CHAPTER 3

Fundamentals of Geyser Operation

3.1 Essential Elements of a Geyser

Geysering is a captivating and mysterious phenomenon. Almost anyone who watches a geyser erupt speculates on its mode of action. The essential elements of a geyser are a reservoir and associated plumbing system in which water can be stored and heated, an adequate supply of water, and a source of heat. While other factors such as gases, earth stresses, dissolved chemicals, and climate can and often do influence geyser action, it is not essential that they participate.

Knowledge of the precise natures of geyser reservoirs is very limited simply because they reside mostly out of view underground. Probings to any appreciable depth are difficult because of internal obstructions and there has been no drilling close to the large geysers. Only in one case, the extinct Te Waro Geyser of Whakarewarewa, has man been able to climb down inside the reservoir itself. Although the opening to Te Waro's original reservoir is now covered with sinter deposits, in 1921 the external vent was "a circular hole with . . . typical round sinter edges of a geyser, just large enough for a man to squeeze his body through". Mr. Martin's investigation has been described:

> The bottom of the shaft is 15 ft [4.6 m] below the surface, and it opens out into a chamber 12 ft [3.6 m] long and 9 ft [2.7 m] high, as shown in the following diagram (Fig. 3-1). In the floor of the chamber are two fissures, one of which, F, is supposed to connect with Pohutu Geyser and whence come the rumblings of fiercely boiling water. Mr. Martin suggested that this curious cavern-formation was due to the action of hot siliceous water and steam on an ordinary fissure passage, the water depositing silica on the walls and floors, and steam eroding the vaulted roof and forming a cavern.

Usually a geyser reservoir is a compact, well defined cavity or an interconnected array of cavities, the walls of which are, for the most part, lined with an

J. S. Rinehart, *Geysers and Geothermal Energy*

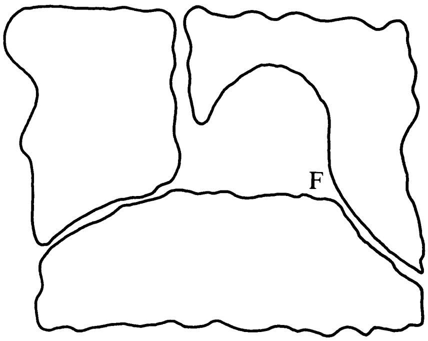

Figure 3-1. Cross section of Te Waro Geyser. (Adapted from Lloyd, 1975.)

impervious layer of siliceous sinter or geyserite that has been deposited by the geyser waters. It is now generally believed that most large voids and geyser tubes are effects rather than the original causes of geyser action. During an eruption, the waters in the reservoir may be merely agitated, partially erupted, or totally emptied, making it difficult from surface observations to estimate its capacity.

One can conjure up a reservoir system to fit almost any type of eruption and many investigators have done so during the past 150 years of geyser studies. Geyser theories have been proposed and numerous models constructed to simulate the actions of natural geysers and to prove or disprove certain theories. The most recent studies were reported in 1978. All of the models, which differ greatly in design, function. Perhaps those that did not were never reported!

Neglecting those instances where geysers are interconnected, six generic types of reservoirs can account reasonably well for most geyser action. These are shown in cross section in Fig. 3-2.

Riverside, Old Faithful, and Beehive, which play sustained jets to considerable heights at more or less regular intervals out of raised cones, probably have single standpipes a few hundred meters long (Type A, Fig. 3-2). At the opposite end of size range, Vixen, a small geyser in Norris Basin, erupts every minute from a 10 cm diameter geyserite pipe only 3 m long.

Deep, narrow shafts (Type B) spawn explosively violent, short-lived eruptions. They start abruptly, develop rapidly, and empty the pool quickly. Round Geyser in Yellowstone puts on a good show, playing to an average height of 25 m for a minute or so every 8 hr.

Some geysers, such as Strokkur, do not build cones but their standpipes have slightly raised rims around the openings and are surrounded by pools of water (Type C). Strokkur's tube is 13.5 m deep and funnel-shaped, 8.3 m in diameter at the top and only 26 cm in diameter 8.3 m down. Its action is quite violent and intermediate between that of a purely columnar geyser like Old Faithful and a pool geyser like Narcissus. Every minute or so a large bubble, a meter or two in diameter, rises to the surface and breaks explosively with the evolution of steam. Some explosions are much larger than others. Although the basin remains nearly full most of the time, the water level lowers several centimeters after each

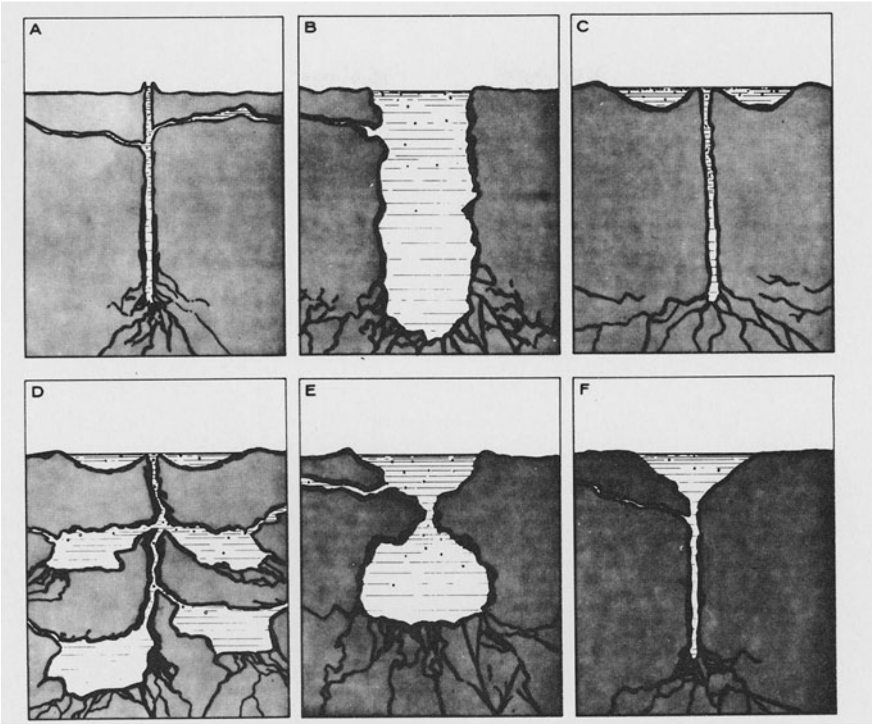

Figure 3-2. Cross sections of generic types of geyser reservoirs.

explosion. Every 10 to 15 min the geyser erupts, throwing steam and a small quantity of water to a height of 20 m or more (Fig. 3-3). The eruption is short-lived, a matter of only a few seconds.

Two large fountain geysers, Grand and Great Fountain, erupt as a series of powerful and sustained fanlike jets of steam and water, each burst being separated by a short period of inactivity. There are fewer pauses in the action of Great Fountain but they are longer in duration, sometimes as much as 30 min. A very logical explanation for this type of activity is that each geyser has several interconnected underground reservoirs, one emptying after another, somewhat as shown in the figure as Type D. Other configurations of pool or fountain geysers look something like Type E for Narcissus, and F for the Great Geysir.

Temperature soundings, recorded seismic signatures, and visual aspects of play are all additional clues as to the nature of the reservoir and its associated water and heat sources. These suggest that very often there is a complex network of two systems of channels, one shallow system feeding the bulk of the water to the reservoir and another deeper system feeding a much smaller quantity of extremely hot water and perhaps also hot volcanic gases.

Most of the water in a reservoir is trapped meteoric water, rain or melted snow, which has followed one of several paths to it. Geysers are located frequently along banks of rivers from which certainly some of their water is derived

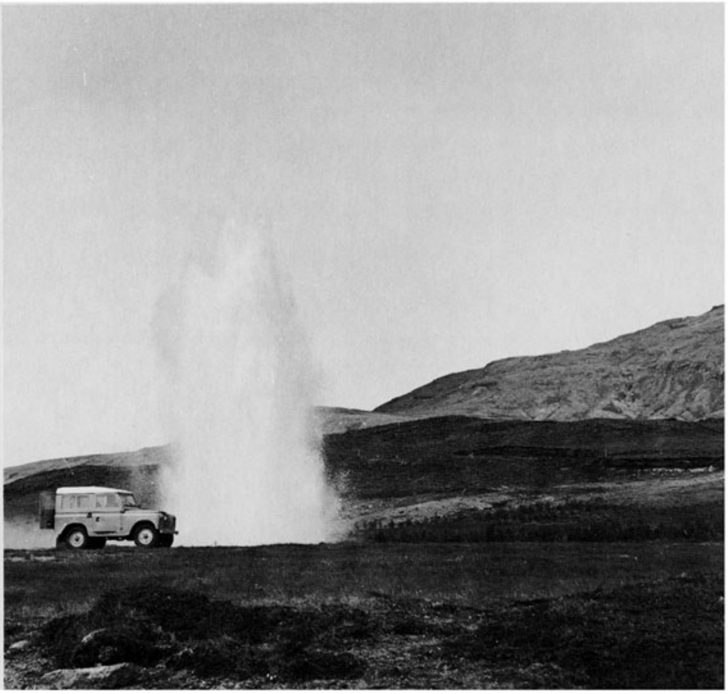

Figure 3-3. Strokkur in full eruption.

