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Thermal measurements in Oak Springs formation at the Nevada Test Site, southern Nevada†

by

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THERMAL MEASUREMENTS IN OAK SPRINGS FORMATION

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Introduction

Temperature measurements were made in several drill holes on and near the Rainier Mesa for the purpose of studying the natural thermal regime of the Oak Spring tuff. The measurements were made with Western Electric type 17A thermistors which were individually calibrated and spliced into multiconductor cables at the U. S. Geological Survey laboratories in Silver Spring. The measurement circuit has been described by Swartz (1954). Four thermal cables, numbered 320, 321, 324, and 325, were used in this study. Various field checks and recent ice baths indicate that the temperatures measured with cables 320 and 321 are accurate to within ± 0.1°C. Less information is available on cables 324 and 325 but their accuracy is expected to be about the same.

Before passing to a detailed discussion of the data, some pertinent general considerations will be outlined briefly. During the rotary drilling of a well, heat is transferred by conduction between the fluid and the wall-rocks of the hole in an amount dependent upon the relative temperatures of the two media, their physical properties, and the configuration of the surface that separates them. The loss of circulating drilling fluid in permeable rocks can result in the convective transfer of additional heat to large radial distance. The heat of hydration of injected cement provides another source of artificial disturbance of the thermal regime associated with drilling. After the cessation of drilling the temperatures at all depths return asymptotically to their predrilling values, although the rate of return is generally different for each depth (Lachenbruch and Brewer, in press). When studying the natural thermal regime from temperature measurements made in drill holes it is important either to show that the drilling disturbance has decayed to negligible values or to correct for its effect.

Below the zone of appreciable annual temperature change (about 60 feet) the natural thermal regime is determined by the local topographic configuration and temperature history of the earth's surface, by conductive heat transfer from the earth's warm interior, and by convective transfer from the natural circulation of fluids through rock interstices and fractures. Even after the decay of the thermal disturbance due to drilling, the drill hole might introduce an artificial disturbance, inasmuch as it offers a new avenue for vertical circulation of natural fluids through the rock. In the ideal case of a flat isothermal earth surface underlain by homogenous rocks with no circulation of interstitial fluid, heat conducted from the earth's interior would result in a linear increase of temperature with depth with a negative gradient equal to the ratio of heat flow to the thermal conductivity of the rock. This is seen from the relation

conductive heat flow = thermal conductivity $\times$ thermal gradient.

The complicating effects of topographic irregularities, spacial variation in thermal properties, fluid circulation and climatic change can often be treated conveniently as corrections to this simplified picture.

A generalized interpretation of the natural thermal regime in the Rainier Mesa is shown in figure 1. It forms a convenient background for the more detailed discussion of individual installations that follows.

Drill hole UCRL-4

On September 9, 1957 thermistor cable 321 was installed in drill-hole UCRL-4 to a depth of 498 feet. The thermistors which are positioned at 50-foot intervals were read periodically until the cable was withdrawn on September 17 prior to the Rainier test. On October 22, 1957 thermistor cable 320 was installed to a depth of 498 feet and read periodically until January 17, 1958 at which time it was removed from the hole. To check the data for consistency the cable was raised 25 feet first on October 27, and again December 19. Thus each thermistor was read at three depths 25 feet apart.

Selected data from this installation are presented in figure 2. The constancy of temperature with time indicates that thermal equilibrium has been established within the limits of measurement accuracy. At depths greater than about 150 feet the gradient is relatively constant and equal to about 41°C/km. From figure 1 it is clear that in the vicinity of UCRL-4 horizontal planes are not isothermal owing chiefly to the upward conduction of heat in the nearby mesa. The observed gradient can be corrected for the effects of topography by passing a reference plane through the 150 foot depth and calculating the effects of horizontal temperature variation along it by the method of Birch (1950). The correction amounts to about 15 percent yielding a corrected gradient of about 35°C/km. Barring other sources of disturbance this is the gradient to be identified with the local outward flow of heat from the earth's interior. The departure of the profile

