas), temperature measurements have given a reciprocal gradient of 92 feet in sands and 42 feet in shales, corresponding to an approximate heat conductivity of 4.6×10^{-3} and 2.1×10^{-3}, respectively. In a typical West Texas well, the reciprocal gradient in lime was found to be 130 feet, giving a heat conductivity of about 6.5×10^{-3}.

The specific heat of sediments and igneous rocks varies chiefly with the amount of free water contained. The lowest values—about 0.2—are found in rocks which do not contain any water (granite), while the highest values—about 0.7—are exhibited by sediments

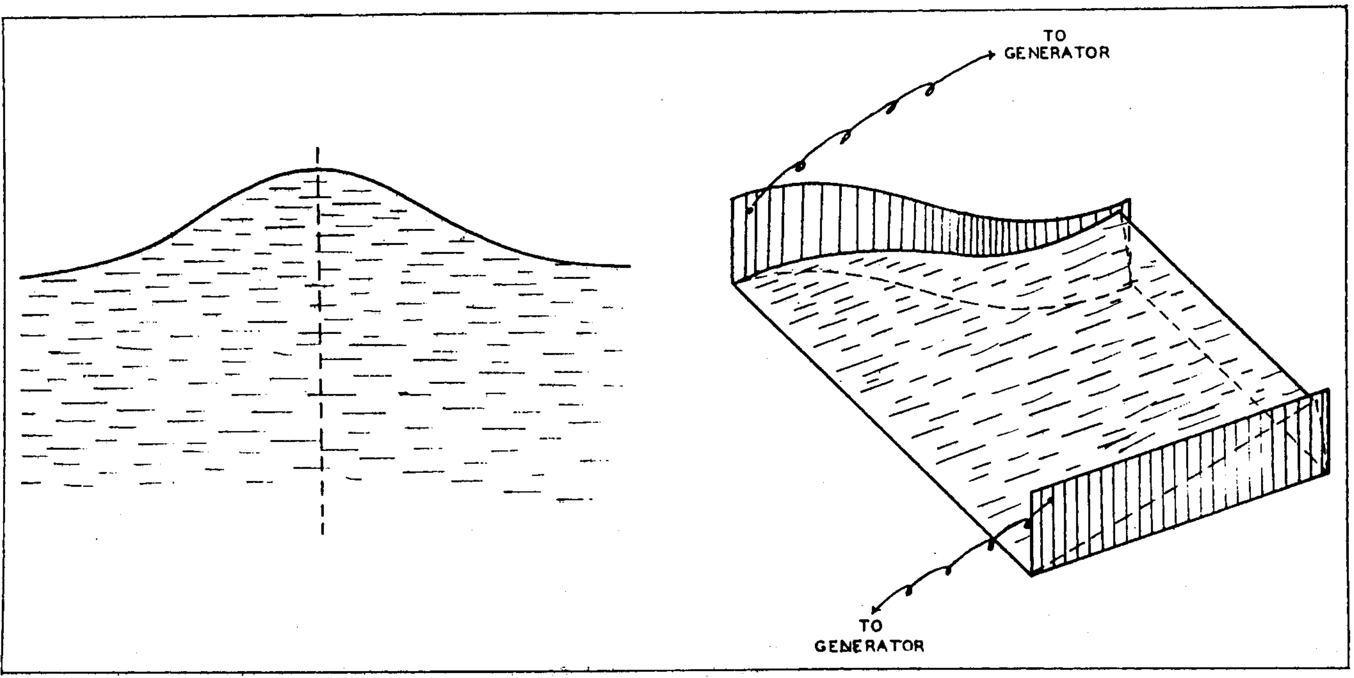

Figure 1-7. Topographic high (left) and its model (right).

of high porosity (non consolidated sands).

The temperature distribution in the earth's crust is independent of the specific heat of the formations unless the latter are not in thermal equilibrium.

