TEMPERATURES IN SOME SPRINGS AND GEYSERS IN YELLOWSTONE NATIONAL PARK

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HISTORICAL NOTE

The discovery of the springs and geysers in the wonderful region now known as Yellowstone National Park was made in or about the year 1806 by John Colter (or Coulter), who left the Lewis and Clarke expedition to go back to the head waters of the Missouri River to hunt and trap. In 1844, James Bridger, a noted Rocky Mountain guide, described the wonderful springs and geysers, but his stories, like Colter's, were discredited by journalists who refused to believe such remarkable tales. In the meantime, rumors of a somewhat reliable character came from army officers, prospectors, and other private parties, but no authentic information seems to have been obtained until 1869 when Messrs. Cook and David E. Folsom published a report in the *Lakeside Monthly* of Chicago.

In 1871, a geological and geographical survey of the region was begun by F. V. Hayden, who was so impressed with its wonders that he immediately suggested to Congress the desirability of setting aside the area for a national park. This was done by Act of Congress on March 1, 1872. Hayden continued the survey in the summer of 1872 and again in 1878.

[1] Published with the permission of the Acting Director, U.S. Geological Survey.

Hayden's reports[1] for the years 1871, 1872, and 1878 contain elaborate records of the temperatures in the springs and geysers. The observations were made chiefly by Dr. A. C. Peale. Subsequently a few observations were reported in 1888 by Gooch and Whitfield,[2] and more recently (1909) Schlundt and Moore[3] included a few observations in their report on the radioactivity of the thermal waters in the Park.

DATA OF OBSERVATION

The observations tabulated in Table I were made during the interval July 7–18, 1922. Two maximum thermometers were used. One of them recorded with an accuracy of 0.1 to 0.3° F.; the other one had been in use for a long time and occasionally recorded too low, sometimes to the extent of 1.0° F. The observations with the second thermometer were used merely as a rough check on the readings with the first thermometer. The thermometers were exposed directly to the water at a depth of about 1 foot. They were removed slowly from the water and held for a short time just above the surface. This precaution may or may not be necessary in general, but it was found that some thermometers fail to break the mercury column at the proper point when cooled quickly. The Rangers of the National Park Service made a great number of observations for me, working independently and using one of the two thermometers with which the tests were made. These independent observations provide additional assurance that errors due to manipulation have been practically eliminated.

[1] F. V. Hayden, *Fifth Ann. Rept., U.S. Geol. Survey of Montana and Portions of Adjacent Territories*, 1871; *Sixth Ann. Rept. U.S. Geol. Survey of the Territories*, pp. 1–187, 1872; *Twelfth Ann. Rept., U.S. Geol. and Geographical Survey of the Territories*, Part 2, pp. 1–503 ("Yellowstone National Park"), 1878 (Section II, "Thermal Springs," pp. 63–426, by A. C. Peale.)

See also A. C. Peale, "Lists and Analyses of the Mineral Springs of the United States," *U.S. Geol. Survey Bull. 32*, p. 184, 1886.

[2] F. A. Gooch and J. E. Whitfield, "Analyses of Waters of the Yellowstone National Park," *U.S. Geol. Survey Bull. 47*, 1888.

[3] H. Schlundt and R. B. Moore, "Radioactivity of the Thermal Waters of Yellowstone National Park," *U.S. Geol. Survey Bull. 395*, pp. 23–24, 1909.

TABLE I

OBSERVED TEMPERATURES

(Distances are estimated)

Name	Observed Temperature Cent.	Observed Temperature Fahr.	Air Temperature Cent.	Air Temperature Fahr.	Remarks
	Mammoth Hot Springs				
Angel Terrace	71.3	160.3	20.6	69	Algae
Jupiter Terrace	71.3	160.3	21.7	71	Algae. Reading July 7, 1922
Same	71.2	160.2	22.2	72	Reading July 18, 1922
None	71.4	160.5	8.9	48	A new spring about 700 feet southwest from main spring of Jupiter Terrace. Reading July 8, 1922
Same	71.8	161.2	22.2	72	Reading July 18, 1922
None	72.0	161.6	22.8	73	60 feet southwest from Devil's Thumb. Source of spring beneath shell of calcium carbonate
	Norris Geyser Basin				
None	91.9	197.4	11.1	52	About 400 feet from camp; 500 feet from hotel. Water bubbles about 1 foot above level
None	91.4	196.6	11.7	53	Spring on small stream, about 200 feet from preceding spring. Muddy water. Quartz grains
None	90.0	194.0	13.9	57	Geyser south of hotel. About 4 feet in height. Water muddy, lime color. Observed temperature probably too low as it was impossible to hold the thermometer in a fixed position
None	90.5	194.9	15.6	60	Spring, bubbling about 1 foot above level. Location about 50 feet east of preceding geyser
None	84.0	183.2	13.9	57	Spring. 100 feet west of highway; 400 feet south of hotel
None	90.0	194.0	13.3	56	Spring about 100 feet from Arsenic Spring; 250 feet from Constant Geyser; 180 feet from Hurricane Pool
None	92.2	197.9	16.7	62	Spring; 100 feet south of Onyx Spring
None	89.1	192.3	16.1	61	Spring; 50 feet south of Onyx Spring
Onyx Spring	87.7	189.9	15.0	59	Intermittent, height about 18 inches. Pool about 20 feet diameter
None	87.8	190.0	14.4	58	Spring in Porcelain Basin; 80 feet from Onyx Spring. Water light blue. Intermittent, bubbles 2 feet in height, pool 10 feet diameter
None	90.0	194.0	12.8	55	Spring near edge of Porcelain Basin. Water blue
Whirligig Geyser	87.7	189.9	16.1	61	Water clear; height 20 feet. Diameter of pool 20 feet
Tea Kettle	89.3	192.7	18.3	65	Spring and slanting geyser; both intermittent. Old vent of Whirligig Geyser
Constant Geyser	86.7	188.1	11.7	53	Intermittent, height 40 feet; diameter of pool about 35 feet
Hurricane Pool	90.6	195.0	10.6	51	Water light blue. Diameter of pool about 50 feet. 90 feet from Hurricane Spring or underground river
None	92.2	197.9	12.8	55	Spring of clear water, about 100 feet from Hurricane Spring and about 50 feet from floor of basin. 8 feet diameter
None	90.1	194.1	13.9	57	Mud spring, 2 feet diameter. On floor of basin about 100 feet from Mud Geyser
Mud Boiler	93.5	200.3	16.1	61	Spring, adjacent to and connected with Mud Geyser
Baby Growler	91.8	197.2	14.4	58	Spring of muddy water about one-third distance up the slope and about midway between Mud Geyser and Black Growler
None	86.1	187.0	21.7	71	Spring in pool, 20 feet in diameter. Location, 100 feet east of Congress Pool.
Black Growler	85.5	185.9	23.3	74	Steam and probably some gas escaping from vent about 3 inches by 7 inches. No water

TABLE I—*Continued*

Name	Observed Temperature Cent.	Observed Temperature Fahr.	Air Temperature Cent.	Air Temperature Fahr.	Remarks
					Norris Geyser Basin—*Continued*
None	67.2	153.0	33.3	92	Pool 25 feet in diameter, bubbling gently. Location, 90 feet east of Minute Man Geyser
None	93.2	199.7	23.9	75	Small spring from fracture in rock. Location, about 225 feet from Monarch Geyser and 450 feet from Minute Man Geyser. Monarch Geyser bubbling very feebly
Fearless Geyser	93.1	199.6	18.3	65	Clear water, bubbling gently. Pool about 25 feet in diameter
None	93.3	199.9	18.3	65	Spring of black mud. Location, near center of first large basin east of highway
None	84.9	184.8	18.3	65	Spring of white mud. Location, near preceding spring
None	93.4	200.2	17.8	64	White mud spring, black on edges. Bubbling violently. Location, near preceding spring
Bath Tub Spring	92.3	198.1	20.6	69	Clear water
Emerald Spring	89.6	193.3	17.2	63	Clear water
Cinder Pool	92.1	197.8	18.9	66	White mud and cinders. Location, on 100 Spring Plain. Pool about 40 feet in diameter
None	92.2	198.0	16.7	62	Spring of clear water. Diameter of pool about 20 feet. Location, about 250 feet west of Cinder Pool
None	90.1	194.1	16.7	62	Sulphur Spring in rock fracture on north edge of One Hundred Spring Plain
Beryl Spring	91.1	196.0	14.4	58	Bubbling violently. Location, west side of highway, about 5 miles southwest from Norris Ranger Camp. Elevation 7,296 feet
					Lower Geyser Basin
Mammoth Paint Pots	94.9	202.8	23.3	74	
None	93.4	200.1	23.3	74	Spring of gray mud, 12 inches diameter, 6 feet deep. Location about 70 feet north of Mammoth Paint Pots
None	80.6	177.1	25.6	78	Spring bubbling gently. Intermittent. Diameter of pool, 6 feet. Location, west of Paint Pots, on dome which measures about 100 feet at base
None	92.9	199.2	25.6	78	Intermittent, but bubbling actively at time of test. Diameter of hole 8 inches. Location about 10 feet from preceding spring
None	93.3	199.9	25.6	78	Spring on highest point of lower basin, 300 feet west of Mammoth Paint Pots. Goes dry. Activity just beginning when test was made. Clear water
None	87.7	189.9	30.0	86	Spring in pool, 25 feet diameter. Location, about 1,000 feet west of Fountain Hotel
None	92.6	198.7	30.0	86	Second test of preceding spring. Flow discontinued immediately after test was made
None	88.4	191.2	28.9	84	Spring of clear water bubbling moderately in pool 25 feet in diameter. Location, about 1,200 feet west of Fountain Hotel. This and the two following springs are at the vertices of a triangle. The side from the first to the second measures 60 feet, from the second to third 40 feet, from the third to the first 30 feet
None	92.7	198.8	27.2	81	Spring bubbling violently. Diameter 8 inches
None	92.6	198.6	27.2	81	Spring bubbling violently. Diameter 12 inches
Clepsydra Geyser	91.8	197.3	30.0	86	Silica
Jelly Geyser	91.5	196.7	35.0	95	Silica; test made at first appearance of water
Jet Geyser	93.1	199.6	32.8	91	Silica; water flows from small hole in large fracture
Prismatic Lake	65.4	149.8	30.0	86	Test about 15 feet from shore line
Excelsior Geyser	89.6	193.3	27.8	82	Thermometers placed in bubbling water near edge of pool about 400 feet in diameter. Level of the water is about 20 feet below the surface of the ground

