THE HOT SPRINGS OF ICELAND

BY

THORKELL THORKELSSON
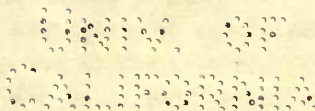
WITH 13 PLATES

(The plates referred to in the text will be found at the end of Part III.)

On the occasion of my exploration of the hot springs in the south-west of Iceland in the summer of 1904, it was shown that the gases from these springs contain radioactive emanations, and at the subsequent investigation in the laboratory, it was again proved by Prof. K. PRYTZ and myself[1], that the gases emanating from the springs contain argon and helium. As these investigations seemed to justify the opinion that a more extensive exploration of the radioactivity of the Icelandic springs would, on account of the isolated position and the volcanic nature of the island, contribute considerably to an elucidation of the question as to what extent radioactive substances are to be found in the earth, as well as their significance with regard to the earth's temperature, I undertook, in the summer of 1906, a new expedition to the hot springs of Iceland.

I received from the Carlsberg Fund for the expenses of this expedition, 5800 Kroner, (£ 322. 4. 6), — 5000 Kroner for the journey, and 800 Kroner for the examination of the materials collected on the journey. I herewith tender the directors of the Carlsberg Fund my respectful thanks for this support.

The experimental part of the preparations for the journey, as well as the analytical work necessary to determine the composition of the hot spring gases, by means of the sample gases taken, was carried out, with Prof. K. PRYTZ's permission, in the "*Polytekniske Læreanstalts fysiske Laboratorium*" (the physical laboratory of the Polytechnic Academy) in Copenhagen. For this permission, and for his kind advice in regard to the experimental work, I offer Prof. K. PRYTZ my heartfelt thanks. I also thank Mr. S. JÓNSSON, who accompanied me on my journey in 1904, for his interest in these investigations, evidenced by his willingness to enter a second time on the hardships of the journey, in order to help me in the scientific work. The results I have attained through this expedition, are to a great extent due to his capable assistance.

The present treatise will deal freely only with the scientific work done on the journey and in the laboratory, together with its results, disregarding for the most part the equipment and the details of the journey. But for the sake of orientation, I have included a small map of Iceland (Fig. 1), on which our route and the spring districts visited are marked.

[1] K. PRYTZ og TH. THORKELSSON: Oversigt over det kgl. danske Videnskabernes Selskabs Forhandlinger 1905, p. 317.

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I have divided my treatise into three parts. The first contains a description of the springs we examined, while the second part treats of the methods employed in the investigation, and the third enumerates and discusses the results of the experiments.

In the third part, besides viewing the nature of the springs from a new stand-point, — which these experiments seem to justify, – I have included several well-known theories, in so far as the latter are borne out by the present investigations; and thereby have endeavoured to make the subject under consideration more consequent and complete.

I.

Description of the Springs.

Mývatn.

The hot springs at Mývatn have, in the course of time, often been described by scientific visitors to the spot. JOHNSTRUP[1], who visited these springs in 1871, has given a very detailed description of them, and has constructed a map of the surroundings of the springs. I will therefore content myself with a very short, summary description, and I must refer those who require more detailed information regarding these districts, to JOHNSTRUP's excellent treatise. Nevertheless, in order to make the positions clearer, I have included one of JOHNSTRUP's maps of the springs, (Fig. 2). We stayed at Mývatn from the 19th. June to the 1st. July 1906. During the first few days we pitched our tent a little to the north of the springs, to the east of *Námafjall* (Námafjeld on the map). But at that place a proper supply of water was not to be had, so that we were obliged to gather snow from the crevices of the surrounding lava, and use the water obtained by melting it, both in our experiments and for drinking purposes. This had of course great disadvantages, and as we could not keep our horses from straying from this place, we eventually moved nearer to the farm of Reykjahlíð. Thence we paid several visits to the springs.

The hot springs at Mývatn are found chiefly at two places, viz. at *Krafla* and at *Námafjall*. The hot springs at Krafla are for the most part solfataras of little or no significance, which are situated here and there in a large ravine which reaches from north to south to the immediate west of Krafla.

On the eastern slope of the ravine nearest to the south, is *Litla Víti*, an energetic and extremely noisy fumarole, which reminds one, on account of the whistling sound emitted, of *Öskurhólshver* (the roaring hill) at *Hveravellir*. As Litla Víti is externally very different to the small solfataras which lie a little to the

[1] Den naturhistoriske Forenings Festskrift. København, 1890.

north in the same ravine, we had intended to take samples of the gases from this spring, but we had unfortunately to give up the idea, as on closer examination it became evident that to collect the gas at that place would be an exceedingly dangerous undertaking.

To the north-west of the ravine mentioned, and separated from it by a high ridge of gravel, are the three lakes shown on the map. The largest of these, which is situated farthest west, covers the bottom of the wellknown crater *Stóra Viti*, or *Helvíti*. The lake is enclosed on all sides by the steep edges of the crater. Towards
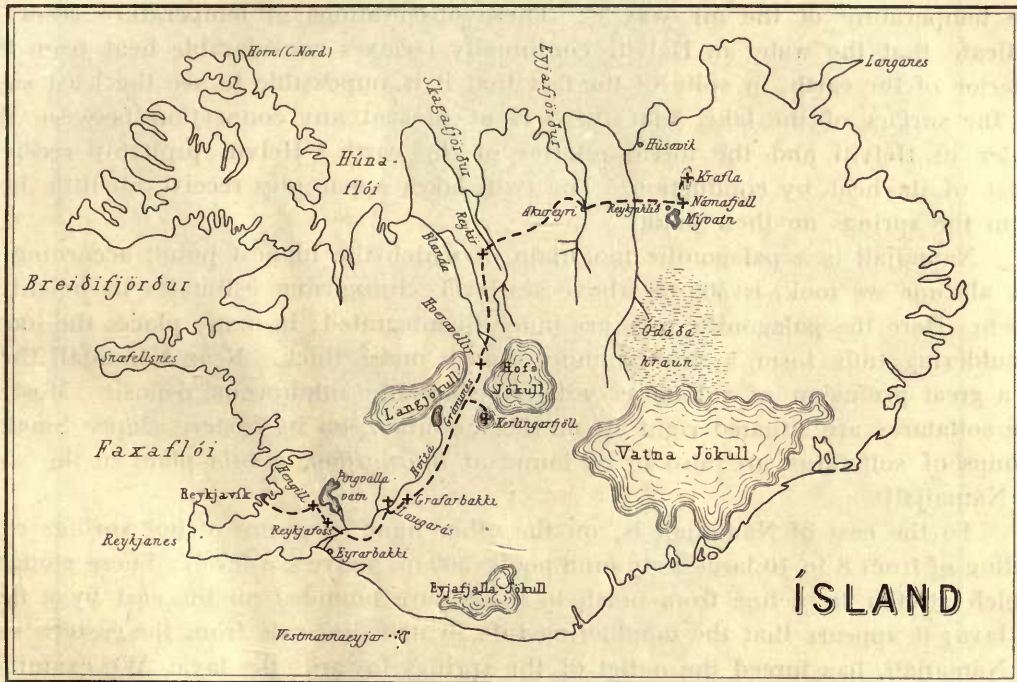

Fig. 1. Iceland.
(Showing route and spring districts visited.)

the east, where the brink of the crater is highest, it reaches, according to a measurement made by means of an aneroid barometer, the altitude of 55 m. above the level of the water. To the west the edge only reaches the height of about 20 m., on account of the declivity on which it stands. The two other lakes were, when we visited the spot, formed into one single lake. This is most probably not because a subversion has taken place, but is simply the result of the surface of the two lakes becoming higher, so that they communicate. Like Helvíti, these twin lakes are surrounded by rather high banks sloping down to the surface of the water, but unlike Helvíti, the north-eastern and eastern slopes are covered with active solfataras. The photograph (Plate I, *a*) shows these twin lakes, from the south;

the light-coloured sections to the right represent the position of the solfataras. The light colour is chiefly to be attributed to the sulphurous deposit from the springs. We examined here the gases from two springs, viz. *Krafla No. 1*[1], immediately to the east of the northern lake, and *Krafla No. 2*, to the north-east of the southern lake. The springs were identical in outward appearance, both being small pools of turbid water, with strong gaseous exhalations. Their altitude above the surface of the lakes was 10 cm., while they were 615 m. above the level of the sea. The temperature of the water in the twin lakes was 11.5° C. on the surface; the surface temperature of the water in Helvíti, taken at the same time, was 14°; whilst the temperature of the air was 3°. These observations of temperature seem to indicate that the water in Helvíti continually receives considerable heat from the interior of the earth, in spite of the fact that it is impossible to see the least sign, on the surface of the lake, that there is at present any connection between the water in Helvíti and the torrid interior of the earth. Helvíti probably receives most of its heat by conduction. The twin lakes apparently receive no little heat from the springs on their banks.

Námafjall is a palagonitic mountain of which the highest point, according to the altitude we took, is 500 m. above sea-level; JOHNSTRUP estimates its height at 498 m. Here the palagonitic tuffs are much disintegrated; in many places the loose, mouldering tuffs form a stratum more than a metre thick. Near Námafjall there is a great profusion of solfataras with considerable sulphurous deposit. Most of the solfataras are situated right up on the mountain, on its eastern slope. Smaller groups of solfataras are also to be found at *Bjarnarflag*, a tufa plain to the west of Námafjall.

To the east of Námafjall is, on the other hand, a group of hot springs consisting of from 8 to 10 large ugly mud pools (360 m. above sea-level). These sloughs, which stretch in a line from north to south, are bounded on the east by a field of lava; it appears that the mouldering tufa, which descends from the eastern side of Námafjall, has forced the outlet of the springs towards the lava. We examined the gases from three places in this group of sloughs.

The gas sample numbered *Námafjall No. 1* is from the largest slough in the group, the position of which is to the extreme north-west (Plate I, *b*). *Námafjall No. 2* is taken from a smaller cavity by the edge of the lava, to the east of No. 1. *Námafjall No. 3* comes from the slough second in point of power; it is situated a little south of the centre of the group.

Besides the above mentioned sloughs, we saw some in a groove on the east of Námafjall, high up at the top of the mountain. These springs were surrounded on all sides by solfataras, so that we could not approach them, but they appeared to be very active. The southern part of Námafjall is flat on top, and in the centre of this plain is a little isolated group of sloughs, consisting of 3 springs; the gas, marked *Námafjall No. 4*, is taken from this group, (490 m. above sea-level).

[1] Cf. Part III, Table I.

Fig. 2. The hot spring district at Mývatn.
(JOHNSTRUP.)

Námafjall No. 5 is from a little solfatara in *Bjarnarflag*. The soil was so damp at this place, that it was possible to collect the gases by packing the humid tufa around the funnel, so that the gases were forced through the tubes into the collecting bottle.

To the west of Bjarnarflag, — and named after it, — is *Bjarnarflagshraun*, a wild disorderly stretch of lava, ejected from a cleft of craters in *Jarðbaðshólar*, to the south-west of Bjarnarflag, (Plate II, *a*). Here and there, among this lava, warm damp gases exude from fissures and cavities. We made an examination of the gases emitted, in two places, viz. *Reykjahlið No. 1*, which was taken just by the crater cleft (354 m. above sea-level); and *Reykjahlið No. 2*, from the western part of Bjarnarflagshraun (326 m. above sea-level). These emissions of gases are not confined to Bjarnarflagshraun, although they are more in evidence there. Both in the lava to the east of Námafjall, and in the older lava as far down as the farm of Reykjahlíð, we found similar exhalations.

A short distance south of Reykjahlíð there is a large fissure in the lava, *Stóragjá*; the water at the bottom of it was 29.4° C. (JOHNSTRUP took the temperature of the water in the same rift; he found it 30° C.) Since the temperature of the water was, as far as we could perceive, quite uninfluenced by variations in the temperature of the atmosphere, the relatively high temperature must doubtless be attributed to terrestrial heat.

We noticed hot exhalations at several places in the neighbourhood of Stóragjá, which also shows that an arm of the terrestrial heat at this place branches out as far as Mývatn.

Reykir in Skagafjörður.

The hot springs near the farm *Reykir* in *Skagafjörður* are usually called *Reykjalaugar*. We spent eight days at these springs, from the 13th. to the 20th. July 1906. On account of most unfavourable weather, our stay was longer than we had arranged for. We pitched our tent on the eastern (right) bank of the river, (*Svartá*), which runs past the farm. The site of our tent was 45 m. above sea-level; the farm itself is situated about 8 m. higher, on a hill of conglomerate and sandstone. On the same hill, to the south and south-east of the farm, are most of the hot springs. These are a striking contrast to the dirty, fætid mud springs and solfataras at Mývatn. The water is clear, and a luxuriant stretch of grass reaches to the brink of the springs, whereas the soil by the springs at Mývatn is bare and waste. We tested the gases from three of the most important springs in this neighbourhood. The sample *Reykir No. 1* is from *Sundlaugarhver*, the most southerly spring in the group. The warm water from the spring is used to impart to the adjacent swimming-bath ("sundlaug") a tepid temperature. *Reykir No. 2* is from *Hornahver*, which is situated to the south of the church, and *Reykir No. 3* from *Bæjarlaug*; the latter is to the east of the church. These three springs can be distinguished on the illustration (Plate II, *b*), by the vapour which rises, condensed

into a white mist, from the hot water of the springs. In the illustration, which is taken from the north, the swimming-bath is seen farthest away, Hornahver in the middle, and Bæjarlaug in the foreground. The farm is not shown in the photograph, as it lies nearer and more to the right. The picturesque mountains to the south-west, *Mælifellshnjúkur* (and others) are invisible also, as they were enveloped in mist. We also tested the gases, whilst staying at this spot, from two more distant springs. *Reykir No. 4* is from *Fosshver*, a little spring near the beautiful waterfall *Reykjafoss*, two kilometres to the north of Reykir. Here hot water gushes up through rifts in the rocky conglomerate on the eastern bank of Svartá. The water has a temperature of 65°, and there are very active gaseous exhalations. *Reykir No. 5* is from *Skíðastaðalaug*, situated on the other side of Svartá, about a kilometre to the west of Reykir; hot water issues from three places here at a temperature of 67° to 68°. There is a considerable volume of water. The peculiarity of this spring is that there are apparently no gaseous exhalations from the spring itself. But gases are emitted through a little pool 1 m. west of the most southerly spring. The temperature in this pool was 17.3° C.; at the same time the temperature of the air was only 4° C. The sample gas which was examined comes from this place.

A fact which characterises all the springs explored at Reykir is that the water shows a weak alkaline reaction. The spring water also contains chlorides and carbonates, and sulphates to some small extent.

Hveravellir.

Hveravellir is situated in a hollow by the northern border of the great field of lava called *Kjalhraun*. According to the altitude taken by the barometer, the place where we pitched our tent was 635 m. over sea-level; Þorv. Thoroddsen made it 632 m., very near to our estimate.

Among previous descriptions of the springs at Hveravellir, the following are noteworthy: — "*Reise gennem Island*", vol. II, pp. 637—639, by Eggert Ólafsson and Bjarni Pálsson, 1752; "*Iceland, the Journal of a Residence in that Island during the years 1814 and 1815*", vol. II, pp. 203—209, by E. Henderson.