(Fig. 3-4). Part of the water has made a long circuitous journey downward through heavily fractured and altered hot rock where it is first heated and then convected back to the surface. It is possible that some of the water that enters the reservoir is magmatic.

The bulk of the heat supplied to the geyser is by injection of hot water or steam directly into the reservoir and channels already filled with hot water. Heat conduction through the walls of the reservoir plays only a minor role.

The most definitive indicators that such injections are occurring are deep-down temperature measurements. At the 270 m level in Solitary, these injections are intermittent and sporadic but have a high frequency of occurrence compared to the number of eruptions and hence only produce an average effect (Fig. 2-9). The temperature of the injected water, about 170°C, is not especially high, certainly well below the boiling point of about 230°C at the pressure produced by a hydrostatic head of 270 m. Water of this temperature must rise toward the surface where it will mix in the other water before it can be effective in precipitating an eruption.

In Old Faithful, evidence indicates that mixing of water occurs below the 175 m level, ruling out the entrance of surface waters at very shallow levels. The bulk of the hot water is apparently injected as large surges spaced 20 to 30 min apart. The first of these after an eruption provides the energy for a series of steam

Figure 3-4. Riverside Geyser at beginning of steam phase.

bubbles and causes a series of seismic signals to begin. Succeeding surges supply additional energy. Any one of the surges could possibly trigger an eruption although a definitive causal relationship has not been established.

From temperature-depth measurements made on 25 geysers and springs in Yellowstone, it was found that in 16 of them a maximum temperature was reached before hitting bottom and the temperature increased very little at lower depths, suggesting that in many cases effusion of hot water takes place somewhere higher up from the bottom.

In order to appreciate the behavior of geysers, it is necessary to understand:

- why a geyser erupts;
- how the energy is supplied;
- how an eruption is initiated;
- how an eruption is terminated;

- why the behavior of geysers differ so much from each other; and
- why a single geyser may come into existence, change its behavior pattern, or cease.

Mackenzie after his original visit to Iceland published the first scientific theory of geyser action. He assumed that an eruption was caused by the expansive force of steam that accumulated in an invisible underground cavity. This idea was popular with some of the early investigators. Krug von Nidda visualized several branching cavities where steam collected, eventually forcing the water out and up through the geyser tube, thereby emptying it and opening a passage for the steam. Allen and Day felt that in the sinter-lined, steam-tight cavities, expansion and contraction of the steam contained in them caused the fluctuations in the surface level of water observed in many geysers. While none of these theories is universally applicable, each is partially correct.

Bunsen developed a theory intended to explain the action of the Great Geysir only. Although accepted for a long time, it does not seem to apply to the action of the Great Geysir but is fairly realistic in describing the action of a simple columnar geyser. Bunsen believed, on the basis of his temperature measurements, that the temperature at all points in the Great Geysir rose steadily from one eruption to the next with the temperature approaching the closest to the boiling point curve to be at the midpoint in depth, about 20 m. Consequently, boiling, which could be induced by the decrease in hydrostatic pressure caused by a 1 or 2 m overflow of water, would begin there. The steam generated by the boiling would further reduce the pressure; boiling would then begin to move downward, generating more and more steam and causing a full-fledged eruption.

Much has been learned in recent years concerning the principles of geyser action. From these, it is now possible to derive fairly realistic analytical solutions for typical geyser systems and to predict probable behavior patterns on the basis of measured physical parameters of the geysers.

3.2 Properties of Water and Steam

No matter which theory is proposed, it is obvious that two of the basic determinants in geyser behavior are the hydrologic and thermal properties of water and steam. Water transports and stores temporarily the heat energy that powers a geyser. In addition, it possesses several important properties upon which geyser action critically depends. It is a fluid, and, similar to most fluids, its specific gravity decreases as its temperature increases. Since a geyser's heat sources are generally nonuniformly distributed, high temperature gradients and hence corresponding high density gradients develop within the system. These density gradients are the driving force that establishes and maintains circulation throughout the whole geyser basin, both the large saturated rock masses and the individual geyser reservoir systems. The boiling point of water is pressure sensitive, increasing with increasing pressure. In geysers, boiling is temporarily suppressed by the pressure of overlying waters, the hydrostatic head, and excess heat is stored only to be catastrophically released at a later time. And finally, the approximately 1500 fold increase in volume which occurs when liquid water varporizes into steam is capable of performing a prodigious amount of mechanical work, specifically, the propulsion of a large amount of hot water and steam at high velocity from the orifice of a geyser.

Deeply circulating thermal systems are large-scale convective fluid systems. Cold, relatively high-density water that falls on the surface percolates downward to replace heated, less dense water that is thus buoyed upward. The deep circulation patterns with dimensions of the order of a few thousand meters, take place principally through faults and fractures. Close to the surface, especially in the upper 60 to 70 m, many interconnected channels develop which often enlarge upward, and the porosity of sediments and fault breccia will increase. At shallow depths, the density of water varies markedly with depth due to high temperature gradients existing there. Consequently many secondary convection patterns develop. The velocities of flow of the fluids have been calculated to be of the order of a few centimeters a day.

The free circulation occurring in many hot pools is generally not present in geysers. The violent eruptive behavior of geysers depends on the fact that constrictions in the reservoir plumbing restrict circulation (Type E, Fig. 3-2), allowing instabilities to develop where denser cooler waters overlie lighter warmer waters. Excessively high temperatures are required to create the higher than normal density differences needed to develop the buoyant forces adequate to break through the constriction and erase the unstable situation. Rapid massive circulation takes place during this time, often exposing superheated water to lower pressures where it is likely to burst explosively into steam.

The heat energy content of a substance or a system of substances is referred to as *enthalpy,* E. Most thermal processes involved either decreases or increases in the enthalpy of systems or transfer of enthalpy from one part of the system to another. When the enthalpy of a substance is increased by the addition of heat, its temperature may rise or its temperature may remain the same, the substance simply undergoing a phase transformation such as melting or boiling. Substances vary greatly, by more than a factor of five, in the amount of heat required to effect phase transformations and temperature changes. The amount of heat required to increase the temperature of a unit mass of a substance one degree is defined as its *specific heat.* Pure water has the highest specific heat, c, of any substance. A commonly used basic unit of heat energy is a *calorie,* cal, defined as the amount of heat required to raise the temperature of one gram of water 1°C. The *British Thermal Unit,* BTU, is the amount of heat required to raise the temperature of one pound of water 1°F, equivalent to about 1/4 cal. The specific heat of water varies slightly with temperature but not enough to affect appreciably any of the geyser calculations referred to here. Under standard sea level air pressure, 760 mm of mercury, water boils at 100°C (212°F). The conversion of liquid water to steam requires a relatively large amount of energy, 540 cal/g, defined as the *heat of vaporization,* σ. Boiling will stop unless heat is continually added to the water to make up for the heat carried away by the steam, or unless the water is in a metastable superheated condition with its temperature higher than its normal boiling point. The steam bubbles when they first form are very small and uniformly distributed through the liquid. Their initial smallness results from the fact that a steam bubble can derive its heat only from its immediate surroundings. Superheated water will suddenly begin to boil violently, frequently internally and explosively, forming thousands of small bubbles of steam, using up all of the excess heat to do this, while the surrounding liquid cools down to its normal boiling temperature.

A very unusual phenomenon exhibited by many hot springs is the sustained presence of superheated water at the surface. The degree of superheat varies from a fraction of a degree to 3°C and, rarely, more. It always persists as a blob, recently migrated from depth, and never covers the surface uniformly. Usually the presence and extent of the blob can be observed visually but an almost sure test is to toss some foreign matter such as sand into the spring. The superheated water will explode into violent boiling, leaping up sometimes a few meters, hissing and roaring. Soon the temperature of the water drops to its normal boiling point. The earliest Icelandic travelers used to toss sod into the major geyser pools to make them boil up. The temperature of the water in springs that constantly churn is almost always above the ambient boiling point.

