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Tectonophysics - Elsevier Publishing Company, Amsterdam
Printed in The Netherlands

HEAT TRANSFER MEASUREMENT IN A GEOTHERMAL AREA

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(Received April 15, 1970)

GL03552

SUMMARY

In Japan, there are about twenty geothermal areas, where heat is transferred by various processes, such as fumaroles, steam wells, hot springs, steaming grounds, evaporation from hot pools and thermal conduction through the earth. In this paper, our methods of heat transfer measurement which have been used at Owakudani and Sounzan geothermal areas of Hakone Volcano are outlined. Total mass discharge from these areas amounts to 129 kg/sec and total heat transfer amounts to $10.64 \cdot 10^6$ cal./sec which is equivalent to $1 \cdot 10^{22}$ erg/year, corresponding to a moderate volcanic eruption a year.

Assuming that the geothermal areas of Japan have the same scale as Owakudani and Sounzan areas put together, heat transferred from all geothermal areas of Japan may be estimated roughly to be $2 \cdot 10^{23}$ erg/year. Adding to this, the energy $7 \cdot 10^{23}$ erg/year released by the volcanic activity, $1.1 \cdot 10^{24}$ erg/year by the common hot springs, and $7.3 \cdot 10^{24}$ erg/year by the normal heat flow of non-volcanic regions, we can estimate the total energy released from the whole of Japan, exclusive of that by earthquakes, to be about $9 \cdot 10^{24}$ erg/year.

HEAT TRANSFER OF A GEOTHERMAL AREA

It is very difficult to estimate the total energy discharged from a geothermal area where heat is transferred by various processes, such as fumaroles, steam wells, hot springs, steaming grounds, evaporation from hot pools and thermal conduction through the earth, because we do not yet have complete methods to measure the quantity of heat transferred by the above mentioned processes. When we intend to develop and utilize geothermal energy, it may be most important to know the geothermal energy reserve and its possible production. Natural heat transfer from the geothermal area is a main factor giving good information about the scale or the dimensions of the geothermal reservoir and is sometimes an index to show the minimum possible generation. Thus, it is necessary to establish a method of measuring the heat transfer of geothermal areas.

Heat discharged from a geothermal area can be defined as the heat flowing from deep ground to the surface in unit time interval through a finite geothermal area. However, if horizontal heat transfer between adjoining areas is considered, this effect must also be taken into account. Total heat transfer Q of geothermal areas can be written as:

$$Q = Q_1 + Q_2 + Q_3 + Q_4 + Q_5 \qquad (1)$$

where Q_1 is heat transferred by steam flow, Q_2 by thermal water flow, Q_3 by evaporation from hot pool, Q_4 by thermal conduction through the earth, Q_5 by gas flow. In the steam flow, Q_1, above mentioned, steam from the steam well, natural fumarole and steaming ground is included. The heat transferred by gas flow, Q_5, is generally negligible compared to the others.

As the types of heat transfer stated above, excluding thermal conduction, are phenomena of heat transportation by substantial mass flow, it is necessary to know the rate of mass flow and the specific heat of the geothermal fluid. Measurement of these quantities are, quite common in the laboratory but very difficult in an actual geothermal field. Therefore, it is very important to devise a simple method suitable for measuring in the natural geothermal field. In this paper, we intend to outline our method of heat transfer measurement.

HEAT TRANSFER MEASUREMENT IN A GEOTHERMAL AREA

Mean ejection velocity of the steam

It is necessary to know the mean velocity of the steam flow, to calculate the mass discharge from a steam well. Generally, as the velocity distribution in a cross section is not uniform, one needs to average the velocities measured at many points; however, as it is impossible to measure at many points in a small cross section, the maximum velocity v_{max} at the center is measured and the mean velocity v is calculated as follows:

$$\bar{v} = \frac{1}{\pi r_0^2} \int_0^{r_0} 2\pi r \, v_{max} \left(\frac{r_0 - r}{r}\right)^{\frac{1}{n}} dr = \frac{2n^2}{(n+1)(2n+1)} v_{max} \qquad (2)$$

where r_0 represents the radius of the well and n, a constant depending on Reynold's number. Here the velocity distribution in any section of the well is assumed to vary exponentially. When Reynold's number R_e is from 10^5 to 10^6, n ranges from 4.2 to 7.5, so that by taking the middle value we can get the mean velocity from the expression below:

$$\bar{v} = 0.77 \, v_{max} \qquad (3)$$

Density of steam

We have known many methods to measure the density of natural steam regarded generally as the mixture of vapour and small water-drops, but most methods which require complex equipment attached to the well head are not suitable for our present purpose. The direct steam sampling method is a relatively suitable method for natural geothermal fields. This method consists of sampling a certain volume of the steam under the same condition as at the well heat and then weighing it. Fig.1 and 2 show the principle of direct steam sampling method and a set of the equipment. If the temperature of the sampling tube is lower than the well-head temperature, then even if the pressure at the beginning is kept the same, steam condenses in the tube and the pressure falls causing further inflow of steam into the tube. If the temperature of the tube is higher than that of the well head, the effects may be different. To evaluate the error brought about by such inequalities of temperatures, the following method is adopted. Supposing that saturated water of density ρ_1' mixing with dry saturated vapour of density ρ_1'' produces wet saturated vapour of dryness x_1 and density ρ_1 we can write:

$$\rho_1 = \frac{\rho_1' \ \rho_1''}{x_1 \ (\rho_1' - \rho_1'') + \rho_1''} \tag{4}$$

If heat q per unit volume is added to the wet saturated vapour, thereby changing it to a new state of wet saturated vapour (shown with suffix 2), its

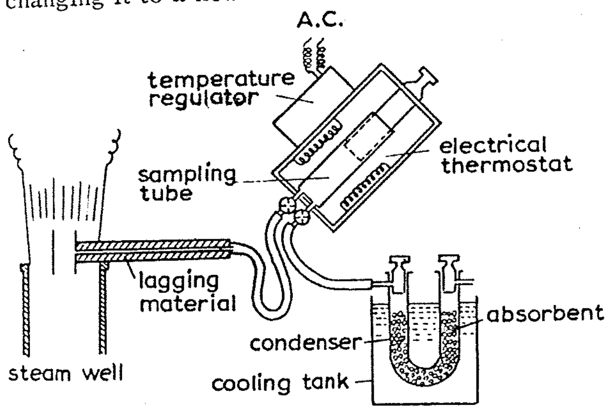

Fig.1. Direct steam sampling method.

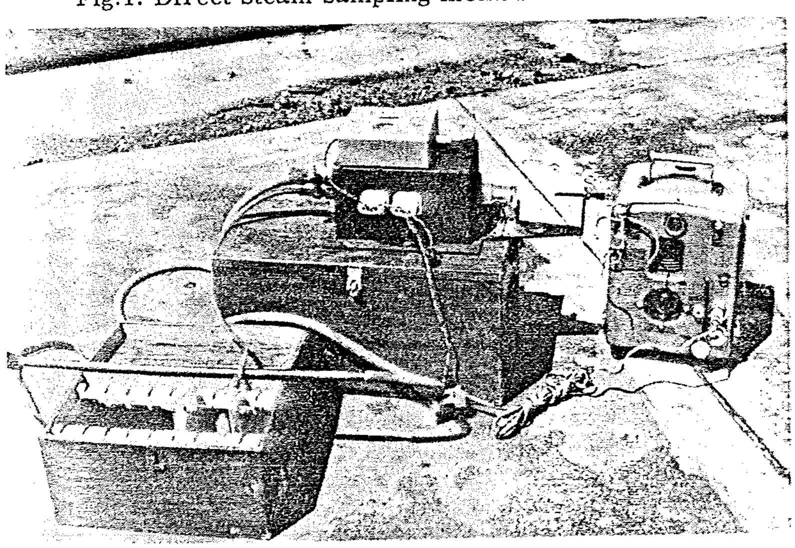

Fig.2. Direct steam sampler.

density can be written as follows:

$$\rho_2 = \frac{\rho_2{}' \, \rho_2{}''}{x_2\,(\rho_2{}' - \rho_2{}'') + \rho_2{}''} \tag{5}$$