But the most exhaustive description of the springs at Hveravellir is by Þorvaldur Thoroddsen [1], who stayed at Hveravellir from the 24th to the 26th August 1888, made a map of the neighbouring spring district, and enumerated the most important springs. Apart from the more detailed examination of the composition of the gases, our efforts in this locality were chiefly confined to ascertain what changes the springs had undergone since Thoroddsen explored them in 1888. As a basis for this investigation, it is necessary to use Thoroddsen's map, which is therefore reproduced here (Fig. 3).

The springs are situated on two dome-shaped silicious sinters. The sinter to the north-west is the less prominent, and most of the springs are insignificant in

[1] Ymer, 1889, p. 49; and Geogr. Tidsskrift 10, 26, 1889—1890.

THE HOT SPRINGS
AT
HVERAVELLIR,
SURVEYED IN 1888 BY
Þ. THORODDSEN.

Tent

S.

M.N.

M.S.

N.

Eyvindarhver

Öskurhóll

Bláhver

Brœðahverir

Gamli Strokkar

25 50 100 200 Feet (Danish).

+ + + Lava

Silicious Sinter

Gravel and sand

Grass

● ● ● ● Hot Springs

✕ ✕ ✕ ✕ Mud and sulphur Springs

Fig. 3.

comparison to those on the south-easterly dome. In order to identify each parti-
cular spring, we measured with a line the distances between the springs on the
north-western dome. The position of the springs in the south-eastern group was
arrived at by measuring the distance from a given base. In making this survey
we used a line and optical square. On the basis of these measurements I have
made the accompanying map, which shows the relative distances of the springs in
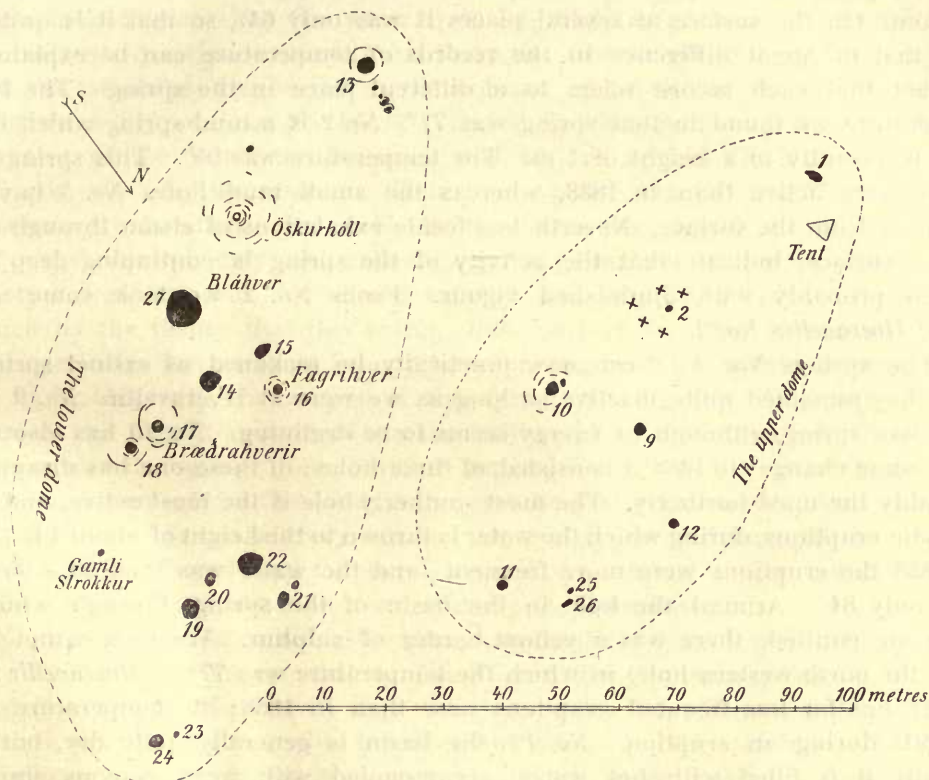the two groups (Fig. 4). The relative position of the two groups, and the bearings,

Fig. 4.

are taken from Thoroddsen's map, as these were not ascertained by direct obser-
vation. On comparing this map with Thoroddsen's, there are several points of
disagreement, both in the relative position of the springs and in the distances
between them.

These deviations, which can hardly be caused by changes in the position of
the springs, but must naturally be put down to the inaccuracy of the maps, are
nevertheless not of such a nature, as to cause doubt as to the identity of the
respective springs. On the other hand, if we compare Thoroddsen's description of
each particular spring with our observations, they will be found to be, in all the

main points, in agreement; in several places, however, there are insignificant dis-
agreements which show that the springs have undergone some change since 1888.
In the following remarks concerning the individual springs, particular attention
has been paid to these changes, and I must refer those who desire more detailed
information as to the external characteristics and appearance of the springs, to the
previously mentioned treatise by Thoroddsen in the Swedish periodical "Ymer".

No. 1 has a temperature of 77° C., instead of 64° according to Þ. Thoroddsen.
In this spring the temperature is dependent on the place where the measurement
is taken. On the surface at several places it was only 64°, so that it is quite pos-
sible that the great difference in the records of temperature can be explained by
the fact that each record refers to a different place in the spring. The highest
temperature we found in that spring was 77°. *Nr. 2* is a mud spring which throws
mud incessantly to a height of 1 m. The temperature was 95°. This spring seems
to be more active than in 1888, whereas the small mud holes *No. 3* have dis-
appeared from the surface. Nevertheless feeble exhalations of steam through cracks
in the surface, indicate that the activity of the spring is continuing deep down,
though probably with diminished vigour. From No. 2 we took some sample
gases, *Hveravellir No. 2.*

The springs *Nos. 4—8* can now practically be reckoned as extinct springs, at
least they remained quite inactive as long as we were at Hveravellir. *No. 9* is still
an active spring, although its energy seems to be declining. *No. 10* has also under-
gone some change; in 1888 it consisted of three holes; of these one has disappeared,
probably the most northerly. The most southerly hole is the most active, and it has
periodic eruptions, during which the water is thrown to the height of about 1 ft. (3 dm.).
In 1888 the eruptions were more frequent, and the water was then 90°—95°, now
it is only 84°. Around the hole in the basin of the spring, through which the
gases are emitted, there was a yellow border of sulphur. We took sample gases
from the north-western hole, in which the temperature was 77°, — *Hveravellir No. 10.*
No. 11 has far less frequent eruptions now than in 1888; its temperature is 81°,
and 91° during an eruption. *No. 12*: the basin is generally quite dry, but occa-
sionally it is filled with hot water, accompanied with weak gaseous emissions.
The temperature was 86°, but on another occasion it was only 56° (Þ. Thoroddsen
65°). *No. 13, Eyvindarhver,* seems to be unchanged, temperature 87°. *Öskurhóll*
(the roaring hill), which seemed in 1888 to have become defunct, has now resumed
its steam exhalations, accompanied by an ear-splitting din. The steam is ejected
with such power, that even in a strong wind, a column of steam rises perpendi-
cularly for at least a metre's height (Plate III). The steam exhalations have perio-
dical maxima and minima. The temperature is 91°. *Bláhver* is unchanged, the
surface temperature is the same as in 1888, viz. 82° on the east side of the basin,
and 76° on the west. Sample *Hveravellir No. 27* is from this spring. Springs
Nos. 14 and 15 have about the same temperature now as in 1888, viz. 81° and 64°,
as compared to 82° and 67°, respectively; but the exhalations have become much

less. *No. 15* gave no visible exhalations whilst we were at the springs. *No. 16* has developed into an extremely beautiful spring, with a regular-shaped cone of creamish-yellow silicious sinter (Plate IV). In other respects this spring does not seem to have changed particularly during the last 18 years; there are now fairly strong gaseous exhalations, and the temperature is 93.5° (previously 89°). On account of the picturesque appearance of this spring, we have called it *Fagrihver* (the beautiful spring). From Fagrihver we gathered the gas *Hveravellir No. 16.* Nos. 17 and 18, *Brœðrahverir*, are still the most active springs in this neighbourhood, although they do not eject the water quite so high as previously. According to Þ. Thoroddsen's description, they threw the water to a height of 7—10 feet, in 1888; in 1906 we estimated the height of the column at 1.5 m. In *No. 17* the thermometer showed 81°, and in *No. 18* 84°. *Gamli Strokkur* is now quite extinct; the temperature of the water in the basin was 27°, as against 37° in 1888. *Nos. 19 and 20* are only slightly altered. Their temperature was 85° and 57°. In No. 19 there were no exhalations, and in No. 20 they were very slight. *No. 21* is a spring which gushes continuously and actively; we measured its temperature twice; the first time it was 90°, but the second time it was only 72°. This can partly be explained by the theory that this spring, like most of the other springs at Hveravellir, is periodic; but as there is a stream running near by, which to some extent mixes its waters with the waters of the spring (No. 21), the temperature of the latter must be largely dependent on the volume of cold water which flows from the stream into the spring. It is therefore not impossible that the difference between the two measurements of the temperature can be partly accounted for by this fact.

Besides the springs already referred to, which have all been mentioned and numbered by Þ. Thoroddsen, I append a brief description of the hot springs at this place which have not been dealt with by Þ. Thoroddsen.

No. 22 is a basin of considerable size to the south of No. 21, with a temperature of 75°. In the water-course east of No. 21 are the two springs which we have marked *Nos. 23 and 24*. No. 23 is a little cavity in the silicious sinter, through which hot water is ejected with considerable force. No. 24, which is situated by the northern side of the large dome of silicious sinter, covers a large surface. Vapours issue with such force from the edge of the sinter that the water in the basin of the spring is kept continually rippling. The temperature is 95°.

Nos. 25 and 26 are two pools situated side by side a little to the north-west of No. 11. Both these pools are filled with clear water, without any silicious deposits; as to outward appearance they therefore much resemble No. 1. There were active exhalations in both these springs. From No. 25, in which the temperature was 81°, we took specimen gases, *Hveravellir No. 25*; the temperature of No. 26 was 89°.

The foregoing comparison of the conditions of the springs in 1888 and 1906 seems to point out that the thermal activity at Hveravellir was less during our visit, than when Þ. Thoroddsen explored them, particularly the springs on the upper

dome, which are now both fewer and less prominent than in 1888. On the lower dome the thermal activity has also on the whole declined. There are, however, some exceptions, the most conspicuous being Öskurhóll, which has now resumed its resonant exhalations of vapour, well-known from Ólafsson's and Henderson's descriptions. Amongst other springs which seems to have increased in force since 1888, Nos. 16, 23 and 24 are noteworthy. It would of course be premature to conclude from the preceding observations, that the thermal activity at Hveravellir is in a continual state of decline. Many of the changes noted can be traced to more accidental grounds. Precipitation and other meteorological conditions have doubtless great influence on the springs, and that is at least the most plausible explanation of Öskurhóll's changeability.

But the matter presents another aspect, when one compares the springs on the lower and upper domes of silicious sinter; for one must then suppose that the question of meteorological influences is essentially eliminated. The accompanying observations show with considerable certainty that the activity of the springs on the upper dome has decreased appreciably more than on the lower dome. This is in agreement with previous observations from other places, and shows that in general hot springs have a tendency to find the lowest level, — a result which would be reached on purely physical considerations.

In the lava-field Kjalhraun to the south-east of the above-mentioned springs, there are considerable thermal exhalations. These exhalations are chiefly grouped about an imaginary line from Hveravellir, in a southerly direction, about 43° to the east. Curiously enough, Kerlingarfjöll lies in the same line, if it be produced. We examined in two places the gases which thus streamed out through rifts in the lava. Of these, *Kjalhraun No. 1* was taken about 110 m. south-east of the most south-easterly dome of silicious sinter. The exhalations, of which the temperature was 87°, produced a whistling sound as they were emitted from the holes in the lava.

Kjalhraun No. 2 was taken up in the lava about 1 kilometre south-east of Hveravellir. The temperature of the exhalations was 88°.

Our visit to Hveravellir extended over 4 days. On the 26th. July, we left Hveravellir, and pitched our tent at *Gránunes*, whence we made excursions to the springs at *Kerlingarfjöll*. It was originally our intention to camp west of *Áskarðsfjall*, just to the north of Kerlingarfjöll, but as the early part of the summer of 1906 was unusually cold in Iceland, there was not sufficient pasture at that place for the horses during our stay. We were compelled therefore to choose Gránunes as our camping-ground, although it was at least three times as far away from the springs. The double journey between Gránunes and the springs took more than 6 hours, and moreover we had to make a difficult crossing over the river *Jökulkvisl*. We stayed at Gránunes for 6 days, but on account of unfavourable weather we could only make two excursions to Kerlingarfjöll, viz. on the 28th. and 31st. July 1906.

The hot springs at Kerlingarfjöll.

The springs at Kerlingarfjöll are, in spite of their great number, homogeneous pools, with a strong odour of sulphuretted hydrogen, and with turbid water, which is kept continually in agitation, as if boiling, on account of its high temperature and the active exhalation of gases.

On account of the high altitude of the place (940 m. and more), all the ravines and hollows were filled with snow whilst we were at Kerlingarfjöll, except where the warmth of the springs had melted the snow. The springs are engaged in a continual struggle for the mastery with the snow, and in this way the most remarkable snow-figures are formed. The snow cannot remain in the immediate neighbourhood of the springs, not being able to resist the warmth emitted by them, but a little farther away we saw in several places large steep walls of snow, over 10 m. high.

During the winter, when the cold is at its greatest, these snow walls can advance nearer to the springs and perhaps embrace them entirely; but by the summer the heat from the springs has obtained the upper hand, and the snow has to withdraw.

Under these conditions, the snow does not so readily melt on the surface as near the earth, which receives heat from the springs, and the masses of snow thus undermined break off (Plate V), and large pieces of snow are precipitated towards the springs. We saw several steep, isolated masses of snow, from 6 to 10 m. high, which had in this way become detached from the rest, and which, on account of the sloping ground, glided slowly down towards the springs. At other places, we saw the misty vapours rise from the middle of a large expanse of snow. These vapours evidently came from smaller isolated hot springs, which had not yet succeeded in getting rid of their covering of snow, and had therefore to let a small hole suffice as an outlet for the vapours up through the snow.

The hot springs which we visited at Kerlingarfjöll are all to be found in a large valley, almost in the shape of a right angle, the sides of which are intersected by a great number of smaller valleys or ravines. The whole of the spring district, which is called by the one name *Hveradalir*, falls naturally into three divisions, viz. *Vestur-Hveradalir* (Plate V), to the west, nearest to the outlet of the valley, *Mið-Hveradalir* (Plate VI), the middle part of the valley, where it turns to the east, and *Austur-Hveradalir*, farthest in the valley, towards the east.

From *Vestur-Hveradalir* one can see some of the springs in Mið-Hveradalir, but on account of the bend in the valley toward the east, Mið-Hveradalir seems to be the end of the valley. Not one of the springs in Austur-Hveradalir can be seen until one has come to Mið-Hveradalir, and the majority of them are not to be seen before one is quite close to them.

The springs in Hveradalir are mostly found in the sides and at the bottom of the small ravines. An exception is found in a very large spring situated high up

on the large gravel ridge which separates Austur-Hveradalir from Mið-Hveradalir. As this spring is visible from Mið-Hveradalir, it can serve as a guide to anyone seeking the hot springs in Austur-Hveradalir.