Complex Cases

It has been seen that the temperature distribution in parallel media follows very simple rules. When the basement rock or the surface of the ground are not horizontal, or when the sediments are tilted, the factor C of equation (2) varies from point to point in a very irregular manner and it is therefore impossible to solve this equation for T, the temperature of the ground. In such complex cases the temperature can be determined accurately only by direct measurements. However, when the nature of the formations and their approximate shape and dimensions are known, fairly good temperature determinations are frequently possible by using either one of the two following indirect methods:

measurements on an electrolytic model,
graphical means.

The temperature distribution in non-uniform materials, for instance in sediments lifted by an intrusion, is a function of the following factors:

heat conductivity of the sediments and of the intrusion,
geometry of the intrusion,
angle of formation dip,
surface topography,
miscellaneous minor influences.

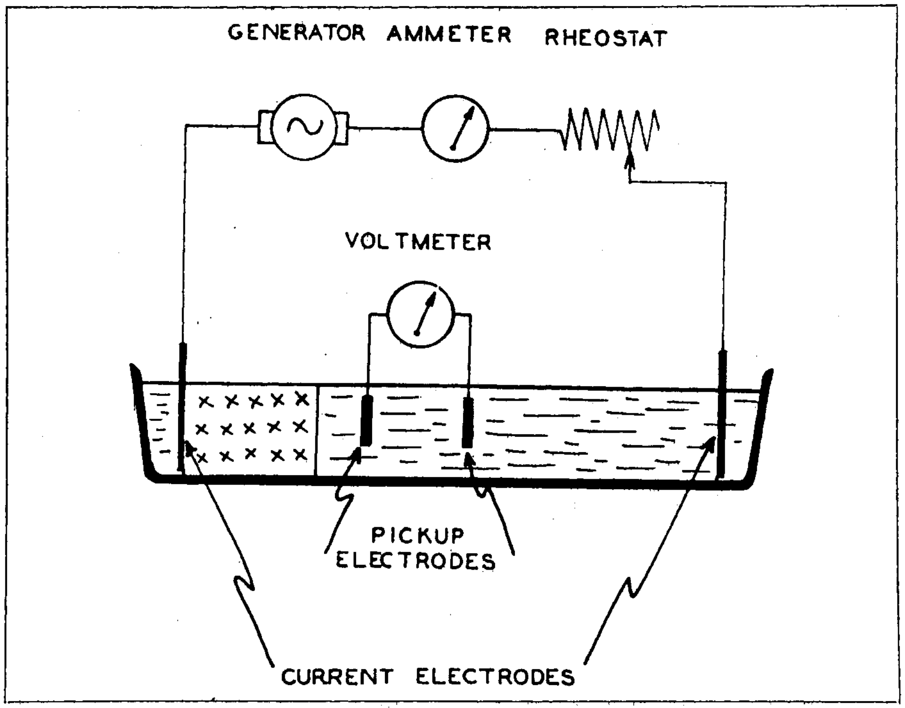

Figure 1-8. Electrodes and circuit arrangement for electrolytic scale models.

The graphical method is usually not applicable to such complex cases and will therefore not be discussed here. On the other hand the electrolytic model method is universal and very simple to apply. Many of the data which will be discussed in this work were obtained with electrolytic models.

Electrolytic Models

The applicability of an electrolytic model to the investigation of heat flow in three-dimensional media is based on the three following facts:

1. The flow of heat through solid bodies is analogous to the flow of electricity in conductive materials: it is therefore possible to use an electric flow through conductors to simulate a flow of heat through the earth's crust.
2. A model may have any size provided it is geometrically similar to the object it simulates. In practice, a model whose dimensions are of the order of one or two feet may frequently be used successfully to

TABLE 2

Heat Conductivity of Common Substances

($\times 10^3$ C.G.S.)

