of the internal inhibitory (synchronizing) system located in the basal forebrain (*5*). A cholinergic link of muscarinic type was postulated between this system and the reticular activating system (*13*), and between the latter and cortical neurons (*14*). Centrally acting anticholinergic drugs, scopolamine and atropine (but not peripherally acting methyl-scopolamine) abolished and physostigmine (a cholinesterase inhibitor) restored both PRS and RCPV phenomena (*15*). All these observations and our results are compatible with the view that RCPV represents a steady potential correlate of a Pavlovian active internal inhibitory process.

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16. Supported by PHS grant NB 06385 and PHS training grant GM 81-09 to J.L.Y. and J.T.H. We thank Miss S. L. Allen for her assistance.

9 September 1968; revised 8 November 1968

Old Faithful: A Physical Model

Since 1938 the Rangers at Yellowstone National Park have used the duration of eruption of Old Faithful to predict the time interval between eruptions. The relation, displayed by a graph on the wall of the Old Faithful Ranger Station, was established by the U.S. National Park Service, reported by Rinehart (*1*), and rediscovered by Geis (*2*). Using the above relations and Rinehart's (*1*) seismic data, Geis (*3*) postulated a physical model for Old Faithful that is similar in many respects to Bunsen's discredited geyser model (*4*). Recent work of White (*5*) showed that (i) large voids and geyser tubes are effects rather than causes of geyser action; (ii) most of the water erupted from geysers comes from fractures and porous and permeable rock deep underground, rather than from large chambers, which are not the source indicated by research drilling; (iii) hot water predominantly of meteoric origin circulates to depths of a few thousand meters underground where it is heated to temperatures far above the surface boiling point, and this heated water, rising in a huge convection system, in turn heats the rock in the upper several hundred feet of the system, and carries with it all the energy required for geyser action; and (iv) after a geyser eruption has occurred, the local underground rock is left relatively chilled due to extraction of heat from the system as water flashed to steam.

Geis (*3*) proposes that the underground configuration of Old Faithful is in the shape of a "U" with one end open to the surface and the other opening into a single closed underground chamber which generally is completely emptied during an eruption but sometimes is incompletely emptied. Geis further states: "An eruption would take place when the U portion of the cavity was sufficiently full to splash a quantity of water over into the hot, *dry* [my italics], back half of the cavity. The water would immediately flash boil to steam, forcing the water out of the U section of the cavity" (*3*).

If this model is correct the temperature in the cavity will immediately come to, and remain fixed at, the boiling point of water as soon as liquid is splashed into the cavity. If this boiling temperature is kept constant during flash boiling, and if the cavity is spherical, then the rate of heat flow into the cavity is given by the formula derived by Ingersoll, Zobell, and Ingersoll (*6*):

$$q = 4\pi kRT_s\left[1 + \frac{R}{(\pi\alpha t)^{1/2}}\right] \quad (1)$$

where q is the rate of heat flow, k is the thermal conductivity, R is the radius of the cavity, T_s is the initial difference in temperature between the cavity (kept at constant temperature) and the surrounding rock, α is the thermal diffusivity, and t is the time. Integration of Eq. 1 in respect to time yields an equation giving the total heat Q flowing from the surrounding rock into the cavity for any time interval, t_1 to t_2. If we assume generously large values for T_s, equal to 10°C, and R, equal to 224 cm, and reasonable values for k and α (*7*), the amount of heat that could be supplied to the cavity to flash boil water during the 1st second after splashing would be about 4.46 $\times 10^6$ cal and less than about half that amount during each succeeding second.

At the initiation of an eruption, Geis (*3*) demonstrates, the water level in the "dry cavity" side of the U is at the same level as that in the open end, so that the total gas pressure in the closed cavity must be equal to atmospheric pressure. Thus, water splashed into the "dry" cavity would start boiling at about 92°C, the average boiling point at the elevation of Old Faithful, the initial enthalpy of evaporation would be 544 cal/g, and the specific volume of the steam that formed would be about 2200 cm³/g. Therefore, the maximum volume of steam produced would be 0.22×10^7 cm³ in the first second. Even after 30 seconds of continuous "flash boiling," a maximum of only 1.2×10^7 cm³ of steam could be produced regardless of whether a large or small amount of water had splashed into the cavity. This is only about 25 percent of the volume of water that must be displaced. In actuality much less steam would form, because the pressure in the "sealed" cavity must increase as soon as liquid water started flashing to steam. This, in turn, would raise the boiling point of water and would decrease the term T_s in Eq. 1. The pressure in the cavity would be balanced by the weight per unit area of a column of water rising in the open end of the U. An increase of just 3 m in the head of water in the geyser tube would raise the boiling point of water in the closed cavity by about 10°C and would halt further formation of steam if T_s were 10°C or less. An increase of 30 m in the head of water would raise the boiling point in the cavity about 50°C.