The time we had for our stay at the hot springs being very limited, and a great amount of time being spent in collecting specimens of the gases, we had to content ourselves with a rapid examination of the remaining springs. We were able, however, to substantiate that the springs resemble each other strongly. We did not see any mud springs or mud volcanoes here, with thick mud, of which there are so many examples at *Mývatn, Hengill* and *Krísuvík*; where one would expect to find such mud springs, the water was only muddy on account of the deposit of small particles. The great rainfall at Kerlingarfjöll has the effect of adding so much water to the springs, that the small particles produced by the action of the springs, can be continually conveyed away by the water. The streams, which are found in the small ravines, and which eventually unite into a river, *Áskarðsá*, which runs through the main valley, are greyish-white from the particles which the water carries from the springs. Áskarðsá bears away proportionally more suspended substances than the other glacier rivers.

The hot springs in Vestur-Hveradalir and Mið-Hveradalir have, on the whole, a greater volume of water than the springs in Austur-Hveradalir, which is naturally to be attributed to the higher altitude of the latter. In Austur-Hveradalir there are even a considerable number of solfataras with sulphur deposits, but as JOHNSTRUP has shown, the deposit of sulphur in solfataras only takes place when the soil is sufficiently dry and porous to permit the mixture of the atmosphere with the gases of the springs, under the surface of the earth.

With regard to the individual springs, I will content myself with describing one spring in Austur-Hveradalir, which is distinguished from all the other springs we saw in this place, by its activity and outward appearance. This spring, which is situated close to the stream running through the main valley, is a steam spring of the same kind as *Öskurhóll*, at *Hveravellir*, only it is still more powerful. Vapour and gases are emitted with indescribable force through a little hole in the rocky ground, and the emissions of vapour are accompanied by a deafening noise. When one considers that a large extent of the valley around the actual spring is filled with mist, which comes mostly from the vapour of this spring, one can form some slight idea of the tremendous amount of steam emitted by the spring. We called this spring *Öskrandi* (the Bellower). (Plate VII, *a*.)

The specimens of gases collected at Kerlingarfjöll were as follows: *Kerlingarfjöll No. 1 and 2*, from the same ravine in *Vestur-Hveradalir*, to the west of Áskarðsá, *No. 1* nearer to Áskarðsá, *No. 2* higher up in the ravine. *Kerlingarfjöll No. 3* comes from a large spring reservoir in *Mið-Hveradalir*. *Kerlingarfjöll No. 4* is from a little spring in *Austur-Hveradalir*, near Öskrandi. Altitudes: Vestur-Hveradalir 945 m.; Mið-Hveradalir 980 m.; and Öskrandi 1000 m.

Grafarbakkahverir.

We stayed here from the 4th. to the 7th. August 1906. Þ. THORODDSEN, who visited these springs in the summer of 1888, has described them in "Geografisk Tidsskrift"[1]. The elevation of the springs is 60 m. above sea-level. The most important springs are situated on a little narrow eminence on *Litla Laxá*'s right (northern) bank, (Plate VII, *b*). Farthest to the north there are two fountain-springs or geysers; the one towards the south spouts highest, about 1.7 m., while the northern one throws a column of water only 0.7 m. high, (Plate VIII, *a*). In 1888 the reverse was the case; according to Þ. Thoroddsen's statement the northern spring then spouted higher (4 ft.; the other 2 ft.). In both of these springs the temperature of the water between the eruptions was 95° (Þ. Th. 97°). But during the eruptions the temperature was 99.3° in the northern spring, and 98.4° in the southern.

With regard to the frequency of the eruptions I refer the reader to Part III, Table II—III. About midway between the eruptions a large quantity of boiling water is emitted from a fissure 0.4 m. long.

From this spring, which we named *Klofi*, we took the sample gas *Grafarbakki No. 1*.

Básahverir is the name of two deep hot-water basins, surrounded by sod. There is very little gas emitted from these springs; the depth of the water was about 3 m. The surface temperature was, in the northern basin 95°, and in the southern, 91.5°; but at the bottom, the temperature was 96,7° and 93.8° respectively. To the extreme south-west, close to the right bank of Litla Laxá, is *Vaðmálahver*, with a regular-shaped basin in which the water is in a state of continual agitation. The surface temperature was 98.4° (Þ. Th. 96°); at the bottom, 99.4°.

The same series of springs is continued on the opposite bank of Litla Laxá; close to the river there are two springs, of which the larger, like Klofi, rises out of the rocky ground, through a fissure 0.4 m. long. We obtained the sample *Grafarbakki No. 2* from this spring. A little farther on in the same direction, and higher up on the hill on which the farm *Grafarbakki* is situated, is a large boiling spring. The water from this spring is used by the inhabitants of Grafarbakki for drinking purposes.

Smaller groups of springs can be seen still farther away in a south-westerly direction towards the farm *Gröf*. We only visited the nearest of these groups, which lies on the left side of Litla Laxá, to the west of the above mentioned hill. The springs here are for the most part insignificant pools with gaseous exhalations. The gas sample *Grafarbakki No. 3* comes from the most northerly spring in this group.

In all the springs examined here, the water is alkaline and contains chlorides. In the two *Básahverir*, there are also traces of sulphates in the spring water. The gases in each case, showed positive reaction on being tested for sulphuretted hydro-

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[1] Geogr. Tidsskr. **10**, 18, 1889—90.

gen and carbon dioxide. The stones and pieces of rock which were around the springs, and which come in contact with the spring water, were covered with a thin shell of silicioussinter.

Laugarásshverir.

The farm *Laugarás* is situated on an elevated ridge 67 m. above sea-level. A little to the west of the ridge, probably 50 m. above sea-level, most of the hot springs are grouped together within a small space. The most important springs, taken from north to south, are the following: — *þvottahver*, 96°, sample *Laugarás No. 1*; *Draugahver*, 100° and *Suðuhver*, 98.5°, from which the sample *Laugarás No. 2* is taken.

Down by the river Hvítá, about 200 m. to the south of the springs, there are also some smaller hot springs. The specimen *Laugarás Nr. 3* is taken from the most easterly spring of this group. The spring water in the above mentioned springs is alkaline and contains chlorides and carbonates with traces of sulphates. In the gases were found traces of sulphuretted hydrogen, but no carbon dioxide. There were much smaller deposits of silicious sinter on the stones around the springs here than at Grafarbakki.

With regard to their outward appearance, these springs remind one very much of the springs at Reykir and Grafarbakki, and many plants uncommon in Iceland thrive exceedingly well in the warm soil around them. But the great heat of the water hinders the growth of plants, however, in such close proximity to the springs as is the case at Reykir in Skagafjörður.

We remained three days at Laugarás, from the 8th. to 11th. August 1906.

The hot springs at Reykjafoss in Ölfus. — Ölfushverir.

We spent from the 12th. to the 16th. August here. These springs are by the highway, and have therefore been more often visited than any other Icelandic springs, with the exception of those at *Stóri Geysir*. A good account of their topography and history is given in þ. Thoroddsen's description in the "Geografisk Tidsskrift"[1].

The best known spring at this place is *Litli Geysir* which has formerly been a very strongly spouting-spring. When R. BUNSEN visited Litli Geysir in 1846, it spouted regularly at even intervals; but it has now quite ceased spouting. The largest geyser at present is *Grýla* or *Grýta* (Plate VIII, *b*); it is situated 1 km. to the north of *Reykjafoss*. Grýla emits steam for a short period after an eruption, which is quite unusual with Icelandic springs.

Of the specimens of gases we examined in this spring district, there are 3 from *Hveragerði*, (Plate IX, *a*), to the west of Reykjafoss (25 m. over sea-level), viz. *Reykjafoss No. 1*, from a basin with clear alkaline water, which contained chlorides and

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[1] Geografisk Tidsskrift **17**, 98, 1903—1904.

traces of sulphates. This spring lies to the extreme south of the alkaline springs here, only 2 m. from the spring examined in 1904 as "Reykjafoss Nr. I"[1] which seems to be extinct, at least there are no further exhalations. *Reykjafoss No. 2 and 3* come from two small mud pools in Hveragerði, to the south-west. These springs, containing sulphuretted hydrogen, naturally gave an acid reaction. The fourth sample of gases, *Reykjafoss No. 4*, was taken from a little hot spring to the east of *Varmá*, just below the neighbouring waterfall (Reykjafoss).

The warm springs around Reykjafoss really constitute the southern part of a larger spring district which stretches towards the north with varying intervals of space, to the east of the highest point of the mountain *Hengill*. In this district there are solfataras, mud pools, clear, alkaline water basins and geysers, so that nearly all the more general kinds of springs in Iceland are represented here.

Apart from the springs around Reykjafoss, we were only able to examine the most northerly groups of springs in this district. These are named: —

Henglahverir.

Our sojourn at these springs lasted from the 17th. to the 20th. August 1906.

They are situated on the eastern slope of the mountain *Hengill*, where a large number of, for the most part, very strong hot springs are in evidence, collected in several separate groups. The distances between the groups are greatest in the direction from north to south; it is in some cases almost 1 km. On the other hand, the differences in their elevation are proportionately much less, in that they are all situated at the place where the slope of the mountain towards *þingvalla-vatn* lessens. It appears as if the hot springs here resort preferably to depressions in the ground. The southern groups go under the name of *Ölvisvatnslaugar*, while the northern are called *Nesjavallalaugar*. On the whole, the thermal activity in Hengill is at least as great as at any other of the places we have visited, with perhaps the exception of Kerlingarfjöll. In appearance, these hot springs most resemble the springs at Mývatn and on Kerlingarfjöll, in as much as they are either solfataras or mud springs.

On account of the great number of these springs, I must refrain from a detailed description of them, though they are in many respects highly interesting, and content myself with a summary account of the most important groups.

To the extreme south there is an isolated mud pool in the centre of a grass plot. One cannot see the spring itself until one is close to it, as it gives off, in contrast to most of the other hot springs, very little steam. On the other hand, one can hear at a distance of 200 m. the rippling sound made by the large bubbles of the gases forcing themselves up through the mud, which is of a pulpy nature. Each bubble is from 1 to 2 litres in size, and when it emerges from the surface and the mud closes in again this peculiar sound is emitted. This mud pool seems

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[1] K. Prytz og Th. Thorkelsson loc. cit. p. 325.

to have been in existence only for a short time. A little to the north of this spring, and higher up on the mountain slope, there is a small group of springs, which, on account of its dome-shaped deposit of silica, reminds one to some extent of the hot springs at Hveravellir.

Farther to the north, and on about the same level as the mud pool previously mentioned, is a rather large group of springs consisting of mud pools and solfataras. The springs are situated around a powerful steam volcano, which, with an ear-splitting report, throws up a strong column of steam. From this group we took two gas samples: *Hengill No. 1* and *Hengill No. 2*. *No. 1* is from a spring to the south of the steam volcano. The spring water, which had an acid reaction, and contained sulphates to a considerable extent, but no chlorides, had a yellowish tint on account of deposited particles of the same colour. *No. 2* comes from a little spring immediately to the north of the steam volcano.

The nearest group of springs to the north, is situated at a much greater altitude. The distance between these groups is presumably about 600 or 700 m. In the group which is seen to the left in the picture (Plate X), there are several solfataras and mud pools, but the most peculiar is perhaps a spring with a temperature of 23.3°, which lies just to the north of the group. This spring contains a large volume of water, which has deposited a yellowish-white layer, about 4 or 5 cm. thick, in its bed. This layer consists chiefly of precipitated sulphur, which, it follows, the spring water must contain. How this sulphur is produced cannot at present be decided; at any rate it does not seem probable that it has been occasioned by the imperfect combustion of sulphuretted hydrogen in the atmosphere. JOHN-STRUP's [1] theory on the formation of sulphur in Iceland cannot therefore be applied to this case, even though it seems in most other places to give the most feasible explanation of the formation of sulphur around the solfataras.

In a north-eastern direction from the last-mentioned group of springs, there is another large group situated directly north of a high grass bank. This group, which is seen in the foreground to the right of the illustration (Plate X), was on a level with the site of our tent, which was, according to the elevation we took, 300 m. above sea-level. At this place there are two large mud volcanoes, which throw up mud and water incessantly to a height of about half a metre (Plate IX, *b*). The specimen *Hengill No. 3* is taken from a little spring just to the north of the mud volcano shown in the illustration.

Some distance north of the groups of springs already mentioned, there are yet three more groups. Of these the one to the extreme south-east consists almost exclusively of solfataras (Plate XI). In the middle group, which is to be seen in the background of the photograph, (Plate XII), we collected the specimen *Hengill Nr. 4*. It seems that the thermal activity around this group is increasing in extent. For instance, we noticed that the grass upon a little plot which in our opinion must recently have been covered with grass, had mostly been destroyed by the

[1] loc. cit.

heat. Nearest to the springs the remnants of vegetation were quite black, farther away they were whitish, and finally yellowish, as a transition to the natural green colour. On the whole the terrestrial heat is probably on the increase in the hot springs here. This is confirmed, amongst other things, by the fact that in the group to the extreme north-west, there is a large mud volcano, which appears to have come recently into existence. This mud volcano (Plate XII) is about 5 m. in diameter, and we estimated its depth, reckoned from the edge of the spring down to the surface of the mud, at 2 m. The mud is continually thrown up to the level of the edge of the basin, that is, about 2 m. high. About 10 or 12 m. south of the mud volcano, we saw a peculiar little spring which also appears to be quite recent. As the illustration shows (Plate XIII) the spring has piled up the thick mud around its mouth, and in that way a sharp-pointed cone has been raised; this is on account of the mud indurating as soon as it is thrown from the outlet of the spring, and therefore obtaining sufficient solidity to stand upright in a conical form.

II.
The methods employed in the experimental work.

1. Testing the Radioactivity.

The investigation of the radioactivity of the hot springs comes under two heads, viz.: testing the radioactive emanations contained in the gases from the springs, and the examination of the sediment and mud taken from them, with a view to determining the radioactive substances they may contain.

The apparatus which I have employed to gauge the radioactive emanation, is reproduced in the accompanying outline drawing, (Fig. 5). The apparatus consists of four parts: the electroscope (E), the ionisation chamber (I), the battery (B), and a reading microscope (not shown in the illustration).

The electroscope (E) differs from an Elster Geitel electrometer in that it has only one aluminium leaf, and that the electroscope vessel is entirely of brass. In order to be able to observe the leaf, the electroscope vessel is provided with two circular windows, 15 mm. in diameter. The window in the front of the vessel is closed by a plane sheet of glass, through which the charged leaf may be observed, while the leaf receives the light necessary to the observation through the window on the back side of the vessel, this window consisting of a sheet of opaque glass. The rod (g), which holds the aluminium leaf, passes airtight through the amber cork, and its lower end is made to screw on to a brass cylinder (k) 12 cm. high and 2 cm. in diameter. This cylinder is enclosed in the ionisation chamber, — a sheet

metal vessel of the same shape, 22 cm. high and 13 cm. in diameter, and provided with two tubes (*l*) through which the gases to be examined are introduced. The ionisation vessel and the inner cylinder (*k*) are concentrical and together form a condenser.

