[AMERICAN JOURNAL OF SCIENCE, VOL. 252, JANUARY 1954, PP. 38-54]

DOES THE COLD OF WINTER AFFECT THE THERMAL INTENSITY OF THE HOT SPRINGS IN YELLOWSTONE PARK*

GEORGE D. MARLER

ABSTRACT. Because of their location Yellowstone's hot springs are subject to extreme seasonal climatic changes. This has led to a theorizing that hydrothermal functioning would be less intense in winter than in summer. This paper presents quantitative data taken from summer and winter observations on temperature and function of many of the hot springs in the Upper Geyser Basin, so that comparisons might be made in determining if there are seasonal variations in the intensity of the thermal energy. The temperature determinations cover most of the important springs located in the Upper Basin. The statistical data on hot spring activity are largely confined to the larger eruptive units, whose functions follow a pattern of activity that would lend itself to a comparative study. Some of the factors known to influence hot spring behavior, which might lead to a misinterpretation of data, are briefly considered.

INTRODUCTION

Observations of Yellowstone Park's hot springs since their discovery in 1870 have been confined almost wholly to the summer season. With the exception of Old Faithful Geyser few or no studies of a scientific character have been made of geyser activity during the winter months. These hot springs are located in one of the coldest sections of the United States, a fact which has given rise to a frequent query as to whether or not the cold of winter might measurably retard the functioning of some of the eruptive springs. That winter might prolong the length of the eruption intervals for at least some geysers was made plausible by the behavior of the Daisy Geyser on windy days. During the history of the Daisy all who have observed its eruptive pattern over a few weeks' period have become aware that the length of the average eruption interval is increased as a result of the wind; the stronger the wind the greater the delay. It was explained that convection carried the surface water, chilled by the wind, into Daisy's well, necessitating a longer period than would otherwise be the case to heat the water to the critical temperature of an eruption (Lystrup, 1934, p. 26). The same explanation has been given as one of the reasons for a lack of activity of the Great Geyser in Iceland when winds are blowing over its surface.

If the eruption interval of a geyser can be measurably lengthened by increased surface cooling in summer, it would seem that subzero conditions, which are so common in the geyser basins of Yellowstone Park from November until April, would not only greatly aggravate this condition of delayed activity but could, theoretically at least, produce quiescence in the Daisy and all geysers of its type. Prior to the record which was kept of the Daisy during the 1951-1952 winter there is no evidence that statistical data on its winter activity suitable for comparative study were ever obtained. One object in carrying out the 1951-1952 winter observations was to supply these data so that intelligent deductions would be possible in determining if increased

* Report on winter observations of hot spring activity in the Upper Geyser Basin for the winter of 1951-1952, and for November and December 1952. Published with the permission of Conrad L. Wirth, Director, National Park Service, Washington, D. C.

surface cooling resulting from the winds were a true explanation for the Daisy's less frequent performance on windy days. Should surface cooling affect its eruptive pattern, it would be logical to assume that other geysers which have inverted cones would also be responsive to these same external conditions and that a winter study would determine if there were seasonal variations in their behavior. It was further believed that temperature studies, in connection with detailed records of geyser activity, would furnish sufficient data for valid conclusions.

WINTER OBSERVING DONE PRIOR TO 1951

From 1925, and for the succeeding seven seasons, Dr. E. T. Allen and Dr. Arthur L. Day, as representatives of the Geophysical Laboratory, made intensive studies of Yellowstone's hot springs. It seemed desirable for them to supplement their summer studies by winter observations. To accomplish this they sought the cooperation of the National Park Service, which resulted in the stationing of a park ranger in the Upper Basin during the winter months. In commenting on the need for winter studies they state: "Up to the time of the present investigation (1925-), scientific observation in the Yellowstone Park has been entirely confined to summer and early autumn, but as no satisfactory basis for a hot-spring theory appeared possible without some knowledge of seasonal influences on temperatures and geyser activity, some arrangement for winter observation seemed imperative. Accordingly a definite program of observation was undertaken at the Upper Basin by permanent Park Rangers, in connection with their regular duties in protecting wild life" (1935, Preface, IV).

This program of observation was carried on for five successive seasons, from 1925 to 1930. Allen and Day report that the park rangers who were stationed in the Upper Basin during this period were all agreed that so far as their observations went, the season of the year had no perceptible effect on spring discharge or geyser activity.[1] It should be stated that these conclusions were very largely based on subjective premises. There is no evidence that a continuous daily record of any geyser's activity was kept by the rangers, or that summer records of sufficiently detailed character were available, which records would be imperative if comparative data of a scientific character were to be made. Further, during each succeeding winter a new ranger was assigned to the task. Park Ranger R. M. Baker spent the longest period, from October to May 1928, "and again the next season till February 1929." These short periods of observation could hardly suffice to acquaint the rangers with the idiosyncrasies in behavior which a number of the geysers show. Without accurate summer data or detailed personal knowledge of a hot spring's behavior, and in the absence of a quantitative winter record, observations such as were made during the 1925 to 1930 winters are little more than generalizations.