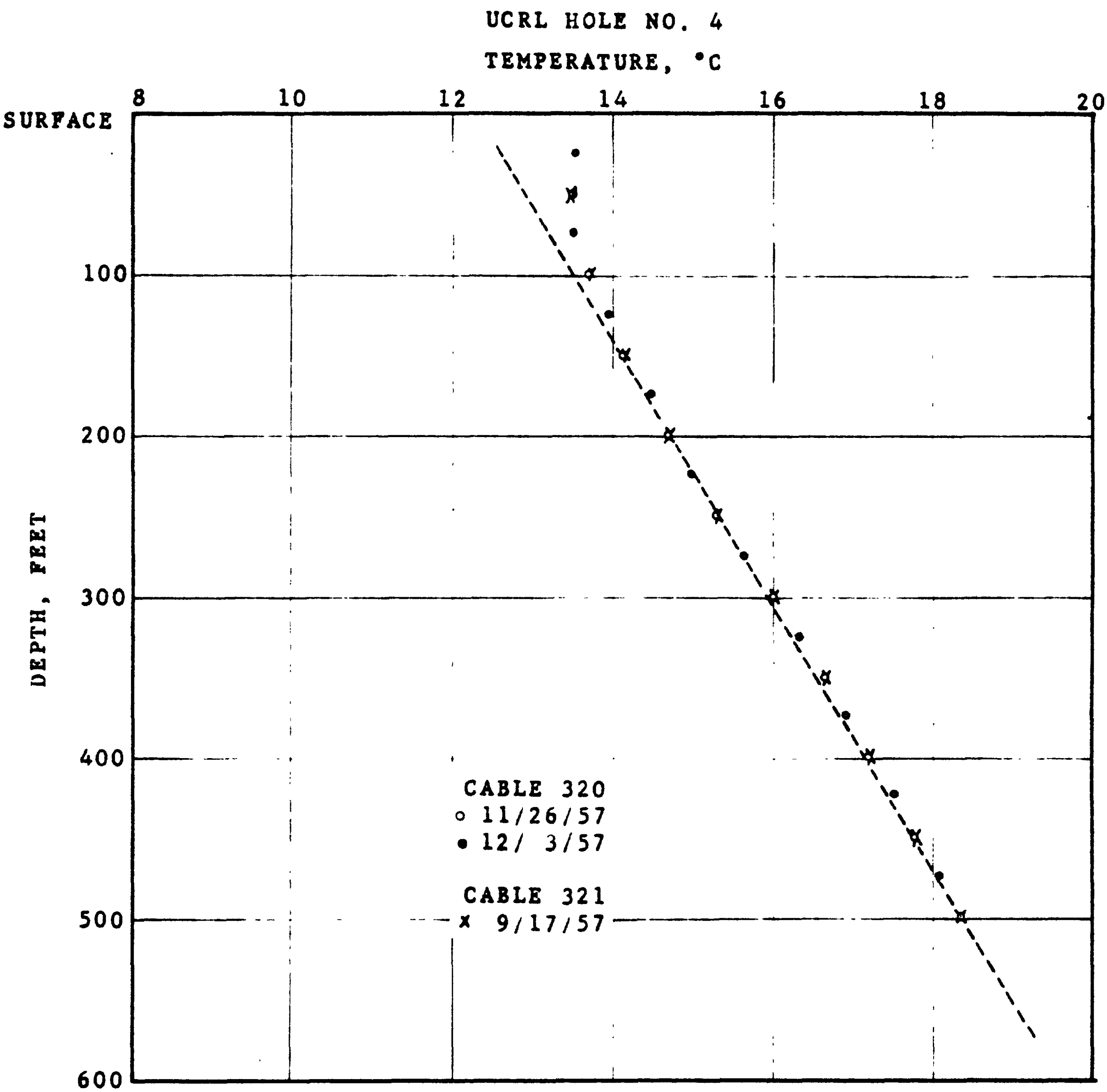

UCRL HOLE NO. 4
TEMPERATURE, °C
8
10
12
14
16
18
20
SURFACE
100
200
300
400
500
600
DEPTH, FEET
CABLE 320
○ 11/26/57
● 12/ 3/57
CABLE 321
× 9/17/57

FIGURE 2

at UCRL-4 from linearity in the 50- to 150-foot depth range could be caused by very local topographic effects, by vertical heat transport from near surface fluid circulation, or by a systematic climatic trend in the last decade. The details however are unimportant for the purpose of the present study. In any case the temperature at 50 feet is probably close to the mean annual surface temperature which we therefore take to be 13.4°C. This datum will be used later.

Hagestad drill hole

Drilling at the Hagestad hole commenced on July 13, 1957 and the final cementing was completed about three weeks later.

Cable 321 was installed to a depth of 812 feet on August 24, 1957. It was removed for bailing September 1, and reinserted to a depth of 802 feet on October 4. The cable was removed again for water sampling on December 19 and reinserted the same day. It was finally removed on January 18, 1958. On January 27, 1958 cable 324 was installed to a depth of 1,710 feet. This installation provided measurement points at 50-foot intervals between the depths of 710 and 1,710 feet.

From the selected data shown in figure 3, it is clear that the various operations associated with drilling created a sizeable thermal disturbance that was still appreciable throughout most of the upper 800 feet one year after drilling. In order to study the effects of this disturbance it is important to consider the probable temperature of the drilling fluid relative to the ambient temperature in the rock penetrated by the well. According to the Slumberger logs, the mud temperatures were about 19°C on August 1. Since this is probably close to the mean air temperature during the time of drilling, and since the water was stored in surface tanks and reservoirs, it is reasonable to assume that it is representative of fluid temperature throughout the operation. Thus as