When in use, the electroscope, the inner cylinder and the testing vessel are firmly connected by means of screw threads, but under transport these three parts of the apparatus are detached; a brass cover is then screwed on to the bottom of the electroscope in order to protect the lower surface of the amber against moisture and dust. A distinctive feature of thi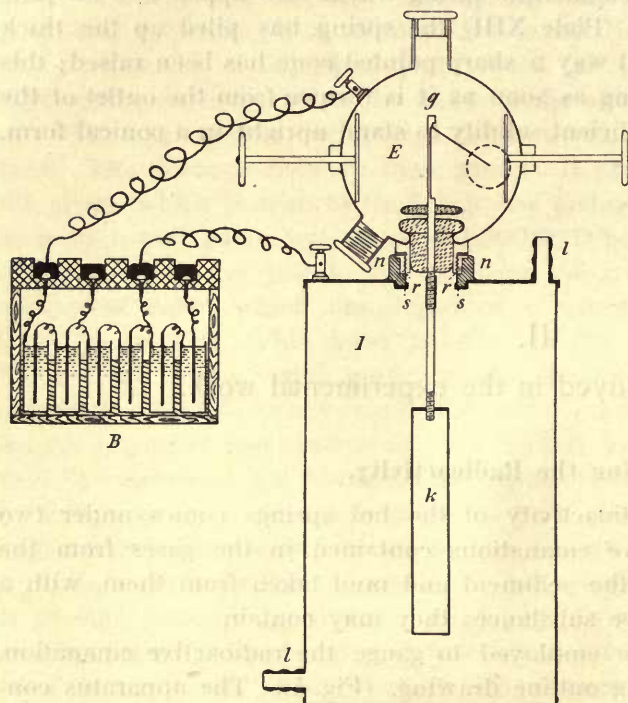s testing apparatus is the adjustment of the neck of the vessel into which the electroscope is screwed. The ebonite ring (*n n*) establishes a firm connection between the brass ring (*r r*) and the lid of the vessel. For this purpose the lid is fitted with a raised rim, which fits hermetically into the ebonite ring. The electroscope is attached to the testing vessel by means of a worm on the inner side of the brass ring (*r r*). The distance between the brass ring and the rim (*s s*) is about $^1/_2$ mm., so that the electroscope vessel is insulated from the ionisation chamber. A thin india-rubber ring is placed between the outside of the brass ring and the electroscope in order to make the connection between the electroscope and the ionisation chamber airtight.

Fig. 5.

The electroscope vessel and the ionisation chamber, when connected, form the outside of a perfectly closed condenser (a Faraday case). The inside of the condenser is represented by the aluminium leaf, the rod (*g*) and the cylinder (*k*). But when the connection is broken, we have in the electroscope vessel and the ionisation chamber two separate closed condensers of which the inner surfaces are in connection with each other.

Such a system of condensers establishes the theory that the fluctuations in the charge of the inner system of conductors is proportionate to the changes in the potential difference between the two outer conductors, provided that the

potential difference between the inner systems and either of the outer conductors is constant.

This can be demonstrated in the following manner.

In a closed condenser, the charge that the inner system of conductors carries is expressed by

$$E = c(v_1 - v_2),$$

where c, the capacity of the condenser, and v_1 and v_2 are respectively the potentials of the inner and the outer system of conductors. In the above mentioned apparatus the charge e, held by the inner cylinder (k), the rod (g) and the aluminium leaf, can be analogically expressed by the formula: —

$$e = c_e(v_i - v_e) + c_b(v_i - v_b), \tag{1}$$

c_e and c_b are the respective capacities of the electroscope and the ionisation chamber, and v_i, v_e and v_b are the potentials of the inner cylinder, the electroscope vessel and the ionisation chamber respectively. Leakage from the inner cylinder will cause a change in e, v_i, v_e and v_b and we get in the same way as before

$$e' = c_e(v_i' - v_e') + c_b(v_i' - v_b'), \tag{2}$$

when the new values of the variable quantities are marked. Subtracting (2) from (1) we have

$$e - e' = c_e\big((v_i - v_e) - (v_i' - v_e')\big) + c_b\big((v_i - v_b) - (v_i' - v_b')\big).$$

Assuming that the potential difference between the electroscope vessel and the rod (g) remains constant, we have

$$v_i - v_e = v_i' - v_e'. \tag{3}$$

Hence we get

$$e - e' = c_b\big((v_i - v_b) - (v_i' - v_b')\big)$$
$$= c_b\big((v_i - v_i') - (v_b - v_b')\big)$$
$$= c_b\big((v_e - v_e') - (v_b - v_b')\big)$$
$$e - e' = c_b\big((v_e - v_b) - (v_e' - v_b')\big), \tag{4}$$

which affords the required proof.

Equation (4) shows that the leakage is equal to the product of the capacity of the ionisation chamber and the change in the potential difference between the electroscope vessel and the ionisation chamber. The leakage is, on the other hand, independent of the electroscope capacity and of the absolute potential of the inner cylinder.

A possible objection to the above demonstration is that the formula (1) is not applicable because the two condensers regarded separately are not entirely closed, but as I have shown in Phys. Zeitschr.[1] the formula holds good, provided that the electroscope and the ionisation chamber form a single closed condenser when a conductive connection is established between them.

[1] Phys. Zeitschr. **7**, 834, 1906.

When the apparatus is to be used to measure radioactivity, it must be remembered that the activity is generally proportionate to the leakage from the inner cylinder divided by the time. Therefore in these measurements it is necessary to record the time, as well as to measure the leakage.

It is evident from equation (4) that measurements made by means of the testing apparatus may be executed in two different ways. In the first place by allowing the potential difference between the electroscope vessel and the inner cylinder to remain constant, when the amount of the leakage is obtained by determining the potential difference between the electroscope vessel and the ionisation chamber at fixed intervals. Secondly, the rate of leakage is obtained by determining the time that elapses before the potential difference between the inner system of conductors and the electroscope vessel has acquired a fixed value, after having made a given alteration in the potential difference between the electroscope vessel and the ionisation chamber. For reasons of a practical nature I preferred to use the latter method of observation.

We have a good criterion as to the identity of the potential differences between the electroscope vessel and the inner system of conductors, when the deflection of the aluminium leaf is constant.

The measurements were made in the following manner. One's first care is to see that the potential difference between the electroscope vessel and the ionisation chamber remains constant, e. g. by connecting them with the poles of a constant battery, or at any rate by connecting them with a thin copper wire, so that the potential difference becomes zero. Then the inner system of conductors is charged until the aluminium leaf makes a suitable deflection.

The potential difference between the aluminium leaf and the electroscope vessel was about 300 volts in my experiments. The microscope is then adjusted so that a clear outline of the leaf is seen in the neighbourhood of a mark in the eye piece, — two threads crossways will serve this purpose.

The deflection of the leaf decreases gradually on account of the leakage from the inner cylinder, and by adjusting the microscope one ensures that the edge of the leaf can be seen moving towards the fixed mark in the eye piece.

Note is taken of the time at which the image of the edge coincides with the mark. The potential difference between the electroscope vessel and the ionisation chamber is altered, so that the deflection of the leaf becomes greater, and the time at which the next coincidence of the edge of the leaf and the mark in the eye piece takes place is also noted. Let t represent the number of seconds between the two periods of coincidence; then the rate of leakage per second is given by

$$E = \frac{e - e'}{t} = \frac{c_b}{t}\left((v_e - v_b) - (v'_e - v'_b)\right)$$

or

$$E = \frac{c_b u}{t},$$

when $u = (v_e - v_b) - (v'_e - v'_b)$ is the change in the potential difference between the electroscope vessel and the ionisation chamber that has been produced.

The most convenient way of charging the inner system of conductors is by means of influence. A rod provided with an insulated handle, is brought into contact with the rod g, and a charged body, a rod of sealing wax for instance, is brought close to the upper end of the charging rod until the leaf has made a suitable deflection. Then the charging rod is taken off and the cover of the electroscope vessel put on. In order to impart a sufficient charge to the inner cylinder it is necessary that the end of the charging rod toward which the rod of sealing wax is brought, be flat shaped.

In order to produce the potential difference between the electroscope vessel and the ionisation chamber I used 10 small dry cells (Hellesen's pattern). These were embedded in paraffin in two wooden boxes containing four and six cells respectively. In each box the cells were connected in a series, and one pole of every alternate cell was attached to one of the copper stoppers which formed the bottom of the small holes in the thick ebonite plate in the lid of the box, (see Fig. 5). The copper stoppers render the holes mercury-tight, and when the battery is to be used the holes are filled with mercury. When the poles of the cells are to be connected to the electroscope vessel and the ionisation chamber, the ends of the connecting wires are placed in the mercury. In transit the holes in the ebonite plate are emptied of their contents of mercury, and then the poles of the cells are represented by the copper stoppers in the bottom of the holes. In this way the cells are protected against injury by accidental overstraining. Hence the cells remained constant during the whole journey.

Of course the connections between the testing apparatus and the battery are arranged at the beginning of every experiment, that is to say, before the adjustment of the microscope, so that one is able to make the greatest change in the potential difference that the cells in use permit, without altering the adjustment of the microscope. If the inner cylinder is charged positively, then the positive terminal of the battery should be connected with the electroscope vessel.

As the change produced in the potential difference between two consecutive observations depends on the rate of leakage, one must endeavour as far as possible to arrange that the intervals of time to be measured be kept within certain limits, preferably about one minute. If the intervals are much longer, the measurement takes too long, whilst on the other hand, if the interval be much shorter, the inevitable errors will proportionally be so great as to affect seriously the accuracy of the final results.

When the ionisation is small and the downward movement of the leaf is correspondingly slow, one does not need to move one end of the connecting wire farther forward than one hole in the battery case at a time; the established alteration in the potential difference $(v_e - v_b)$ then amounts to about 2.9 volts, i. e. double

the E. M. F. of one cell. This is the least variation in the potential difference that can be produced by means of the above mentioned battery boxes.

The increase in the deflection of the leaf effected by such a variation of potential difference amounts to very nearly 3 mm., as seen in the eye piece of the microscope. As it would easily be possible to distinguish $\frac{1}{30}$ of this, I was enabled, according to equation (4), to detect with this testing apparatus a decrease in the charge corresponding to $4.9 \times \frac{2.9}{30} \times \frac{1}{300} = 1.6 \times 10^{-3}$ E. S. units, the capacity of the ionisation chamber being 4.9 cm. in absolute electrostatic units.

When the ionisation is stronger, a correspondingly greater change is produced in the potential difference ($v_e - v_b$). By means of the two battery boxes I was able to make in all ten different changes in the potential difference, viz. 2.9; 2×2.9; 3×2.9 etc. up to 10×2.9 volts. In my opinion a greater alteration of the potential than 29 volts is not necessary, because, if the ionisation is too intense to be measured with sufficient accuracy by means of a potential variation of 29 volts, we are running the risk of there being an absence of saturation current in the testing apparatus, on account of the potential of the aluminium leaf and connecting conductors being restricted. In this case it is more reliable to introduce the active gas in smaller quantities into the ionisation chamber, and in this way avoid testing gases too intensely ionised.

The chief advantage of the method of measurement just described is that it is only necessary to know the small potential difference between two conductors, i. e. the electroscope vessel and the ionisation chamber, in order to compute the ionisation, it not being necessary to determine the high potential of the inner system of conductors exactly. But so few cells were required in order to gauge the small potential differences, that we could take them with us on the journey. Hence I was enabled to use the microscope instead of the magnifying glass in observing the aluminium leaf, the rate of leakage being measured in this case by comparison with the E. M. F. of the small cells taken with us, instead of by means of a scale, which would have had to be ganged every time the testing apparatus was set up.

The observation is preferably made by means of the microscope than by means of the magnifying glass, as the measurement can be made with greater speed without diminishing the accuracy. It is of great importance that the measurements be made expeditiously in the study of radioactive substances, as they are generally of an extremely changeable nature. Microscopic observations also save time, when the discharge through slightly ionised gas is to be determined.

Although the leaf can only be seen within a very restricted potential interval on account of the magnifying power of the microscope, the special method of observation here employed renders it possible to use the microscope for measuring at least as great a potential fall as a magnifying glass, i. e. much greater than can ordinarily be measured by the microscope.

From this it is evident that this method of observation is equally suitable for

measuring slight and strong ionisation, since it combines the advantages of the ordinary microscope observation in measuring slight ionisation, with the superiority of the magnifying glass in measuring strong ionisation. Thus we can dispense with the auxiliary condensers for varying the sensitiveness of the testing apparatus.

The change in the deflection of the aluminium leaf is observed by the ordinary methods of observation, but on account of the change in the position of the leaf, the capacity of the electroscope is also slightly altered. By my method of observation, however, the capacity of the electroscope remains quite unaltered throughout a series of observations, because the deflection of the leaf is identical at every observation.

Owing to the special arrangement of the electroscope and the ionisation chamber shown in Fig. 5, the measurements are quite independent of the moisture of the atmosphere. For the only place where the insulation may be defective on account of moisture is the surface of the amber stopper, and owing to the arrangement of the apparatus, this may easily be dried by means of metallic sodium. The electroscope vessel is provided with a side tube, in which the sodium is put when the upper surface of the amber is to be dried. The lower surface of the stopper is most conveniently dried by separating the electroscope vessel from the ionisation chamber, and closing the bottom of the vessel by the previously mentioned cover, in which a small piece of sodium is placed beforehand. On account of the small space to which the action of the sodium is confined the surface of the amber is quite dry after a few minutes.

In the first measurements of radioactivity on our journey, we noticed some remarkable anomalies in the results, but as all the testings were carried out in a tent, where considerable variations in the temperature are liable to occur, we soon perceived that these anomalies were due to air currents set up by the variations of the temperature in the electroscope vessel, the deflection of the mobile aluminium leaf being altered by the slightest movement of the air in the electroscope. In order to get rid of these disturbances, the electroscope was enveloped in a coating of thick pasteboard, covered with tin-foil. This isolation of the electroscope against heat proved to be sufficient to nullify the effect of the changes in the temperature.

When the emanation in a gas was to be measured by means of the above described apparatus, I first determined the amount of leakage through ordinary atmospheric air, then a measured quantity of the gas to be examined was introduced into the ionisation chamber. The gas was filtered through a compressed plug of cotton wool which retained the disintegration products present in the radium emanation (Ra A, Ra B, Ra C).

The time of the introduction of the radioactive gas into the ionisation vessel was noted. Then the leakage was tested several times in the course of an hour, and from these measurements the amount of radium emanation introduced with the active gas into the ionisation chamber was calculated.

The calculations were carried out in the following manner: On account of the special application of the dry cells, u is, in the following equation,

$$E = \frac{c_b u}{t},$$

(5)

always equal to $2.9n$ volts, or $\frac{2.9n}{300}$ abs. electrostatic units where n is a whole number within the limits 1 to 10.

The equation (5) may be written thus,

$$E = \frac{2.9 c_b}{3000000} \times \frac{10000}{\left(\frac{t}{n}\right)} = \frac{2.9 c_b}{3000000} a.$$

(6)

The factor $\frac{2.9 c_b}{3000000}$ is constant, therefore instead of calculating E, I confined myself to calculating its proportional $a = \frac{10000}{\left(\frac{t}{n}\right)}$. In this manner the calculations are restricted to the determination of the reciprocal value of $\frac{t}{n}$ in a table of reciprocals. Then the values of a are corrected by subtracting the value of a corresponding to the natural leakage in atmospheric air. Now the corrected values of a are marked out as ordinates on millimeter squared paper, while the abscissae represent the time reckoned from the introduction of the active gas into the ionisation chamber. Through the points marked, an even curve is drawn, showing how a increases immediately after the active gas is introduced into the ionisation vessel.