TABLE I—*Continued*

Name	Observed Temperature Cent.	Observed Temperature Fahr.	Air Temperature Cent.	Air Temperature Fahr.	Remarks
					Upper Geyser Basin
Blue Star	85.0	185.0	22.8	73	No bubbling
None	91.3	196.3	26.1	79	Bubbling gently. 5 feet diameter. 30 feet from Chinaman; 50 feet from shore of Firehole River, 40 feet above level of Firehole River
Chinaman	93.4	200.1	22.8	73	Bubbling moderately
None	93.7	200.7	23.3	74	Spring in rock fracture about 300 feet from Beehive in line with Butterfly Geyser. Bubbling rapidly
Giantess Geyser	93.7	200.7	24.4	76	Pool 30 feet diameter. Bubbling gently and intermittently
Tea Kettle	93.9	201.1	23.9	75	
Vault	83.3	181.9	23.9	75	Quiescent
Butterfly Geyser	91.7	197.0	24.4	76	Bubbling moderately at one point on edge of 12 foot pool. Eruptions probably discontinued
Topaz Spring	95.1	203.1	24.4	76	6 feet diameter. Bubbling
Doublet Pool	90.2	194.4	24.4	76	Quiescent
Algous Pool	93.1	199.6	25.0	77	5 feet diameter. Bubbling freely from fracture in rock
Ear	94.3	201.7	23.3	74	Pool 4 feet by 8 feet, bubbling moderately on one side
Tortoise Shell	96.2	205.1	21.7	71	At base of Castle Geyser. Bubbling violently. Silica
Crested Pool	93.6	200.4	22.2	72	25 feet in diameter. Bubbling very feebly
Big Cub	93.9	201.0	26.7	80	Cone 3 feet high; 2 feet in diameter at top. Silica
Lioness	94.5	202.1	23.3	74	Cone 2 feet high; 6 feet diameter. Silica
Burning Pool	90.4	194.8	28.3	83	Test immediately after eruption in Grand Geyser
Burning Pool	92.7	198.9	28.3	83	Spouting 5 feet, large volume of water
None	94.0	201.2	25.0	77	Spring, bubbling gently, 60 feet from Bulger; 50 feet from Witches Cauldron
Bulger	92.8	199.0	24.4	76	Bubbling pool, 4 feet by 7 feet
Witches Cauldron	94.1	201.4	24.4	76	Silica cone, 2 feet diameter on inside
Churn	93.6	200.4	24.4	76	Narrow cone on edge of left bank of Firehole River
Spasmodic	94.0	201.2	27.2	81	
None	93.9	201.0	27.2	81	2 feet diameter; 30 feet from center of Spasmodic
Economic Geyser	73.9	165.1	28.9	84	Almost extinct. Algae
Saw Mill Geyser	88.9	192.1	28.9	84	In eruption
Beauty Spring	79.3	174.8	29.4	85	Quiescent. 60 feet diameter
Chromatic Spring	88.2	190.8	26.7	80	Quiescent
Ink Well Spring	93.3	200.0	25.0	77	Right bank of Firehole River
Oblong Geyser	94.3	201.8	27.2	81	Pool 15 feet by 40 feet; bubbling moderately on edge
Giant Geyser	94.8	202.7	26.7	80	Bubbling violently 26 hours after eruption Cone 12 feet high, broken on one side; 6 feet inside diameter
Mastiff Geyser	94.4	201.9	30.0	86	30 feet from Giant Geyser
Rocket	93.7	200.7	27.8	82	50 feet from Grotto Geyser. Cone 5 feet high. Bubbling water, 12 feet below top of cone
Grotto Geyser	93.9	201.0	26.7	80	Cone 8 feet high, very irregular. Bubbling water, 12 feet from top of cone
Spa	89.5	193.1	25.6	78	Spring. 8 feet by 15 feet
None	82.5	180.5	25.6	78	Quiescent pool, 50 feet diameter. Location about 100 feet from bridge over Firehole River. and about 1,000 feet southwest from Spa on the opposite side of the highway
Riverside Geyser	94.0	201.2	32.8	91	
None	88.8	191.8	25.0	77	Bubbling pool 6 feet diameter, 250 feet from Spa on opposite side of the highway
Morning Glory Pool	77.6	171.6	25.6	78	30 feet diameter. Quiescent
Fan Geyser	93.6	200.5	26.7	80	Possibly extinct. Bubbling at end of pool 5 feet by 12 feet

TABLE I—*Continued*

Name	Observed Temperature		Air Temperature		Remarks
	Cent.	Fahr.	Cent.	Fahr.	
					Upper Geyser Basin (Black Sand Basin)
Daisy Geyser	86.9	188.4	28.3	83	Surface drainage
Comet Geyser	94.2	201.6	28.3	83	
Splendid Geyser	93.3	199.9	30.0	86	
Brilliant Pool	89.3	192.7	30.0	86	
Punch Bowl Spring	93.8	200.8	28.3	83	12 feet diameter, bubbling on edge. Silica
None	93.4	200.2	28.3	83	Bubbling spring 2 feet diameter, 50 feet southwest of Punch Bowl Spring
Black Sand Pool	92.9	199.3	28.9	84	40 feet diameter, quiescent
None	85.3	185.5	32.2	90	Quiescent spring, 400 feet east of Black Sand Pool. At bottom of hole
Spouter	93.3	199.9	30.0	86	25 feet diameter. Bubbling violently
None	93.0	199.4	30.0	86	Bubbling spring 12 inches in diameter, 30 feet from Spouter
Rainbow Pool	71.7	161.0	25.6	78	
Handkerchief Pool	84.1	183.4	25.6	78	
Emerald Pool	68.1	154.6	32.2	90	
Cliff Spring	88.8	191.8	32.2	90	
Three Sisters	82.2	179.9	28.9	84	Middle pool
Old Faithful Geyser	93.4	200.1	16.1	61	Temperature of steam at depth of about 10 feet. No variation in temperature could be detected over an interval of about 40 minutes
					Thumb
None	85.4	185.8	21.1	70	Pool 30 feet in diameter bubbling gently near the edge. 80 feet south of Paint Pots. Clear water
Paint Pots	93.2	199.8	22.2	72	
None	93.2	199.8	23.3	74	Pool 30 feet diameter, bubbling in center and near edge. 90 feet from shore of lake and 120 feet from Lake Shore Geyser
Lake Shore Geyser	92.6	198.6	21.1	70	Behavior very erratic
Fishing Cone	76.9	170.4	20.0	68	
None	91.7	197.1	18.9	66	Pool 30 feet in diameter about one-fourth mile north of Fishing Cone
None	93.9	201.0	18.3	65	Pool 30 feet in diameter. About 40 feet from highway
Tom Thumb	92.8	199.1	20.6	69	Reading probably too low on account of violent bubbling
None	94.6	202.3	18.3	65	Small spring adjacent to Tom Thumb
					Mud Geysers (About 4 miles south of Crater Hills)
None	49.6	121.3	17.2	63	Spring in pool 25 feet by 60 feet. 150 feet from Mud Volcano
None	47.1	116.7	26.7	80	Mud spring near pool 150 feet in diameter
None	68.9	156.0	28.3	83	Near preceding spring
None	65.1	149.1	25.6	78	Spring, 4 feet from edge of pool. 150 feet in diameter
None	65.5	149.9	26.7	80	Spring in 150 foot pool, 5 feet from edge
None	79.6	175.2	23.9	75	Mud Spring about midway between Dragon's Mouth and Mud Volcano
None	81.3	178.4	28.9	84	Mud spring, 4 inches in diameter, near preceding
None	84.9	184.8	19.4	67	Mud spring, 3 inches diameter, 200 feet from Mud Volcano
None	86.6	187.9	18.9	66	Mud spring, near preceding spring
Mud Volcano	86.6	187.8	23.9	75	Source of flow inaccessible
Dragon's Mouth	76.8	170.2	30.6	87	Source of flow inaccessible

The location of the geyser and spring localities in the Park is shown on the map, Figure 1.

COMPARISON OF DATA OF OBSERVATION

Table II is a comparison of observed temperatures by four different observers. Hayden's maximum value of 165° F. at the Mammoth Hot Springs is 3.4° F. in excess of my maximum value of 161.6° F. The difference is so small that no particular significance can be attached to it. The higher temperatures obtained by Schlundt and Moore in the Excelsior Geyser and by Gooch and Whitfield in both the Constant and Excelsior geysers are probably due to the selection of different points in these large pools for the tests. The temperature of the Constant Geyser undoubtedly varies between eruptions. My observed values exceed those of the other observers in the remaining eighteen observations. This result might perhaps be interpreted as an increase in the temperature of the rocks from which the waters obtain their heat. The methods and conditions of measurement, however, seem to me to preclude such an inference. The agreement of the observed temperatures in Old Faithful Geyser is of marked significance.