[1] Reports now on file in the Superintendent's Office made by the rangers do not lend support to the conclusion that geyser activity and discharge are independent of the season of the year. Allen and Day's conclusions of no seasonal changes in thermal intensity would seem to have been wisely based on comparative temperature studies.

Comments of Allen and Day on the results of the 1925-1930 winter observations express satisfaction with the results obtained by the park rangers. The authors draw rather definite conclusions in interpreting hot spring activity from the winter observations, yet their summarization clearly reveals that these observations on geyser behavior were wholly subjective, and hence of little scientific value in formulating any geyser theory. "As to the results, all the observers were agreed that, so far as they could decide from qualitative observations, neither spring discharge nor geyser activity was perceptibly affected by weather or the season. As regards *pronounced* seasonal variations, it is believed that the judgment of these men, carefully selected for this work, may be safely trusted. Smaller systematic differences, to be sure, might be overlooked by an observer who depended entirely on estimates" (Allen and Day, 1935, p. 246). It is these smaller "systematic differences" that are of paramount importance if accurate determinations in seasonal variations are to be made. "Qualitative observations" of geyser activity have little scientific value when it is measurable variations in comparative data that are sought.

During the winter of 1949-1950 District Ranger Ruben Hart was stationed in the Upper Basin. Being of a scientific bent, Mr. Hart, with the cooperation of the Naturalist Division, by using an "automatic geyser recorder," secured an unbroken record of 2605 eruptions of Old Faithful Geyser. The record covered a period from "November 30, 1949 and continued through April 30, 1950." From this record Hart made some interesting statistical observations (1950, p. 37). Old Faithful was the only geyser he studied. Apart from monthly temperature records of many of the hot springs made by the park rangers stationed in the Upper Basin from 1925-1930, it can safely be said that Hart's report was the first scientific contribution to a winter study of any geyser in Yellowstone Park.

TYPES OF GEYSERS STUDIED

Two classes of geysers are recognized in Yellowstone Park: they are referred to as *cone* and *fountain* in type. In general the cone type geyser, Old Faithful being representative, is nozzled down to a small aperture, so that only a small amount of its water is exposed to the atmosphere. The fountain geyser is an inverted cone with a large surface exposure of water resting above the constricted portion of its orifice. The cone geyser is in a large measure insulated against wind and cold and theoretically should be largely immune to influences from these factors. If measureable influences from cold and wind are to be detected, those geysers with a large surface exposure to the atmosphere, such as the Grand, Oblong, Daisy, etc., should be the ones where such influences would most likely be manifest: hence it was to this latter class of geysers that special effort was directed in the winter observations begun November 1, 1951. The cone type geysers were not overlooked: the eruptive patterns of many were checked with the same care as were those of the fountain geysers.

One of the seeming disadvantages of a winter project of observation such as was started in 1951 is that to make the data conclusive several seasons of continuous observation — winter and summer — are required. With but one or two winters of observation it is not possible to eliminate completely those influences due to a shifting of the thermal energy from one spring to another. Exchange of function is the biggest single factor in producing the great irregularity of many geysers (Marler. 1951. p. 329). Without an appreciable time range in data, the influences resulting from a shift of the thermal energy might become confused with the season and interpreted as weather influences.

Cold is more intense in the geyser basins some winters than others. It is possible that prolonged and severe cold could result in retardation of the function of some geysers. a slowing up which would not be measurable with the average winter temperature conditions in the basins. So far as temperatures were concerned. the 1951-1952 winter was unusually benign in Yellowstone Park. No periods of extreme cold. such as December 1924 or January 1936, were even closely approached.

COMPARATIVE DATA, SUMMER AND WINTER, ON SOME OF THE GEYSERS

In presenting the data collected on the geysers that were under observation, space in this paper will not permit the showing of more than average eruption intervals for the periods covered by the comparisons. The detailed statistics on daily temperature, weather. and eruption times are on file in the Yellowstone Park Library. The comparative eruption data. with explanation of factors other than weather which are known to influence the eruption times of many of the geysers, should, however. give a substantial basis for drawing conclusions on whether winter influences geyser activity.

Daisy Geyser.—The Daisy lies about one mile northwest of Old Faithful. Its high degree of regularity and frequency have contributed to making it one of the most popular and better known of the geysers. Over the greater portion of its history only Old Faithful among the major geysers has exceeded it in the frequency of its eruptive periods. Unlike Old Faithful, the Daisy is known to have subterranean connections with other thermal units.

On July 10, 1951 the Splendid Geyser, which has underground connections with the Daisy, became rejuvenated after over 50 years of dormancy. This resulted in very erratic functioning of the Daisy for the remainder of the season. It was feared that Splendid's activity would make it impossible to get enough of Daisy's winter function for comparative data. Fortunately, from November 9 until December 20 it played without any apparent influence from connecting units. During this period 140 eruption intervals were checked. The average interval was 108.2 minutes. From May 1. 1951 until July 10 when the Splendid became active. the average eruption interval was 105 minutes; from July until October 1, during the period of Daisy's erratic function, it was 140 minutes.