Water boils when its *vapor pressure,* p, pressure exerted by the water as it evaporates to form a bubble, which increases with increasing temperature, is just equal to the ambient pressure. Thus when the ambient pressure is lower, as at higher elevation, water at the ground surface will boil at a lower temperature. Deep within reservoirs, where the ambient pressure is higher, the water must attain a higher temperature before it will boil. Change in boiling point as a function of altitude is plotted in Fig. 3-5. Water boils at 100°C in the geyser areas of New Zealand, Iceland, Japan, and Kamchatka, which are all approximately at sea level. Yellowstone is at an elevation of 2200 m where water boils at a much lower temperature, 93°C. This lower boiling point adds to the ease with which the geysers can erupt since steam will form at a relatively much lower temperature.

The weight of superincumbent waters inhibits the development of most boiling hot springs and all geysers. The boiling point of pure water as a function of depth below the surface is plotted on a small scale to great depths in Fig. 3-6a. Figure 3-6b is a similar plot showing more detail at shallow depths. Down to about 10 m, the gradient is roughly 0.6°C/m. The curve breaks sharply at a depth of about 300 m and then straightens out at about 800 m with a much more gradual gradient, 0.02°C/m. Curves for mineralized waters do not differ appreciably.

The depth versus boiling point curve is not difficult to interpret and is extremely helpful in understanding geyser action. Assume that a small mass of water whose temperature is 110°C resides at a depth of 6 m. Since its temperature is lower than the ambient boiling point, the water will be in liquid form (Fig. 3-6 b); however it is superheated with respect to ground surface. Its temperature will

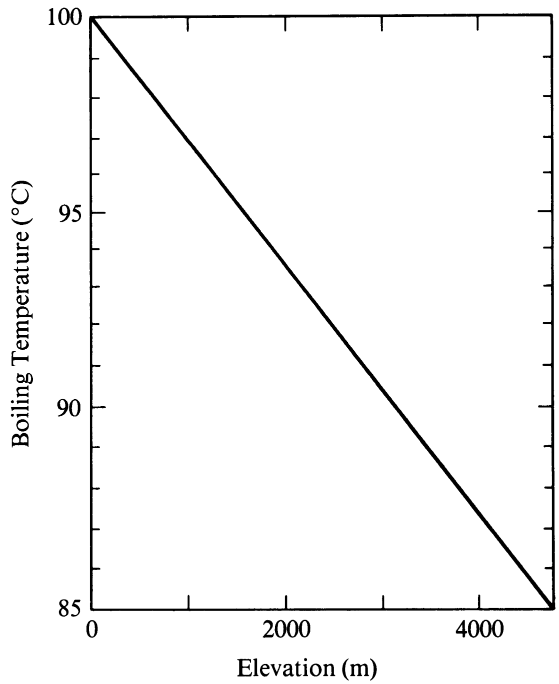

Figure 3-5. The boiling point of water as a function of elevation above sea level.

remain constant (the vertical line, ab) and it will be in liquid form until it reaches the depth corresponding to its crossing the boiling point curve. At that point, 3.7 m in depth, it vaporizes, gathering the heat to do so from its surroundings, and forms a bubble. As the bubble moves on upward, its temperature will decrease since it is in contact with cooler fluids. Either one of two things can happen. It will give up all of its excess heat to its surroundings and collapse, or the bubble will survive its journey through the cooler water, finally arriving at the surface where it bursts.

The amount of heat acquired from the earth by the water in one of Yellowstone's boiling springs by virtue of its residence in the earth can be calculated readily. The annual average mean air temperature there is 5°C. Thus, since precipitation is fairly uniform throughout the year, it can be assumed that the meteoric water which falls begins its journey through the earth at this temperature. At Yellowstone water boils at a temperature of 93°C. Its increase in enthalpy, ΔE, has therefore been its change in temperature times the specific heat of water or

$$\Delta E = (93 - 5) \times 1 = 88 \text{ cal.}$$

If the spring boils constantly, then it must be continually being supplied additional heat, most likely by small quantities of superheated water. Assuming that

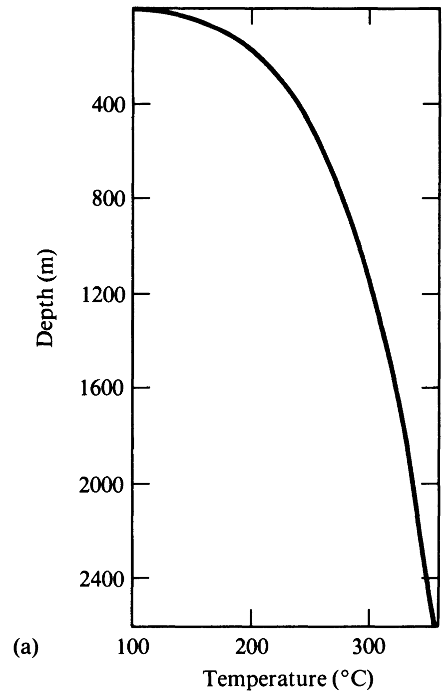

Figure 3-6a. The boiling point of water as a function of depth of overlying water.

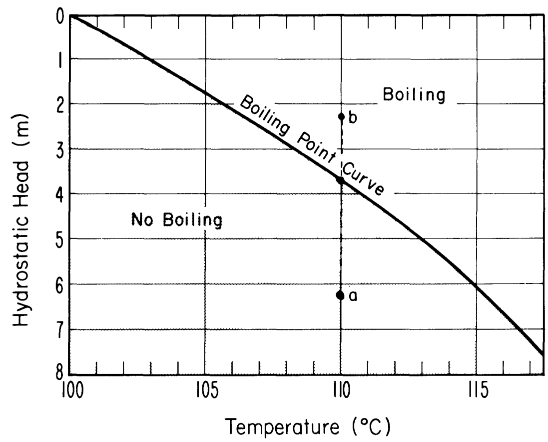

Figure 3-6b. Same as Fig. 3-6a except to different scale.

this latter water enters at a temperature of 110°C, the amount, m_w, of it needed to convert 1 g of the 93°C spring water into steam is given by

$$m_w\,(110 - 93) = 540$$

or

$$m_w = 32 \text{ g}.$$

The relative amount of steam formed when a given quantity of superheated water boils, releasing its excess heat, can be calculated in a reasonably straightforward manner. Let E_1 be the enthalpy of 1 g of the superheated water having a mean temperature of t_1, and E_2 the enthalpy of 1 g of the residual liquid which, as a result of the enthalpy, σ, carried away by the steam, has lowered its temperature to t_2, the ambient boiling point. Assuming that the evaporation and cooling process take place adiabatically, without gain from or loss of total energy, then

$$E_1 = E_2 (1 - x) + \sigma x \tag{3-1}$$

where x is the fraction of water transformed to steam. Solving Eq. (3-1), x is given by

$$x = (E_1 - E_2)/(\sigma - E_2).$$

For 100°C water cooled to 100°C, $(E_1 - E_2)$ is approximately 10 cal/g. $\sigma - E_2$, is close to 540 cal/g, the heat of vaporization of water at 100°C under standard conditions. Thus,

$$x \approx 1.85\%.$$

The results of more precise calculations taking into account variations in specific heat with temperature for two values of t_2, 100°C and 110°C, are listed in Table 3-1 for superheated temperatures up as high as 310°C. At this temperature almost exactly one-third of the liquid flashes into steam. For a high altitude region like Yellowstone, a reasonably good estimate can be obtained by simply appropriately sliding the temperature scale, treating 110°C superheated water as if it were at 117°C relative to a 100°C boiling point.

Bubbles are created below the surface as steam forms, usually as a very large

Table 3-1. Properties of Water and Steam (Adapted from Golovina and Malov, 1960)

Temperature (°C)	Enthalpy of Water (cal/g deg)	Specific Volume of Steam (ml/g)	Enthalpy of Steam (cal/g deg)	wt % of Evaporated Liquid for the Evaporation Temperatures of 100°C	110°C
100	0.312	1674	1.756	—	—
110	0.339	1210	1.728	1.87	—
115	0.352	1050	1.714	2.77	—
120	0.365	891	1.701	3.68	1.87
130	0.391	668	1.676	5.45	3.74
140	0.416	508	1.652	7.20	5.55
160	0.464	307	1.611	10.5	9.0
180	0.511	195	1.575	13.8	12.4
210	0.582	106	1.530	18.7	17.5
310	0.800	18.5	1.340	33.7	33.2

number of small ones which frequently coalesce later into a few large ones. The mechanical work required to push the water away to form the steam bubbles amounts to about 40 cal/g; the energy going into free surface energy in the bubbles is only about 0.1 cal/g. Thus an estimate can be made of the number of bubbles likely to form. Assume that an average radius of a bubble is $r = 0.2$ cm and its wall thickness is $w = 2 \times 10^{-4}$cm. If the specific volume, ml/g, of steam equals V_{s_0}, then the number, N, of bubbles forming during evaporation of 1 g of water is

$$N = (3/4\pi)\,(V_{s_0}/r^3).$$

The mass, m_b, of bubble walls per gram of steam is

$$m_b = A_b w = (3V_{s_0}/r)w$$

where A_b is the combined area of the bubbles. Substituting the values assumed for r and w, 0.2 cm and 2×10^{-4}, respectively, and the specific volume of 100°C steam, 1674 ml/g, $m_b = 5$ g. Thus, the mass of liquid in the bubble walls is very much larger, five to 10 times that of the steam. Under appropriate conditions it may be expected that practically all of the unevaporated water will be utilized to create the walls of bubbles to form a mist.