In the years 1883 and 1884, the late Professor W. H. Hallock made a detailed study of the temperatures in the Giantess Geyser. An unpublished report prepared for the United States Geological Survey contains the statement that the temperature of the water at the surface varies from 90° C. (194.0° F.) to 93° C. (199.4° F.). Another statement is to the effect that the temperature at the surface sometimes rises 1.2° F. above the normal boiling-point of 199° F. The latter value of 200.2° F. is in close agreement with my observed value of 200.7° F. at a depth of about 12 inches, due account being taken of Professor Hallock's value of 0.70° F. for the rate per foot at which the temperature increases with the depth near the surface of the water. The fact that the difference between the two readings is only 0.2° F. is probably accidental as a variation of 0.5 inch in the height of the barometric column produces a change of about 1° F. in the boiling-point. Furthermore, Professor Hallock found an excess of 0.9° C. (1.6° F.) by boiling water from the geyser in a metal vessel.

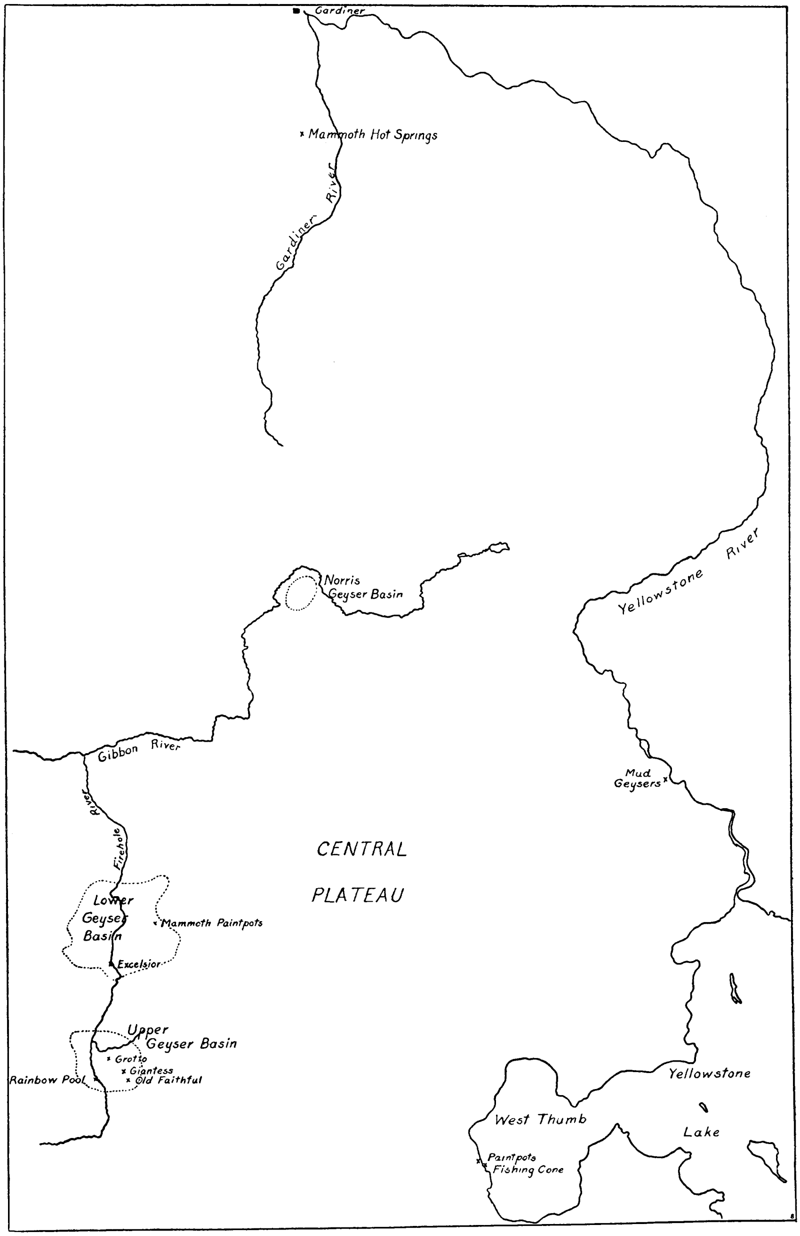

FIG. 1.—Outline map showing the principal geyser and spring localities in the Yellowstone National Park. Scale, 1 inch = 7 miles or 1 cm = 2.8 miles (approx.)

TABLE II

COMPARISON OF OBSERVED TEMPERATURES

Name	Hayden	Gooch and Whitfield	Schlundt and Moore	Present Paper	Remarks
	1872–78	1883–86	1906	1922	
	°F.	°F.	°F.	°F.	
	Mammoth Hot Springs				
None	92–162	137.0–152.6	89.6–159.8	160.2–161.6	Hayden report 1872
None	63–165	....	....	....	Hayden report 1878
	Norris Geyser Basin				
Constant Geyser	....	197.6	....	188.1	The thermometer used by Schlundt and Moore was not self-registering
Fearless Geyser	....	190.4	....	199.6	
Porcelain Basin	....	....	123.8–152.6	190.0–194.0	
Clepsydra Geyser	192	....	....	197.3	
Excelsior Geyser	....	197.6	197.6	193.3	
Jet Geyser	195	....	....	199.6	
	Upper Geyser Basin				
Bulger	189	....	....	199.0	
Giant Geyser	194	....	....	202.7	
Giantess Geyser	199	199.4	....	200.7	
Grotto Geyser	198	....	....	201.0	
Handkerchief Pool	....	....	179.6	183.4	
Oblong Geyser	195	....	....	201.8	
Old Faithful Geyser	200	183.2–190.4	190.4	200.1	Gooch and Whitfield observed temperature of water which had collected in pools on the surface of the ground at Old Faithful Geyser
Saw Mill Geyser	176–185	....	....	192.1	
Spasmodic	193	....	....	201.2	
Splendid Geyser	....	199.4	....	199.9	
Vault	172	....	....	181.9	
	Thumb				
Fishing Cone	160	....	....	170.4	
Paint Pots	132–190	....	....	199.8	
Springs near Yellowstone Lake	130–191	....	....	185.8–199.8	

COMPARISON OF THE OBSERVED TEMPERATURES WITH THE THEORETICAL BOILING-POINT

Table III gives the elevation as a function of the boiling-point. It is an auxiliary table for use in interpolating the theoretical boiling-point for any desired elevation. The table is based on the "Smithsonian Meteorological Tables,"[1] 1918.

TABLE III

RELATION BETWEEN THEORETICAL BOILING-POINT AND ELEVATION ABOVE SEA-LEVEL

Theoretical Boiling-Point (°F.)	Mean Temperature of Air. Latitude 44°–45° 50° F. Elevation Feet	80° F. Elevation Feet
185	15,351	16,382
186	14,755	15,746
187	14,160	15,113
188	13,570	14,482
189	12,980	13,851
190	12,393	13,225
191	11,809	12,601
192	11,224	11,977
193	10,642	11,357
194	10,065	10,741
195	9,487	10,124
196	8,912	9,510
197	8,337	8,898
198	7,768	8,289
199	7,198	7,682
200	6,632	7,077
201	6,068	6,475
202	5,502	5,872
203	4,942	5,273
204	4,383	4,677
205	3,828	4,085
206	3,270	3,490
207	2,718	2,900
208	2,166	2,310
209	1,617	1,725
210	+1,069	+1,142
211	+ 523	+ 559
212	− 19	− 20
213	− 561	− 601

[1] Smithsonian Institution, *Smithsonian Misc. Coll.*, Vol. LXIX, No. 1. Washington, D.C., 1918.

The boiling-point of the water at the surface of a spring is of course controlled by the pressure actually existing at that surface, and therefore fluctuates with the barometer. A change of 1 mm. of mercury height corresponds to 0.037° C. or 0.067° F. in the boiling-point. This variation is superposed upon the differences in the normal boiling-point which accompany differences in elevation. Under constant weather conditions, such as may exist for several days at a time, the variations in boiling-point over an area such as the Park are due principally to the differences in elevation of the springs above sea-level.

Table IV is a comparison of the observed temperatures with the theoretical boiling-points of pure water interpolated from Table III. According to Tables 58 and 73 of the 1905 edition of Landolt and Börnstein's *Physikalisch-Chemische Tabellen*, the addition of 14.78 gm. of sodium chloride to 100 gm. of water raises the boiling-point 2.4° C. (4.3° F.) when the boiling-point of pure water is 200° F. It appears from this result that the elevation of the boiling-points in the springs and geysers due to dissolved constituents is a negligible quantity, for the amount of dissolved solids reported by Gooch and Whitfield[1] from the areas in which my observations were made varies from 268 to 1,869 parts per million; the corresponding elevation of the boiling-point must therefore be a small fraction of a degree, certainly less than 0.5° F. As the elevations are not known with certainty, two values have been selected with the object in view of establishing upper and lower limits between which the true values must fall. An excellent check on my interpolations from the map has been supplied by C. H. Birdseye, Chief Topographic Engineer of the United States Geological Survey, who placed some unpublished records of elevations at my disposal. With the exception of the data on Beryl Spring, all of the data tabulated in the remarks column, Table IV, have been supplied by Mr. Birdseye. His value at the Mammoth Hot Springs is slightly less than my minimum value, but the difference is so small that the resulting evaluations are the same.