Furthermore, Geis's model shows no channels for supplying water to the geyser and disregards all water chemistry. Local meteoric water and local leaching of rock by water are inadequate to explain the enormous amounts of dissolved materials discharged by Old Faithful—approximately 500 metric tons of dissolved material each year (300 metric tons of NaCl) from this one geyser.

Geis's model for Old Faithful is deficient in other respects. Just before an eruption, the water level in the geyser conduit is not situated at the level of the "reservoir" as he illustrates (*3*). Between eruptions, the water level in Old Faithful's conduit rises to within a few meters of the orifice and commonly splashes over the top at irregular intervals for 4 to 5 minutes before an eruption. This necessitates a high-temperature "pressurized" reservoir at depth. Work by the U.S. Geological Survey in Yellowstone National Park shows that the silica content of hot spring waters may be correlated with temperatures of aquifers supplying the water to springs and geysers. The silica content of water from Old Faithful (*4*, p. 429) indicates that the water comes mainly from rocks with a minimum temperature of 205°C (*8*). At that temperature, a pressure equal to a head of water of at least 180 m is required to maintain a water-steam system. Under these conditions, water is not likely to flash to steam by splashing back into a hot cavity that already would be saturated with pressurized steam. Also, the volume of steam that could form by flash boiling is smaller at high temperatures than at low temperatures (*9*).

Geis's theory demands that heat conducted through rock provide all the energy which drives eruptions of Old Faithful. My associates and I (*10*) reported a minimum figure of 1.1×10^8 cal/sec (*11*) for the heat discharged by hot water in Upper Basin where Old Faithful is located. The area of hot-spring activity is about 11 km², so that a heat flux of about 1100 μcal cm^{-2} sec^{-1} is required to furnish the heat. Such a heat flux is 500 to 700 times larger than the global average and could not be supplied by conduction through rock with the existing temperature gradients. White's conclusion that, after an eruption, the local underground rock is heated by very hot water rising up into the geyser from deeper and much hotter parts of the system is far more plausible.

In regard to the percentage of reservoir water ejected during an eruption, Geis proposes that, "in cases of complete eruption, the cavity is left essentially empty. . . ." But in a tracer experiment in 1963, more than 24 consecutive eruptions were required to clear Old Faithful of introduced rhodamine B.

White's (*5*) model for the hydrology and eruptive mechanism of a geyser may be applied directly to Old Faithful. In an enlarged portion of the geyser tube, convective overturn of water tends to equalize temperatures. In the tops of the local convection cells, temperatures may be at boiling or even slightly superheated; but deeper in the same cells, where hydrostatic pressures are greater, temperatures may be much below boiling. Still deeper, in the relatively narrow channels of the geyser system, temperatures are close to the boiling point (as demonstrated by nearly all recent research drilling in Yellowstone National Park), and steam bubbles are generated as rising water encounters lower hydrostatic pressure. Steam bubbles rising into relatively cool local convection cells will collapse, probably contributing to the seismic activity reported by Rinehart (*1*). When the generation of steam bubbles becomes so rapid that they begin to lift the overlying water, an eruption ensues. As the hydrostatic retaining pressure is "unloaded," a finite amount of water flashes to steam. Steam and water are expelled together from hundreds of meters down and the ascending mixture cools itself and the enclosing rock by a process approximating adiabatic expansion of the fluid. Because of the very high rate of discharge of water during eruption, the relatively slow influx of hot water into the geyser tube from the deep aquifer "reservoir," and the cooling effect of the boiling process, the generation of steam bubbles slows and eventually the bubbles can once again rise through the overlying water without causing ejection. At this point, the eruption ceases and the adiabatically cooled water left in the geyser settles back down the tube.

I postulate that after an eruption of short duration, the deep passages of the geyser are left sufficiently hot so that the pressure exerted by the cooled water trickling downward is insufficient to terminate boiling completely. Thus, deep boiling continues uninterrupted. In contrast, after an eruption of long duration the deep rock is left cooled to such an extent that deep boiling is temporarily prevented by the pressure of the overlying water remaining in the geyser tube. Eventually, the slow upward percolation of hot water from below reheats the overlying water and the rock to the eruption point, a longer time being required after a long eruption.

The available data do not yet permit confident choice among the many possible explanations of the bimodal character of eruptions of Old Faithful.

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7. The volume of the hot, dry cavity is assumed to be as large as the volume of the water-filled cavity at the bottom of the U, which, according to Geis's theory, accommodates just that volume of water ejected from Old Faithful in a single large eruption. E. T. Allen and A. L. Day (*4*, p. 184) estimate the eruptive volume at 38,000 to 46,000 liters. A sphere with a radius R equal to about 224 cm can accommodate 46,000 liters. Values, in centimeter-gram-second units, for k and α were taken as 7.5×10^{-3} and 10^{-2}, respectively.
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11. This figure has since been revised to 1.25 $\times 10^8$ cal/sec.
12. Publication authorized by the director, U.S. Geological Survey.

23 September 1968; revised 28 October 1968