Metals	Copper	1000
	Iron	160
	Silver	1000
	Steel	110
Minerals	Calcite	10
	Pyrite	25 to 40
	Quartz	6 to 30
Non-Sedimentary Rocks	Basalt	5 to 7
	Granite	5 to 8
	Slate	6
Sediments	Chalk	2 to 3
	Clay	2 to 3
	Coal, lignite	0.5 to 1
	Dense limestone	5 to 8
	Rock salt	8 to 15
	Sand, porous lime (water)	3 to 5
	Sand, porous lime (oil or gas)	3^- to 5^-
	Shale	2 to 4
Fluids	Air	0.05
	Natural gas	0.1
	Crude oil	0.3
	Water	1.4
Miscellaneous	Concrete	1 to 2

simulate several cubic miles of formations.

3. The electrical conductivity of the elements of the model may have any value, but their ratio must equal the thermal conductivity ratio of the corresponding elements of the ground.
4. The temperature distribution in the ground is simulated by the potential distribution in the model.

A model designed according to the foregoing principles gives perfect temperature data if the geometrical and thermal characteristics of the formations to be investigated are known. When a few of these characteristics can be only approximately determined, one has to use a model which does not simulate perfectly the actual conditions to be investigated. The data obtained under this condition are nevertheless useful if used in a qualitative manner. In particular, it permits to understand the basic influence of almost any factor upon the temperature distribution in the ground.

A comprehensive study of the temperature in the earth's crust by the electrolytic model method would require several man-years but would probably be of great value. For the present work only those measurements which were necessary for a good understanding of the temperature distribution in sediments were investigated, in particular the effect of the following factors:

salt domes,
salt ridges,
intrusions having a low heat conductivity,
formation dip,
superficial relief,
petroleum reservoirs,
ore deposits,
faulting.

Actual measurements on more complex cases, in particular on combinations of several of the preceding factors, were not carried out because reasonably correct qualitative data can usually be obtained by simply altering adequately the temperature patterns obtained for the elementary cases.

Many Simplifications Permissible

Theoretically, a model must be geometrically similar to the object it simulates. However, if the object is symmetrical about a plane or about an axis, only an adequate part of the model may be used rather than the complete model. For instance, many of the formations listed above, are of revolution about an axis. Under this condition it will usually suffice to carry the electrical investigation on a sector only. For example, the temperature distribution in and about the salt dome whose cross-section is shown on Figure 1-3 can be fully investigated by simply using the model shown to the right of the figure. This is of great practical importance because the preparation of the models is thus considerably facilitated. Furthermore, measurements can be carried out easily inside the formation, as will be apparent from an examination of Figure 1-3. These inside measurements would be difficult to make in a simple manner if complete models were used. The data obtained for one face of the wedge shown to the right of Figure 1-3 are applicable to any other section of the formation passing through the axis of symmetry.

A similar simplification can be made for the study of an anticline for example. Because such a structure is symmetrical about two planes at right angles, only a half slice of the formation need be investigated (Figure 1-4). Of course, if the object to be investigated does not possess any symmetry, it is necessary to use a full model if accurate results are desired.