In the case of radium emanation, the curve has a characteristic shape, so that we are able from the form of the curve to decide whether the ionisation is due to radium emanation or not. Of course, if the curve of a is to be taken as a criterion as to whether the gas does or does not contain radioactive emanations other than radium emanation, it is necessary to take care that the disintegration products of the radium emanation are not carried along with the gas into the ionisation chamber, as they will, on account of their ionising power, alter the curve perceptibly. It is well known that the increase of ionisation immediately after the introduction of the active gas, is due simply to the production of these substances from radium emanation.

If the ionisation due to the emanation or its proportional a, — which amounts to the same, — is to be used as a measure of the amount of radium emanation, then it is necessary to provide for a saturation current when the testings of leakage are carried out; if not, the ionisation is not proportional to the leakage. In the second place it must be remembered that the ionisation is a function of time. Therefore it is only on condition that the ionisation is always tested at equal periods after the introduction of the gas in question into the ionisation vessel, that it may be depended upon to determine the amount of radium emanation in the gas.

But when, as in our case, a considerable number of experiments in very varying circumstances have to be carried out, it is exceedingly difficult in every experiment consistently to test the ionisation at equal periods after the introduction of the gas into the ionisation vessel. I have therefore, as already mentioned, pre-

ferred constructing an even curve showing the progress of a in the first hour, by means of values of a obtained at fixed points of time. Then I have from the curve deduced the mean values of a corresponding to 10, 20, 30, 40, 50, and 60 minutes after the active gas was introduced into the ionisation vessel. Every one of these values of a therefore could be employed in determining the amount of emanation in the gas. But in order still further to eliminate possible errors in the measurements, I have, instead of using one of these six values, used their mean value

$$a_m = \frac{1}{6}(a_{10} + a_{20} + a_{30} + a_{40} + a_{50} + a_{60})$$

which also, as may be easily shown, is proportionate to the amount of the emanation. For if the amount of emanation, A', at the above fixed points of time produces an ionisation represented by a'_{10}, a'_{20}, a'_{30}, etc., while another amount of emanation, A'', is represented by the analogical quantities a''_{10}, a''_{20}, a''_{30}, etc., we get the relations: —

$$\frac{A'}{A''} = \frac{a'_{10}}{a''_{10}} = \frac{a'_{20}}{a''_{20}} = \frac{a'_{30}}{a''_{30}} = \frac{a'_{40}}{a''_{40}} = \frac{a'_{50}}{a''_{50}} = \frac{a'_{60}}{a''_{60}}$$

$$= \frac{a'_{10} + a'_{20} + a'_{30} + a'_{40} + a'_{50} + a'_{60}}{a''_{10} + a''_{20} + a''_{30} + a''_{40} + a''_{50} + a''_{60}} = \frac{a'_m}{a''_m}.$$

By letting A be equal to a_m, the emanation is expressed in an arbitrary unit, besides which, it is dependent on the apparatus used. Therefore it was very important for me to find a unit for the emanation that was well defined and could be easily reproduced, so that the results of my experiments at any time could be compared with results of other scientists in the same domain. The simplest way out of the difficulty would have been to make use of the unit that ST. MEYER and H. MACHE [1] have proposed for use in expressing the radium emanation contained in spring gases. According to their definition, the unit is the amount of emanation that by means of its ionising power sets free per second an electrostatic unit of positive electricity and an equal quantity of negative electricity. The emanation is calculated per litre of spring gases.

My measurements could be easily expressed in terms corresponding to this definition of the emanation unit. In the first few seconds after the introduction of the gas liberated from the disintegration products of the emanation, the ionisation in the ionisation chamber is due solely to the emanation. Therefore if a, in equation (6), is replaced by a_0, then E in the same equation is simply the emanation expressed in the unit proposed by ST. MEYER and H. MACHE, or

$$A = E = \frac{2.9\,c_b}{3000000}\,a_0 = 4.73 \times 10^{-6} a_0. \tag{7}$$

Nevertheless I have not used this emanation unit in the computation of my experiments because I am of the opinion that the ionisation caused by the emanation is not only dependent on the amount of the emanation, but to a certain extent is

---

[1] Phys. Zeitschr. 6, 693, 1905.

also dependent on the form of the ionisation chamber. I have therefore preferred comparing the emanation in the hot spring gases with the emanation evolved by a known quantity of radium per second. In this way the unit of emanation becomes independent of the shape of the ionisation chamber, because the known quantity of emanation is measured in exactly the same way as that which it is desired to determine. It is taken for granted in this, as in every other case where measurements of emanation are to be made, that the ionisation is proportionate to the emanation, other conditions being equal.

As the unit of radium emanation, I have adopted the amount of emanation evolved per second by the radium in one gr. uranium in natural minerals. A similar used by unit is BOLTWOOD[1] in his researches of some American hot springs.

In order to obtain the value of a_m in the proposed unit, I dissolved about 0.1 gr. uraninite from Joachimthal in dilute nitric acid. The solution was put into a bottle that could be made airtight. Then the solution was freed from emanation by boiling, and the bottle closed. The radium contained in the solution incessantly evolves emanation, which is stored up in the bottle. After standing three or four days, the emanation evolved is completely removed from the solution by pumping and boiling, and the emanation thus collected is introduced into the ionisation chamber, where it is measured in the ordinary way.

According to two analyses, for which I am deeply indebted to Cand. polyt. V. FARSÖE, the uraninite used in these experiments contained 23.8 % uranium. If p gr. uraninite are dissolved, the radium in the solution evolves per second $0.238\,p$ emanation units. On this basis, and by making proper allowance for the decay of the emanation, the amount, q, of radium emanation in the solution at any given time, may be calculated. Of the emanation q, the fraction aq is transformed every second; here, the transformation coefficient a is, according to RUTHERFORD and SODDY[2], computed at 2.16×10^{-6}. Then with respect to the solution, the total increase of the emanation in the infinitesimal interval dt, is given by the differential equation,

$$\frac{dq}{dt}\, dt = 0.238\,p\,dt - aq\,dt.$$

Hence we get by integration,

$$q = \frac{0.238\,p}{a} + Ce^{-at}.$$

By letting $q = 0$ when $t = 0$, we get the integration constant,

$$C = -\frac{0.238\,p}{a}.$$

Therefore,

$$q = \frac{0.238\,p}{a}(1 - e^{-at}).$$

In this formula the transformation coefficient $a = 2.16 \times 10^{-6}$, e the base of the

[1] Amer. Journ. Sci. 18, 378, 1904.
[2] See RUTHERFORD: Radio-activity 2. ed. 1905, p. 247.

natural logarithms, p the weight (in grams) of the uraninite employed, and t the time in seconds reckoned from the moment the solution was sealed up; p and t are found by experiment.

From the last equation we get q in the above proposed unit (per gram uranium per second), while a direct measurement of the emanation in the ionisation chamber gives the emanation in the arbitrary unit by means of a_m. The factor γ, which a_m is to be multiplied by to express the emanation in the right terms, is given by the equation,

$$q = \gamma\, a_m.$$

As a mean of two experiments I got

$$\gamma = 1.347.$$

According to measurements made by RUTHERFORD and BOLTWOOD[1], natural minerals contain 3.8×10^{-7} gr. of radium per gram of uranium. Therefore the proposed unit of emanation is produced by 3.8×10^{-7} gram of radium per second. Thus we are enabled to refer this unit to CURIE and LABORDE's[2] unit of emanation.

In the proceeding exposition I have taken it for granted that the relation between the emanation contained in the ionisation chamber and the ionisation factor a_m is constant. But this only holds good when the testings are carried out at even density of the atmosphere. A change in the density of the atmosphere causes a corresponding change in the relation between the emanation and the ionisation produced. If alterations in the ionisation called forth by small variations in the atmospheric density are assumed to be proportionate to the alterations of the density, I have

$$\frac{E-E'}{E} = \mu\, \frac{d-d'}{d},$$

where E and E' represent the ionisation produced by the same emanation, i. e. when the density of the air is d and d' respectively, and μ a factor of proportionality. Setting aside the moisture of the air, I refer all the measurements to the pressure of 760 mm. mercury, and 18° C., so that $d = 0.001213$.

By direct measurements of a given quantity of emanation, I determined the leakage due to the emanation, at 766 mm. pressure and 20° C., to 889 arbitrary units. The same emanation caused the leakage to be 852, at a pressure of 618 mm. and 20° C. The density of the air at 766 mm. and 20° is $d = 0.001215$, and at 618 mm. and 20° C., $d' = 0.000980$. Then we have from the experiments mentioned,

$$\mu\, \frac{0.001215 - 0.000980}{0.001215} = \frac{889 - 852}{889}$$

or $\mu = 0.215$. From the formula,

$$\frac{E-E'}{E} = \mu\, \frac{d-d'}{d}$$

[1] Amer. Journ. Sci. 22, 1, 1906..
[2] Comp. rend. 138, 1180, 1904.

we get,

$$E = \frac{E'}{1 - \mu \dfrac{d - d'}{d}}$$

which with sufficient accuracy may be transformed into

$$E = E'\left(1 + \mu \frac{d - d'}{d}\right)$$

inasmuch as the quantity $\mu \dfrac{d - d'}{d}$, in the experiments in question, never exceeds 0.02. All the measurements of emanation are corrected according to the last formula. After having thus determined the amount of emanation, E, introduced into the ionisation chamber, the emanation, C_t, contained in 1 ccm. spring gas at 760 mercury and 20° C. is computed by simple proportion, when the reduced volume, V, of the gas employed in the experiment, is known.

Therefore,

$$C_t = \frac{E}{V},$$

C_t denoting the emanation contained in 1 ccm. of spring gas at the moment the gas was introduced into the ionisation chamber.

Supposing that the gas has been t seconds in the collecting tube, the emanation C_0 contained in 1 ccm. of spring gas at the time the gas was collected, is given by the formula

$$C_t = C_0 e^{-2.16 \times 10^{-6} t}$$

or

$$C_0 = C_t e^{2.16 \times 10^{-6} t}.$$

When C_t and t are known, C_0 can be calculated by means of this formula. Of course, the formula is not applicable except when the gas contains only radium emanation. C_0 is the emanation per gram of uranium per second contained in 1 ccm. of spring gas at the moment the gas was collected from the spring. From the foregoing it is obvious that the ultimate determination of the emanation contained in the spring gases is only to be obtained by somewhat prolonged calculations. As examples showing how these calculations are carried out, I cite here in extenso the measurements of the emanation of two samples of Icelandic spring gases, with the necessary calculations.

Reykir No. 5, Skíðastaðalaug.

Sample of gas collected on 16th. August 1906 at 5 p. m. Barometer: 746 mm. mercury. Temperature: 11° C. The volume of the collecting bottle, 102.2 ccm.

The sample was introduced into the ionisation chamber on the same day at 8.30 p. m. Barometer 746 mm. Air temperature 6° C.

Measurements of the ionisation:

Time.	Leakage. $\dfrac{1000}{\left(\dfrac{t}{n}\right)}$	Leakage due to the emanation in the gas.
8ʰ 24 p. m.	26.1	0.0
8ʰ 34 »	87.0	60.9
8ʰ 36 »	90.9	64.8
8ʰ 40 »	102.0	75.9
8ʰ 43 »	108.7	82.6
8ʰ 58 »	113.6	87.5
9ʰ 02 »	108.7	82.6
9ʰ 24 »	116·3	90.2
9ʰ 28 »	123.5	97.4

Hence we get, by means of the curve, the values of $\dfrac{10000}{\left(\dfrac{t}{n}\right)}$:

$$
\begin{aligned}
10 \text{ minutes} \quad & a_{10} = 76.5 \\
20 \quad\quad » \quad & a_{20} = 82.4 \\
30 \quad\quad » \quad & a_{30} = 86.2 \\
40 \quad\quad » \quad & a_{40} = 89.1 \\
50 \quad\quad » \quad & a_{50} = 92.2 \\
60 \quad\quad » \quad & a_{60} = 95.0
\end{aligned}
$$

showing an average of $86.9 = a'_m$.

The density of the air at 746 mm. and 6° C. is $d = 0{,}001242$. The corrected value of a_m is therefore

$$
a_m = 86.9 \left(1 + 0.215 \, \frac{1213 - 1242}{1213}\right) = 86.5.
$$

The amount of emanation in question is thus

$$
E = 86.5 \times 1.347 = 116.5
$$

while the reduced volume of the spring gas investigated is

$$
V = \frac{102.2}{1 + 0.00367 \times 11} \, \frac{736}{760} = 95.1 \text{ ccm.}
$$

The spring gas contains therefore at the time of examination, an amount of emanation which is expressed by: —

$$
C_t = \frac{E}{V} = 1.225.
$$

Multiplying 1.225 by $e^{2.16 \times 10^{-6}t}$, t being 12600 seconds, we obtain the amount of emanation contained in 1 ccm. of the spring gas at the time of collection. Therefore

$$
C_{\mathrm{I}} = 1.225 \times e^{2.16 \times 10^{-6} \times 12600} = 1.26 \text{ per gr. uranium per second.}
$$

Hveravellir No. 27, Bláhver.

Sample of gas collected on 23rd. August 1906 at 8.30 p. m. Barometer 696 mm. Temperature 37°. The volume of the collecting bottle, 198.7 ccm.

The sample was introduced into the ionisation chamber on 27th. August 1906 at 6.00 p. m. Barometer 703 mm. Air temperature 11° C.

Measurements of the ionisation:

Time.	Leakage.	Leakage due to the emanation in the gas.
5^h 50 p. m.	28.0	0.0
6^h 05 »	568	540
6^h 06 »	588	560
6^h 09 »	658	630
6^h 11 »	645	617
6^h 26 »	699	671
6^h 30 »	714	686
6^h 31 »	714	686
6^h 48 »	754	726
6^h 52 »	780	752

Hence we get, by means of the curve, the values of $\dfrac{10000}{\left(\dfrac{t}{n}\right)}$:

$$
\begin{aligned}
10 \text{ minutes} \quad & a_{10} = 612 \\
20 \quad » \quad & a_{20} = 656 \\
30 \quad » \quad & a_{30} = 686 \\
40 \quad » \quad & a_{40} = 715 \\
50 \quad » \quad & a_{50} = 740 \\
60 \quad » \quad & a_{60} = 763 \\
\hline
& a'_m = 695
\end{aligned}
$$

Corrected according to the density of the atmosphere

$$a_m = 695 \left(1 + 0.215 \, \frac{1213 - 1150}{1213}\right) = 702.6,$$

$$E = 702.6 \times 1.347 = 946.4,$$

$$V = \frac{198.7}{1 + 0.00367 \times 37} \times \frac{649}{760} = 149.1 \text{ ccm.,}$$

$$C_t = \frac{E}{V} = 6.34.$$

The emanation, C_{II}, from the spring gas is therefore:

$$C_{II} = 6.34 \times e^{2.16 \times 0.3366} = 13.1 \text{ per gr. uranium per second,}$$

t being 336600 seconds.

As many investigators, especially German, have employed of late the unit of emanation in spring gas proposed by MACHE and MEYER, it is important to be able to compare this unit directly with the one employed in these experiments.