Between the two enthalpies i_1 and i_2 of the above states of the vapour, the following relation exists:

$$i_2 = i_1 + \frac{q}{\rho_1} \tag{6}$$

Furthermore, putting the enthalpy of the saturated water as $i_1{}'$ and that of the dry saturated vapour as $i_1{}''$, we get:

$$i_1 = i_1{}' + x_1\,(i_1{}'' - i_1{}') \tag{7}$$

likewise:

$$i_2 = i_2{}' + x_2(i_2{}'' - i_2{}') \tag{8}$$

From eq. 4–8, the density of the second state can be shown to be:

$$\rho_2 = \frac{\rho_2{}''\,\rho_2{}'\,(i_2{}'' - i_2{}')}{\left[(i_1{}' - i_2{}') + x_1(i_1{}'' - i_1{}') + \left\{\frac{x_1(\rho_1{}' - \rho_1{}'')}{\rho_1{}'\,\rho_1{}''} + \frac{1}{\rho_1}\right\} q\right](\rho_2{}' - \rho_2{}'') + \rho_2{}''(i_2{}'' - i_2{}')} \tag{9}$$

For example, assuming the temperature of the first state as 100°C and that of the second state as 105°C or 95°C, the difference between ρ_1 and ρ_2 can be shown to be a function of q with parameter x_1. The relations between $(\rho_1 - \rho_2)/\rho_2$ and q are shown in Fig.3. As q is the heat going into or out of the sample tube of steam, it depends on the time for which the steam remains inside the tube which is not kept exactly at the true natural steam temperature. For example, using a glass injector of 100 cm^3 as the sampling tube and putting it in an electrical thermostat kept at 5°C higher or low temperatures for about 1 sec, produces an error of about 10%.

Mass and heat transferred by wet steam

If the mass flow of wet steam, water and dry saturated steam are shown by m, m' and m'' respectively, the following relations exist:

$$\frac{m}{\rho} = \frac{m'}{\rho'} + \frac{m''}{\rho''} \tag{10}$$

$$m = m' + m'' = a\,\overline{v}\,\rho \tag{11}$$

where a is the cross section of flow, ρ the density of the wet steam and $\overline{v}$ is the mean velocity at the section. When the density of the wet steam and the mean velocity are measured, m' and m'' can be written as follows:

$$m' = a\,\overline{v}\,\rho'\,\frac{\rho - \rho''}{\rho' - \rho''} \tag{12}$$

$$m'' = a\,\overline{v}\,\rho''\,\frac{\rho' - \rho}{\rho' - \rho''} \tag{13}$$

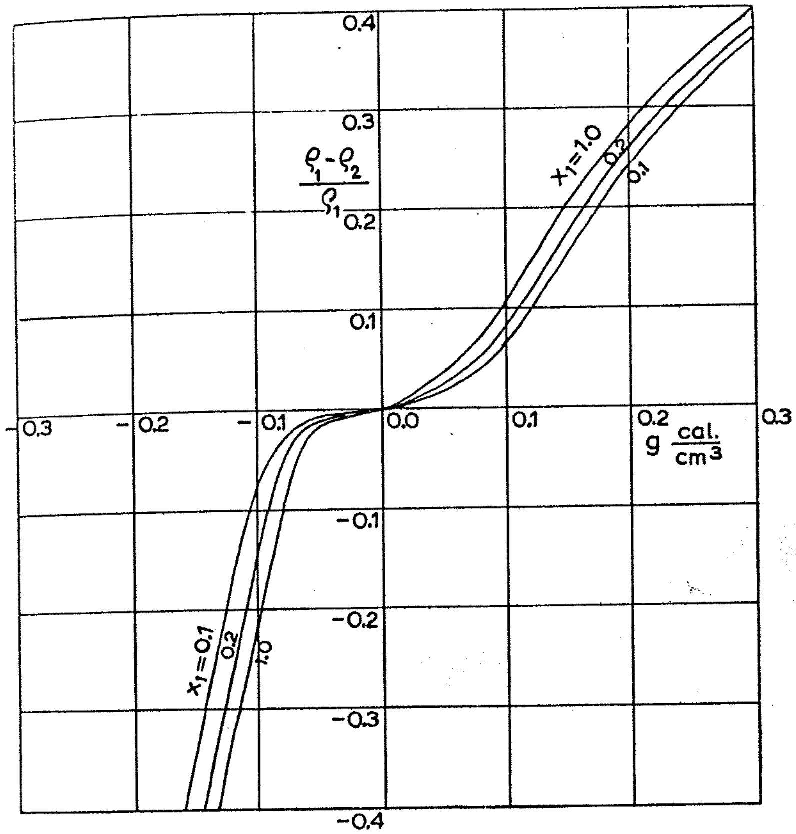

Fig.3. Estimated error $(\rho_1 - \rho_2)/\rho_2$ as a function of added heat q to the unit volume saturated vapour in the steam sampler, depending on the dryness x.

where ρ' and ρ'' are already known from the steam table as a function of the steam temperature.