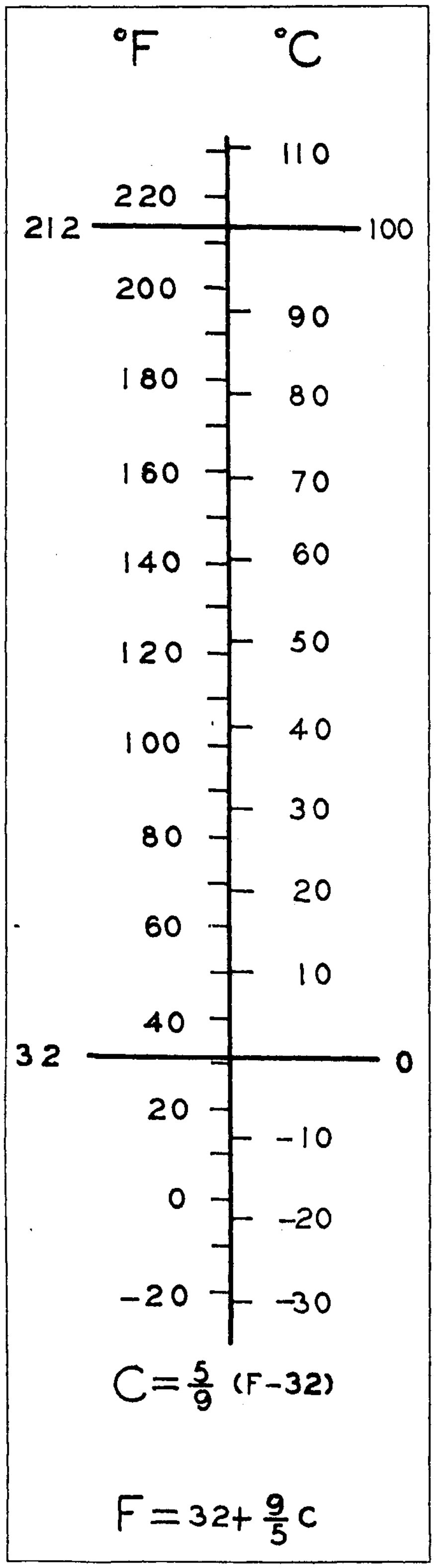

Figure 1-9. Temperature conversion chart.

The materials recommended for the construction of a model are water and conducting rubber. When this latter material is not available, a thick paste of well mixed sand and clay can be used instead. This paste is easily modeled to the required shape.

The materials are placed in a rectangular container, 24 x 24 inches for example. For the investigation of salt domes and other structures which are symmetrical about an axis, the container is tilted (Figure 1-5) in order to obtain for the water the correct wedge shape mentioned above.

The heat flow is simulated by an electric flow obtained by placing a flat electrode at each of two opposite ends of the model (see Figure 1-6).

The effect of surface relief can be approximately investigated by curving one of the current electrodes (Figure 1-7). This procedure simulates the case of a uniform temperature for the ground surface, which is not an unreasonable assumption when the topographic changes are not very large. In the case of high mountains or very deep depressions the data thus obtained are in error, and a more accurate procedure is desirable. This will be discussed in a later article.

Alternating current is preferable to direct current for simulating the heat flow, but d.c. may be used if so desired. In this case a relatively high voltage (more than 50 volts) is necessary because it permits disregarding the polarization potentials at the pickup electrodes. Almost any conventional tester or analyzer may be used for d.c. measurements.

To obtain the section of an isogeotherm the null-method is recommended for the potential measurements; one of the pickup electrodes is held stationary at a point P while the other electrode is placed in contact with the model. Every point registering a zero reading is situated on the equipotential surface passing through P. The line joining these points is a vertical section of an isogeotherm. By repeating the preceding procedure after electrode P is moved to various stations, for instance at points situated 10 volts apart, a family of isogeotherms is obtained.

To obtain the temperature values in a hypothetical vertical bore hole which is in thermal equilibrium, voltage measurements are made along a straight line, using one of the current electrodes as a reference point.

For a complete investigation of the temperature distribution in a formation, it is advisable to make both types of measurements.

The electric circuits used for this work are represented on Figure 1-8.

The experimental procedure described above, although extremely simple, is perfectly adapted to the investigation of the temperature in areas which are in thermal equilibrium, even if the conditions are extremely complex. On the other hand, the investigation of unsteady states necessitates serious modifications.

The unsteady states commonly found are caused by the following factors:

1. Diurnal and annual temperature changes in the superficial earth layer (about 100 feet thick),
2. Fluid intrusions,
3. Mud circulation in rotary holes,
4. Setting of cement behind casing.

Although cases No. 2, 3 and 4 are of great practical interest as far as the logging of wells by temperature measurements is concerned, no scale model experiment could be made for this work and only empirical data on the subject will be presented.