This may be done in the following manner. According to equation (7) on page 207 the relation between the leakage in the ionisation chamber and the emanation expressed in the units of Mache and Meyer is given by

$$A = 4.74 \times 10^{-6} a_0.$$

In some experiments I made special efforts to measure the ionisation immediately after the introduction of the radioactive gas into the ionisation chamber. From these experiments I deduced

$$a_0 = 0.6 a_m$$

consequently

$$A = 2.84 \times 10^{-6} a_m.$$

If, in measuring a_m, v ccm. is used instead of 1 litre of the spring gas, the above equation is transformed to

$$A = \frac{2.84 \times 10^{-6}}{\frac{v}{1000}} a_m = 2.84 \times 10^{-3} \frac{a_m}{v}.$$

On the other hand, I calculated the emanation in accordance with the formula

$$C = 1.347 \frac{a_m}{v}.$$

Hence it is clear that my unit may be transformed to the unit of Mache and Meyer by multiplying the amount of emanation expressed in my units, by the factor

$$\frac{2.84}{1.347} \times 10^{-3} = 2.11 \times 10^{-3}.$$

Accordingly, the emanations of the two samples quoted, expressed by the units of Mache and Meyer, are

Reykir No. 5 . . . . 2.66 × 10⁻³ (E. S. E.)
Hveravellir No. 27 . . . 27.6 × 10⁻³ (E. S. E.)

It was important to ascertain how far the radioactive emanation contained in the Icelandic spring gases is due exclusively to radium, and whether the gases contain some other radioactive emanations. I shall now mention two methods by which I endeavoured to ascertain this point, viz. (1) by examining the ionisation curve, which shows how the ionisation in the ionisation chamber increases during the first hour after the introduction of the active gas; (2) by determining the coefficient of decay for the emanation contained in the spring gases. A third method, especially applicable to the investigation of rapidly changing emanations, will be mentioned later.

If, in determining the nature of the emanation, one bases one's observations only on the ionisation curve, great care must be taken in the filtration of the gas before introducing it into the ionisation chamber. The slightest quantity of disintegration products of the emanation, escaping into the ionisation chamber with

the emanation, will cause a perceptible alteration in the ionisation curve. On this account this method is always a little unreliable, and I therefore laid particular stress on the second method.

In order to determine the coefficient of the rate of decay of the emanation, I took two samples of every spring gas to be examined, one sample about 100 ccm., the other about 200 ccm. As soon as possible, (after t_1 seconds), the 100 ccm. of the gas were examined to ascertain the emanation contained, whilst the 200 ccm. of the gas were examined after about four days (t_2 seconds).

By means of the measurements above described, the emanation contained in 1 ccm. of the spring gas under examination, at the moment when the gas was introduced into the testing vessel, was then calculated. Let A_{t_1} and A_{t_2} represent the emanations calculated per 1 ccm. of spring gas, while the indices t_1 and t_2 signify the time in seconds that the testings took place after the collection of the gas, then A_{t_1} is the emanation in 1 ccm. of the spring gas after having been t_1 seconds in the collecting bottle, and A_{t_2} has an analogical significance. Therefore A_{t_2} is the remainder of the emanation A_{t_1} after $t_2 - t_1$ seconds.

In order to calculate the rate of decay (α') of the emanation by means of the two experiments, it is necessary to suppose that the emanation decays in accordance with a known law. By supposing that the emanation decays according to an exponential law I get

$$A_{t_2} = A_{t_1} e^{-\alpha'(t_2 - t_1)}.$$

Hence I have

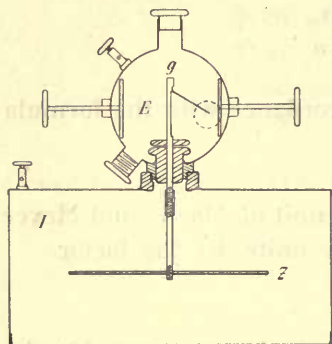$$\alpha' = \frac{\log A_{t_1} - \log A_{t_2}}{t_2 - t_1}.$$

Fig. 6.

The values of the rate of decay entered in Table I are calculated in accordance with this formula.

The examination of the radioactive substances in solids, i. e. mud and sediments, was done by measuring their ionising power. The apparatus for measuring the ionisation produced by solids was, in principle, the same as that employed in examining the emanation. The same electroscope was used, but the ionisation vessel had different dimensions. The vessel I in Fig. 6 is 12 cm. high and 26 cm. in diameter. A circular, horizontal plate of zinc, Z, 16 cm. in diameter, is connected by a brass rod 6 cm. in length to the rod, g, in the electroscope. The brass rod is attached to the centre of the plate. The substance to be examined is pulverized finely and spread in a thin layer over the bottom of the vessel, which is easily removed from the upper part. The radium rays emitted by the substance will then ionize the air in the testing vessel and consequently augment the leakage.

One can form an estimate of the sensitiveness of the apparatus from the following measurements. I dissolved 0.201 gram of nitrate of uranyl, ($UO_2(NO_3)_2 + 6H_2O$),

in water, and mixed the solution with 31 gram of dry mud powder which I had previously proved to be quite inactive. After desiccation and pulverisation the mud, which has now become active on account of the uranium contained in it, is again examined.

In the case of inactive mud the leakage $\left(\frac{1000}{\left(\frac{t}{n}\right)} \right)$ was 13.9. With the active mud the leakage was 153. Hence the increase in leakage was 139. Under ordinary conditions I could perceive an increase in the leakage corresponding to $\frac{1}{10}$ of the natural leakage, or 1.4 of the arbitrary units before described. Hence I conclude that, by means of this apparatus, it is possible to detect 0.00201 gram of nitrate of uranyl contained in the mud sample, or, as I usually in every experiment examined about 30 grams of the desiccated mud, I was thus able to detect radioactive substances in the sample, provided they produced the same ionising effect per gram of the examined matter as 0.00067 gram of the nitrate of uranyl.

The nitrate of uranyl contains 47.6 % uranium. Therefore 31.9×10^{-5} gram of uranium per gram of the mud is the smallest amount of uranium to be detected by this method.

According to McCoy[1] 1 gram of radium, in equilibrium with its disintegration products, is equally as active as 3.8×10^6 gram of uranium, while Soddy and Mackenzie[2] found 1 gram of radium as active as 14.6×10^6 gram of uranium. Taking the average of these measurements, and estimating the activity of radium at 9×10^6 times the activity of uranium, I must have been able to detect, by means of the above described apparatus, 3.5×10^{-11} gram of radium contained in 1 gram of dry mud.

According to Strutt[3], and Eve and McIntosh[4], the rocks on an average contain 1.4×10^{-12} gram of radium per gram of the mineral, i. e. $\frac{1}{25}$ of what I was able to detect.

At each of the hot spring groups investigated by us, I examined for radioactivity 5—10 different samples of mud, silicious sinter and other deposits from the hot springs, but without detecting any trace of radioactive substances. On this account I must conclude that the amount of radium contained in the sediments, mud etc. of the hot springs examined, does not exceed 25 times the amount of radium contained in common rocks.

2. The collection of spring gases.

The spring gases were preferably collected from springs where the gas evolved bubbled through water or mud, because we judged that the gas collected here was less likely to be mixed with atmospheric air than that collected from

[1] Phil. Mag. 11, 185, 1906.
[2] Phil. Mag. 14, 272, 1907.
[3] Proc. Roy. Soc. 77, 472, 1906.
[4] Phil. Mag. 14, 231, 1907.

from vents in the dry, porous soil. In every case the method employed in collecting spring gases was the same as that described by Travers, as shown in Fig. 7.
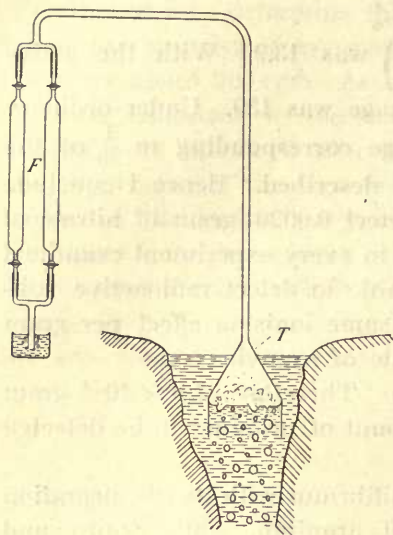

Fig. 7.

The gas emanating from the spring was gathered up by the enamelled funnel, *T*, and conducted through a tin tube into the collecting bottle. The pressure acting upon the gas collected in the funnel was great enough to force the gas through the connecting tubes and the collecting bottle. Care was taken that the gas, after having passed through the collecting bottle, always bubbled through water, in order to make sure that atmospheric air could not by any means be introduced into the collecting bottle. In order to facilitate the exclusion of atmospheric air from the collecting bottles in the beginning of the experiment, they were filled with water and then connected with the conducting tubes, out of which the atmospheric air is driven beforehand by the current of spring gas. The flow of the water from the bottle was regulated by means of stop-cocks according to the evolution of the spring gas, so that we were sure that the pressure of the gas above the water in the collecting bottle was never lower than the atmospheric pressure; had this been so, it would have caused the water from the funnel to be sucked up into the conducting tubes.
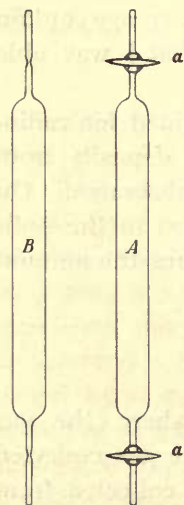

Fig. 8.

Fig. 8 *A* shows the kind of bottle in which the spring gas to be examined for radioactivity was collected. Every bottle is provided with two tubes capable of being closed airtight by means of the stop-cocks *a*. I took with me on the journey 8 sets of these bottles, each set consisting of two bottles, one containing 100 ccm. and the other 200 ccm. The bottles were provided with etched numbers, and before the journey they were measured by weighing them filled with water.

As already mentioned two samples of spring gas, 100 ccm. and 200 ccm., were collected from each hot spring investigated. In order that the gas in the samples might be as homogeneous as possible, the two samples were collected simultaneously by connecting the collecting tubes parallel to the conducting tube, by means of *T*-tubes, as shown in Fig. 7 *F*. Before closing the stop-cocks, we took care that the spring gas, by passing slowly through the tubes for a time, had assumed the pressure and temperature of the surrounding air.

On closing the collecting bottles, we observed the temperature of the air in

the immediate vicinity of the bottles, the standing of the barometer and the exact time.

The samples of gas for the quantitative analysis were collected in the same way, in bottles (Fig. 8 B) containing about 150 ccm. These bottles were of a similar shape to those containing the gas to be examined for radioactivity, but the tubes had no stop-cocks, being closed by melting. The samples taken to determine inactive gases contained in the spring gas were at first collected in the sheet iron vessel B in Fig. 9. The volume of the vessel was about 5000 ccm., and the collection of the gas was performed in the usual way. The vessel was then brought to the tent, where the sulphuretted hydrogen, the carbon dioxide, the oxygen and hydrogen were for the most part withdrawn from the spring gas. The arrangement of the apparatus is shown in Fig. 9. The circuit P, F, M, O, C, K consists of the Prytz pump [1] P, the collecting bottle F, the glass tubes M, O and C containing respectively peroxide of manganese, oxide of copper, and metallic copper filings, and the absorption bottle K containing hydroxide of potassium to absorb the carbon dioxide. The vessel B, containing the spring gas, is attached to the circuit by means of the T-tube between F and M, while the lower end of the vessel B is connected by an indiarubber tube to the water reservoir N. By lifting N to the necessary height, the gas in B was continually submitted to a slightly greater pressure than that of the atmospheric air. The gas in the circuit could find an outlet through the T-tube T inserted between the pump and the collecting bottle.
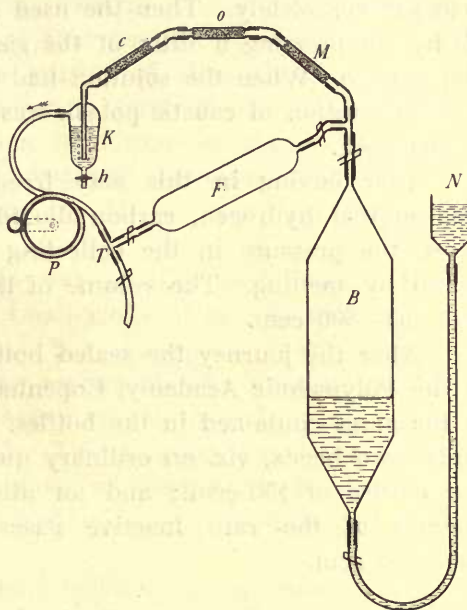
Fig. 9.

We began operations by filling the collecting bottle, F, with water, and then closing it by clipping the two indiarubber tubes forming the inlet and outlet of the bottle. Keeping the T-tube T open, we pumped out the rest of the circuit by means of the Prytz pump, and washed it out a few times by refilling it with gas from the vessel and pumping it out again with the pump. Finally this part of the circuit was filled with spring gas up to the pump. The clips over the entrance tubes of the bottle F were then unscrewed and the bottle being in a slanting position, the water ran out of it through T, the bottle being filled at the same time with spring gas from the vessel B. As soon as the bottle is full of spring gas, the tube T and the connecting tube between the vessel B and the circuit are

[1] K. PRYTZ: Zeitschr. f. Instrumentenkunde. 1905, p. 193.

closed. By pumping the gas in the circuit in the direction shown by the arrow, the sulphuretted hydrogen and the carbon dioxide are absorbed. The gases absorbed in the circuit are soon replaced by fresh spring gases introduced by opening the tube connecting the vessel with the circuit.

When the continued circulation of the gas does not further reduce the pressure in the circuit, showing that the absorption of the sulphuretted hydrogen and the carbon dioxide is nearly completed, the oxide of copper and the copper filings are heated, in order to destroy the free hydrogen and oxygen. When the spring gas contained carbon dioxide in exceptional quantities, it might happen that the caustic potash in the absorption flask K would not be sufficient to absorb the carbonic acid gas completely. Then the used solution of caustic potash was removed from K, by compressing a little of the gas above the solution, and then opening the stop-cock h. When the solution had mostly run out, the stop-cock was turned off. A fresh solution of caustic potash was then sucked into K by reducing the pressure in the flask.

After having in this way freed the gas in the circuit of its contents of sulphuretted hydrogen, carbon dioxide, oxygen, hydrogen and other combustible gases, the pressure in the collecting bottle was reduced a little, and the bottle closed by melting. The volume of the bottles used to collect these gas samples was 500—800 ccm.

After the journey the sealed bottles were brought to the Physical Laboratory of the Polytechnic Academy, Copenhagen, where I undertook a closer examination of the gases contained in the bottles. Of course, this investigation naturally came under two heads, viz. an ordinary quantitative analysis of the gases contained in the bottles of 150 ccm.; and an attempt to trace and partly to determine the amount of the rare inactive gases collected in the larger bottles containing 500—800 ccm.

3. Analysis of the gases.

In the quantitative analysis I aimed at a determination of the relation between the following gases contained in the spring gas: sulphuretted hydrogen, carbon dioxide, oxygen, hydrogen, methane, and nitrogen, plus the inactive gases.

In the analysis work I employed a Pettersson analysis apparatus from the firm of Franz Müller (Dr. H. Geislers Nachf.) Bonn a/R.

The measuring tube contained 35 ccm., and the smallest divisions corresponded to $\frac{1}{10}$ ccm. so that I could with considerable accuracy read $\frac{1}{100}$ ccm. In connection with this apparatus I used absorption pipettes for absorbing sulphuretted hydrogen, carbon dioxide, and oxygen, and an explosion pipette.