Heat transfer by the steam is therefore:

$$Q = m' i' + m'' i''$$

$$= \frac{a \overline{v}}{\rho' - \rho''} \{ \rho' i'(\rho - \rho'') + \rho'' i''(\rho' - \rho) \qquad (14)$$

relative to 0°C.

Mass flow from a natural fumarole

To measure the mass flow from a natural fumarole of irregular shape, we can use a simple collector made of an empty drum over the fumarole. When the steam is ejected from an upper tube of the collector, we can perform steam flow measurements with the above mentioned method.

For weak steam flow from so-called steaming grounds, Benseman (1959) has devised a calorimeter suitable for geothermal field use. We have also devised a calorimeter similar to his apparatus, and this is shown in Fig.4. Air is made to enter through the inlet and is blown off through the outlet by a fan in the calorimeter. The mass of steam coming from the bottom of the calorimeter is given by:

$$m = \overline{V}(\sigma_{w2} - \sigma_{w1}) \tag{15}$$

where $\overline{V}$ is the volume of air passing through the calorimeter, and σ_{w1} and σ_{w2} are the absolute humidities of the air at the inlet and the outlet of the calorimeter.

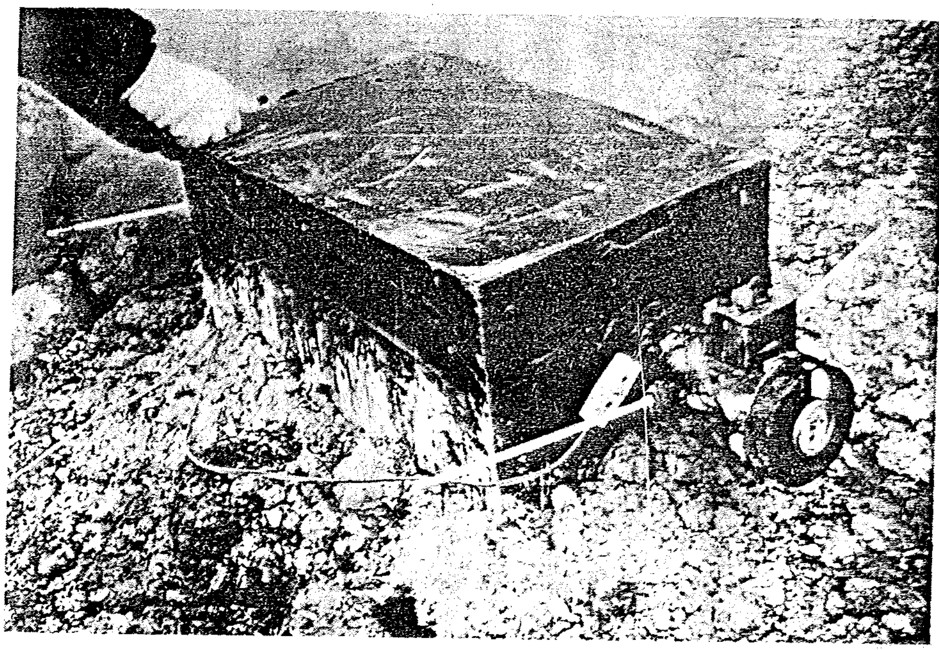

Fig.4. Geothermal calorimeter.

The heat Q transferred by steam through the bottom of the calorimeter can be written as:

$$Q = \overline{V}\sigma C_p (t_2 - t_1) + \overline{V}(\sigma_{w2}\ i_2 - \sigma_{w1}\ i_1) \tag{16}$$

where σ is the density of the air, C_p the specific heat of the air, and i_1 and i_2 are the enthalpies of the steam at temperatures t_1 and t_2. Absolute humidities of the air σ_w can be written as:

$$\sigma_w = \frac{289.4\ F f_m}{t + 273} \quad \text{g/cm}^3 \tag{17}$$

where f_m is the saturated vapour pressure at temperature t°C, and F the relative humidity.