Superheated water in a geyser contains more than ample energy to hurl water and steam to great heights at high velocity. Its expansion into steam provides the motive power for doing this. Many geyser jets are thrown to a height of 30 m. This requires the jet to have an initial velocity, v_o, neglecting frictional effects, given by

$$v_o = (2gh)^{1/2}$$

where g is the acceleration of gravity and h is the height. To throw water 30 m high, v_o must be equal to at least 2.42×10^3 cm/s. The kinetic energy, KE, per unit mass of such a jet is

$$\begin{aligned} KE &= \tfrac{1}{2}\, v^2 = \tfrac{1}{2}[2.42 \times 10^3]^2 = 2.9 \times 10^6 \text{ ergs/g} \\ &= 0.29 \text{ joules/g or } 0.07 \text{ cal/g}, \end{aligned}$$

a value very small compared to the 40 cal/g of energy used to expand the steam while it is being generated.

The volume occupied by 1 g of erupted fluid is determined mainly by the volume of the steam. For 110°C superheated liquid water changing into steam at 100°C, 1.87 percent transforms into steam generating 31.3 ml/g of steam; for 115°C water, 2.77 percent transforms, making 46.3 ml/g of steam.

The steam generating capacity of the larger geysers is extremely high, exceeding that of many industrial boilers. This is because vaporization occurs not only at the surface of the vent but in the numerous bubbles of steam contained in the body of water. During an eruption of Velikan, for example, the area, bubble surface area plus area of the water exposed to the atmosphere, from which boiling is occurring has been calculated to be about 70,000 m^2, an area more than 10,000 times that of its 4.5 m^2 exposed opening.

In its first stage of eruption, a large geyser develops enormous power. Its magnitude is given by

$$\text{Power} = (\text{KE})/\tau$$

where τ is the length of time taken for the superheated water to be discharged from the geyser. Velikan, which takes about 17 s to discharge its 100°C to 115°C, 13.5 metric tons of water, initially develops power at a rate of 180 to 260 kw, generating steam at a rate of 53 to 54 metric tons/hr. The rate of generating mechanical power during an eruption of Old Faithful is between 100 to 200 kw.

3.3 Geysering from a Pool: Fountain or Pool Geysers

The action of a simple fountain or pool geyser is easy to understand qualitatively. An eruption is initiated when deep-lying bodies of hot water abruptly overturn convectively, bringing superheated water up to a shallow level where a portion of it explosively transforms into steam. Before this happens, a certain amount of steady state convection may be established with convection cells and mixing zones developing. Such patterns are easily delineated by throwing bits of thin paper into the pool to be carried along by the convection currents.

Narcissus, Giantess, and Artemisia are classic examples of fountain geysers. Narcissus operates on an alternating two and four hour schedule. Following the eruption which is preceded by the two hour interval, the basin is completely emptied by suction through fissures in the bottom of the reservoir. It then begins to slowly fill with hot water, becoming completely full after about three hours. Temperature of the water (Fig. 2-7) in the lower chamber gradually increases during this time whereas the water in the wide-mouthed basin slowly cools, presumably by evaporation. Every hour or so there is an excursion of hot water upward accompanied by downward movement of cooler water. Finally, one of the rising blobs of superheated water contains enough excess heat energy to remain superheated after its encounter with the cooler upper basin water, exploding into steam as it approaches the surface and violently agitating the water in both chambers. Blob after blob of superheated water begins to move upward giving rise to a succession of explosions, which, after a few moments, erase all temperature and density gradients. The explosions cease and the eruption is over.

Following the four hour interval, the reservoir almost but not quite empties itself through bottom fissures after the eruption is finished. The next eruption takes place after only a two hour interval, indeed even before the upper basin is completely full of water. During this filling, the water temperature rises faster. This happens in other fountain geysers, notably Kotegu in Kamchatka.

Both Giantess and Artemisia in Upper Geyser Basin have surface basins of considerable size and depth filled with water that during an eruption domes up, breaking into a series of violent splashes. Giantess's basin is elliptical, 8 by 10 m in diameter and about 8 m deep and sits in a mound which slopes in a staircaselike terrace toward the bank of the Firehole River. Artemisia's basin is circular, 15 m in diameter and 14 m deep.

In the power of its eruption, Giantess far exceeds Artemisia even though the latter's basin is much larger. At the time of an eruption, a great mass of hot water is hurled 18 m in the air with higher spurts shooting up to heights of 75 m. After about 36 hr these stop, to be followed by a powerful steam phase lasting 12 hr. Much more water is discharged during the eruptive bursts of Artemisia but less violently. The water in its pool suddenly domes up, bursting into jets shooting in every direction but with none reaching heights greater than 10 m. Play is very regular; it lasts for nearly a half hour with about a 12 hr quiet period.

The Great Geysir, though now inactive, also functioned as a fountain geyser. The discernible part of its plumbing consisted of a 3 m diameter, 20 m deep tube topped by a 16 m diameter 1 m deep basin. It took 10 to 12 hr to refill after an eruption. An eruption was heralded by the water doming at the surface. The initiation appeared to be located at about the 10 m depth.

Round Geyser is a 6 m deep cylindrical shaft about 1 m in diameter. For several hours before an eruption, its waters circulate in a well developed single convection cell, water rising at the center and descending at the rim, with the bottom temperature staying between 115°C and 120°C. Suddenly for no observable cause, the water begins to flow over the edge, followed in a few seconds by almost instantaneous vaporization of all the water in the reservoir, throwing steam and spray in one big burst to a height of 20 to 30 m.

3.4 Geysering from a Pipe: Columnar or Cone Geysers

A majority of columnar or cone geysers erupt from fairly small vertical or nearly vertical, fairly uniform tubes, usually ejecting a single steady jet of hot water and steam, emptying all or most of the tube in a few minutes. The water supply in the simplest of these is a steady flow of superheated water into the bottom of the tube, up it, and finally out through the surface. During the water's upward course, as it fills the tube after an eruption, it cools and soon there develops a column of water cooler at its top than at its bottom. As hot water continues to flow, a few steam bubbles can be expected to develop at those locations in the column where the temperature of the upward flowing water is higher than the ambient boiling point. The bubbles will ascend rapidly at first but will then be cooled in the overlying water, often collapsing and disappearing. Eventually a metastable energy state develops within the tube which is relieved by the ensuing eruption.

Experiments on models of such a geyser indicate that it will erupt only if there is a constriction in the geyser tube where rising steam bubbles are caught. The eruption seems to be triggered when all of the water below the constriction has been heated to the boiling point with no water cool enough to condense the steam bubbles. Bubbles entering the constriction become trapped and lift the overlying cooler water up and out of the geyser as a mass, precipitating an eruption by reducing the hydrostatic pressure on the lower-lying hotter waters. Further, constriction may lead to the current becoming swifter and the evolution of steam bubbles more rapid.

Temperature measurements corroborate the applicability of the model. Eruptions were found to be initiated at a relatively shallow depth by steam bubbles powerful enough to push out a plug of overlying water. Sometimes it is necessary for the overlying water to be pushed up and out in increments. At Old Faithful, as many as 20 large splashes occur before an eruption gets underway. The temperature-depth curves in all the geysers show an upper regime of cooler water separated by a mixing zone, apparently at a constriction, from deeper, hotter water.

In models without constrictions, the steam bubbles rise into the upper cooler water where they collapse at first but as the water becomes hotter, get all the way to the surface where steady boiling commences. The action of these models corresponds to the behavior observed in natural boiling hot springs.

By making a number of fairly realistic assumptions, it is feasible to carry through an analytical analysis of the hydraulic and thermal regimes of a simple columnar geyser and to predict in considerable detail certain features of its behavior. The analysis shows that two stages of equilibrium develop. First, the geyser tube fills with hot water before boiling starts; and second, boiling begins within the tube with the level at which it takes place moving progressively downward during the eruption, reaching some final level by the end of the eruption. This final level is usually very much deeper down in the tube than the point at which vigorous boiling started. The greater the difference between these two levels the greater the tendency of the geyser to erupt.