To transport the gas to be examined conveniently and safely from the collecting bottle to the measuring tube, I proceeded in the following way: The end of the sealed tube of the collecting bottle was knocked off while held under the surface of mercury, and a short indiarubber tube, which could be closed by a clip

was pushed on the rest of the glass tube, while it still remained under the mercury, in order to prevent atmospheric air getting into the bottle. Then the other end of the bottle was immersed in the mercury, and knocked off in the same way. This end of the bottle was then connected, by means of an indiarubber tube, with a mercury reservoir that could be raised and sunk to adjust the pressure of the gas in the bottle. Of course, care was taken that the indiarubber tube was quite filled with mercury before it was pushed on the glass tube. The other tube of the collecting bottle, that which was first broken, was then connected, by means of the above mentioned indiarubber tube, with the entrance tube of the measurer, and we were ready to conduct the gas under investigation from the bottle into the measuring tube. I endeavoured, by keeping the mercury reservoir in a suitable position, to avoid rarefaction of the gas in the bottle, so that possible small leakages in the indiarubber connection could not result in a mixture of atmospheric air with the gas examined. As it was a very difficult matter to force the air completely out of the measuring tube and the accompanying inlet tube by means of mercury, the remaining atmosphere was excluded by washing the measurer a few times with small quantities of the gas, before the gas to be used for analysis was introduced.

The subsequent conduct of the analysis was roughly as follows. The sulphuretted hydrogen was first absorbed by a small globe of pure peroxide of manganese moistened by thick phosphoric acid. The absorption took place above mercury in an absorption pipette. Then the carbon dioxide was absorbed by a strong solution of caustic potash, and the oxygen was destroyed by a solution of pyrogallic acid in a solution of caustic potash. This solution was made according to a prescription of HEMPEL[1], by mixing 5 grams of pyrogallic acid dissolved in 15 ccm. of distilled water with 120 grams of hydroxide of potassium dissolved in 80 ccm. of distilled water.

After having measured the volume of the remaining gas, a known amount of oxygen or air, and if necessary a mixture of 2 volumes of hydrogen and one volume of oxygen, was admitted, and the gases mixed brought to explosion in the explosion pipette. After the explosion the remnant gas was examined for carbon dioxide and oxygen in the same way as before. Of course the gas after every absorption was drawn back to the measuring tube and its volume determined. By repetition of the test I made sure of a complete absorption in every case.

4. Investigation of the rare inactive gases contained in the spring gases.

The bottles containing the gas collected for investigation of the rare, inactive gases, were opened in the same way as the other collecting bottles, except that in this case I employed water instead of mercury to shut out the air.

I used the arrangement shown in Fig. 10 in the subsequent treatment of the

[2] HEMPEL: Gasanalytische Methoden. 3. Aufl. 1900, p. 133.

gas. The measurer A, volume 800 ccm., is connected, by means of the hard glass tube C, to the collecting bottle F containing the gas under investigation.

The gas is cut off from the surrounding air by water. The hard glass tube C contains, in three separate compartments, reduced copper, copper oxide and solid hydroxide of potassium. The part containing the copper and the copper oxide is heated, and, by conducting the gas several times through the tube, possible small remnants of combustible gases, oxygen and carbon dioxide in the gas are destroyed.

At last all that remains now consisting only of nitrogen and rare, inactive gases, is left behind in the measuring tube A, where its volume is determined. In the meantime I have, by means of the mercury air pump, exhausted the hard glass tube M, containing a mi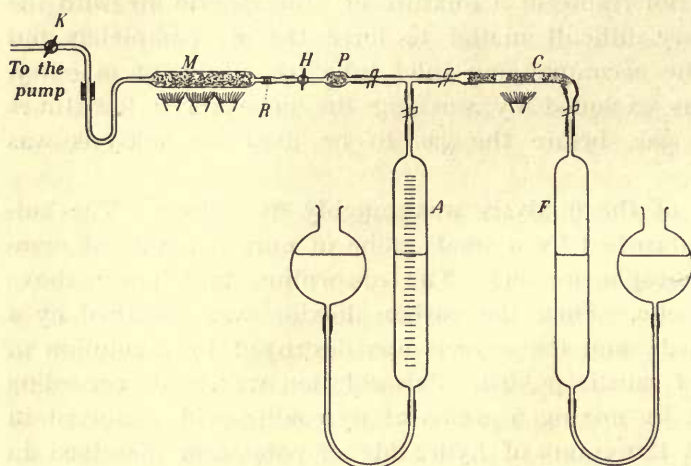xture[1] of 1 part of magnesium powder, 5 parts of freshly burned lime (CaO) and 0.1 part of metallic sodium; the tube is kept at red heat for about two hours, while the mercury pump works constantly to remove the gases evolved by the hot Mg-CaO-Na mixture. When the mixture has been heated so long that the gas evolution has for the most part ceased, the communication to the pump is interrupted by closing the stop-cock K, and then the gas in the measurer A is admitted

Fig. 10.

to the absorption tube by opening the stop-cock H. On its way to M the gas is desiccated by phosphorus pentoxide in the tube P. Then the gas is passed through the porous plug R, which is inserted in order to avoid too violent entrance of the gas into the empty tube M. After the absorption of the nitrogen the tube M, while still hot, is emptied by means of the mercury pump, and the remaining gas is collected above mercury in a collecting tube.

Although the remaining gases obtained as above described consist mainly of rare, inactive gases, yet small amounts of hydrogen and carbon monoxide evolved from the mixture, and perhaps even a trifle of nitrogen, are found.

The remaining work is to purify the rare, inactive gases from these impurities, and to separate the argon and helium.

As I had so many gas samples, (nearly 20), the following order of experimenting with these gas samples turned out to be the most practicable. First, all

[1] HEMPEL l. c. p. 150.

the samples were entirely purified from the small amount of nitrogen they contained, then the hydrogen and the carbon monoxide were destroyed, and at last, having determined the volumes of the remaining gases, — now only consisting of rare, inactive gases, — the argon and the helium were separated.

In these three different operations, viz. the absorption of nitrogen, the destruction of hydrogen and carbon monoxide, and the separation of argon and helium, I make use of an arrangement in all essentials similar to that shown in Fig. 11. One end of the tube connection R, K, P is attached to the automatic mercury pump, while the other end is closed by the porous plug C, which, together with the bend b of the tube R, is constantly covered by mercury in the glass vessel N. All the india-rubber connections between the tubes are made airtight by mercury. Having emptied the tubes up to the plug C by means of the mercury pump until a complete vacuum is attained, the gas is sucked into the system of tubes R, K, P through the porous plug C, by sinking the tube containing the gas into the mercury of the vessel N, until the plug is in contact with the gas. In the glass tube K, the form of which varies according to the purpose of the experiment, the gas is passed over

To the water jet pump

Fig. 11.

the agent intended to react on it. The remaining gas can now very easily be collected again in the collecting tube by means of the pump, and in order to make sure that the reaction is complete, the gas is twice passed through the tubes R, K, P. It is evident that one could go on indefinitely in this way, but it was
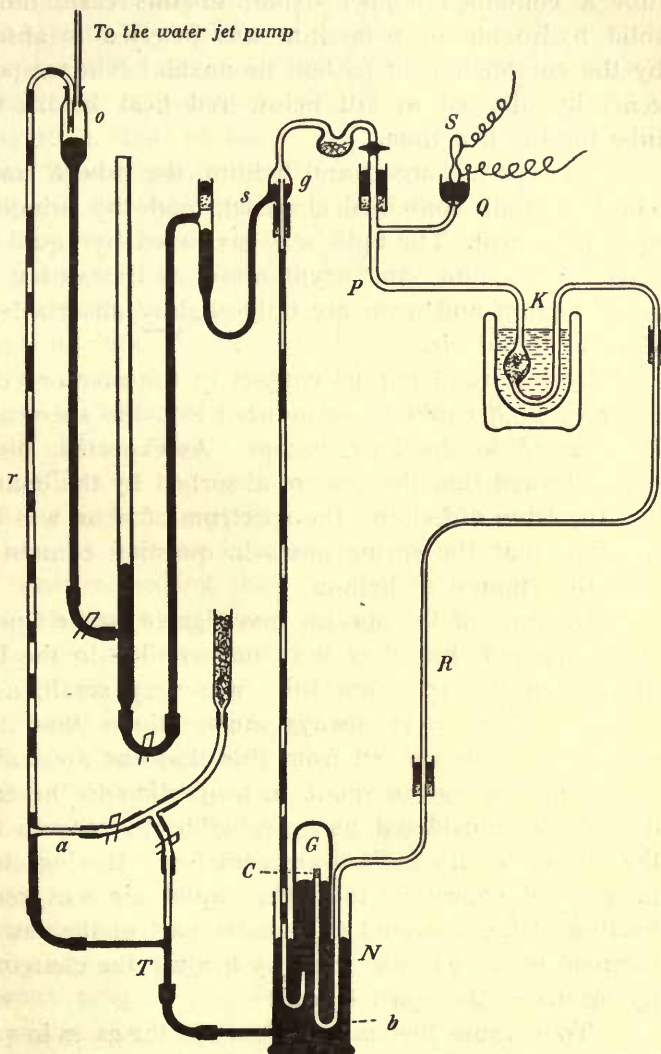
usually sufficient to pass the gas twice through the agent in order to obtain the result aimed at by the experiment.

With respect to the glass apparatus K, it was a hard glass tube containing the before mentioned Mg-CaO-Na mixture when nitrogen was to be absorbed.

When hydrogen and carbon monoxide were to be destroyed, the combustion tube K contained copper oxide; in this case, moreover a glass tube containing solid hydroxide of potassium was inserted to absorb the carbon dioxide formed by the combustion of carbon monoxide. The temperature of the copper oxide was generally allowed to fall below red heat before the gas was pumped out of the tube for the last time.

To separate argon and helium, the tube K had the form indicated in Fig. 11. The little bulb contained charcoal, made by bringing fragments of cocoanut shells to a great heat. The bulb was environed by liquid air before the gas was admitted. Then argon, xenon and krypton are, as DEWAR has found, retained by the charcoal, while helium and neon are only slightly absorbed by the charcoal at the temperature of liquid air.

By means of porous contact in the mercury cup Q, the gas contained in the tubes P, K, R could be introduced into the spectrum tube S, so that it could be investigated in the spectroscope. As expected, the investigation with the spectroscope showed that the gas not absorbed by the charcoal contained helium. Besides this spectrum of helium, the spectrum of neon was in many cases very conspicuous, showing that the spring gases in question contain neon in quantities comparable with the amount of helium.

In some of the spectra investigated, some lines due to mercury and hydrogen also appeared, but they were only visible in the beginning when the pressure of the gas in the spectrum tube was very small, and disappeared under increased pressure. They were always much fainter than the strong lines due to helium and neon. I concluded from this that the amount of hydrogen contained in the remaining gas was so small, in proportion to the amount of helium and neon, that it could be considered as a negligible quantity in the consecutive measurement of the volume of the helium-neon mixture. Having collected the helium-neon mixture in a small collecting tube, the liquid air was removed, and by the consequent heating of the charcoal the greater part of the gas absorbed became free. The last remnant of the gas was freed by heating the charcoal to some two hundred degrees by means of the spirit lamp.

To measure the small volumes of the gases in question, I employed a volumenometer, — originally designed by Professor K. PRYTZ, — in a slightly modified form. The apparatus as I used it is illustrated by Fig. 12. The two vertical glass tubes A and B are provided with divisions, and communicate underneath; but their upper ends are closed by the porous plugs M and N, which are covered by mercury. By raising the mercury reservoir Q, which is connected by the indiarubber tube L to the measuring tubes A and B, the air is expelled from the tubes. The remaining

air is drawn out through the porous plugs *M* and *N* by means of the mercury pump. The exhausted tube *B* is now used as a barometer tube, while the volume of the gas under examination is gauged in tube *A*.

To introduce the gas into the measuring tube *A*, the uppermost part of the latter is narrowed, the outward diameter being only 6 mm., so that the collecting tube *G* may be pushed over it. By sinking the collecting tube G, the gas contained in it is sucked through the porous plug into *A*, provided that the pressure in *A* is less than that of the atmosphere. The apparatus has turned out to be exceedingly convenient for rapid and accurate measurements of small volumes of gas, which are collected by means of the mercury pump in the collecting tubes. This method ensures that the gas is quite safely transported into the measuring tube. Besides this, the measurements of the volume can be performed at a suitably low pressure, so that considerable accuracy can be obtained in spite of the volumes to be measured being extremely small.

In order to prevent impurities of air being carried by the mercury through the indiarubber tube into the tubes *A* and *B*, the glass tube connecting the indiarubber tube with the measuring tubes is provided with an air receiver *F*. This receiver is shown in section in Fig. 12. The air carried by the mercury through the inlet *b*, is collected in the space beneath the porous plug *k*. There is usually great pressure in this space, and the gas collected is therefore forced up through the plug, and escapes into the atmosphere. On the other hand, the mercury resting above the plug prevents the air from penetrating into the plug. When the apparatus is arranged in this way, the small amount of gas under ordinary pressure contained in the porous plug is seldom rarified, and never to such an extent that it cannot be contained in the bulb of the receiver, without any danger of the air escaping into the measuring tubes.

Fig. 12.

Before abandoning this section on the apparatus and methods employed in this investigation, I shall briefly describe the mercury air pump I used. It is an air pump with falling mercury. The construction of the glass tube through which
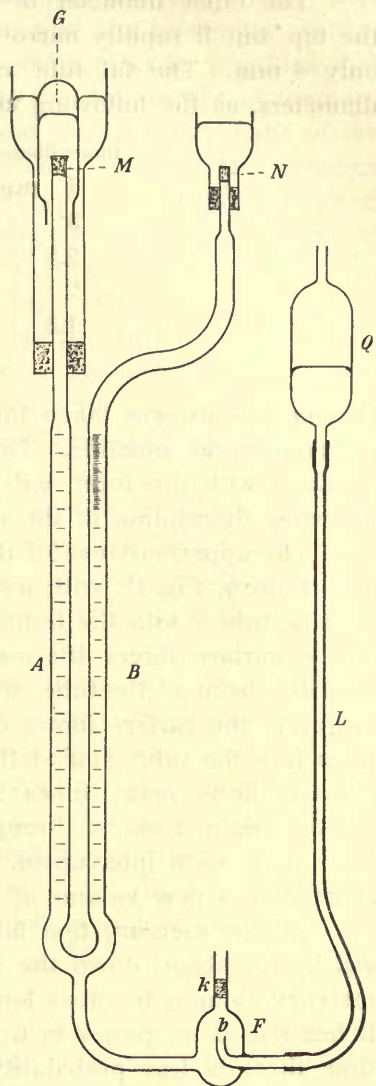
the mercury falls, and the manner in which the mercury falls into the tube, are distinguishing features of this pump.

The outer diameter of the fall-tube is 8 mm., the inner diameter 4.5 mm. at the top, but it rapidly narrows so that the inner diameter, 5 mm. from the top, is only 4 mm. The fall-tube consists of many capillary tubings of different inner diameters, as the following table shows.

Inner diameter	Length of the tube reckoned from the top
4 mm.	0.5— 5 cm.
3 »	5 — 20 »
2.5 »	20 — 42 »
2 »	42 — 55 »
1.3 »	55 — 76 »
2 »	76 —152 »

Of course, care was taken that the passage from one dimension to another should be as even as possible. The fall-tube is consequently conical and the advantage obtained with this form, will presumably appear with sufficient clearness from the following description of the working of the pump.