From December 20. 1951 until January 1953 the Daisy was inactive the greater part of the time due to the activity of either the Splendid Geyser or Brilliant Pool. During the November-December 1951 period of activity the longest interval checked on the Daisy was on November 29. This interval was 130 minutes; the wind was 20 miles per hour from the southwest; the temperature 30° F.[2] The shortest interval, 85 minutes, was on November 24, at which time the air was calm and the temperature 30°. The highest temperature recorded at the time of an eruption was on November 30 and was 41°; the coldest was on February 24 and was –28°. Despite a loss of 69° in temperature, the eruption on February 24 was on the same length interval as the one on November 30—105 minutes. At the time of both eruptions there was a slight breeze from the north.

Giant Geyser.—During the 1951 season the Giant was unusually active. From May 1, when the observations began, and for the remainder of the year, the Giant played with greater regularity and frequency than during any previous observation period for which there is a record.

In the middle of January 1952 the Giant suddenly began playing on even shorter intervals than had characterized it during the 1951 season. From January 17, 1952, and for the remainder of the year, it played with unprecedented frequency and regularity. The average eruption interval during this period was slightly over 2 days—57½ hours. The extreme variations from this average were 88 and 34 hours. Eighty percent of the eruptions came within 10 hours of the average. The Giant has the distinction of being the first geyser in Yellowstone Park with a complete yearly determination of its activity. During 1952 it erupted 137 times.

The Giant is definitely a cone type geyser; it is connected underground with over 50 other known units. Some of these units, such as the Purple Pools, have large surface exposures. In spite of the great surface area of water which is known to belong to its plumbing, its regularity was undisturbed, so far as could be determined, by winter conditions. It is noteworthy that the shift[3] from a plus 5- to a plus 2-day average interval occurred in mid-January. This would scarcely suggest a delayed function due to the cold of winter.

Grand Geyser.—Although the functional characteristics of the Grand are very distinct from those of the Daisy, their surface conditions bear marked similarities. Both have large surface areas exposed to the atmosphere; both are in a state of overflow for about the same period prior to an eruption. In spite of this surface relationship there has never been any suspicion that winds were a factor in delaying the Grand's activity. If surface cooling delays geyser activity it would seem that all open crater geysers like the Grand and the Daisy would be influenced in some measure by external temperatures.

Not only do the Grand's eruptive periods seem to be uninfluenced by any degree of wind but they also show an equal independence in function with respect to the season. Its eruptions appear to come with as great a frequency when subzero conditions prevail as during maximum summer temperatures. The eruption data on the Grand for the 1951 summer when compared with the data collected during the following winter should bring out this fact very forcefully. From May 25, until September 15, 1951, 136 eruption intervals were determined. The average eruption interval was 20 hours. The minimum interval during this period was 11 hours, the maximum 38 hours. From November 9, 1951 until April 28, 1952, 208 eruption intervals were deter-

[2] All weather temperatures given in this paper are Fahrenheit readings.

[3] For cause of shift see Yellowstone Nature Notes, Vol. 26, No. 6, page 67.

mined. The average interval was 14¾ hours. The maximum interval during this period was 22 hours, the minimum 8½ hours. Some of the shortest intervals during the winter were at the times of subzero weather. The coldest temperature recorded at the time of an eruption was on February 24; it was –32°, and the interval was 13 hours, this being nearly 2 hours under the winter average.

Starting on November 22, 1952, an arctic mass of air moved over the geyser basin, and for 10 days the temperature ranged well below zero. The average minimum temperature during these 10 days was 17.4° below zero. During this period 12 eruption intervals of the Grand were determined; the average time was 13.3 hours. For the preceding 10 days, from the 12th to the 21st inclusive, 10 eruption intervals were determined, with an average interval of 15.5 hours. The average minimum temperature during this period was 14.6° above zero.

Castle Geyser.—All observations to date indicate that the Castle is a self-contained unit, although its functional history suggests influences from subterranean connections with another spring or springs. For long periods it will show a degree of regularity on more than one eruption schedule: at other times it becomes very irregular, infrequent, and unpredictable. This behavior is characteristic of all geysers known to have underground connections with other units.

During all of the 1951-1952 winter the Castle showed a high degree of regularity and frequency. From November 5 until April 26, 125 eruptions were observed; 89 eruption intervals were determined. For from 5 to 7 days the intervals would vary from about 12 to 13½ hours, then one interval of about 20 hours would intervene to be followed by the shorter intervals for the period indicated. The 13.1-hour average for the winter is shorter than any summer average for which there is a record. It continued playing on the 13.1-hour average until July 10, 1952, following which date, and for the remainder of the year, the average eruption interval was 14¾ hours.

Oblong Geyser.—During the 1951-1952 winter no detailed data were kept on the Oblong. Frequent observations indicated a pattern of play comparable to its summer performance. From November 1, 1952 until January 1, 1953 an effort was made to record as many eruption intervals as possible. During this period 12 such intervals were determined. The Oblong is a fountain type geyser with a large area exposed to the atmosphere. This, however, was no deterrent to the frequency of its winter function. Of the eruption intervals checked, the longest was 4 hours; the shortest 2 hours and 55 minutes; the average, 3.4 hours. For 11 eruption intervals checked from June through August 1952 the average interval was 3.7 hours.