Heat transfer by hot springs

The heat Q_2 transferred by hot springs is given by:

$$Q_2 = \sum^{n} C \rho \overline{V}_w (\theta - \theta_0) \tag{18}$$

where θ is the spring temperature, $\overline{V}_w$ the volumetric flow rate, C the specific heat, ρ the density and n the number of hot springs. Base temperature θ_0 should actually be the annual mean of the ground temperature, but could conveniently be made 0°C which is the base for the measurement of enthalpy.

Heat flow through the earth by conduction

In geothermal areas, heat flow Q_4 through area a having geothermal gradient $\mathrm{d}\Theta/\mathrm{d}Z$ and thermal conductivity k is given by:

$$Q_4 = \sum a\, k \frac{\mathrm{d}\,\Theta}{\mathrm{d}\,Z} \tag{19}$$

where Σa corresponds to the total geothermal area.

When the geothermal gradient along the bore hole is available, we can use the thermal conductivity of the core, but since it is generally impossible to get boring data about a whole geothermal area, we measure thermal conductivity and thermal gradient near the ground surface. We used, to measure the thermal conductivity near the ground surface, a hot bar which is heated uniformly by buried Ni–Cr filament. The relation between time τ and temperature Θ of the bar can be shown to be as follows (Kaziwara, 1960):

$$\Theta = A \log \tau + B + \frac{1}{\tau} (C \log \tau + D) \tag{20}$$

where A, B, C and D are constants which depend on the characteristics of the bar and the soil. We can get the thermal conductivity k of the soil, putting the heat generated by the bar per unit time as q', from the relation:

$$k = \frac{q'}{4 \pi A} \tag{21}$$

since A could be determined by the method of least squares. The value of $\mathrm{d}\,\Theta/\mathrm{d}\,Z$ is usually shown to be the difference between ground temperatures at 1 m depth and 0.5 m depth from the surface.

AN EXAMPLE OF PRACTICAL MEASUREMENT

Around the central cones of Hakone Volcano, there are some geothermal areas, of which Owakudani and Sounzan are the main ones. At Owakudani, there are about 40 fumaroles or simple steam wells drilled for land-slide prevention, and about 20 small hot springs. Ground temperature at Owakudani is remarkably high and some parts of this area form the so-called steaming ground where weak steam is ejected. The distribution of the steam wells and the fumaroles are shown in Fig.5. Mass and heat discharged from steam wells and fumaroles are summarized in Table I.