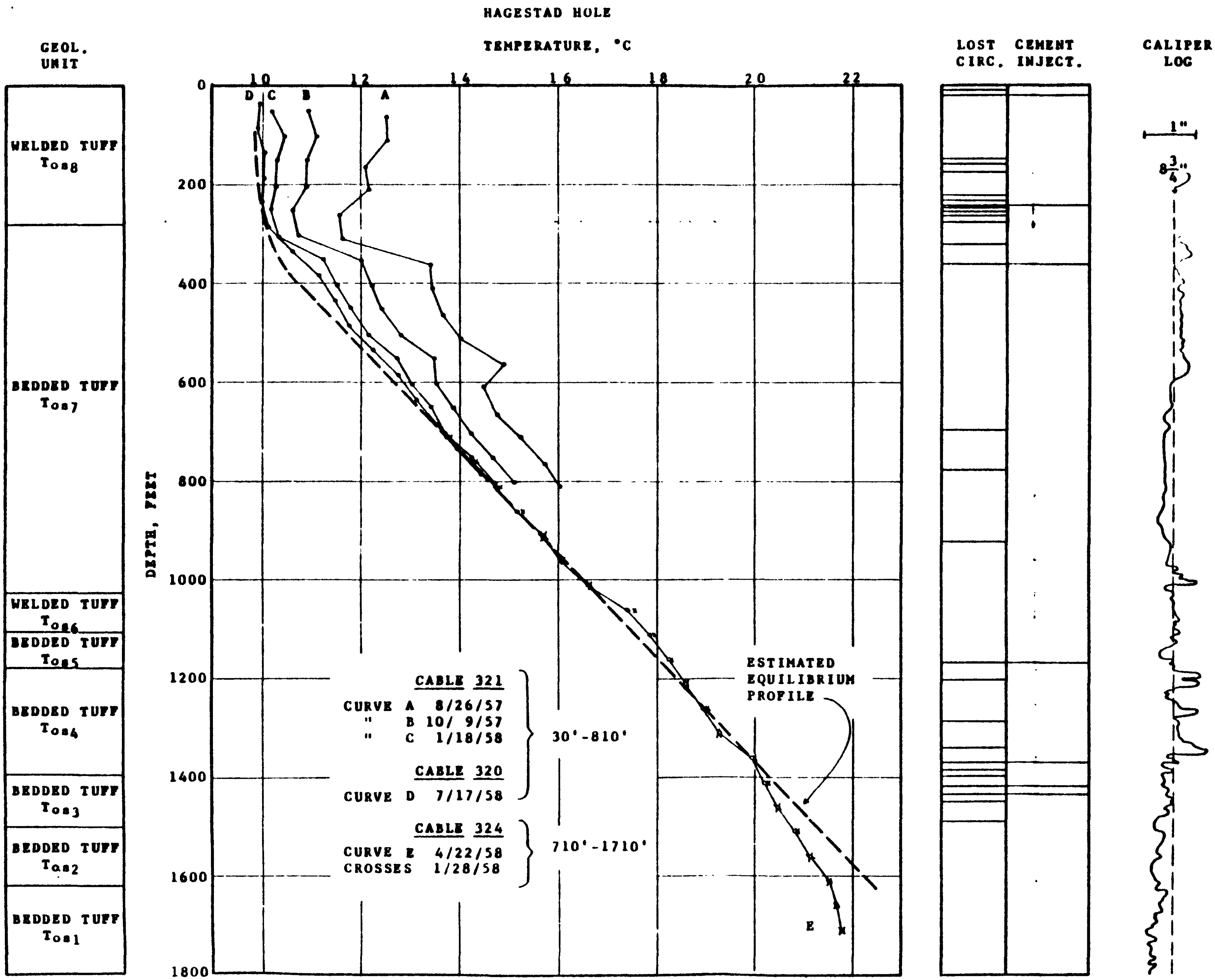

HAGESTAD HOLE
TEMPERATURE, °C
GEOL. UNIT
WELDED TUFF T_{os8}
BEDDED TUFF T_{os7}
WELDED TUFF T_{os6}
BEDDED TUFF T_{os5}
BEDDED TUFF T_{os4}
BEDDED TUFF T_{os3}
BEDDED TUFF T_{os2}
BEDDED TUFF T_{os1}
DEPTH, FEET
10 12 14 16 18 20 22
0 200 400 600 800 1000 1200 1400 1600 1800
D C B A
E
ESTIMATED EQUILIBRIUM PROFILE
CABLE 321
CURVE A 8/26/57
" B 10/ 9/57
" C 1/18/58
30'-810'
CABLE 320
CURVE D 7/17/58
CABLE 324
CURVE E 4/22/58
CROSSES 1/28/58
710'-1710'
LOST CIRC.
CEMENT INJECT.
CALIPER LOG
1"
8 3/4"

FIGURE 2

4a

the fluid traversed the hole it would be expected to warm the upper portion and possibly to cause cooling toward the bottom. At horizons where the fluid penetrated the walls larger volumes of rock would be disturbed and the rate of dissipation of the disturbance would be correspondingly slower. Roughly speaking, doubling the radius of the disturbed zone would increase the decay time of the thermal disturbance by a factor of four.

The heat of hydration of injected cement can also cause a lingering disturbance if the cement permeates the wall rocks to appreciable radial distances. Inasmuch as the cement is generally injected into horizons where the fluid loss is large, the two effects tend to augment one another at depths at which the fluid temperature is greater than ambient, and to appose one another at horizons where natural temperature is above that of the drilling fluid.

If none of the fluid or cement permeated the wall rocks, the thermal disturbance would be confined to relatively small radial distances and the drilling anomaly would probably be negligible by the time of the January 1958 readings (Lachenbruch and Brewer, in press). Thus it is likely that thermal anomalies in Hagestad hole which persist into 1958 occur at highly fractured or permeable horizons. A rough indication of the locations of these strata is provided by the records of lost circulation and cement injection. However for various reasons a large share of the fluid or cement lost to the formation might occur at horizons other than those indicated in such records. More continuous information is contained in the caliper log where highly fractured less competent beds generally correlate with intervals of anomalously large hole diameter (oral communication with D.J. Stuart). For this reason the caliper log, cementing and lost circulation records are all presented for correlation with the temperature in figure 3.