[1] *Op. cit.* See F. W. Clarke, "Water Analyses from the Laboratory of the United States Geological Survey," *U.S. Geol. Survey Water-Supply Paper 364*, pp. 17–24, 1914.

TABLE IV

COMPARISON OF OBSERVED TEMPERATURES WITH THEORETICAL BOILING-POINTS

Number of Springs and Geysers	Elevation (Feet)	Observed Temperatures (°F.)	Theoretical Boiling-Point Mean Air Temperature 50° F.	Theoretical Boiling-Point Mean Air Temperature 80° F.	Average Theoretical Boiling-Point (°F.)	Remarks
	Mammoth Hot Springs					
4.....	6,300 6,400	From 160.2 to 161.2	200.6 200.4	201.3 201.1	200.8	Elevation of sign post near Devil's Thumb, 6,264 feet
1......	6,264	161.6	200.7	201.4	201.0	
	Norris Geyser Basin					
12.....	7,400 7,500	From 197.2 to 200.3	198.6 198.5	199.5 199.3	199.0	Elevation of sign post at Norris Junction, 7,463 feet
1......	7,296	196.0	198.8	199.6	199.2	Elevation marked on post at Beryl Spring, 7,296 feet
	Lower Geyser Basin					
9.....	7,200 7,300	From 197.3 to 202.8	199.0 198.8	199.8 199.6	199.3	Elevation of threshold of main entrance to Fountain Hotel, 7,245.59 feet
	Upper Geyser Basin					
36.....	7,300 7,400	From 196.3 to 205.1	198.8 198.6	199.6 199.5	199.1	
1......	7,341	200.1	198.7	199.6	199.2	Elevation of sign post near Old Faithful Geyser, 7,341 feet
	Thumb					
7.....	7,700 7,800	From 197.1 to 202.3	198.1 197.9	199.0 198.8	198.5	Elevation of sign post at junction of roads at West Thumb, 7,773 feet
	Mud Geysers					
3.....	7,700 7,800	From 184.8 to 187.9	198.1 197.9	199.0 198.8	198.5	

The terraces are at a considerable distance above the base of Devil's Thumb, consequently my minimum estimate of 6,300 feet elevation for this region must be sufficiently accurate for the purpose intended. All of the remaining elevations contained in Mr. Birdseye's list fall between the upper and lower limits which I have adopted. The fourth and fifth columns of Table III thus give the limiting boiling-points for both elevation and temperature of air column. An average of the four quantities thus tabulated must give a very close approximation to the true boiling-point. These quantities are given in column six.

A comparison of these theoretical values with the observed shows that the temperatures of a great number of the springs and geysers at Norris Basin, Thumb, and the Lower and Upper Geyser basins are a little lower than, equal to, or slightly higher than the temperature of the boiling-points at the respective localities. The temperatures in the Mammoth Hot Springs are 40° F. below the boiling-point; in the Mud Geysers, 11° F. below.

It is impossible to obtain correct readings in Mud Volcano and Dragon's Mouth. The true temperatures there are undoubtedly above the boiling-points although the temperatures in small springs in the immediate vicinity are quite low in comparison with the temperatures in similar outlets in other parts of the Park.

Some of the springs and geysers discharge into large pools. The temperatures of these flows are obviously too low. In some of them, the water is agitated so violently that it is impossible to obtain a correct reading with a maximum thermometer. Beryl Spring, about 5 miles southwest from the Norris Geyser Basin, and a spring near the highway at Thumb, known by the Rangers as Tom Thumb, are good examples of this kind of thermal activity.

According to my observations and computations, the temperature of the steam discharged from Old Faithful Geyser is 0.9° F. above the boiling-point. Hayden obtained a difference of 1.0° F. My values, 203.1° F. in Topaz Spring and 205.1° F. in the Tortoise Shell at the base of Castle Geyser, both in the Upper Geyser Basin, are abnormally high. My results may be in error although there are no indications that such is the case. The abnormal values may be attributed, possibly, to superheated steam or to some of the

numerous anomalies to which the boiling-point is subject—such as the variation in barometric pressure, the removal of dissolved air by continuous boiling, and numerous other causes.[1] The removal of dissolved air, for example, may raise the initial boiling-point of a body of water to more than 270° F.

Peale[2] states that a number of his observed temperatures are above the boiling-point. A temperature of 209° F. was found in a sputter hole of the North Group of the Shoshone Geyser Basin.

Professor Hallock found from an extended series of observations that the temperature of a spring near the Giantess Geyser was usually 1.35° C. (2.4° F.) higher than the theoretical boiling-point. Springs of this kind are easily recognized by their peculiar surfaces and by the small bubbles of steam that rise singly to the surface and burst after a lapse of time. As these springs are in a state of unstable equilibrium, violent ebullition is induced, oftentimes, apparently without any cause. A small stick or a few grains of sand thrown into the pool will start the boiling process. As soon as boiling begins the temperature drops to normal. A very small gust of wind is frequently a sufficient cause, but a cold wind may prevent boiling altogether.

CAUSE OF FLOW IN SPRINGS AND GEYSERS

Flow in springs which have temperatures below the boiling-point is supposed to be caused by convection, hydrostatic pressure, and possibly by the pressure of confined gas or gas developed in small quantities by chemical reactions. Certain flows in Norris Geyser Basin may perhaps be attributed in part to gas pressure for the reason that the discharge from Black Growler apparently consists of gas other than water vapor which is discharged under considerable pressure. No water flows from this outlet.

The mechanism of geyser discharge was explained in a general way by Bunsen,[3] who based his deductions on his observations of temperatures in the Great Geyser of Iceland. Observations were made to a depth of about 80 feet in the geyser tube. The observed

[1] See Thomas Preston, *The Theory of Heat.* Section II, "Evaporation and Ebullition." Third ed., by J. R. Colter. New York: Macmillan Co., 1919.

[2] F. V. Hayden, *op. cit.*, p. 422 and p. 285, report of 1878.

[3] F. V. Hayden, *op. cit.*, pp. 418–421, report of 1878.

temperatures approached the boiling-point at a depth of about 40 feet. Bunsen inferred from these observations that hot water rises gradually from great depths in the geyser tube until it reaches a point where the pressure is sufficiently released to produce boiling. Bunsen believed that the construction of a sinter cone or any other process that raised the level of the water at the mouth of the geyser would ultimately produce sufficient pressure to prevent the formation of steam and thus cause a geyser to be transformed into a spring. Jaggar[1] has shown by detailed experiment that Bunsen's conclusion is not necessarily correct. He proves that it is possible to have two kinds of discharge, continuous and spasmodic, each operating under the influence of hydrostatic pressure. The flow of hot water is continuous and no steam is developed until the sinter cone reaches a certain height; at this point sufficient pressure is produced to confine the steam. An explosion ultimately results, ejecting large volumes of water and steam.

The two types of discharge are illustrated in the sketches A and B, Figure 2. Sketch A represents a geyser of the Excelsior type in which water from source (*b*) is discharged continuously at the lower level (*a*) after being heated by the hot rocks at great depths. In the Old Faithful type of geyser, Sketch B, the outlet (*d*) is higher than the source (*b*). The additional force required to lift the water through the vertical height (*bd*) is provided by the development of steam at some point (*f*), Sketch B, either by release of pressure in the ascending water column or by the addition of heat due to convection in case the column stands temporarily at a fixed level such as (*e*), Sketch B. Jaggar shows that it is possible to have a continuous flow with a reversed head, a condition brought about by first establishing continuous flow, Sketch A, and then gradually lowering the hydrostatic level of the source (*b*) to (*c*) until it is a little below the level of the outlet (*a*). A delicate balance between thermal and hydrostatic forces is thus introduced as a result of the velocity head due to convection, and the diminished density of the rising column of water. Further lowering of the source (*c*) causes ebullition followed by an eruption of extraordinary violence. The eruptions, once started,

[1] T. A. Jaggar, "Some Conditions Affecting Geyser Eruption," *American Journal of Science* (4), Vol. V (1898), pp. 323–33.

continue so long as hydrostatic conditions remain unchanged. It is thus possible for a continuous flow to become intermittent and vice versa. Under natural conditions, changes in hydrostatic level are brought about by variation in mean level of ground water, by construction of cones, and by formation of new outlets.

Unless steam is developed so slowly at the lower levels that it cannot lift the water column, or unless the vent is so large that thermal equilibrium is not attained throughout its cross-section, the transmission of heat by convection must be a negligible quantity, as I

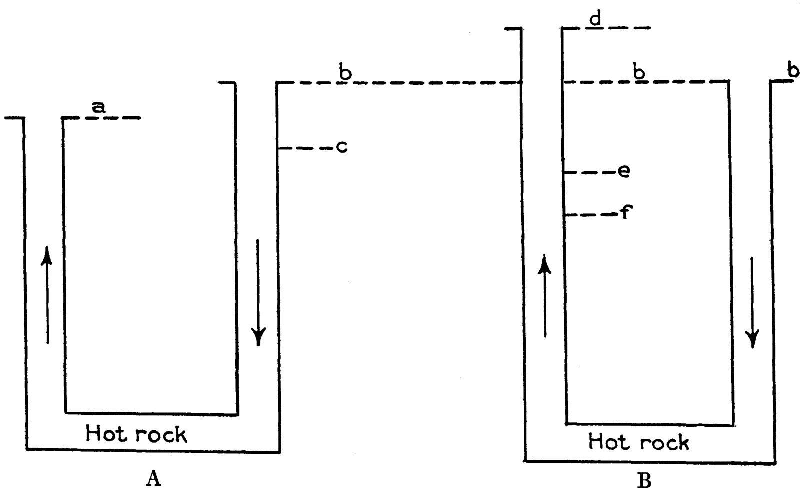

FIG. 2.—Diagram to illustrate two types of discharge in geysers and hot springs

have found no evidence of convection in deep wells whose diameters do not exceed 8 inches: a transverse section of the water column merely acquires the temperature of the rocks at that level. In steady flow, a steady thermal state is established between the water column and the adjacent rocks. A reduction in the velocity of the water increases the rate at which heat is transferred from the rocks to the water; conversely, an increase in the velocity diminishes the rate: the first condition tends to add to the reversed head described by Jaggar, the second to reduce it. Both effects are evidently eliminated in the course of time by a return to constant discharge.