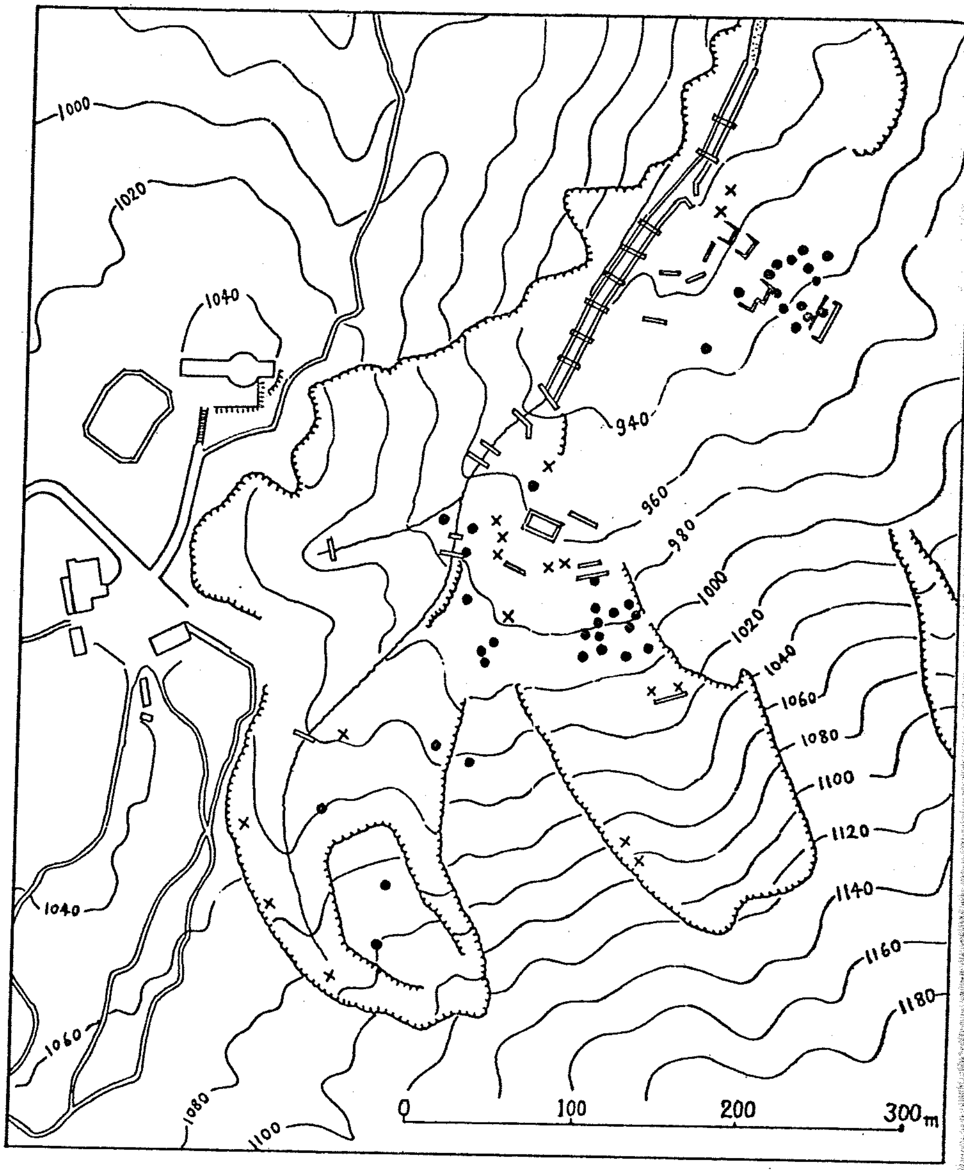

Fig.5. Distribution of steam wells and fumaroles at Twakudani. ● = steam wells and fumaroles, x = weak fumaroles not observed.

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TABLE I

Summary of mass and heat discharged from steam wells and fumaroles at Owakudani

Mass transfer			Heat transfer		
As dry steam (kg/sec)	as thermal water (kg/sec)	total (kg/sec)	by dry steam (kcal./sec)	by thermal water (kcal./sec)	total (kcal./sec)
2.9	20.5	23.4	$1.8 \cdot 10^3$	$2.0 \cdot 10^3$	$3.8 \cdot 10^3$