The dashed line in figure 3 represents an interpretation of the predrilling temperature based on measured temperatures and supplementary drilling information. Before discussing this equilibrium profile we shall consider the transient departures from it. From curves A, B, C, and D, figure 3, it is seen that the drilling disturbance was profound throughout most of the welded tuff unit which occupies the upper 280 feet. This was caused by the deep penetration of these highly fractured rocks by drilling fluid whose temperature was roughly 10°C greater than ambient, and to some extent perhaps, by the penetration of cement.

In the 240 to 340 foot depth interval the thermal anomaly is small which indicates that relatively little fluid was lost there. The lost circulation recorded for this interval probably entered the formation higher up, for according to the drilling records the cement injection at 230 feet did not succeed in sealing off the permeable zones.

A second zone showing pronounced effects of drilling heat lies between the depths of 340 and 580 feet. Lost circulation is recorded at the top of this zone and over 200 sacks of cement were injected about 40 feet lower. Although there is nothing in the drilling record to further define this zone, the thermal evidence suggests that an excessive circulation loss occurred throughout it, and hence that the rocks were probably highly fractured. This conclusion is supported by the caliper log in which this interval is characterized by an anomalously wide hole (see fig. 3).

The lack of early temperature data for depths greater than 800 feet makes it difficult to interpret the details of the drilling disturbance at depth. However the region from 600 to

1,000 feet probably suffered only a minor disturbance. For according to the present interpretation most of the drilling effects were dissipated by the time of the January readings.

In the region from 1,000 to 1,200 feet the temperatures decreased slightly from January to April 1958 indicating that this hump in the curve is probably a lingering transient effect of drilling. At the top of this zone is a welded tuff unit whose low acoustic velocity suggests that it is intensely fractured. It might have received a lot of drilling fluid which at that depth was probably only slightly warmer than the wall rock. The rocks of this zone might also be disturbed by absorption of the cement injected at the 1,170-foot depth. The circulation loss recorded at 1,200 feet probably correlates with the anomaly in the caliper log at that depth but the thermal disturbance was evidently minor since the ambient temperature at 1,200 feet was about the same as the temperature of the drilling fluid.

Below 1,200 feet the drilling fluid probably cooled the rocks with the effect becoming more pronounced with increasing depth. The hump in the curve in the vicinity of the 1,400-foot depth may represent the superimposed warming effect of the injection of more than 150 sacks of cement.

The persistence of the negative anomaly below 1,400 feet is puzzling, for if it were due solely to transient drilling effects, we would expect to observe some recovery over the three month period for which observations are available. Since this zone is probably below the water table, drilling fluid penetrating the formation there might be expected to stagnate, whereas higher up it might drain off. This effect would make the decay of the drilling effect slower at depth, but great quantities of interstial drilling fluid would be required to produce the effect observed. It should be noted in this connection that lost circulation was recorded at 4 horizons below 1,800 feet.

It is also possible that a continuing circulation of water through casing perforations is responsible for the thermal anomaly below 1,400 feet. Such perforations occur near 1,000 feet and 1,900 feet. According to the Haliburton test, the formation pressure at 1,900 feet was capable of raising the fluid only a few hundred feet, and water flowed from the perforations at 1,000 feet. If this flow continued the fluid level would rise to some equilibrium height, probably between the depths of 1,400 and 1,600 feet, and thereafter it would flow out at the 1,900 foot level at the rate at which it was being supplied at the 1,000 foot level. Such circulation could result in depressed temperatures at depth.

The straight line used to represent the predrilling temperature below 400 feet is based on the assumption that the thermal conductivity does not undergo large systematic changes, and that the vertical component of natural fluid circulation is unimportant. With the possible exception of the lower few hundred feet, departures from this straight line seem to be reasonable consequences of the thermal effects of drilling. If the rocks below 1,400 feet were saturated and those above were dry, it might seem reasonable to explain the change in gradient at this depth by a 50 percent increase in thermal conductivity. Information contained in other chapters of the present report obviates this alternative however.

The vanishing gradient in the upper 300 feet is evidently due to downward percolation of surface water, and perhaps air circulation, through the highly fractured welded tuff unit (Tos_8). Presumably the convective heat transport by such fluid movement completely dominates the steady conductive flow upward. An alternative explanation for this feature is a systematic climatic warming in the last century but such a hypothesis is inconsistent with data from UCRL-4.