Professor Hallock's elaborate observations in the Giantess Geyser established the fact that the temperatures of the water between

the depths of 30 and 60 feet fluctuate over a range of 5° C. (9.0° F.); furthermore the temperatures diminish with depth between the limits 45 and 60 feet. He concludes that there is a reservoir between the depths of 30 and 60 feet which is filled from a side entrance leading to a much larger reservoir at an assumed depth of about 250 feet. The water in the large reservoir is heated gradually to the boiling-point at that level when a preliminary eruption releases the pressure sufficiently to develop a considerable quantity of steam. The eruption thus initiated continues until the reservoir is practically exhausted.

DEPTH TO THE SOURCE OF THE EXTRANEOUS HEAT IN THE THERMAL WATERS

The extraneous heat in the springs and geysers in Yellowstone National Park is undoubtedly due to intrusive lava masses. The depth at which the intrusives are located does not seem to be capable of very accurate determination. Schlundt and Moore[1] state that not more than 1 per cent of the heat required to produce the hydrothermal activity in the Park at present can be attributed to the radium content of the rocks in contact with the waters. The only remaining possibilities of a radioactive source are heat developed at very great depths, either at present or in the remote past. Pirsson and Schuchert[2] believe the source of the heat to be deep seated as evidenced by the hot springs and geysers on the shore of Yellowstone Lake, an immense body of cold water, 300 feet in depth, but bearing no trace of excess heat. Hague[3] reaches the conclusion that the superheated waters are situated only short distances below the surface. He says:

> The thermal waters of the Yellowstone National Park are characterized by frequent variations of temperature, progressive transitions in chemical composition, lack of uniformity in mode of occurrence, and shifting in points of discharge; in other words, they lack the essential characters of primitive waters derived from deep seated sources.

[1] *Op. cit.*

[2] L. V. Pirsson and C. Schuchert, *A Text Book of Geology*, Part I, p. 220. New York: Wiley & Sons, 1915.

[3] Arnold Hague, "The Origin of the Thermal Waters in the Yellowstone National Park," *Science*, Vol. XXXIII (April 14, 1911), pp. 553–68; *Bull. Geol. Soc. America*, Vol. XXII (1911), pp. 103–22.

As there are no deep wells in the Park, estimates of the depths to the heat sources must be based on temperature data obtained from springs and deep wells located in regions where lava flows and intrusives abound. A region resembling to a certain extent the conditions in the Park is found at Thermopolis, Hot Springs County, Wyoming, at a distance to the southeast of about 130 miles. Table V contains temperatures in three hot springs at Thermopolis. The

TABLE V

TEMPERATURES IN SOME HOT SPRINGS AT THERMOPOLIS, WYOMING

Big Horn				Black Sulphur				White Sulphur			
Depth		Observed Temperatures		Depth		Observed Temperatures		Depth		Observed Temperatures	
Meters	Feet	Cent.	Fahr.	Meters	Feet	Cent.	Fahr.	Meters	Feet	Cent.	Fahr.
0.0	0	7.2	44.9*	0.0	0	7.2	44.9*	0.0	0	7.2	44.9*
0.6	2	56.2	133.2	3.0	10	54.9	130.9	0.2	0.5	51.0	123.8
0.6	2	56.3	133.4	3.0	10	54.8	130.6	0.2	0.5	51.1	123.9
0.6	2	56.3	133.4	3.0	10	55.0	131.0	0.2	0.5	51.2	124.2
1.5	5	56.3	133.4	.....	.....	......	....	.....	.....	......	....

* Mean annual temperature interpolated from Climatological Data, U.S. Weather Bureau.

temperature of 133.4° F. in the Big Horn Spring, the hottest of the three, is approximately 28° F. lower than the temperatures in the Mammoth Hot Springs and about 70° F. lower than that of the springs and geysers in the remaining areas listed in Table I. A least-square adjustment of the data of the Garrett and McManigal flowing wells, Table VI (and VII), gives for the average gradient (b), the value

$$b = 0.1810^\circ \text{ F. per foot.}$$

$$1/b = 1^\circ \text{ F. in } 5.5 \text{ feet.}$$

Assuming this value of b, a mean annual temperature of 44.9° F., and an excess of soil temperature over air temperature of 1° F., the temperature of 133.4° F. is reached at a depth of 483 feet. The thermometers were lowered to the point of entrance of the water into the McManigal well; nevertheless the observed temperature may be too high on account of the possibility that the water percolates upward from greater depths. A more satisfactory estimate may be made from the data obtained from four non-flowing oil wells,

Table VIII, located on the Warm Springs anticline about 6 miles east of the Big Horn Spring. The wells range in depth from 895 to 945 feet. The average gradient deduced from the four wells is

$$b = 0.04768° \text{ F. per foot.}$$
$$1/b = 1° \text{ F. in } 21.0 \text{ feet}$$

The corresponding depth to the source of heat in the Big Horn Spring is 1,835 feet.

The preceding estimates are based on the assumption that no heat is lost by the water in transit from the source to the surface of the ground. The voluminous discharge of the Big Horn Spring no doubt justifies the assumption. My observations in the McManigal well, Table VI, show a loss of 1° F. in 370 feet. A considerable

TABLE VI

TEMPERATURES IN FLOWING WELLS AT THERMOPOLIS, WYOMING

F.S. McManigal Well. Location, East Side of Big Horn River, about ¾ Mile Northwest of Big Horn Springs, Thermopolis, Wyoming					W. B. Garrett Well. Location, West Side of Big Horn River, about 1 Mile Northwest of Big Horn Springs, Thermopolis, Wyoming				
Depth		Temperature		Gradient (b)	Depth		Temperature		Gradient (b)
Meters	Feet	Cent.	Fahr.	°F. per Foot	Meters	Feet	Cent.	Fahr.	°F. per Foot
0.0	0	7.2	44.9*	$b=0.2065$	0.0	0	7.2	44.9*	$b=0.1655$
3.0	10	49.6	121.3	$1/b=4.8$	144.8	475	51.4	124.6	$1/b=6.0$
6.1	20	49.6	121.3	....	144.8	475	51.4	124.5	....
30.5	100	50.1	122.2	....	......	......	......	......	....
30.5	100	49.9	121.8	....	......	......	......	......	....
112.8	370	50.1	122.2	....	......	......	......	......	....
112.8	370	50.2	122.3	....	......	......	......	......	....

* Mean annual temperature interpolated from Climatological Data, U.S. Weather Bureau.

volume of water was being discharged when the test was made. Observations in flowing wells in various parts of the United States show that the heat loss is practically negligible for moderate or rapid discharge, but for very low velocities, the water acquires almost the temperature of the rocks at the different levels. The two depth-temperature curves of the deep well at Astoria, Oregon (Fig. 3), prove this point conclusively. The first curve (*ab*) was obtained from observations made when the discharge of water was very small; the second (*cd*), after the flow had been discontinued for

TABLE VII

Temperature Gradients in Flowing Wells*

County and Town	No. of Wells	Range of Depth (Feet)	Gradient (b) (°F. per Foot)	Probable Error (r_b) $\times 10^5$	$1/b$ Feet per °F. (1)	(2)	(3)
			Colorado				
Alamosa, Alamosa	27	300–840	0.03273	88	30.5	29.9	30.8
Conejos, La Jara†	5	150–325	0.02102	339	47.6	44.6	45.7
Denver, Denver†	15	152–635	0.02024	125	49.4	51.6	50.0
Fremont, Florence†	5	800–1,650	0.03021	146	33.1	31.1	32.1
Lake, Leadville	1	400	0.05500	......	18.2	18.2	18.2
Larimer, Loveland	1	1,365	0.07546	......	13.3	13.3	13.3
Montrose, Montrose	1	825	0.02873	......	34.8	34.8	34.8
Otero, La Junta†	13	412–1,113	0.02624	93	38.1	36.0	37.2
Pueblo, Arkansas Valley	7	660–1,402	0.02186	117	45.7	42.5	44.3
Rio Grande, Del Norte	1	450	0.02222	......	45.0	45.0	45.0
Saguache, San Isabel†	17	126–800	0.03062	158	32.7	......	......
			Idaho				
Ada, Boise	4	424–600	0.07892	3,731	12.7	10.1	11.3
Canyon, Nampa	1	114	0.07982	......	12.5	12.5	12.5
Elmore, Cleft	1	450	0.05200	......	19.2	19.2	19.2
Lincoln, Bliss	1	483	0.03872	......	25.8	25.8	25.8
Nez Perce, Lewiston	3	100–314	0.04048	1,169	24.7	15.7	20.9
Owyhee, Central†	11	165–1,035	0.05604	350	17.8	......	......
			Montana				
Custer, Miles City	1	456	0.02610	......	38.3	38.3	38.3
Flathead, T. 22 N., R. 23 W.	6	232–274	0.16875	2,430	5.9	6.0	6.0
Sanders, T. 21 N., R. 24 W.†	6	52–275	0.11050	1,530	9.0	7.2	8.4
			Oregon				
Harney, Andrews†	6	75–150	0.23778	2,522	4.2	3.2	3.2
			Utah				
Beaver, Milford†	14	100–750	0.05644	337	17.7	15.9	15.3
			Washington				
Walla Walla, Walla Walla	3	563–611	0.02097	49	47.7	47.5	47.6
Yakima, T. 12 N., R. 20 W.	8	512–886	0.02932	110	34.1	......	......
			Wyoming‡				
Hot Springs, Thermopolis	2	370–475	0.18096	1,340	5.5	5.4	5.5

* N. H. Darton, "Geothermal Data of the United States," *U.S. Geol. Survey Bull. 701*, 1920.