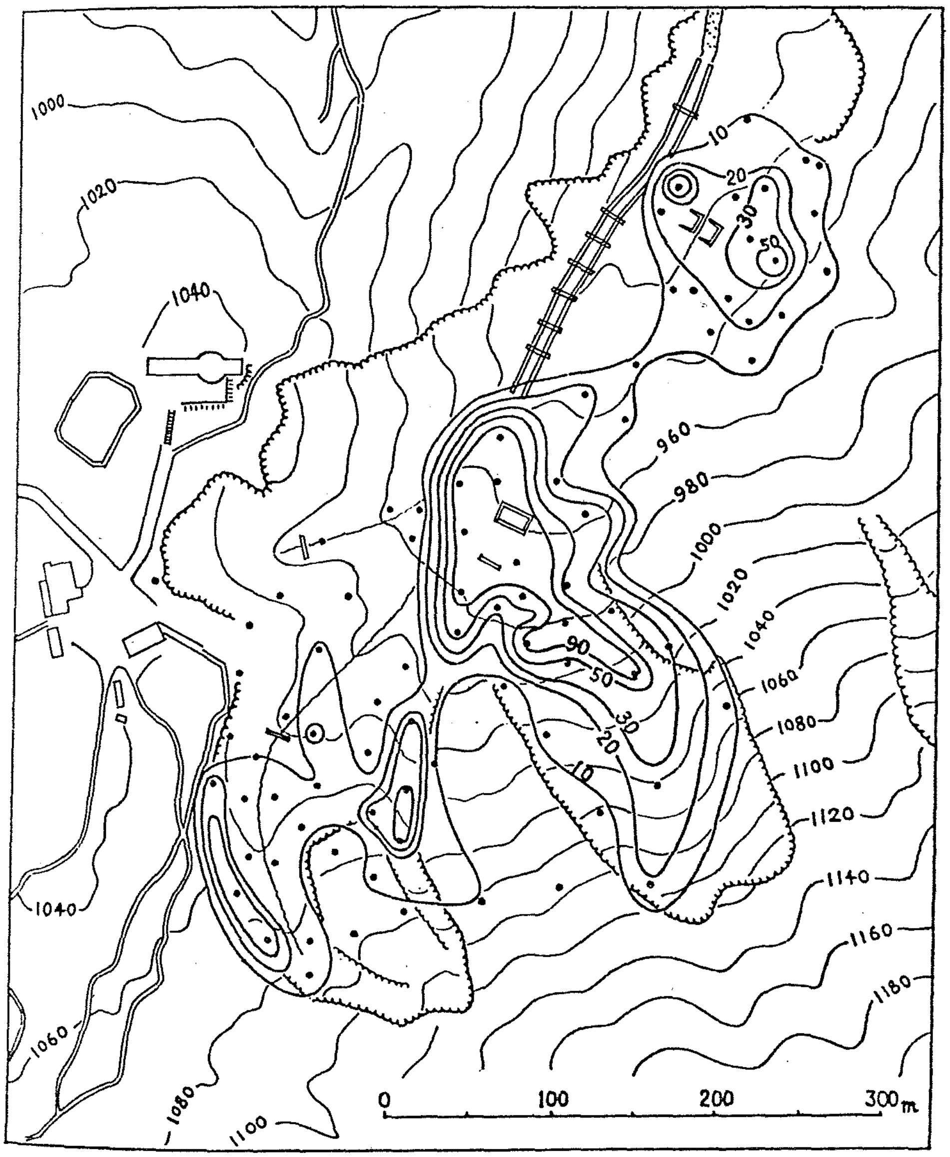

Fig.6. Distribution of ground temperatures at 1 m depth at Owakudani.

Hot spring waters of this area are collected by pipe lines and supplied to hotels in the vicinity for bathing purposes.

Total mass and heat transferred by hot springs were estimated to be $20.4 \cdot 10^8$ g/day and $8.7 \cdot 10^{10}$ cal./day respectively.

Fig.6 shows the distribution of ground temperatures at 1 m depth at Owakudani. Thermal conductivity of the soil measured by the method mentioned before was, in average, $0.31 \cdot 10^{-3}$ cal./cm · sec · °C, which is nearly equal to that of the dry soil. The thermal gradients at 0.75 m depth range from 0.002 °C/cm to 0.37 °C/cm.

In Fig.7, relations between 1 m depth temperature and temperature gradient at 0.75 m depth are shown, from which we can calculate the mean temperature gradient for the areas between isothermal contours shown in Fig.6. Calculating the areas between isothermal contours and multiplying them by the temperature gradients and the thermal conductivities, we can evaluate the heat flow by conduction through the whole area. The result so obtained was $2.4 \cdot 10^4$ cal./sec.

Towards the lower region of Owakudani valley, there is a hotel with a hot spring called Kaminoyu. As it is known that the heat of Kaminoyu