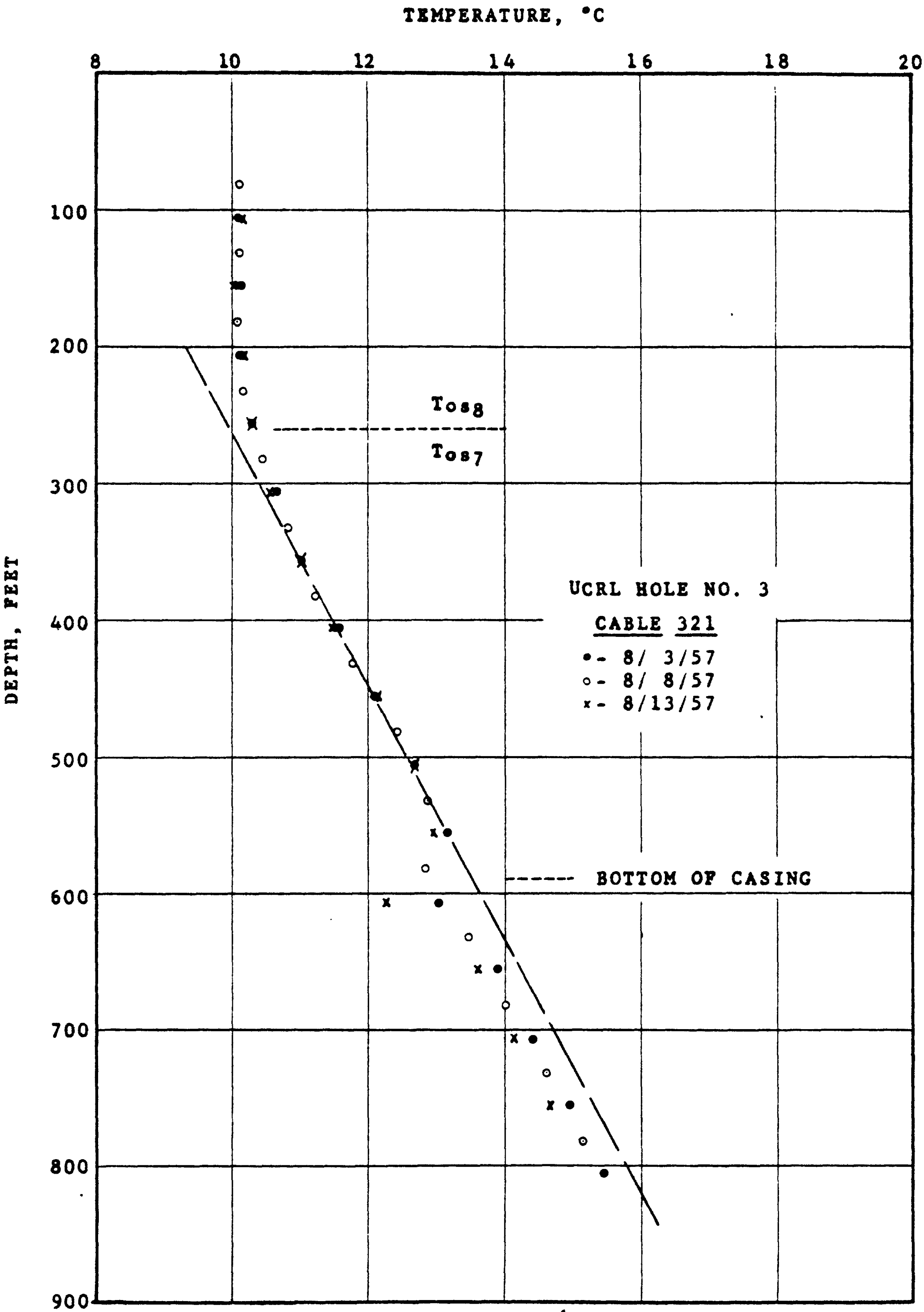
The gradient of the straight line drawn on figure 3 is about 31°C/km. The effects of topographic relief are negligible at this installation.

Drill hole UCRL-3

Cable #321 was installed in drill-hole UCRL-3 to a depth of 806.5 feet on July 27, 1957. It was raised 25 feet on August 7 and removed after reading on August 8, prior to an HE shot of a few tens of pounds in the U12-C tunnel which is about 1,500 feet from UCRL-3. The cable was installed again to a depth of 756.5 feet on August 12 and finally removed on August 22.

From the data presented in figure 4 it is probable that the thermal effects of drilling were no longer significant at the time of measurement at UCRL-3. As in the Hagestad hole the thermal gradient vanishes in the welded tuff unit Tos_8, presumably because of the active circulation of natural fluids in the fractures. After a thin transition zone the temperatures increase almost linearly to some depth between 560 and 580 feet. At this horizon there is a striking offset of about 3/4°C followed by a roughly linear increase to the 800-foot depth.

The large local gradients associated with the offset in the 560 to 580 foot zone could be maintained only by convective heat transfer associated with moving fluids. It is possible that at or near this horizon the hole intersects an inclined brecciated zone along which fluid, probably air, is



TEMPERATURE, °C
8
10
12
14
16
18
20
DEPTH, FEET
100
200
300
400
500
600
700
800
900
Tos8
Tos7
UCRL HOLE NO. 3
CABLE 321
• - 8/ 3/57
o - 8/ 8/57
x - 8/13/57
BOTTOM OF CASING

FIGURE 4

9a

moving downward and passing into the hole at the bottom of the casing. (The presence of the casing adds uncertainty to the exact location of this hypothetical fracture.) In order to sustain the circulation pattern it is necessary of course that the fluid leave the hole at greater depth. The downward component of such circulation would cause the fluid to be absorbing heat at all depths to produce the cooling effect observed. In support of this hypothesis it will be noted that prior to the high explosive blast on August 8, the temperatures were not changing with time. However on August 13, the first observation after the blast (x's in figure 4), a pronounced thermal disturbance was observed at and below the region of the temperature offset. Subsequent observations show that the disturbance dissipated slowly and travelled downward in the well. It is possible that the blast resulted in a temporary increase in flow along the hypothetical brecciated zone, and an attendant increase in heat transport by the moving fluid.