Assume that the geyser tube is vertical and uniform in cross section and extending so deep that it can be considered infinitely long. Assume further that V_w milliliters of T_1 degree absolute water enters per square centimeter of cross section of the tube per second and that T_1 is greater than sea level boiling point, 100°C or 373°K. Assume also that in the beginning, the geyser tube is filled with water whose temperature is constant, T_1, from the bottom of the tube up to a depth, d_1, the depth at which the hydrostatic pressure has decreased to the point where the T_1 degree water will boil. The temperature of the water is assumed to decrease from d_1 on up to the surface in such a way that at nowhere in the tube is the vapor pressure of the water high enough to overcome the ambient hydrostatic pressure and have boiling occur. The upward flow of water will eventually lead to local boiling regimes within the tube. Such boiling episodes may occur a number of times before an eruption starts but one will finally precipitate it.

At any depth, boiling will vaporize m_s of each m_w g of the ascending water where

$$m_s = m_w(T_1 - T)\,\sigma. \tag{3-2}$$

T is the temperature of the residual water after boiling has occurred and σ is the heat of vaporization of the water, 540 cal/g. The much lighter, newly-formed steam displaces a portion of the denser water, reducing the hydrostatic pressure, usually allowing boiling to take place at depths greater than d_1 unless the flow of water into the geyser tube is exceptionally high. The magnitude of this effect can be calculated.

The volume of steam, V_s, formed from the m_s g of vaporized water is

$$V_s = m_s/\rho_s = m_w(T_1 - T)/\sigma\rho_s \quad (3\text{-}3)$$

where ρ_s is the density of the steam in the bubbles. Thus the approximate average density $\bar{\rho}$ of the column of fluid at depth becomes

$$\bar{\rho} = m_w/(m_w + V_s) = 1/\left[1 + (T_1 - T)\sigma\rho_s\right] \quad (3\text{-}4)$$

since the density of water is nearly equal to one.

Now the gradient of the hydrostatic pressure is given by

$$dp/dd = \bar{\rho}(d) \quad (3\text{-}5)$$

which can be rewritten as

$$(dT/dp)(dd/dT) = 1/\bar{\rho} \quad (3\text{-}6)$$

where p is the vapor pressure of water at depth d.

Substituting from Eq. (3-4)

$$dd = \left\{(dp/dT) + \left[(T_1 - T)/\sigma\rho_s\right] (dp/dT)\right\} dT. \quad (3\text{-}7)$$

On integration from the surface, located at depth d_1, at which boiling commenced, where the temperature is assumed to be just at boiling, 373°K, to an equilibrium depth, d_e, down to the which boiling now extends as a consequence of the reduction in hydrostatic pressure resulting from presence of steam bubbles in the overlying waters, gives

$$d_e = p_{T_1} - p_{373} + \int_{T=373}^{T_1} \left[(T_1 - T)/\sigma\rho_s\right](dp/dT)dT. \quad (3\text{-}8)$$

Using as units of pressure centimeters of water makes

$$p_{T_1} - p_{373} = d_1 \quad (3\text{-}9)$$

provided the water lying above the depth, d_1, is too cold to boil.

The integral in Eq. (3-8) can be evaluated by means of the empirical relationship

$$(1/\sigma\rho_s)(dp/dT) = 1.145 - 0.009t - 0.00004t^2 \quad (3\text{-}10)$$

where t is the temperature in °C and the pressure in the steam bubbles is equal to the ambient hydrostatic pressure. For convenience, setting Δd_1 equal to the value of the integral, then

$$\Delta d_1 = \int_{t=0}^{t_1} (t_1 - t)(1.145 - 0.0019t - 0.00004t^2)dt \quad (3\text{-}11)$$

where

$$t_1 = T_1 - 373.$$

From Eqs. (3-8) and (3-9), it is seen that

$$d_e = d_1 + \Delta d_1. \quad (3\text{-}12)$$

This equation implies on the basis of the assumptions made that if boiling starts at depth d_1, it will propagate deeper down, finally reaching another equilibrium at the greater depth $(d_1 + \Delta d_1)$. The value of Δd_1 is strongly temperature dependent, becoming quite large for water temperatures much above 100°C. Some computed values of Δd_1, the distance from the first to the new equilibrium position, are listed in Table 3-2.

Having estimated values of Δd_1, it is possible to estimate the duration of play of a columnar geyser as a function of water temperature but first it is instructive to develop a relationship between water temperature and height of play.

The rate of boiling governs the height of the eruption. To reach a height, h, the water droplets must leave the geyser orifice with the velocity, v_o, given by

$$v_o \geqslant (2gh)^{1/2} \tag{3-13}$$

where g is the acceleration of gravity, 980 cm/s^2. The volume of fluid, steam and water, passing through each square centimeter of orifice area per second is also numerically equal to v_o or

$$v_o = V_s + V_w \tag{3-14}$$

where V_s and V_w are the volumes of steam and water, respectively. The volume of steam in the ejected mixture of fluids is given by Eq. (3-3). According to Table 3-1, the density of steam at atmospheric pressure is 1/1674 g/ml. Since σ = 540 cal/g, V_s in the same units is given by

$$V_s = 3.1\ t_1\ m_w = 3.1\ t_1\ V_w \tag{3-15}$$

where t_1 is the difference between the ambient boiling point at the orifice and the temperature of water deep within the tube.

The ratio of volume of steam to volume of water exiting from the orifice is therefore approximately equal to $3t_1$. This result indicates that whereas at geyser temperatures ranging from 110°C to 120°C ($10° < t_1 < 20°$) only 2 to 4 percent by mass of the water is transformed into steam (Table 3-1) and the volume of the ejected steam will be 30 to 60 times that of the ejected water droplets.

Substituting the above results in Eq. (3-14) gives

$$q_w = (2gh)^{1/2}/(3t_1 + 1) \tag{3-16}$$

where q_w is the rate of flow of water just deep enough in the geyser that no steam

Table 3-2. Computed Values of Δd_1 for Several Geyser Water Temperatures (Adapted from Thorkelsson, 1940)

Temperature of Geyser Water (°C)	d_1 (m)	Δd_1 (m)
101	0.4	0.6
110	4.3	56.9
120	9.8	226.0
130	17.1	505.0

has yet formed, the temperature here being $(373 + t_l)$°K. Velocities required for various temperature waters to maintain a continuous 50 m high eruption are listed in Table 3-3.

Normally the upward flow velocity is not this high so that the water level in the tube drops. When there is no upward flow, this boiling completely empties the tube. The times required to empty a 20 m long tube under these conditions are listed for several temperatures in the same table. If there is some but not totally adequate upward flow to maintain a steady condition, then the velocity, $dd/d\tau$, with which the water level falls is given by

$$dd/d\tau = q_w - V_s \tag{3-17}$$

where τ is time.

Substituting for q_w in Eq. (3-16) and solving for h gives

$$h = \Delta d_l - \Delta d = 0.57\ t_l^2 - \Delta d. \tag{3-18}$$

According to this equation, the geyser eruption will be the highest at the beginning when $\Delta d = 0$, subsiding gradually as the lower waters participate more and more in the eruption and Δd increases. It takes some time at the beginning for an eruption to get up to full speed since the cooler overlying waters must first be thrown out. Neglecting this effect, the maximum, equal to $0.57\ t_l^2$, therefore varies as the square of the number of degrees of superheat contained in the waters lying a few tens of meters below the geyser surface opening. Water at 110°C is unable to produce an eruption greater than 57 m high.

The eruption will stop when equilibrium is reached at the depth $(d_l + \Delta d_l)$. The time required to reach this state, τ_l, is the length of play of the geyser which can be theoretically calculated. In order to develop a 50 m high eruption with 120°C water, the water must flow up the tube at a velocity of 51 cm/s. Suppose now that the natural rate of inflow is 1 cm/s. Then the velocity at which the boiling region moves downward is 50 cm/s, requiring

$$\tau_l = \Delta d_l/50\ \text{s} \tag{3-19}$$

to descend from the d_l level to the $(d_l + \Delta d_l)$ level. Using Table 3-2, $\Delta d_l = 226$ m for 120°C water, giving, when substituted in Eq. (3-19) 7 min 32 s for the length of play, a duration of reasonable magnitude. After this time, the eruption

Table 3-3. Water Velocities Needed to Maintain a 50 m High Eruption and Times to Empty a 20 m Long Tube Assuming No Upward Flow (Adapted from Thorkelsson, 1940)

Water Temperature (°C)	Velocity (m/s)	Time to Empty Tube (s)
120	0.51	40
125	0.41	50
130	0.34	60

ceases for lack of hot water and a new eruption could not begin until the tube refilled and the temperature at 9.8 m (see Table 3-2) had reached 120°C.