The Oblong, like several other springs in the Upper Basin, shows effects from spring drainage; the water in its bowl becomes about the same hue as the spring runoff in the Firehole River. The Oblong's crater rests on the bank of the Firehole, the crater rising about 10 feet above the river. Whether at this season of the year the humus-colored water enters the Oblong's water supply directly from the river or represents surface drainage has not been determined. Whatever the source, it acts as no apparent deterrent to the

Oblong's play. In May 1951 while it was clouded with brownish water, an eruption interval of 2 hours and 58 minutes was determined. If the melting snow water does not affect the function of a geyser like the Oblong, it is scarcely plausible that atmospheric temperatures would have any effect in slowing eruptions.

Riverside Geyser.—The Riverside is a cone type geyser, and is perhaps the most regular of the large geysers in Yellowstone Park. Its small surface exposure, like Old Faithful's, should protect it from the atmosphere. As has been pointed out, geysers like Old Faithful and Riverside might be expected to play as frequently and regularly in winter as in summer if atmospheric temperatures were the only factors involved.

During the 1951 season, from May 1 to October 1, the Riverside played 495 times. The average eruption interval was 7 hours and 25 minutes. From November 9, 1951 until April 27, 1952, 572 eruptions took place; the average time was 7 hours and 3 minutes. The shortened winter average persisted during the 1952 season, being an even 7 hours. During most of the years that the author has had the Riverside under observation its seasonal average has been near 8 hours.

Beehive Geyser.—The intervals on the Beehive were carefully checked during the winter observations. Its eruptions do not come with sufficient frequency and regularity to serve as a possible index to atmospheric influences, but its performance is spectacular and all of the eruptions could easily be determined.

References to the Beehive during the first two decades of the Park's history indicate that there were some seasons when it played one or more times each day. During the greater part of the present century it has been relatively inactive, and for 25 years, starting about 1920, many seasons went by with no observed activity. Starting with the 1947 season there was a general increase in geyser activity in the Firehole Basins, in which the Beehive shared. Since the 1947 resurgence it has played on frequent occasions. Starting with 1947 the number of eruptions checked per season were: 1947, 26; 1948, 13; 1949, 28; 1950, 23; 1951, 23; and 1952, 31.

Early in November, 1951 it became apparent that the Beehive was playing with unusual frequency. From November 8, when the recordings began, until April 16, 1952, the Beehive played 113 times. The numbers of eruptions per month were as follows: November, 18; December, 24; January, 22; February, 20; March, 18; April, 11. From May 12 to September 3, 1952, 31 eruptions were recorded. The eruption on September 3 occurred soon after the beginning of an eruption of the Giantess. This eruption of the Giantess completely upset the normal activity of most of the springs on Geyser Hill, including the Beehive. From the September 3 eruption it was dormant until November, when its winter rejuvenation started, with 8 eruptions; during December there were 21, and 3 more occurred up to January 4 when the observations ended.

Old Faithful Geyser.—Since a careful and scientific check had been made of Old Faithful during the winter of 1949-1950, the 1951-1952 winter observations were directed toward other geysers in the basin. Some of the random observations made over the years were indicative that Old Faithful's pattern of activity was essentially the same in winter as in summer. Ranger Hart's automatic recordings bore out these generalizations. During the 1949 season 1540 eruption intervals were determined; 35 minutes was the minimum interval, 88 minutes the maximum: the average eruption interval for the summer, 63.2 minutes. During the following winter 2505 eruption intervals were mechanically determined. The winter record showed a minimum interval of 38 minutes, a maximum of 88, with an average of 63.8. The winter record when compared with the summer one shows an increase of .6 of a minute; the maximum interval, however, for both summer and winter is the same. That the .6 of a minute in the average gain of winter over summer was not due to seasonal influences is indicated by the record of the following summer which shows an average of 63.8 minutes for 1250 eruption intervals, the same as the previous winter average.

The winter observations begun in November 1952 also reveal Old Faithful's independence of outside temperature. The summer record for that season shows that 1289 eruption intervals were determined; 35 minutes was the minimum, 85 minutes the maximum; the average, 64.09. From November through December 1952, 619 eruption intervals were recorded; 39 minutes was the minimum, 77 minutes the maximum; the average, 63.6—.49 minutes less than the summer average. From November 22 through December 1 the temperature in the Upper Basin ranged between 5° and 32° below zero. The time of the average eruption interval during these 10 days of subzero weather was 63.59 minutes.

WHAT TEMPERATURE STUDIES SHOW

During the 1925-1930 winters, Rangers Phillips, Baker, Hanks, and LaNoue made monthly temperature determinations of a number of hot springs in the Upper Basin. Allen and Day's studies of these temperatures indicated that "in winter there is no general decline in geyser activity." They were convinced that the great irregularity manifested by many geysers was not seasonal. As for smaller variations, they state that these "irregularities could only be detected by the aid of elaborate records, but if the quiet intervals of the Daisy Geyser are lengthened perceptibly by strong summer winds, they should be much further prolonged in the extreme cold of Yellowstone winters" (1935, p. 247). No such "elaborate records" were available for comparative data.