The thermal gradient defined by the measurements in the 350 to 550 foot interval is about 35°C/km, but this is probably influenced slightly by the irregular configuration of the surface in the vicinity of the installation. Before this topographic effect can be calculated it is necessary to know how the mean annual surface temperature varies with altitude. From the data from Hagestad hole and UCRL-3, the mean annual temperature at the mesa top is probably about 10°C and from observations at UCRL-4, it is probably close to 13.4°C about 1,000 feet lower in elevation. If we assume that the variation is linear, the mean annual surface temperature decreases about 1°C for every 300 feet increase in elevation. Thus the mesa bluff would be slightly warmer than the rocks interior to the mesa at horizons within 400 feet of the mesa top, and cooler at horizons more than 400 feet from the top. This is illustrated in figure 1. If we add to these, the assumption that the mesa bluff is not retreating actively, the maximum topographic correction to the gradient is about 10 percent. This leads to a corrected gradient of about 38°C/km.

Drill hole at Ranier ground zero

On January 28, 1958 cable 325 was installed in the ground zero hole which was drilled from the top of the mesa 14 feet from the vertical projection of the point of detonation for the Rainier shot. For this installation temperature elements were distributed throughout the depth range from 225 to 845 feet, with the bottom element about 55 feet above the point of detonation. On July 7, 1958 the cable was raised 15 feet and readings were continued.

According to information provided by H. W. Oliver, drilling of the ground zero hole began on October 18, 1957, about one month after the Rainier shot, and was completed on December 6. Fishing operations for equipment lost in the hole continued through most of January 1958. Although this hole is less than 1,000 feet deep the duration of the drilling disturbance was probably twice as great as at the Hagestad hole, and comparable amounts of drilling fluid were lost to the formation. Thus for the most recent temperature observation, August 1958, the time elapsed since drilling is not large relative to the duration of the distrubance, and it is not yet possible to separate in detail the many possible causes of thermal disturbance.

In the previous section it was concluded that the temperatures measured in the upper 560 feet at UCRL-3 were close to their equilibrium values but that those in the lower

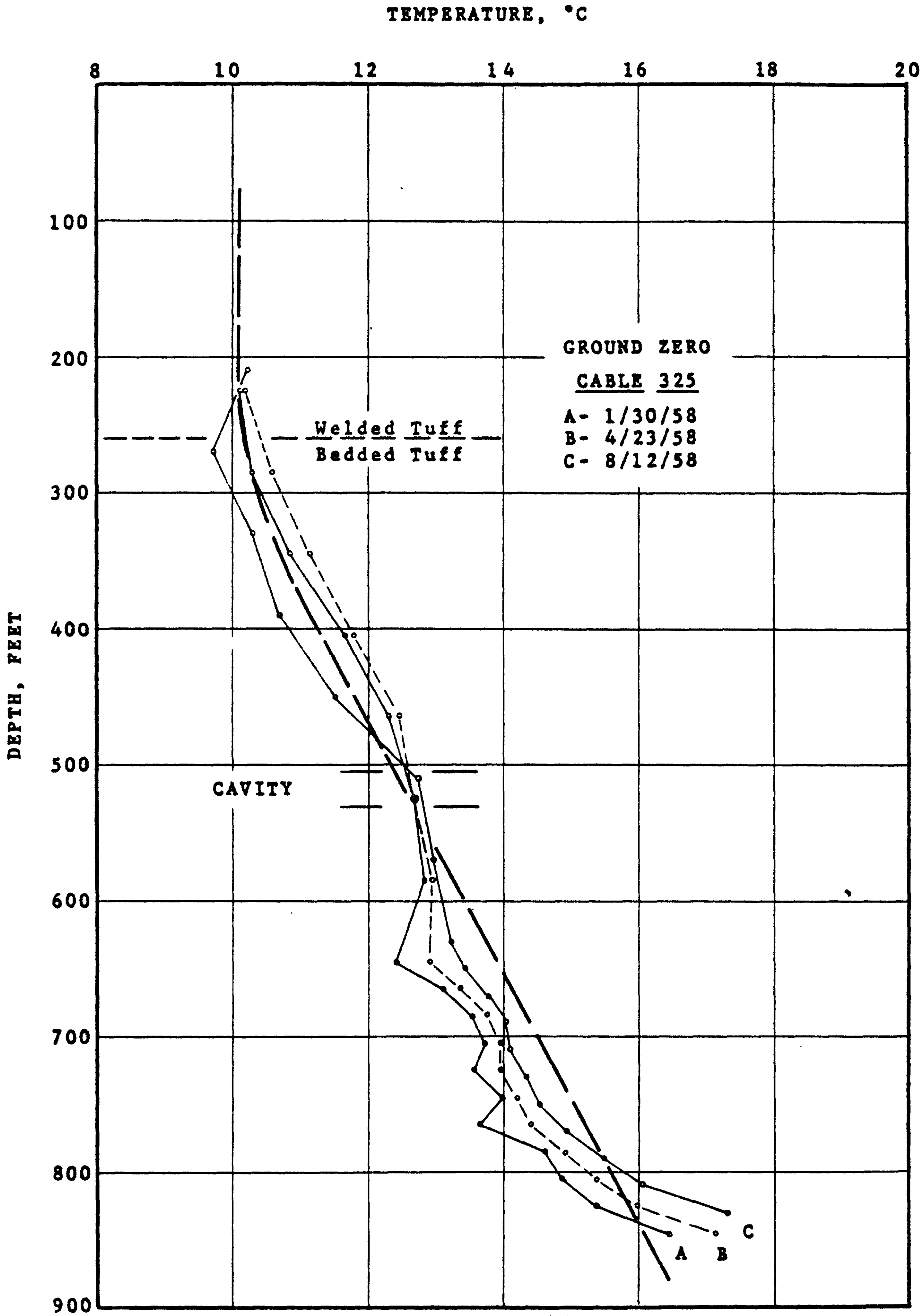

TEMPERATURE, °C
8
10
12
14
16
18
20
DEPTH, FEET
100
200
300
400
500
600
700
800
900
GROUND ZERO
CABLE 325
A- 1/30/58
B- 4/23/58
C- 8/12/58
Welded Tuff
Bedded Tuff
CAVITY
A
B
C