† Other towns included.

‡ Observations by the author.

TABLE VIII

Temperature Gradients in Mines and Non-Flowing Wells*

County and Town	No. of Wells	Range of Depth (Feet)	Gradient (b) (°F. per Foot)	Probable Error (r_b) $\times 10^5$	$1/b$ Feet per °F. (1)	(2)	(3)	Remarks
Colorado								
Las Animas, Trinidad........	1	770	0.02247	......	44.5	44.5	44.5	
Washington, Akron..........	1	670	0.02090	......	47.9	47.9	47.9	
Montana								
Deerlodge, Anaconda†........	2	1,550–1,600	0.02140	126	46.7	46.6	46.7	Mines
Nevada								
Nye, Tonopah...............	3	600–780	0.03363	134	29.7	29.6	29.7	Mine
Storey, Virginia City.........	3	2,017–2,300	0.03238	15	30.9	30.9	30.9	Mine
Wyoming								
Park, Meeteetse.............	1	1,400	0.01786	......	56.0	56.0	56.0	
Weston, Cambria†...........	2	374–1,475	0.01087	581	92.0	37.3	62.5	
Colorado‡								
Fremont, Florence‡...........	3	2,400–3,000	0.02252	29	44.4	44.2	44.3	
Oregon								
Clatsop, Astoria..............	1	3,000	0.01647	......	60.7	60.7	60.7	
Harney, Burns...............	1	3,750	0.02515	......	39.8	39.8	39.8	Lava
Jackson, Medford............	2	725–899	0.02065	99	48.4	47.7	48.0	
Klamath, Klamath Falls......	3	625–1,000	0.03725	537	26.8	24.2	25.5	Lava
Malheur, Vale...............	1	1,295	0.04973	......	20.1	20.1	20.1	Lava
Washington								
Benton, Benton City.........	2	1,325–2,200	0.02285	4	43.8	43.7	43.7	Lava
Wyoming								
Carbon, Rawlins.............	4	1,500–3,000	0.01859	42	53.8	52.9	53.4	
Carbon, Rock River..........	3	2,700–3,000	0.01627	102	61.5	60.9	61.2	
Converse, Big Muddy........	4	2,500–3,250	0.02062	18	48.5	48.5	48.5	
Hot Springs, Grass Creek......	3	700–1,090	0.02046	27	48.9	48.6	48.8	
Hot Springs, Warm Springs....	4	895–945	0.04768	39	21.0	21.0	21.0	
Natrona, Salt Creek..........	10	1,430–2,240	0.02887	67	34.6	33.9	34.3	
Niobrara, Lance Creek........	3	3,000	0.02848	21	35.1	35.1	35.1	

* N. H. Darton, *op. cit.* † Other towns included.

‡ This and following observations by the author.

several weeks. A small flow of gas vitiates the results slightly, but the curve (*ab*) which represents the distribution of temperatures in the flowing water approximates very closely to the curve (*cd*) which represents the true temperatures of the rocks. Observation thus proves that the temperatures at the outlets of flowing wells and springs are dependent upon the velocity of flow; with a sufficiently high velocity, the depth-temperature curve (*a'b*) is practically parallel to the axis of depth, whereas with a very low velocity the temperature of the flowing water, curve (*ab*), differs but slightly from the temperatures of the rocks (*cd*). The maximum temperature attainable is the temperature of the source; the minimum approaches the mean annual temperature of the air at the point of observation; and any temperature falling between these upper and lower limits is a possibility.

In order to establish a more comprehensive basis for estimation of depth to the source of heat in Yellowstone National Park, the temperature gradients in mines, and in flowing and non-flowing wells have been summarized in Tables VII and VIII.

A complete report on the observations will be given in another publication. The gradient (*b*) in column (5) of the tables has been computed from the formula,

$$b=\frac{x_1\Delta y_1+x_2\Delta y_2+\ \ldots\ldots\ x_n\Delta y_n}{x_1^2+x_2^2+\ \ldots\ldots\ x_n^2}=\frac{\Sigma x\Delta y}{\Sigma x^2} \qquad (1)$$

wherein

x = depth in feet.

Δy = (observed temperature at depth x) − (mean annual temperature of air + 1° F.)

b = gradient expressed in degrees Fahrenheit per foot.

$1/b$ = reciprocal gradient expressed in feet per degree Fahrenheit.

r_b = probable error of b.

n = number of observations.

The quantity 1° F. is added to the mean annual temperature of the air in order to correct for the emissivity of the Earth's surface. The validity of this correction is to be discussed in a subsequent publication.

Formula (1) is based on the assumption that the increments in temperature (Δy) are of equal weight. My observations justify

this procedure since the error of an observation, say at 3,000 feet, does not differ materially from that at any other depth. Other investigators, however, have assumed that the gradients (b) instead of the increments in temperature (Δy) were of equal weight, and in some instances it has been assumed that the weights of the gradients are proportional to the depths. These two assumptions and the preceding assumption of equal weights are contained in the general formula

$$b=\frac{p_1x_1\Delta y_1+p_2x_2\Delta y_2+\ \ldots\ p_nx_n\Delta y_n}{p_1x_1^2+p_2x_2^2+\ \ldots\ p_nx_n^2}=\frac{\Sigma\, px\Delta y}{\Sigma\, px^2},$$

in which $p_1, p_2, \ldots\ p_n$ are the respective weights of Δy_1, Δy_2, $\ldots\ \Delta y_n$. Substituting

$$p_1=p_2=\ \ldots\ =p_n=1,$$

we obtain equation (1). Making the substitutions

$$p_1=\frac{1}{x_1^2},\qquad p_2=\frac{1}{x_2^2},\qquad \ldots\ p_n=\frac{1}{x_n^2}$$

$$p_1=\frac{1}{x_1},\qquad p_2=\frac{1}{x_2},\qquad \ldots\ p_n=\frac{1}{x_n},$$

we obtain respectively,

$$b=\frac{\dfrac{\Delta y_1}{x_1}+\dfrac{\Delta y_2}{x_2}+\ \ldots\ \dfrac{\Delta y_n}{x_n}}{n}=\frac{\Sigma\dfrac{\Delta y}{x}}{n} \qquad (2)$$

$$b=\frac{\Delta y_1+\Delta y_2+\ \ldots\ \Delta y_n}{x_1+x_2+\ \ldots\ x_n}=\frac{\Sigma\Delta y}{\Sigma x} \qquad (3)$$

Equation (2) represents the condition that the gradients, n in number, are of equal weight while equation (3) represents the condition that the weight of each gradient is proportional to the depth. The values of b have been computed from each of the formulas (1), (2), and (3). Their reciprocals ($1/b$) are tabulated in the columns designated (1), (2), and (3) in Tables VII and VIII. Ordinarily the differences between the values obtained by the different methods of computation are not large, but a number of rather marked

exceptions will be found in the tables. The magnitude of the differences varies somewhat irregularly with the probable error (r_b) of the gradient. The values of (r_b) tabulated in column 5 are the probable errors of the gradients tabulated in column 4.

Following are average gradients and their probable errors computed from all of the original observations on which Tables VII and VIII are based. Formula (1) was used in making these computations.

FLOWING WELLS

163 observations, $b=0.03413\pm0.00182$	$1/b=29.3$
159 observations, $b=0.03226\pm0.00126$	$1/b=31.0$
154 observations, $b=0.03189\pm0.00084$	$1/b=31.4$

MINES AND NON-FLOWING WELLS

57 observations,	$b=0.02389\pm0.00060$	$1/b=41.9$
31 observations	in 7 oil fields of Wyoming, $b=0.02358\pm0.00078$	$1/b=42.4$
26 observations	exclusive of oil fields in Wyoming, $b=0.02447\pm0.00094$	$1/b=40.9$
25 observations	exclusive of oil fields in Wyoming, $b=0.02395\pm0.00083$	$1/b=41.8$

MINES AND FLOWING AND NON-FLOWING WELLS

220 observations, $b=0.02600\pm0.00066$	$1/b=38.5$
216 observations, $b=0.02560\pm0.00052$	$1/b=39.1$
211 observations, $b=0.02531\pm0.00045$	$1/b=39.5$

Nine observations were ultimately rejected in accordance with Chauvenet's criterion in the first and last groups; one in the middle group. Comparison of the values of b in the different groups shows that the largest values of b are obtained from flowing wells. This result may be accidental or it may be due to some peculiar characteristic of flowing wells such as the rise of water from greater depths.

Estimates of the depth to the heat source in Yellowstone National Park based on the preceding values of the gradients are susceptible to an error which is peculiar to regions of intrusives and extrusives. A typical depth-temperature curve in regions of lava

flows is shown in Figure 4. We have here a combination of very steep and very flat gradients with abrupt changes from one to the other in marked contrast to the exceptionally uniform curve (*cd*) of the Astoria well shown in Figure 3, which is a typical depth-temperature curve in sedimentary rocks uninfluenced by lava flows. The two values of $1/b$, 66.5 and 59.9, prove conclusively that the curve is convex to the axis of depth.