That Allen and Day consider atmospheric temperature as one of the factors to be considered in the gains and losses of heat in geysers is indicated by the following: "When the geyser is considered as a system subject to gains and losses of heat, we see as the factors obviously affecting these two vital conditions: (1) cooling at the surface of the water column; (2) rate of influx of the cooler ground water; (3) rate of flow of the magmatic steam, or more directly, the flow of water heated by the steam" (Allen and Day, 1935, p. 247). The studies that had been made of winter and summer temperatures led Allen and Day to conclude that surface cooling in retarding geyser activity "was of a small order of magnitude."

In connection with the 1951-1952 winter observations, the author kept a monthly record of the temperatures of 138 springs in the Upper Basin. This temperature record was started in May 1951 and continued through April 1952. The temperatures were obtained at a depth of about 12 inches, and by immersing the thermometer in that portion of the spring where there was rising convection. A careful study of this record does not reveal any significant relationships between the thermal intensity and the time of the year.

While such a temperature record as the above is important in any study of seasonal influences on thermal activity, an equally great value results from the comparative data furnished for determining the waxing or waning of thermal intensity over the years. Comparisons of the 1951-1952 recordings with those of 1925-1930, shown in the following table, are interesting. The 1925-1930 temperatures given represent averages of monthly readings, and cover the season from November through April. For about half of the listed springs in the 1925-1930 studies, temperatures were determined only during the 1928-1929 winter. Of the 138 springs whose temperatures were determined by the author, only those for which comparative readings are available are included in table 1. The temperatures were taken monthly and represent averages for the November through April period.

The table shows comparative temperatures for 60 springs. These comparisons do not lend support to the pessimism of a declining geyser activity that permeates much of the literature on the hot springs of Yellowstone Park (Allen and Day, 1935, p. 188). Forty-eight of the springs show an average gain in temperature of 2.5°. The average loss for the 12 springs which show a decline in temperature is 4.8°. The average increase for all springs in the study is 1.3°. It is significant that the great majority of the eruptive springs show an increase in temperature. This is in harmony with statistical data that there has been an increase in geyser activity since the 1946 season over that of the preceding 25 years.

The 4.8° decline in temperature of the Morning Glory Pool does not necessarily reflect an overall decline in thermal energy, and the same would be true for other springs. A study of the hot springs discloses that the temperatures of many are cyclic, periods of increase which are followed by periods of waning energy. A decrease in temperature for the Morning Glory was noted in the late thirties, lasting until 1943. From 1944 until 1951 its temperature was equal to or in excess of the 77.3 average shown for 1925-1930. Since June 1951 there has been a decline in temperature. Many non-erupting springs, like the geysers, show great irregularities in temperature. In the case of the geysers, the periods of lessened temperature are reflected by infrequent activity or dormancy.

For the geysers showing a decrease in temperature over that of the 1925-1930 record, the decline in the Sawmill and Vault no doubt results from the fact that some temperatures were taken during 1925-1930 at the time of eruptions or in the early recovery stages following eruptions. Temperatures taken by the author were at the time of a quiet phase, the temperature at this time being less than at the time of an eruption or immediately thereafter. The Sawmill and Vault are as active now as they were when the 1925-1930

TABLE 1

Comparative Temperatures

	1925-1930 Average	1951-1952 Average	Gain or Loss
Morning Glory	77.3°C.	72.5°C.	-4.8°C.
Sentinel	93.7	94.4	+0.7
Mortar	92.8	94.4	+1.6
Fan	92.3	94.1	+1.8
Spiteful	92.1	93.2	+1.1
Riverside	93.9	94.3	+0.4
Spa	82.6	87.0	+4.4
Rocket	93.2	93.8	+0.6
Grotto	93.9	94.4	+0.5
Giant	94.4	96.4	+2.0
Mastiff	93.8	96.1	+2.3
Oblong	91.9	93.2	+1.3
Inkwell	91.7	94.4	+2.7
Daisy	87.9	91.1	+3.2
Brilliant	87.8	91.0	+3.2
Comet	92.7	94.5	+1.8
Splendid	91.9	94.5	+2.6
Punch Bowl	93.7	95.0	+1.3
Black Sand Pool	92.2	92.4	+0.2
Whistle	64.2	94.3	+30.1
Spouter	92.8	92.9	+0.1
Green Spring	75.7	80.5	+4.8
Emerald	67.8	62.8	-5.0
Castle	93.3	93.7	+0.4
Tortoise Shell	94.0	95.6	+1.6
Crested Pool	91.4	93.6	+2.2
Witches Cauldron	93.1	94.4	+1.3
Calida	82.6	80.0	-2.6
Chromatic	82.5	77.7	-4.8
Beauty	75.5	67.0	-8.5
Wave	60.5	63.1	+2.6
Economic	80.1	71.0	-9.1
Turban	90.0	92.8	+2.8
Grand	77.7	80.0	+2.3
Bulger	91.4	93.3	+1.9
Sawmill	89.5	83.0	-6.5
Churn	93.8	80.0	-13.8
Tardy	88.0	91.1	+3.1
Spasmodic	92.0	93.7	+1.7
Lion	93.5	94.5	+1.0
Lioness	94.5	94.9	+0.4
Big Cub	94.0	95.2	+1.2
Little Cub	92.2	94.4	+2.2
Ear	93.8	94.0	+0.2
Beach	86.1	88.2	+2.1
Doublet	80.2	89.7	+9.5
Sponge	94.5	95.4	+0.9
Teakettle	93.4	93.7	+0.3
Giantess	93.6	94.4	+0.8
Vault	87.6	86.1	-1.5
Infant	93.3	93.4	+0.1
Beehive	93.7	95.2	+1.5
Cascade	87.6	86.6	-1.0
Blue Star	86.2	86.3	+0.1
Chinaman	93.5	93.7	+0.2
Old Faithful	94.5	94.4	-0.1
Artemisia	79.9	84.3	+4.4
Gem	77.3	85.9	+8.6
Sapphire	94.0	95.5	+1.5
Silver Globe	91.8	91.7	-0.1