FIGURE 5

11a

portion of the hole were disturbed by a local circulation pattern. A reasonable estimate of the predrilling regime at UCRL-3 can be obtained by linear extrapolation downward of the stable portion of the profile. Such a curve is represented by the heavy dashed line in figure 5. Inasmuch as UCRL-3 and the ground zero hole are only 100 feet apart this curve provides a reasonable estimate of the equilibrium regime in the ground zero hole, and serves as a basis for interpretation of the transient effects.

It is seen from figure 5 that the thermal behavior at ground zero is distinctly different above and below the cavity which is known to occur in the interval from 505 to 531 feet.—/ Between the depth of about 250 feet and the cavity the temperatures vary in an erratic manner from day to day as is shown in figure 6. Such rapid temperature changes could be produced only by a moving fluid, most likely air, for the large heat capacity of water would probably obviate such rapid fluctuations. If this circulation were a simple effect of density instability in a closed system, the temperature would be anomalously high in the upper portion of the interval and low in the lower portion. From figure 6, it is seen that at any instant, practically all depths are either anomalously cool or anomalously warm, and hence the fluid must be entering and leaving the system. Since there are no openings in the casing between the surface and a depth of 845 feet, and the anomaly is confined to the 200 to 550 foot interval, the circulation is not taking place within the

—/The point of reference for the depth measurements in the thermal studies is the ground surface which is about 8 feet below the reference point used in drill records. Thus according to the drilling records the cavity occurs between the depths of 513 and 539 feet.

casing. Thus the effect must be caused by air circulating in the annulus outside of the casing; entering and leaving at different levels. From the thermal data one of these levels is evidently between the measurement points at 224 and 284 feet and the other near the top of the cavity. In support of this point of view it is noted that above the 249 foot depth all or most of the annulus outside of the casing was filled with cement. This horizon is only a few feet above the base of the highly fractured welded tuff cap rock (Tos_8). Thus the air is evidently entering or leaving the system at the base of the cap rock. As mentioned in the discussions of UCRL-3 and the Hagestad hole, thermal evidence indicates that fluid circulates freely throughout this welded tuff cap rock unit. According to the thermal evidence the other level at which fluid leaves or enters the annulus must be near the 500 foot depth. Thus air movements in the annulus could be the result of "breathing" of the cavity in response to changes in atmospheric pressure. An alternative possibility is that air is leaving or entering the system along a transverse fracture near the 500-foot depth. It will be recalled that independent thermal evidence indicated air circulation along such a hypothetical fractured zone at a depth of about 575 feet in UCRL-3. It is likely that these two fractures correlate and that UCRL-3 and the ground zero hole intersect the same inclined fractured zone at a different horizons. Correcting for difference in ground elevation at the installations, the two points on the fracture differ in elevation by about 100 feet and are horizontally removed by 100 feet. Thus the fractured zone would dip away from the mesa bluff at an angle of 45° or more depending on its strike. Further evidence for the presence of such a fractured zone is provided by the existence of the cavity immediately below it. If, as has been postulated, this cavity resulted from collapse following the Rainier shot, it is likely that it would occur beneath a zone of cohesive weakness. These details however are less important than the evident generalization that active circulation of air is probably taking place through fractures deep within the Oak Springs tuff.

No fluid returned to the surface during the drilling of the portion of the hole from the cavity to the bottom at 912 feet. Thus large amounts of water probably penetrated the wall rocks in this interval. Inasmuch as the drilling occurred in late fall and early winter, the fluid temperature was probably close to the mean annual surface temperature of 10°C, or well below the ambient rock temperature at depth. Thus the drilling might be expected to produce a lingering negative temperature anomaly, and this is in fact observed throughout most of the lower portion of the hole. At the time of the last observation its magnitude was probably on the order of ½°C. The pronounced negative anomaly for early observations near the 650 foot depth probably represents excessive fluid loss associated with a blowout recorded for this horizon. The superimposed hump at the 685 foot level probably correlates with cementing of the 4 inch casing at that horizon.