The duration of play is seen to depend on both the temperature and rate of influx of water. When there is no influx of water, τ_1 is given by

$$\tau_1 = 2(1 + 3.1\ t_1)(\Delta d_1/2g)^{1/2} \quad (3\text{-}20)$$

which predicts a 1 min 50 s play if the water is at 110°C and a 7 min 10 s play if at 120°C.

The above calculations, although highly idealized, provide a great deal of insight into why and how certain kinds of geysers operate as they do. Factors that will influence the direct applicability to some extent are:

- the assumption that steam is weightless and has no heat capacity other than its heat of vaporization. This does not affect the results appreciably since such a small proportion of the mass involved is steam;
- the assumption that there are no cooling effects of the geyser tube. In the beginning, they may be relatively quite large but at the time of the eruption they become relatively unimportant. The most serious situation is where the top end of the geyser tube widens out into a basin and surface cooling becomes pronounced, sometimes severely affecting the developing of geyser action; and
- the assumption that the acceleration of water up the tube during an eruption will increase the pressure exerted against the lower waters. An analysis of this effect shows that the rate of propagation of the boiling down the tube is slowed down by the acceleration given the water and cannot exceed a certain limit.

Calculated values of the velocity at which the boiling surface moves downward are listed in Table 3-4 from which it is evident that the maximum rate of boiling is almost constant, 1.05 m/s in the temperature interval 110°C to 130°C. However the rate decreases as the boiling progresses downward and Δd increases. It is obvious from the table that a very high rate of flow of water up the tube, greater than 1 m/s, would be required to prevent boiling from propagating downward. Such a condition would cause a perpetual spouter to develop.

Friction in geyser conduits has not been taken into account. It can also be important in regulating geyser action. Frictional resistance should remain nearly constant all the way up the tube since while it increases near the top due to the higher speed of exiting fluids, it will decrease at the same time by virtue of the

Table 3-4. Calculated Rates of Boiling in Geyser Tube (Adapted from Thorkelsson, 1940)

Water Temperature (°C)	Velocity at Which Boiling Surface Moves Downward (m/s)
110	1.03
120	1.05
130	1.05

fact that more bubbles form there. The net effect of frictional resistance is to suppress boiling since it is a force acting in the same direction as hydrostatic pressure. The effect was well known by Icelandic farmers who prevented certain annoying geysers from erupting by filling their tubes with rocks. Contrariwise, many geysers whose tubes have become partially filled and become constant spouters can be returned to their normal action by the removal of the debris. Or the action may only be somewhat modified as was the case with Littli Geysir in Iceland whose vent is enclosed by stone, probably man-placed. During its frequent periodic eruptions, water and steam shoot forth in all directions from among the rocks. Some jets reach heights of 10 to 13 m. An eruption is presaged by initiation of subterranean splashing and a gradual increase in the amount of steam discharged. The eruption itself builds up slowly, reaching a maximum in about 10 min, after which the water spouts begin to die down and the geyser becomes quiet in about another 10 min.

It has been tacitly assumed in the preceding discussion that the liquid and vapor phases of the geyser waters are uniformly mixed and move together through the system exerting a hydrostatic pressure as if the density of the mixture were inversely proportional to the combined column of steam and water. This is essentially true although near the mouth of the geyser, the bubbles coalesce and form larger bubbles that ascend at a higher velocity than the water.

Another factor not taken into account in the above derivations is variation of the rate of influx of water, due especially to variation in hydrostatic pressure in the geyser tube. Such variation plays an important role in the rate of heating of a buried reservoir. A simplified analytic treatment of this effect indicates that water will flow in more rapidly under low hydrostatic pressure than high. Increasing the rate of water flow causes the boiling to propagate more slowly downward. As a consequence of the slowing down of the rate of propagation of the boiling surface, the geyser eruption lasts longer and produces higher and more frequent bursts than it would when the water is coming in less fast. All of the equations discussed above show fairly well that geyser eruptions of substantial height cannot continue for long periods unless especially large amounts of hot water are supplied from other subterranean channels and cavities serving as auxiliary reservoirs.

Although an eruption could possibly be terminated in a number of ways, it seems most likely that is terminated because the system has either expended all of its excess heat, which is what generally happens in a fountain geyser, or it has thrown out all of its excess hot water, the usual situation in a columnar geyser.

Maximum pressures exist throughout the plumbing system of a columnar geyser just prior to an eruption and as the eruption proceeds, the pressure within decreases. With the development of substantial pressure differentials between the geyser's reservoirs and the surrounding rock mass, the water in the saturated pores and fissures of the rock mass tends to drain into the reservoir. A zone of falling water levels forms around the tube. The scarcity of water, especially in the rock mass which still contains excessive heat, is conducive to the development of vast quantities of steam. This steam first forces all of the remaining liquid water out of the geyser tube and then roars forth to develop the powerful terminal steam phase characteristic of the behavior of most columnar geysers.

3.5 Complex Geyser Systems

Simple columnar and pool geysers can only generate a single thrust of water and steam, or a single series of steam bubbles. More elaborate systems must be invoked to account for the complex behavior of many geysers, especially for the large amounts of water thrown out by some geysers, and for the multiple thrusts seen at Grand Geyser, Great Fountain, and others.

A fairly simple idealized model to analyze, to account for large volumes of discharged water is the one shown in Fig. 3-7. It consists of a standpipe fed from its base by a single large reservoir. There is a fluid heat source entering through channels, a; a reservoir, A; a supply of cold water entering directly into the reservoir through channel, b; and an orifice, c, through which the geyser discharges. The volume of the tube, C, is assumed to be negligible compared to that of the reservoir. These elements interact to produce an eruption, occurring explo-

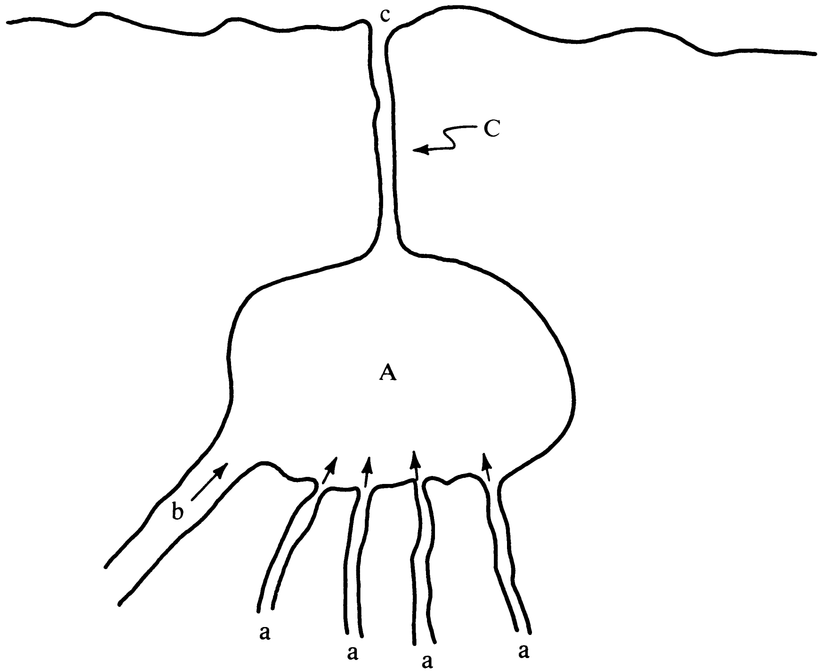

Figure 3-7. Model of complex columnar geyser. (Suggested by Merzhanov et al., 1975, private communication.)

sively as a result of rapid conversion of the excess heat energy, W, of superheated water which amounts to

$$W = c\Delta T \tag{3-21}$$

where c is the specific heat of the water and ΔT is the difference in temperature of the boiling water under the ambient atmospheric pressure, p_o, and the temperature of the boiling point of water under the pressure, p, corresponding to the depth, d, at which the superheated water resides. p is given by

$$p = p_o + \rho g d \tag{3-22}$$

where ρ is the density of the water, taken here to be equal to 1 g/ml. Eq. (3-22) indicates that the higher the value of ρgd, the greater is the energy of superheating and the more violent the eruption.

The first phase following an eruption is the refilling of reservoirs and tubes and the heating of their newly accumulated water. The latter is accomplished by an influx of small quantities of hot, heat-carrying water or steam that rapidly mixes with the cooler water. Some heating is accomplished by heat conduction through the walls of the reservoir but the amount is considered negligible. The rate of flow of the hot water which comes from great depth, is nearly independent of the pressure in the reservoir whereas that of the cold water of shallow origin may vary somewhat, being affected by the difference in pressure between that in the water-bearing bed and that in the reservoir. The heat source may be steam which after condensation is equivalent to water at temperature, T_h, where

$$T_h = T_s + (\sigma/c) \tag{3-23}$$

where T_s is the temperature of the steam.