temperatures were taken. The Economic is dormant, so a decline in temperature would be expected.

While the monthly temperature determinations for the 1951-1952 period do not reflect any relationship between thermal energy and the season of the year, it does not necessarily follow from this that the water in open craters is unaffected by the cold blasts of winter. As has been stated, in recording temperatures during the 1951-1952 study, the thermometer was placed in that section of the spring where there was definite upwelling of water. Temperatures here, as the records show, proved to be relatively constant when taken under similar functional conditions. This was not true at the outer margins of many of the springs. That much cooler water was being carried into the deeper recesses in winter than in summer was apparent at a number of springs, particularly the Daisy and the Grand. In view of the general belief that surface cooling delays the Daisy its case will be considered under the following heading.

HOW SUBTERRANEAN CONNECTIONS WITH OTHER SPRINGS MIGHT AFFECT GEYSER BEHAVIOR

As stated above, the Daisy is known to have underground connections with other springs and geysers. These connections have occasionally been responsible for great irregularity in the Daisy, and at times, dormancy. From late in the last century, until the 1951 season, its eruptive function suffered little from the diversion of any of its thermal energy to other connecting units. Its eruption intervals varied from about 75 to 120 minutes. For weeks at a time there would be little deviation from the average, except on those days when strong winds blew over its surface. For many years it has been observed that a wind of near 20 miles' velocity or over increases the length of the Daisy's quiet phase, and the stronger the wind the longer the interval. Winds of 30 miles' velocity will increase the average eruption interval by at least 20 to 30 minutes. Such observations as this led to the theory that the increased evaporation resulting from the wind cooled the water in the bowl of the Daisy, thereby requiring a longer recovery period between eruptions. Apparently for want of a better theory, the above explanation was the only one given on why winds delayed the Daisy.

That factors other than surface cooling resulting from the wind might be responsible for delaying the eruption time of the Daisy first became apparent to the author during the 1938 season. During that season Bonita and Brilliant Pools and Splendid Geyser, first one and then another, would periodically overflow. Normally the water in these units stands at the upper rims of their craters, except at the time of Daisy's or Splendid's activity, when a pronounced drop in water level in all craters takes place. It was observed that an overflow from any of the units connected with the Daisy reduced it to a dormant status as long as the overflow lasted. Proof that it was the overflow, say, from Bonita Pool (Marler, 1951, p. 335), that was responsible for the Daisy's inactivity was found by damming Bonita's overflow channel with fragmental sinter. Hydrostatic pressure was so sensitive that immediately the thermal energy directed away from Daisy to Bonita was channeled back, and in a short time Daisy responded by erupting. This experiment was repeated a number of times that season, and has been many times since, not only on Bonita but also on Splendid and Brilliant. Without exception the Daisy's response has been to resume normal activity.

These experiments in the Daisy Group suggested that the delayed activity of the Daisy, occasioned by the winds, was not because of surface cooling but because wind blowing over its wide collecting basin served as an agent in increasing the rate of overflow from its crater. Without a wind, water will normally overflow the sides of the crater from 20 to 30 minutes before an eruption. Heavy winds will more than double this time of overflow. This is accomplished by increasing the rate of discharge, thereby dissipating the thermal energy, which in turn increases the length of the interval. The experiments with Daisy's connecting units revealed its high degree of sensitiveness to any loss of water. The winter observations offered further confirmation to the contention that it is loss of water and not loss in surface temperature that delays the Daisy on windy days.