Nearly all of the curves in regions of sediments possess this characteristic; practically none of them is concave to the depth axis. The extension of a straight line passing through points in the lower portion of these curves therefore falls below the observed points at greater depths, consequently estimates of temperatures at greater depths from gradients evaluated from observations at the upper levels (near the surface) are nearly always too low. The extension of our computed distribution of temperatures to greater depths is therefore amply justified if we are dealing with sedimentaries remote from volcanic activity; but it is evident that no such reliance can be placed on the irregular curve of the Burns well shown in Figure 4. Extension of the straight line (*ab*), Figure 4, may be justified, however, for two reasons.

First, the value of the gradient $b=0.02513$, $1/b=39.8$, obtained by comparison of the interpolated mean annual temperature with the observed temperature at the lowest point of observation differs but slightly from the value $b=0.02531$, $1/b=39.5$, found from observations in 211 mines and flowing and non-flowing wells.

Second, the high temperatures found in two flowing wells at Vale, Malheur County, Oregon, about 100 miles to the northeast, suggest the possibility of high temperatures at moderate depths.

Each of the Vale wells is about 60 feet in depth and is located at the base of a basalt ridge. A temperature of 199.5° F. was found at the Vale Naturium; 201.6° F. at the Vale Sanitarium. The two wells were estimated to be about 1,000 feet apart. The observed temperatures are too low as it was impossible to place the thermometers within several feet of the outlets. The gradient in a non-flowing well near Vale, Table VIII, is $b=0.04973$, $1/b=20.1$. Mention may be made also of the average gradient in three non-flowing wells,

Table VIII, near Klamath Falls, Klamath County, Oregon. The average value is $b=0.03725$, $1/b=26.8$. A temperature of 186° F. was found in a hot spring located about 1,000 feet north of the White Pelican Hotel at Klamath Falls. The observed temperature is several degrees too low as the point of observation was 20 feet or more distant from the outlet at the surface. Further evidence of extraneous heat in this region is provided by the fact that considerable heat has been conducted to a house on Pacific Terrace, Klamath Falls, by circulating water through a coil which had been buried in the earth to a depth of about 25 feet.

Summarizing the evidence—if we assume that the source of the heat in the Park is not necessarily magmatic, but is due to heat retained in lava flows such as those found at Burns, Oregon—the value of the gradient $b=0.02513$, $1/b=39.8$, found at Burns, and the almost identical value, $b=0.02531$, $1/b=39.5$, deduced from 211 observations in mines, and flowing and non-flowing wells, located chiefly in the adjacent lava-bearing areas, would seem to provide a sufficiently conservative basis for estimation of depth to the heat source. Moreover, the value, $b=0.02389$, $1/b=41.9$, deduced from 57 mines and non-flowing wells, many of them in sediments somewhat remote from volcanic activity, provides further evidence that the assumed value, $b=0.02531$, $1/b=39.5$, is a conservative estimate for the gradient in the Park; the corresponding value of the depth is to be regarded as an approximation to a maximum. On the other hand, the extraordinary temperatures found at Thermopolis, Warm Springs, Lance Creek, and Salt Creek, Tables VII and VIII, provide a basis for estimation of a minimum depth. The reciprocal gradients, 35.1 and 34.6, deduced from the observations respectively at Lance Creek and Salt Creek, do not differ very greatly from the assumed value, 39.5, but the values 5.5 and 21.0 found at Thermopolis and Warm Springs are marked exceptions. Not much significance is to be attached to the value 5.5, but the value 21.0 is deduced from excellent observations and provides the only substantial basis available for estimation of a minimum depth, unless perhaps we adopt the value 31.4 deduced from 154 flowing wells.

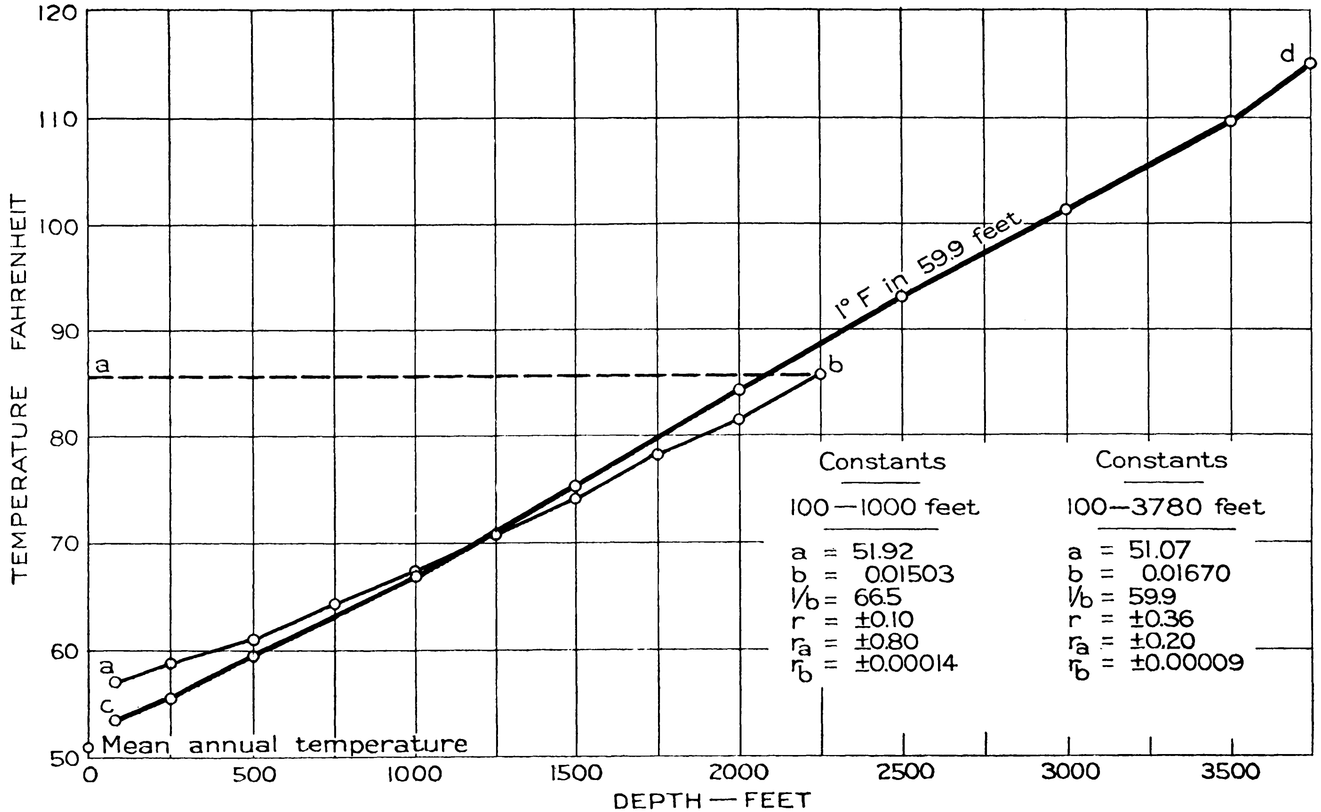

FIG. 3.—Depth-temperature curve. Deep well Chew Ranch No. 1, Lower Columbia Oil and Gas Company. Location, Sec. 25, T. 8 N., R. 10 W., near corporation line of Warrentown; about ½ mile from Lewis and Clark River; about 1½ miles from Columbia River, and about 4 miles from Pacific Ocean near Astoria, Clatsop County, Oregon.

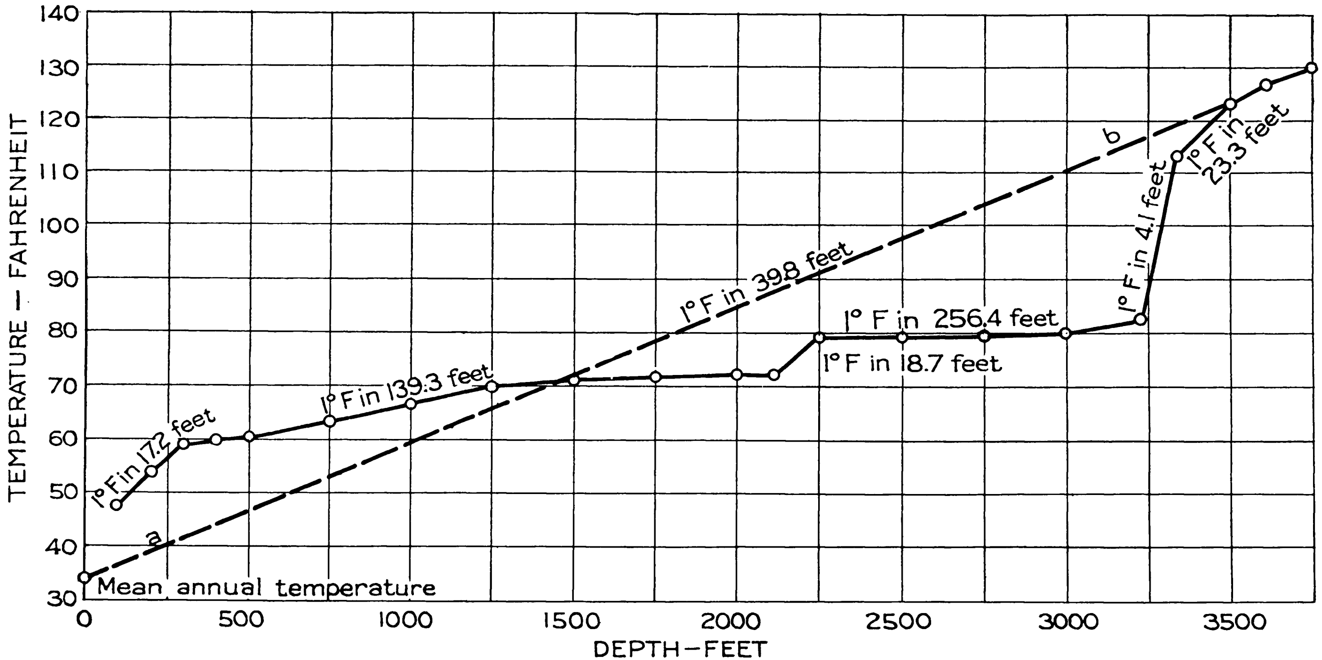

FIG. 4.—Depth-temperature curve. Deep well U.S. Government land No. 1, Central Oregon Oil and Gas Company. Location, Sec. 19, T. 26 S., R. 30 E., near Burns, Harney County, Oregon.