An anomalous increase in temperature and gradient occurs below about 770 feet. In fact the most recent observation at the 830 foot depth yielded a temperature about 1½°C greater than the estimated equilibrium value (indicated by the heavy dashed line, figure 5). This anomaly evidently represents thermal energy from the Rainier shot of September 19, 1957. The point of detonation was at a depth of 899 feet relative to the reference point used for the temperature measurements, and it was offset horizontally about 15 feet. The manner in which this positive anomaly is increasing with time suggests that it represents a delayed effect of the type to be expected when the heat is transmitted from the source by conduction. It is clear from figure 5 that this warming was well-defined at the time of the first reading, about 4½ months after the shot. On August 12, about 11 months after the shot, the thermal anomaly seems to have penetrated to the 770 foot horizon or about 130 feet from the shot point. If the energy was transmitted from the point of detonation solely by thermal conduction theoretical considerations indicate that its effect would not be measurable at a radial distance of 130 feet for several years. In fact if the anomaly observed on August 12 at the 830 foot depth were produced instantaneously by non-conductive transfer at the time of detonation, no observable conductive effect would be expected 11 months later at the 770 foot level. Thus these highly preliminary considerations suggest that temperatures near the bottom of the thermal cables are being effected by conductive energy transfer from the direction of the Rainier chamber, but that at the time of detonation measurable amounts of energy were transferred by non-conductive means to distances on the order of 100 feet. The picture is thoroughly complicated by the thermal effects of drilling since large quantities of thermal energy liberated by the device were probably removed from the system permanently by cool drilling fluid that left the hole and percolated through the tuff. It should be possible to abstract more precise and more reliable information from this installation if observations are continued until after the thermal effects of drilling are dissipated.

Outward earth heat flow

The quantity of heat flowing outward toward the earth's surface and its regional variations are important geophysical quantities which are imperfectly known. Therefore wherever sufficient geothermal information is available it is worthwhile to attempt an estimate of earth heat flow. The Nevada Test Site is of particular interest because this locality is in a region of typical basin and range structure and hence is probably representative of a sizable portion of the continental crust in the United States.

The determination of the heat flow consists of two steps. First we must find the natural geothermal gradient undisturbed by the effects of topography, climatic change or fluid circulation. Second the thermal conductivity of the rocks in their natural state must be found. The product of these two quantities is the natural linear earth heat flow. In the preliminary state of the present study considerable uncertainty is attached to the estimate of both the gradient and the conductivity.

The gradient estimated for the Hagestad hole was about 31°C/km based primarily on measurements in the 700 to 1,000-foot depth interval. At UCRL-3 the gradient was estimated to be 38°C/km after adding a correction of 10 percent for the effects of terrain. The measurements at this site were stratigraphically higher than in Hagestad, but in the same lithologic unit, Tos_7. At UCRL-4 the gradient was about 35°C/km after subtracting 15 percent for the estimated effects of terrain. The stratigraphic units concerned at this site are Tos_1 and Tos_2. The terrain corrections applied to UCRL-3 and 4 are rough approximations which do not take account of topographic details or effects of the finite rate of erosion of the mesa bluff. They indicate the direction and order of magnitude of the expected effect and this is all that is warranted by the available data. For the purpose of the present discussion we can say that the gradients range between 30 and 40°C/km with a mean near 35°C/km.

Laboratory measurements of the thermal conductivity of cores taken from the Oak Springs tuff have been made by Keller and are reported in Chapter 6 of this report. He has measured the conductivity of the samples both in a saturated and dry condition. From the electric log information, however, it seems reasonable that the conductivities in the natural state will be closely approximated by the values for saturated samples. For wet samples the following mean values were given:

Tos_7 $1.63 \pm .33 \times 10^{-3}$ cal cm^{-1} sec^{-1} $°C^{-1}$

Tos_2 $1.36 \pm .25 \times 10^{-3}$

No measurements are available for the unit Tos_1. Considerable variation was found within lithologic units as well as from one unit to the next. However, judging from the linear trend of the temperature profiles, intra-unit variations evidently "average themselves out" over distances of a few tens of feet. In UCRL-4 no significant change of gradient was noted at the boundary of units Tos_1 and Tos_2. Thus a statistical approach to the conductivity is probably justified for the purpose of the present rough approximation. The conductivities of bedded Oak Spring tuff determined in the Silver Spring laboratory and reported in Chapter 6 seem to be somewhat higher than Keller's values, with a mean for samples near saturation of about 2.7×10^{-3} cal cm^{-1} sec^{-1} $°C^{-1}$. This is the same as the mean of 4 measurements on bedded tuff (Tos_7) made in situ in the Rainier tunnel by Lillard with a probe of the type described by Lachenbruch (1957). The three lithologic units involved in this discussion (Tos_1, Tos_2 and Tos_7) are all classified as bedded tuff in contradistinction to friable or welded tuff. Thus we have three sources of information on the conductivity of bedded Oak Spring tuff. Keller's measurements, which are by far the most comprehensive, suggest that it might average 1.36 to 1.63 $\times 10^{-3}$ cal/cm^{-1} sec^{-1} °C^{-1} locally. The Silver Spring measurements (six samples) and the in situ measurements (four tests) each suggest a mean conductivity of about 2.7 $\times 10^{-3}$ cal/cm^{-1} sec^{-1} °C^{-1}. Only one of the 37 tests on saturated bedded tuff reported by Keller in figure 6-3 of this report yielded a conductivity as large as the mean of the Silver Spring and in situ measurements. Hence there is evidently a discrepancy between the two sources. Using a thermal gradient of 35°C/km, with Keller's values for conductivity we obtain an earth heat flow of about ½ microcalorie per cm^2 sec. The same gradient applied to the Silver Spring and in situ measurements yields slightly under 1 microcalorie per cm^2 sec. The latter value is within the range of values considered "normal" for the continental crust. Further work should lead to a more precise evaluation of this quantity.

Acknowledgments

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