Following the rejuvenation of the Splendid Geyser on December 24, 1951, the Daisy was largely dormant for the remainder of the winter. There was a 3-day recovery period in February. Some of the recovery periods lasted for only one eruption, the Splendid then again took over. During the periods of dormancy in the Daisy the water would rise in its basin to just about the overflow stage, where the level would stay constant until the Splendid erupted or the Daisy again became active. During some of Daisy's dormant periods, when arctic air conditions prevailed, the water in the outer margins of its collecting basin froze solidly (pl. 1). That such a situation would greatly intensify surface cooling over evaporation effects from summer winds is patent. Yet it was during such a condition of icing that the thermal energy was observed on two occasions to shift from the Splendid to the Daisy, with the Daisy erupting on a period of overflow no longer than is average in summer.

The fact that geyser activity in open-crater geysers is as intense during subzero weather as during summer eliminates surface cooling from winds as the true explanation for Daisy's delayed activity on windy days in summer. That the Daisy is the only geyser in the Upper Basin whose function has been suspected of being affected by the winds would of itself make such an explanation questionable. The winter observations, as well as the experimental work on the units connected with the Daisy, are convincing that the delayed activity resulting from the wind is caused by the increased rate of discharge. The wind literally rolls a heavier flow of water over the side of Daisy's collecting basin, thereby dissipating its energy. Only one other geyser in Yellowstone Park is known to be affected by the wind—the Morning Geyser in the Lower Basin. It is even more sensitive to wind than the Daisy. The author has no record that the Morning has ever erupted when winds were strong enough to produce a wave action over its large collecting basin. These waves increase the rate of discharge, upsetting a delicate balance. During the 10 days of subzero weather in November 1952, the air was calm, and the Morning's eruption schedule was unaffected.

PLATE 1

During the Daisy's dormant periods, when arctic air conditions prevailed, the water in the outer margins of its shallow collecting basin froze solidly.

REASONS FOR SEASONAL CONSTANCY IN THERMAL ENERGY

A number of theories have been proposed to account for the seeming seasonal constancy in the thermal energy for the hot springs in Yellowstone Park. Allen and Day have given this problem considerable thought, and state: "If surface cooling is important as regards geyser intervals, it is possible that its effects may be modified by variations in the volume of ground water. In the climate of Yellowstone Park, much of the precipitation which in warmer weather finds its way into the ground is withheld from circulation in winter in the form of ice and snow. Reduction from this cause may conceivably go so far that considerably less heat is required to raise the remaining water to boiling, leaving another portion of heat supply free to compensate for the increased losses due to the winter cold. Such variations in ground water may also explain why in winter there is no general decline in thermal activity" (Allen and Day, 1935, p. 227).

If such an explanation as the above should prove valid, Allen and Day admit that it would demand that "changes in volume of ground water must be attended by similar variations in discharge." Winter measurements of discharge have never been attempted. The hot spring activity of winter, however, furnishes some very useful and forceful data. With the exception of the Lion Geyser, all the geysers in the Upper Basin for which records were kept showed an increase in discharge during the 1951-1952 winter over their previous summer record. For some geysers, the Grand, Giant, and Beehive, this increase in discharge, as reflected by their increased activity, was marked. The flow from no spring showed any evidence of diminishing. It is appreciated that such an observation as the latter is subjective, but waning discharge of any spring is immediately reflected by its effects on the algae in the drainage channels. In only one spring was any decrease of flow observed during the winter. This decrease was *not* due to changes in the volume of ground water, but to exchange of function. The Chromatic Pool ceased to overflow in February, and this cessation was immediately attended by an overflow of Beauty Pool. There is periodic exchange of function between these two springs. The shift back to the Chromatic took place in July 1952.

In explaining the absence of any marked seasonal variations in the thermal intensity in the main geyser basins, one important lead has not been given due consideration—the character of the ground through which the springs issue. Allen and Day recognized the great amount of glacial drift that is in evidence in the geyser basins, and that "the prevalence of these gravels in so many thermal districts of the Park indicates the probability that they may underlie large parts, if not the whole of this area." Yet, certain interpretations (Allen and Day, 1935, p. 123, 236) they made from their analyses of hot spring waters, which could have been better explained had they recognized an exchange of function between neighboring springs, prevented them from recognizing the importance of glacial gravels in explaining the seasonal constancy of hot spring activity.

The bore hole put down by the Geophysical Laboratory in 1929 behind the Old Faithful Inn went through 220 feet of gravel. A careful study of the mounds of most of the large cone geysers, Old Faithful, Castle, Giant, etc., reveals that these mounds are mere shields resting upon the glacial drift. The author's observations during the past several years have established that the majority of the hot springs in the Upper Geyser Basin are connected subterraneously, connections which appear logical when it is considered that glacial gravels *in depth* underlie the greater portion of the basin. That the gravels are much more permeable than the rhyolite is of utmost importance in accounting for the circulation and supply of water in this basin; the same is true for the Midway and Lower Geyser Basins.

It is the author's opinion that the major factor in accounting for the seasonal constancy in thermal energy is to be found in the huge storage basins afforded by the glacial gravels. Variations in seasonal precipitation, or the fact that snow and ice retard the replenishment of water during winter, represent such a small fraction of the total ground water that neither shows its effect—that is, from season to season.