It is assumed that the volume, V_A, of the reservoir is much larger than that of the exit channel, V_c, and that any pressure gradients in the reservoir are negligible.

As the reservoir begins to fill, all residual water is at temperature, T_o. As time goes on, the amount of water in the reservoir, which is a mixture of hot and "cold" water, increases at a steady rate governed by the differential equation

$$\rho(dV/d\tau) = q_1 \tag{3-24}$$

and its temperature is constantly changing with mixing in accordance with the equation

$$\rho V(dT/d\tau) = q_h(T_h - T) + q_c\,(T_c - T) \tag{3-25}$$

with $\tau = 0$, $V = V_o$, and $T = T_o$ at the completion of an eruption. The quantity, q_1, is equal to the total rate of inflow of water ($q_h + q_c$), q_h and q_c being, respectively, the rate of influx of hot water or its equivalent in steam, and cold water.

Solving the differential equation yields

$$V = V_o + (q_1/\rho)\,\tau \tag{3-26}$$

and

$$T = T_{e_1} + (T_1 + T_{e_1})\left[1 + (q_1/\rho V_o)\tau\right]^{-1} \qquad (3\text{-}27)$$

where

$$T_{e_1} = (q_c T_c + q_h T_h)/q_1 \qquad (3\text{-}28)$$

is the equilibrium temperature after mixing. Note that until the reservoir is completely filled, the temperature of its water will decrease in the most common situation where more cold water than hot enters it.

The condition of most relevance to geyser activity is when T_{e_1} becomes greater than T_o. The time, τ_1, to fill the reservoir is given by

$$\tau_1 = (V_A - V_o)(\rho/q_1). \qquad (3\text{-}29)$$

The temperature, T_1, at that time is

$$T_1 = T_{e_1} + (V_o/V_A)(T_o - T_{e_1}). \qquad (3\text{-}30)$$

Once the reservoir is full, the inflowing waters begin to fill the exit channel, the rate of rise of the water level in the channel depending upon the rate of inflow of water and the cross sectional area of the channel. The volume of water in the reservoir, of course, remains constant but the pressure there increases due to the weight of the overlying water in the channel. This increased pressure reduces the pressure difference between that of the cold water in the rock mass from which it enters, and the water in the reservoir, usually decreasing the rate of influx of water. The amount of decrease can be approximately determined from the application of Darcy's law which relates permeability to applied pressure. The effect is appreciable for porous material, gravels, and heavily fractured rocks and can be taken into account although the calculations become more involved. For dense competent rock masses, it can be neglected.

For the present, neglecting any variation in flow rate, the time, τ_2, after an eruption when the channel becomes full, assuming that it is of length, D, and uniform cross section, A, is

$$\tau_2 = \tau_1 + AD/q. \qquad (3\text{-}31)$$

The temperature, T_2, is assumed uniform throughout the reservoir and channel at just the time that the channel becomes completely filled. From then on, the pressure stays steady and the total amount of water in the system, reservoir and channel, remains constant.

At the same time the water begins to heat up, eventually precipitating an eruption. It is assumed here that the eruption will occur when T_{e_2}, the equilibrium temperature achieved by mixing of the hot and cold fluids in the reservoir, becomes greater than the boiling temperature, T_I, corresponding to the pressure, p_2, in the reservoir. At this time, steam bubbles form, forcing the water out of the channel, relieving the pressure on the reservoir, and initiating violent boiling. Solving the heat balance differential equation

$$V_A = (dT/dt) = q_h(T_h - T) + q_c(T_c - T) \qquad (3\text{-}32)$$

gives an expression for determining the temperature T at any time:

$$T = T_{e_2} - (T_{e_2} - T_2) \exp\left[-(q_1/V_A)(\tau - \tau_2)\right]. \tag{3-33}$$

The equilibrium temperature as before is given by

$$T_{e_2} = (q_c T_c + q_h T_h)/q_1. \tag{3-34}$$

Any effect of pressure on rate of flow of the cold or hot water would change the values of q_c and hence q_1. In fact, calculations on Velikan's thermal and hydrologic behavior indicate that the reduction in flow might be as much as a factor of 10.

The interval of time, τ_I, from the end of one eruption to the beginning of the next will be the sum of the time to fill the reservoir, plus that to fill the channel, plus that to further heat the water in the reservoir up to its boiling. This total time, not taking into account reduction in flow of cold water, is then

$$\tau_I = \rho(V_A - V_o)/q_1 + (\rho V_A/q_1) \ln\left[(T_{e_2} - T_2)/(T_{e_2} - T_I)\right]. \tag{3-35}$$

A full analysis of the model using the above equations has led to the following conclusions:

$$\text{If } T_{e_1} < T_1 \quad \text{and if} \quad \left\{\begin{array}{l} T_{e_2} > T_I \\ T_1 < T_{e_2} < T_I \\ T_{e_2} < T_I \end{array}\right. \quad \text{it is a} \quad \left\{\begin{array}{l} \text{geyser} \\ \text{boiling spring} \\ \text{hot spring.} \end{array}\right.$$

$$\text{If } T_{e_1} > T_1 \quad \text{and if} \quad \left\{\begin{array}{ll} c(T_{e_1} - T_1) < \sigma & \text{it is a fumarole} \\ & \left\{\begin{array}{l} T_{e_2} > T_I \\ \\ T_{e_2} < T_I \end{array}\right. \left\{\begin{array}{l} \text{geyser or} \\ \text{pulsating spring} \\ \text{boiling spring.} \end{array}\right. \end{array}\right.$$

The results of one numerical calculation are plotted in Fig. 3-8. The geyser parameters used are listed in Table 3-5. These are believed to be reasonably characteristic of Velikan. The total water discharged during one eruption cycle indicates that in addition to its large vent, it must also have a cavity or cavities for storing water, the volume of which exceeds by several times that of the vent. Velikan erupts every 3 to 4 hr, throwing a column of water to a height ranging from 30 to 50 m for about 90 s. This discharge of hot water is followed by 20 to 30 minutes of powerful steam ejection. The vent, 6 m deep with a 4.5 m^2 opening, has a storage capacity of 13.5 metric tons of water. Calculations of the sort discussed in Sec. 3.4 show that the vent would empty itself of water in about 20 s; however, the jet continues playing for more than another minute, clearly indicating that additional water is stored in subterranean cavities. Let the total eruption time be 90 s, and assume that the intensity of the last part of the eruption is only half that of the initial state. Then the additional erupted mass of steam and water, m_1, is

$$m_1 = (m/2)\left[(90 - \tau)/\tau\right] = 1.30 \text{ m to } 2.15 \text{ m} \tag{3-36}$$

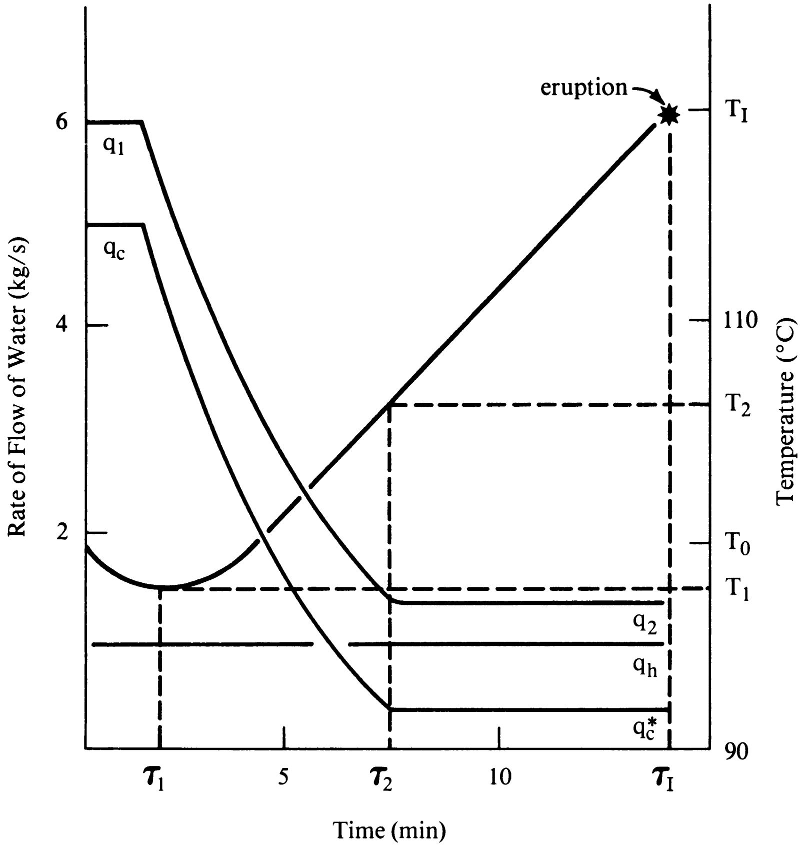

Figure 3-8. Results of sample calculation of the temperature and hydrologic regimes existing in the model geyser of Fig. 3-7. (Courtesy of Steinberg et al., private communication.)