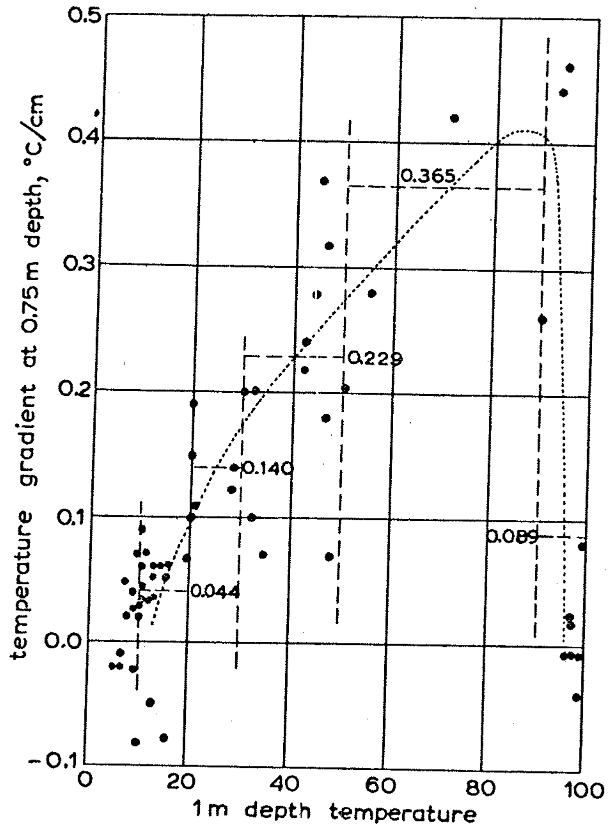

Fig.7. Relations between 1 m depth temperatures and temperature gradients at 0.75 m depth.

hot spring comes from Owakudani, this also has been taken into account in evaluating the total heat discharged from the area.

The results of heat transfer measurements are tabulated in Table II. Heat transfer measurements were carried out for other geothermal areas around the central cones of Hakone Volcano (Yuhara et al., 1969), using the same method as at Owakudani. Their results are also listed in Table II. Finally, we can estimate the total mass and heat discharge from the geothermal areas of Hakone Volcano to be 129 kg/sec and $10.64 \cdot 10^6$ cal./sec respectively. The latter is equivalent to $1 \cdot 10^{22}$ erg/year, corresponding to a moderate volcanic eruption a year.

TABLE II

Mass and heat transferred from geothermal areas of Hakone Volcano

Geothermal area	Type of discharge	Mass discharge (kg/sec)	Heat discharge relative to 0°C (10^6 cal./sec)
Owakudani	fumaroles	–	–
	steam wells	23.4	3.82
	hot springs	23.7	1.01
	conduction	–	0.02
	Kamiyu hot spring	1.2	0.06
	total	48.3	4.91
G-region of	fumaroles	3.5	0.5
	hot springs	0.3	0.01
	conduction	–	0.01
	Ubako hot springs	26.8	1.24
	total	30.6	1.76
Sounzan	fumaroles	2	0.2
	steam wells	9.7	1.11
	Gora hot springs	37.9	2.66
	total	49.6	3.97
Total areas	fumaroles and steam wells	38.6	5.63
	hot springs	89.9	4.98
	conduction	–	0.03
	total	128.5	10.64

HEAT TRANSFER FROM GEOTHERMAL AREAS OF JAPAN

In Japan there are about twenty geothermal areas, but the heat transfer measurements stated above were carried out for only a few of them, which have the same scale as that of Hakone Volcano, as shown in Table III. Thus, assuming that the geothermal areas of Japan have the same scale as that of Hakone Volcano, the total heat discharge from all geothermal areas of Japan can be roughly estimated to be $2 \cdot 10^{23}$ erg/year. On the other hand, according to Sugimura et al. (1963), energy released by volcanic activity of Japan was estimated to be $7 \cdot 10^{23}$ erg/year on the average. We have 1,479 hot spring resorts having 17,126 sources with about $1 \cdot 10^6$ l/min

TABLE III

A few examples of the heat transfer of geothermal areas of Japan

Area	Base temperature (°C)	Heat discharge (10^6 cal./sec)	Reporter
Atosanupuri	10	7.8	Fukutomi (1966)
Noboribetsu--Jigokudani	–	11.2	Fukutomi (1966)
Tamagawa	0	15.2	Iwasaki (1963)
Owakudani and Sounzan	0	10.6	Yuhara et al., (1969)

flow capacity (Murai, 1966). Putting their average temperature as 52°C (Matsunaga, 1965), heat transferred by hot springs amounts to $1.1 \cdot 10^{24}$ erg/year. Total heat flow from the 370,000 km^2 of surface area of Japan, excluding those from volcanic and thermal areas, is about $7.3 \cdot 10^{24}$ erg/year. Finally, the total energy released from the total area of Japan will amount to about $9 \cdot 10^{24}$ erg/year as shown in Table IV. This does not include the energy released by earthquakes.

TABLE IV

Total energy released from the whole area of Japan (excluding that by earthquakes)

Type of energy release	10^{24} erg/year
(1) by heat flow in normal areas	7.3
(2) by volcanic eruptions	0.7
(3) from geothermal areas	0.2
(4) by hot springs	1.1
Total	9.3

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