POSSIBILITY OF INCREASE IN FUNCTION IN WINTER

The great increase in activity of most of the geysers during the 1951-1952 winter over their previous summer functioning seemed to lend credence to the possibility that, instead of a lessening of thermal manifestations during the winter, there was an increase in their intensity. No such general increase characterizes the average winter, however, as was made evident by the fact that the Giant, Riverside, and Grand not only continued on through the 1952 season playing on shorter intervals but through the summer showed additional decrease in average time. The increase in function during the winter over the previous summer, if it proves anything for most geysers, shows how independent they are of the season of the year. The increased activity of the Grand and the Giant are readily explicable when the behavior of other eruptive springs with which they have underground connections is taken into consideration.

The cases of the Riverside and the Beehive are not so easily understood as are those of the Giant and Grand. The author has observed for a number of seasons that in October the Riverside played on a shorter interval than during the previous summer. The activity of the Beehive during the 1951-1952 winter, and starting again in the winter of 1952-1953, was so far in excess of the activity in any recent summer season as to suggest that it, as well as the Riverside, erupts more frequently in winter than in summer. Only several winters of continuous observation could establish whether or not this is the case.

Should it be proven that some geysers play more frequently in winter than in summer, it would be logical to assume that for the basin as a whole there should be a general increase in thermal energy in winter over summer. The fact that there is no movement of ground water from the surface downward during most of the winter suggests the possibility of increased temperatures for circulating ground water.

CONCLUSION

The latitude and altitude of the geyser basins of Yellowstone Park subject them to one of the most rigorous climatological conditions in the United States, so far as temperature is concerned. The mean annual temperature determined by the U. S. Weather Bureau in the southeastern section of the park, where the main geyser basins are located, is 35°. The mean temperature for the 6-month period from April through October is 48.9°, while for the remaining 6 months it is 18.8°. The winter shows a departure of 31.1° from the summer mean. This great drop in temperature during the winter would be presumed not only to affect the surface temperature of all springs possessing large open craters but also to have a retarding effect on the function of many of the eruptive springs belonging to the fountain classification. This latter postulation becomes more tenable when consideration is given to the trigger balance which many of the geysers possess.

Some of the geysers, such as the Beehive, heat up to a state where the gains and losses in heat seem to be evenly balanced. That they remain in this state for long periods is evidenced by the observation that a small quantity of detergent will induce an immediate eruption, with no preceding eruption having taken place for weeks. Geysers so delicately balanced between gains and losses in temperature would be presumed to be sensitive to marked changes in atmospheric temperature. That such is not true is shown by the Beehive's winter activity.

The winter studies carried on to date have not succeeded in finding significant differences between the thermal intensity of summer and winter which could be explained as resulting from surface cooling. This lends support to the thesis that the cooling effects of the atmosphere on any spring, or any factor such as wind, which might produce a cooling of the surface water, leave the thermal intensity of that spring unchanged. If results of the investigations to date may be taken as a true indication, the evidence seems compelling that the frequency of a geyser's activity is not adversely affected by atmospheric temperature.

In explaining the seeming immunity of the hot springs to seasonal changes in their energy output, a number of possibilities present themselves: (1) The storage basins from which the hot springs draw their water supply are of such a voluminous character as to leave their discharge unaffected from season to season[4]. (2) The almost complete stoppage during the winter months of surface seepage in replenishing the water supply might result in the circulation of warmer ground water during that season. (3) The underground structure of at least the eruptive hot springs—observation has proven that the majority possess geyser potential—is no doubt of a character that prevents downward convection from reaching that section of the geyser's plumbing where the eruption is initiated. If the above suggestions present a true picture, they pose the chance of greater thermal intensity in winter than in summer. The behavior of the Beehive and Riverside is suggestive. Much additional data are necessary before this intriguing possibility can be answered with satisfaction.

[4] Reference is made only to those springs reposing on the main floors of the geyser basins. Springs on hillsides and glacial shoulders are affected by the season.

ACKNOWLEDGMENTS

The author wishes to express his appreciation to Superintendent Edmund B. Rogers and Chief Park Naturalist David Condon, Yellowstone National Park, and to Dr. L. C. Graton, Harvard University, for their interest and assistance in making possible a study of the thermal intensity in the Upper Geyser Basin of Yellowstone Park during the winter of 1951-1952. Appreciation is also expressed to Dr. Carl P. Swartzlow, Regional Naturalist, and to Mr. Conrad L. Wirth, Director, National Park Service, for their interest in the publication of the report on the winter observations.

REFERENCES

Allen, E. T., and Day, A. L., 1935, Hot springs of the Yellowstone National Park: Carnegie Inst. Washington Pub. 466.

Hart, R. O., 1950, Winter eruption recordings of Old Faithful Geyser: Yellowstone Nature Notes, v. 24, no. 4, p. 37-39.

Lystrup, H. T., 1933, Winds—their effect on geyser activity: Yellowstone Nature Notes, v. 10, p. 26.

Marler, G. D., 1951, Exchange of function as a cause of geyser irregularity: Am. Jour. Sci., v. 249, p. 329-342.

Yellowstone National Park
Wyoming