Estimates of the depth to the heat source may now be made by reference to Figure 5. The boiling-point of water at the surface of the ground in the Park is taken at 200° F. under an atmospheric pressure of 11.5 pounds per square inch. Curve *BCDE* represents the boiling-point of water at given depths in the water column. The temperatures were interpolated from the steam tables of Marks and Davis.[1] The pressures were computed from the formula,

$$\text{pressure (lbs. per square inch)} = 11.5 + 0.434 \times \text{height of water column (feet)}.$$

The critical temperature, 689° F., is found at a depth of about 6,765 feet; below this point water exists as a vapor for a temperature equal to or greater than 689° F.

Line *AC* represents a linear distribution of temperatures on the basis that $1/b = 5.5$, the value obtained from the two flowing wells near the Big Horn Spring, Thermopolis. The point *C* corresponding to a temperature of about 570° F. at a depth of about 2,950 feet represents a probable minimum depth at which steam can be generated by immediate contact of the water with the rocks. The curve *CDE* then represents all such points. There is no reason, however, for believing that these extreme temperatures are to be found at the given depths in Yellowstone National Park. Referring now to the intersections of the lines *AC*, *AD*, with line *BI*, Figure 5, we find the depths at which water can be heated sufficiently to produce ebullition at the surface on the basis that no heat is lost in transit from the source to the surface of the ground. The summary in Table IX includes these values and the additional values based on the assumptions that the reduction in temperature between the source and the surface is 50° F. in one case and 100° F. in the other.

Inspection of Table IX and Figure 5 shows that a depth to the heat source equal to or exceeding 8,000 feet is rather improbable. The heat source at this great depth is not necessarily laccolithic; the heat may be derived from rocks which are spread over a considerable area in the drainage basins shown on the map (Fig. 1) and in which the depth-temperature curves are irregular, like that shown in Figure 4, but in which the increase in temperature is somewhat

[1] L. S. Marks and H. M. Davis, *Tables and Diagrams of the Thermal Properties of Saturated and Superheated Steam.* Longmans, Green & Co., 1910.

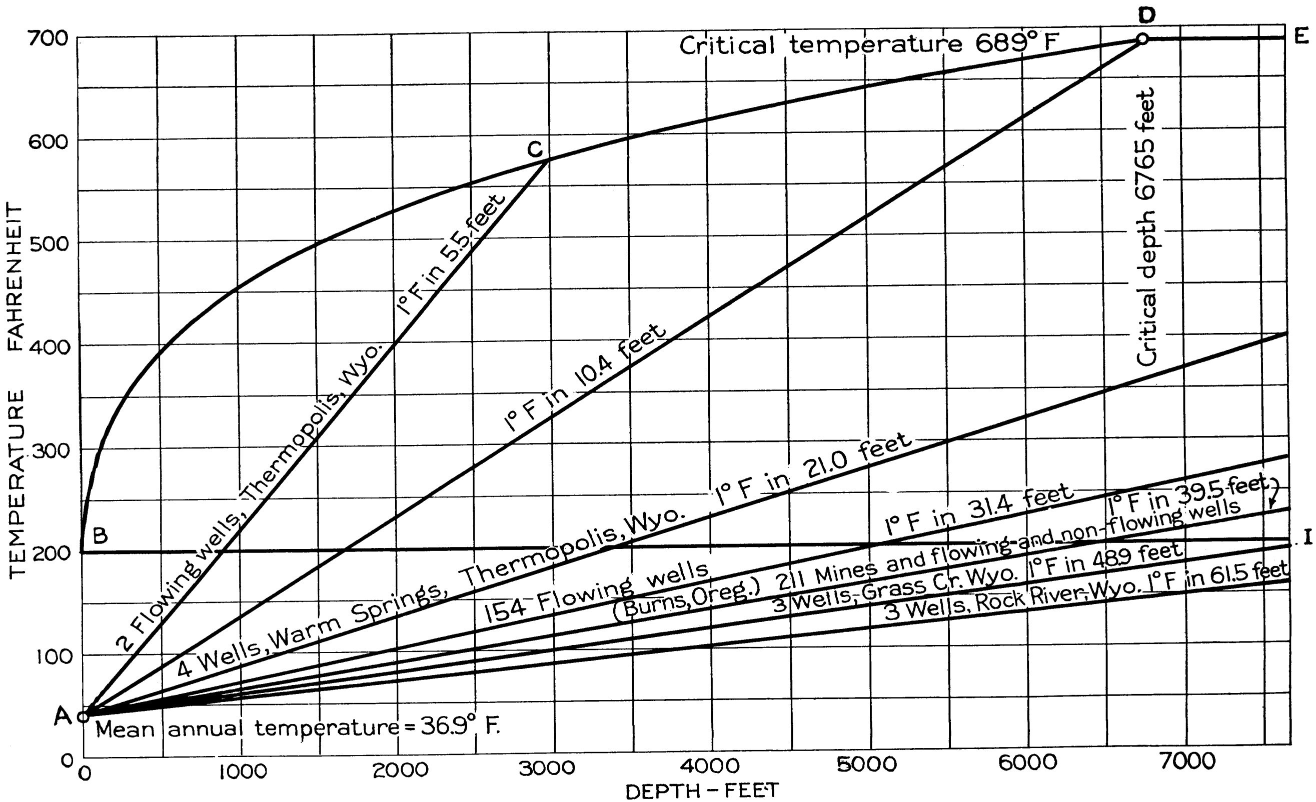

FIG. 5.—Relation between theoretical boiling-point and depth of water column

more rapid than that found in some of the adjacent sedimentary areas. As previously stated, the value $1/b=21.0$ provides a substantial basis for estimation of the minimum depth at which the heat can be obtained. Reference to Figure 5 or Table IX shows that the values may be of the order of magnitude of 3,400 or 4,500 feet. The gradients in certain flowing wells in Colorado, Idaho, Montana, Oregon, Utah, and Wyoming, Table VII, suggest the possibility of reducing the minimum estimate to something like 2,000 feet, but

TABLE IX

Estimated Depths to Heat Source

(1/b) (Feet per° F.)	Depth in Feet for a Reduction in Temperature of			Remarks
	0° F.	50° F.	100° F.	
5.5...	896	1,172	1,448	2 flowing water wells at Thermopolis, Wyoming
10.4...	1,684	2,204	2,723	Critical temperature curve
21.0...	3,400	4,448	5,497	4 non-flowing oil wells at Warm Springs, Wyoming
31.4...	5,083	6,651	8,219	154 flowing wells
39.5...	6,405	8,380	10,356	211 mines and flowing and non-flowing wells
48.9...	7,923	10,367	12,810	3 non-flowing oil wells, Grass Creek, Wyoming
61.5...	9,963	13,036	16,109	3 non-flowing oil wells, Rock River, Wyoming

the evidence of the Burns well, Figure 4, tends to show that these curves cannot be extended with certainty to greater depths.

SUMMARY

The maximum thermometer is not a very satisfactory instrument for measurement of temperatures in springs and geysers, since the agitation of the water and the rapid cooling of the bulb tend to disturb the mercury column. A thermocouple or an electrical resistance thermometer would obviate these difficulties, but, judging from Professor Hallock's experience, the construction of insulation for the leads that will withstand the dissolving action of the hot waters may prove to be a rather formidable task.

The temperatures in a considerable number of springs and geysers at Thumb, Norris Basin, Lower Geyser Basin, and Upper Geyser Basin exceed slightly the boiling-point of water, 198.5 to 199.3° F., at the respective localities. Ordinarily the excess tem-

perature does not exceed 3 or 4° F.; an exception is to be made, however, in the case of the Tortoise Shell Spring at the base of Castle Geyser in which the excess may perhaps reach 5 or 6° F. At Mammoth Hot Springs, the temperatures are about 40° F. below the boiling-point; at Mud Geysers, about 11° F. below.

The minimum depth at which water can be heated sufficiently to produce boiling at the surface of the ground in the Park is estimated to be about 3,400 feet, while depths to the heat source in excess of 8,000 feet seem rather improbable. These estimates are based on the evidence afforded by temperature tests in 154 flowing wells, 8 mines, and 49 non-flowing wells, located chiefly in lava-bearing areas immediately surrounding the Park.

By reference to curve *BCD*, Figure 5, it is readily seen that unless the temperatures at depth are extraordinarily high, and the ascent of the water quite rapid, steam is developed in the rising column of water at depths which are less than something like 300 feet from the surface of the ground.

The behavior of the springs and geysers in the Park has been satisfactorily explained by Dr. T. A. Jaggar on the basis of convection currents and artesian flow of water which has its source in the adjacent mountains.

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