where m is the mass of water contained in the vent just before an eruption. The lower value of m_l applies to 115°C temperature water and the higher figure to 110°C water. The mass, m_s, discharged as steam during the subsequent 20 min play is

$$m_s = x\ m\ \tau_s/6\ \tau \tag{3-37}$$

assuming that the rate of discharge of water has not dropped to one-third of its earlier value. τ_s is the length of the steam phase and x is the fraction of water changed to steam, assumed equal to 0.167. Substituting values, then

$$m_s = 0.22\ m.$$

The mass, m_b, of water forming bubble walls must also be taken into account. From Table 3-1, this is given by

$$m_b = 6\ m_s.$$

Table 3-5. Values Used to Obtain Temperature and Hydrologic Regimes Plotted in Fig. 3-8 (Adapted from Steinberg, Personal Communication)

V_A	$= 2 \times 10^3$ liters
V_o	$= 1.4 \times 10^3$ liters
V_c	$= 10^3$ liters
D	$= 10$ m
q_h	$= 1$ kg/s
q_c	$= 5$ kg/s
q_c*	$= 0.5$ kg/s
T_e	$= 200°C$
T_c	$= 75°C$
T_1	$= 100°C$
T_2	$= 120°C$

q_c*: Flow rate of cold water when geyser reservoir and channel are full.

Thus the total mass, m_T, discharged during the eruption is

$$m_T = m + m_l + m_b \tag{3-38}$$

or

$$m_T = 3.62 \text{ m to } 4.47 \text{ m},$$

the lower amount corresponding to 115°C, and the higher to 110°C temperature water. Since m is the 13.5 metric ton mass of water discharged from the vent, then m_T ranges from 48 to 61 metric tons. The subterranean cavity or cavities within Velikan thus must hold three to five times as much water as the vent.

Other qualitative details of Valikan's behavior support this conclusion: one is that Velikan's vent remains empty for some time after an eruption, finally slowly filling in about 1.5 hr. Assuming that water is entering far underground, such behavior is completely consistent with the notion that at least two subterranean cavities must be filled before water will begin to enter the vent. After the vent is full, water begins to overflow the rim of the basin indicating a constant influx of water. Also, the water level in the basin pulsates up and down in a sort of double and at times triple rhythm, accompanied by periods of local boiling and overflow.

The Atami Geyser is believed to have had a somewhat more complex geyser system than Velikan. It is located very close to the sea coast and was quite active until 1924 when it ceased to erupt, probably as a result of human intervention. Its normal eruption, occurring about every 5 hr, usually consisted of five successive alternate projections of hot water and steam. As the time of the eruption approached, subterranean rumblings were heard, with boiling water intermittently appearing just inside the mouth every 1 to 2 min. After about 45 min of this kind of activity, small quantities of water intermittently flowed out of the mouth, the amount of water and steam, especially steam, increasing with each surge until finally almost entirely steam was roaring out of the opening. Suddenly the flow of steam stopped, to be followed shortly by a tremendous gush of water. After about five such gushes, each interrupted by violent steam flow, with the entire process taking about 2 hr, the geyser became quiet and remained so for about 3 hr with steam lazily rising from its mouth.

Occasionally, Atami exhibited abnormal behavior. The regular sequence of periodic eruptions was interrupted by an extraordinarily long eruption called a *nagawaki,* lasting 12 hr, which was followed by a fairly long, approximately 7 hr, quiet period before the regular sequence of eruptions was resumed. The Japanese refer to such a performance as an *oyakobuke,* meaning mother and daughter eruption.

Extensive studies both in the field and on laboratory models establish rather conclusively that Atami had two large underground storage reservoirs, illustrated in cross section in Fig. 3-9. Cavity, A, which lies at considerable depth, receives water through channel, b, and discharges it through channel, a. A nearby cavity, C, is fed water through channel, d, and discharges through channel, c, into channel, a. It is assumed the eruption is initiated in cavity, A, where the temperature of the water reached a critical value before that in cavity, C. After a certain amount of water and steam have been discharged, the pressure in the exit channel, a, falls low enough that water enters channel, a, and cavity, A, via channel, c, quenching the eruption momentarily. Pressure then again builds up producing

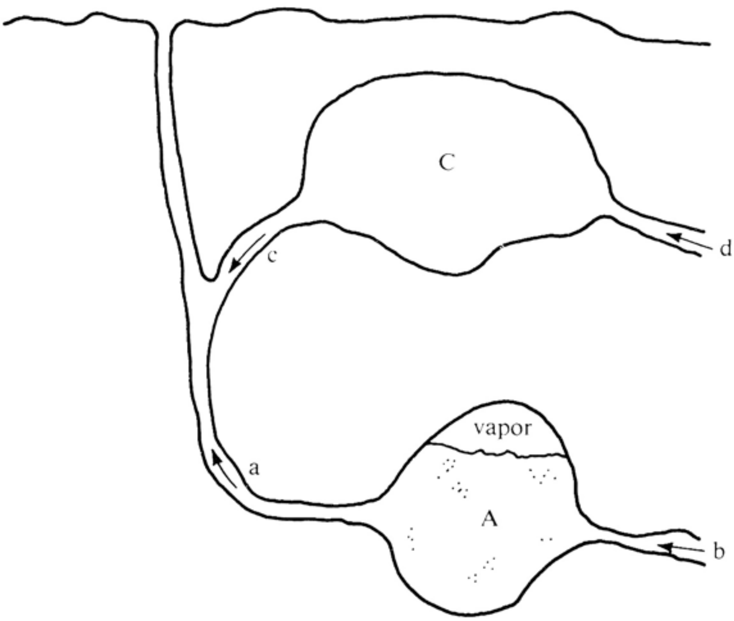

Figure 3-9. Inferred cross section of Atami Geyser. (Adapted from Honda and Terada, 1906.)

a second gush of water from A. After several such interactions all of the excess energy has been expended and activity ceases. The nagawaki undoubtedly originates at considerable depth and is not affected much by the shallower parts of the system.

Model experiments made with somewhat similar systems shown in Fig. 3-10 produce eruptions exhibiting two and sometimes three thrusts. In the experiments, the two reservoirs are filled with water to a level above the connection between the two. Both are heated from below and the actions in the two reservoirs are strongly coupled. The reservoirs cannot ever boil vigorously at the same time since that would create an unstable condition. Assume that the rate of boiling in one reservoir, B, increases slightly. Then the level of the water located above the junction, a, rises, increasing the hydrostatic pressure and hence the temperature which water must attain in the other reservoir, A, to boil. Depression of the rate of boiling in A decreases the number of bubbles in it. Whereupon water flows into A, decreasing the hydrostatic pressure in B, and increasing the rate of boiling in it. Thus, boiling moves from one chamber to the other and water should flow back and forth between the two as first one boils vigorously and then the other. Indeed, such strong oscillatory flow was observed in the experiments by watching the dust and bubbles carried along by the changing currents. Many complete oscillations occur before an eruption. The oscillations also generate tremors resulting from the mechanical forces associated with the water flow.

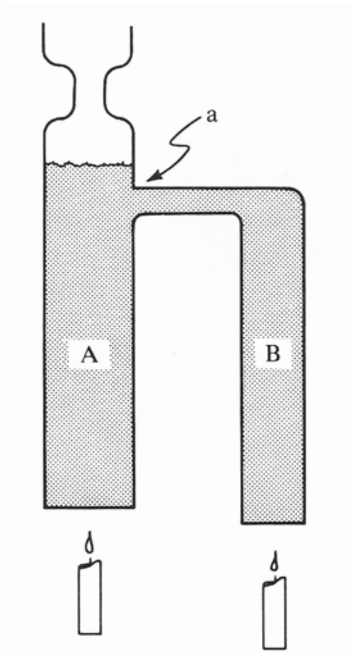

Figure 3-10. Laboratory model corresponding to Fig. 3-9. (After Anderson et al., 1978.)

During an eruption of such a system and even more complex ones, the reservoirs discharge in series. As the first throws water and steam from the orifice, some water also flows into the other reservoirs which increases the pressure and hence suppresses the tendency to boil in them. Another reservoir then starts its eruption, during which it may force enough water back into the first reservoir or other reservoirs to enable them to erupt even a second time.

While the action of simple fountain geysers is understood in a general way, it is almost impossible to specify theoretically and quantitatively the hydrologic and thermal regimes involved in the eruptions of more complex types since very little is known of their individual plumbing systems. Certainly the requisite regimes are strongly dependent on the geometric configurations of the geyser's reservoirs, the source and location of heat and water and most important, the delicate interactions among these.