The uppermost end of the fall-tube is situated in the middle of a concentrical glass bulb g, Fig. 11, with a diameter of 2.5 cm. The mercury is conducted through the side tube s into the bulb g and fills the space around the fall-tube. On account of the surface forces the mercury can stand higher in the space round the tube than the brim of the tube, without flowing into it. By continued influx of mercury, however, the surface forces cannot resist and the mercury suddenly falls from all sides into the tube, and at the same time cuts off the gas contained in it. As the mercury flows many times more rapidly away through the fall-tube, widened at the top, than it enters through the side tube s, the influx of the mercury in the fall-tube is soon interrupted. Then the mercury in g is raised again and after a short time a new volume of mercury falls, as just now described, into the tube.

All the mercury that falls into the tube forms a coherent column, forcing the gas by its weight down the tube. Owing to the conical form of the fall-tube, the mercury column becomes longer the farther it comes down the tube, and therefore it has still more power to drive the compressed gas downwards, and at the same time there is less probability that the gas can escape back through the mercury. At low pressure the resistance of the gas to the falling mercury is quite infinitesimal, and the latter would therefore gain a great velocity, and consequently be liable to disintegrate into small drops, unless the friction in the tapering tube diminished the speed. The conical form of the tube also is conducive to keep the mercury together in one body, for the friction is greater at the lower end of the column. The mercury at the upper end of the column will therefore exert a pressure on the mercury beneath. In my opinion, it is also necessary that the tube should be narrow in the spot where the falling mercury coincides with that standing in

the tube, so that the small gas bubbles collected in this spot may be pushed down the tube together with them ercury. The lower part of the tube becomes wider again, so that the mercury can flow with sufficient rapidity out of the tube. The width of this part of the tube is so adjusted that the mercury in the lower part is still moving downward when the consecutive portion coincides with it, provided that the tube is a vacuum, and that the intervals between the two bodies of mercury are suitable. In this way the fall-tube is exempted from violent concussions of the mercury, and the spot in which the portions of mercury coincide still remains covered by mercury when the succeeding body of mercury closes the upper end of the tube. Thus the pump is entirely without detrimental space. The theory of the working of this pump is the same as that of the Geisler pump. In both cases a known volume of the gas is cut off and then expelled. The sole difference is that the gas volume cut off is greater in the Geisler pump than in the pump just described, but on the other hand the strokes of the pump are much more frequent. With the dimensions above mentioned, the gas volumes cut off in the tube by the falling mercury were about 4 ccm., and the strokes of the pump were, as a rule, about 80 per minute.

The working of the pump is probably as efficient at high as at low pressure, and although it does not perhaps work so quickly as a large Geisler pump, yet I think it may be used with advantage especially in analytical work; amongst other reasons, because it is very cheap and it does not require specially cautious handling.

After working a long time, however, the tube becomes more fragile and at last breaks, but in my experience it is sufficient to attach the fall-tube to the glass bulb g, by means of indiarubber tubing, rendered airtight by mercury, the fall-tube can then be easily replaced. I have, however, used the same fall-tube for a year, and many times during this period the pump has worked incessantly for 7 hours. On the whole, the same tube has sustained the working of the pump during many hundred hours without breaking. By fastening the fall-tube to the wood-work of the pump special care must be taken that no tension arises in the glass for it will inevitably cause a premature fracture of the tube. It is sufficient to fasten the tube in two places to the wood-work.

A great advantage is that this air pump with falling mercury is especially suitable for automatic working. I have used a water jet pump for raising the mercury to the height required. The mode of proceeding is the same as usual, and is illustrated by Fig. 11. The air sucked by the jet pump enters the tubing r through the side tube a, but as the air passage through a is made narrow, which is most conveniently done by means of an indiarubber tube and a screw clip, the air in r, is rarified so that the mercury in the vessel N is raised into r. The air entering at a divides the mercury into small drops which are carried by the air current into the reservoir O, where the mercury is collected, while the air is passed on to the jet pump. The mercury is conducted from the reservoir through the

glass tubings shown in Fig. 11, to the glass bulb g, whence it falls through the fall-tube, and in this way comes back to the vessel N, where it started. The T-tube T is inserted, so that the mercury is not drawn into the tube r when its surface in N is lower than the T-tube. For this reason, the porous plug C is never exposed to the air.

III.
On the results.

In the accompanying table of analyses, Table I, the name and number of the springs, in the first column, refers to the designation given in the description of the surroundings of the springs, (Part I), where particulars of their position and appearance will also be found. In the column headed "Calculated Boiling Point", is given the boiling point of distilled water calculated from the atmospheric pressure at thespring at the time of investigation.

The integral parts of the spring gas are expressed in their percentage to the volume of the gas; thus, the statement that the sample of the spring gas "Krafla No. 1" contains 12.6 % sulphuretted hydrogen, signifies that 100 ccm. of the spring gas in question contains 12.6 ccm. of sulphuretted hydrogen. The volumes are reduced to 760 mm. pressure and 0° Centigrade. Column "R" gives the percentage of the volume of the gas not absorbed by the agents usually employed in analysing gas, i. e. nitrogen, plus rare, inactive gases.

The radium emanation contained in 1 ccm. of the spring gas is expressed in the before-mentioned unit, (cf. p. 30), and is to be found in columns C_I and C_{II} of the table. C_I is calculated from the emanation measured in 100 ccm. of the spring gas a few hours after the gas was collected, while C_{II} is calculated from the emanation measured in 200 ccm. of the spring gas after standing about four days in the collecting bottles.

Probably the first point which strikes one on considering the accompanying table, is the great heterogeneity in the composition of the spring gases. Even samples taken from springs in the same locality sometimes show a considerable lack of uniformity in their composition. As a rule, however, springs in the same group evolve gases of almost the same composition. In cases where there is great incongruity in the gases, it will generally be found that there is a corresponding incongruity in the appearance of the springs. On the whole, the outward conditions and appearance of the springs seem to be to a great extent dependent on the composition of the spring gases. Springs which evolve gas containing sulphuretted hydrogen have generally a most unpicturesque appearance. The spring water becomes turbid through dark mineral particles being suspended in the water. If

Table I.

Springs explored	Date of Investigation	Temperature of the Springs	Calculated Boiling Point	Composition of the Spring Gases in percentage of the Volume									Emanation		Coefficient of decay $a' \times 10^6$	Remarks
				H_2S %	CO_2 %	H_2 %	CH_4 %	O_2 %	R %	N_2 %	A %	He %	C_I	C_{II}		
Krafla No. 1	²²/₆06	86°	98.0°	12.6	80.9	3.5	″	″	3.0	—	—	—	3.01	2.69	2.56	
— No. 2	²²/₆06	82°	98.0°	13.9	73.5	9.3	″	″	3.3	—	—	—	5.30	5.20	2.21	
Námafjall No. 1 . .	²⁰/₆06	76°	98.8°	2.2	37.5	49.0	″	″	5.9	—	—	—	1.74	1.76	2.15	
— No. 2 . .	²¹/₆06	55°	98.8°	—	—	—	—	—	—	—	—	—	1.66	1.57	2.47	
— No. 3 . .	²¹/₆06	94°	98.8°	—	—	—	—	—	—	—	—	—	1.75	1.76	2.16	
— No. 4 . .	²⁹/₆06	c.90°	98.5°	18.4	30.0	″	″	″	2.6	—	—	—	5.55	5.12	2.31	
— No. 5 . .	²⁵/₆06	97°	98.3°	—	—	—	—	—	—	—	—	—	11.1	9.87	2.40	
Reykjahlíð No. 1..	³⁰/₆06	44°	″	″	0.02	″	″	21.1	78.9	—	—	—	0.000	—	—	
— No. 2..	²⁷/₆06	46°	″	—	—	—	—	—	—	—	—	—	0.039	—	—	
Reykir No. 1	¹⁴/₇06	62.0°	99.3°	″	″	″	″	″	100.0	98.49	1.48	0.0132	1.74	1.74	2.16	Sundlaug
— No. 2	¹³/₇06	66.5°	99.3°	″	″	″	″	″	100.0	98.36	1.60	0.0140	1.52	1.25	3.22	Hornahver
— No. 3	¹⁴/₇06	64.2°	99.3°	″	″	″	″	″	100.0	—	—	—	0.82	0.78	2.31	Bæjarlaug
— No. 4	¹⁷/₇06	65°	99.5°	″	″	″	″	″	100.0	—	—	—	2.31	2.15	2.37	Fosshver
— No. 5	¹⁶/₇06	17.3°	99.5°	″	″	″	″	·	100.0	98.34	1.61	0.0146	1.26	1.25	2.19	Skíðastaða-laug
Ölveravellir No. 2	²⁴/₇06	95°	97.6°	2.8	79.5	″	0.9	″	16.8	16.5	0.294	0.0050	4.05	4.28	2.04	
— No. 10	²³/₇06	77°	97.5°	″	44.9	″	1.4	7.0	46.7	—	—	—	5.73	6.25	1.90	
— No. 27	²³/₇06	82°	97.5°	″	40.0	″	1.5	7.0	51.5	—	—	—	12.3	13.1	1.94	Bláhver
— No. 16	²⁵/₇06	93.5°	97.8°	″	46.7	0.7	1.5	5.4	45.7	—	—	—	26.0	27.9	2.00	Fagrihver
— No. 25	²³/₇06	81°	97.5°	″	77.8	″	1.0	0.2	21.0	20.6	0.441	0.0063	18.6	20.0	1.90	
Kjalhraun No. 1..	²⁰/₇06	87°	″	—	—	—	—	—	—	—	—	—	0.021	—	—	
— No. 2 ..	²⁵/₇06	88°	″	″	0.1	″	″	20.7	79.2	—	—	—	0.005	—	—	
Kerlingarfjöll No. 1	²⁸/₇06	94°	96.6°	—	—	—	—	—	—	—	—	—	18.5	—	—	
— No. 2	²⁸/₇06	92°	96.5°	14.4	71.1	11.7	0.3	″	2.5	—	—	—	18.8	17.2	2.64	
— No. 3	³¹/₇06	94°	96.8°	7.4	66.9	21.7	0.9	″	3.1	—	—	—	35.0	42.3	1.80	
— No. 4	³¹/₇06	94.5°	96.7°	13.1	70.7	14.5	0.7	″	1.0	—	—	—	33.5	40.0	1.81	
Grafarbakki No. 1	⁵/₈06	96°	99.9°	″	6.4	″	0.8	1.1	91.7	90.0	1.68	0.0104	7.63	7.11	2.35	Klofi
— No. 2 {	⁴/₈06	97.5°	99.6°	0.1	3.7	″	0.6	″	95.6	93.4	2.15	0.0105	5.86	—	}2.09	
	⁷/₈06	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	6.00		
— No. 3	⁴/₈06	97.0°	99.6°	″	1.3	″	0.9	0.1	97.7	—	—	—	5.50	5.20	2.31	
Laugarás No. 1 . . .	⁸/₈06	96°	99.8°	″	″	″	0.7	″	99.3	97.4	1.93	0.0104	4.48	4.12	2.39	Þvottahver
— No. 2 . . .	⁸/₈06	98.5ᶜ	99.8°	″	″	″	0.7	″	99.3	—	—	—	5.12	5.03	2.21	Suðuhver
— No. 3 . . .	⁸/₈06	93.0°	99.8°	″	″	″	0.5	″	99.5	97.4	2.1	—	3.06	3.26	2.03	
Reykjafoss No. 1..	¹³/₈06	93.0°	99.9°	″	27.0	2.5	0.2	1.0	69.3	67.9	1.36	0.0103	7.65	7.17	2.32	
— No. 2 . . {	¹³/₈06	94°	99.9°	6.7	87.9	0.6	0.3	″	4.5	—	—	—	1.25	1.27	2.12	
	¹⁵/₈06	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	1.47	—	—	
— No. 3 . . {	¹⁴/₈06	96°	99.9°	5.7	85.6	1.4	0.3	″	7.0	—	—	—	2.51	—	—	
	¹⁴/₈06	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	2.88	—	—	
— No. 4 ..	¹⁵/₈06	99.4°	99.9°	12.0	84.5	″	0.2	″	3.3	—	—	—	3.15	3.40	1.90	
Hengill No. 1	¹⁸/₈06	94.5°	98.9°	11.0	73.4	13.5	0.3	″	1.8	1.8	0.0113	0.00059	2.60	2.70	2.05	
— No. 2	¹⁸/₈06	75.5°	98.9°	3.9	79.7	13.2	0.4	″	2.7	—	—	—	3.30	3.55	1.92	
— No. 3	¹⁸/₈06	91°	98.9°	11.2	67.0	17.2	0.6	″	4.0	3.9	0.088	0.0020	4.32	4.16	2.32	
— No. 4	¹⁷/₈06	97°	99.1°	7.4	72.0	16.4	0.9	″	3.3	—	—	—	5.37	5.54	2.09	

there is plenty of water, these particles are constantly washed away, the water consequently attaining a grayish colour. Most of the hot springs at Kerlingarfjöll, and some at Hengill, are of this description. On the other hand, where the small particles find an opportunity of accumulating around the springs, they mix with the spring water, forming a thin pulpy kind of mud. In this way the mud pools and mud volcanoes at Námafjall, (Hlíðarnámur), Hveragerði, etc. have been formed. It is an obvious conclusion that the small particles are produced by the action on the rocks of sulphuretted hydrogen, or of sulphuretted hydrogen and carbonic acid gas combined.

The case is quite different in springs where nitrogen is the chief constituent in the composition of the spring gas. The water is then as clear as ordinary spring water, and only slight sediments are to be found deposited around the springs.

In the warm soil in the immediate vicinity of the springs a vegetation flourishes which is quite luxuriant for the climate, not being checked by the poisonous sulphuretted hydrogen, as is the case in the neighbourhood of the solfataras. Where the temperature of the springs is not very high, as for instance at Reykir, the vegetation has advanced almost to the immediate edge of the spring, leaving only a small outlet for the hot spring water.

Practically the only thing which distinguishes these springs from ordinary well springs is the bluish-gray cloud produced by the condensation of the vapours arising from the hot spring water.

The hot springs at Laugarás are similar, but owing to their intense heat and the consequent violent ebullition of the water, the vegetation has retired to a greater distance from the springs.

With the exception of two geysers, the hot springs at Grafarbakki are of the same nature as those in the two places already mentioned. There is a particularly close resemblance between them and the hot springs at Laugarás.

Although there are, as already shown, only infinitesimal deposits of sediment at the three places mentioned, the spring water nevertheless contains a considerable quantity of dissolved salts.

For instance, we filled an enamelled saucepan with water from a hot spring at Laugarás, and placed it in the water at the edge of the same spring. In this manner the saucepan was kept hot, and after a few hours the water in it had evaporated, leaving behind a considerable amount of white salts, partly crystallized. All the hot springs investigated at Reykir, Laugarás and Grafarbakki were likewise proved by direct test to contain carbonates and chlorides, and most of them also traces of sulphates. At all these places the water was alkaline.

A peculiar feature of the Laugarás and the Grafarbakki "hvers," distinguishing them from the hot springs at Reykir, is that the spring gas contains traces of sulphuretted hydrogen. At Laugarás the sulphuretted hydrogen could only be detected on the spot by means of the most delicate tests, while one of the gas samples from Grafarbakki contained 0.1 $^o/o$ of sulphuretted hydrogen when it was analysed in Copenhagen. That no sulphuretted hydrogen was found in the other

gas samples from Grafarbakki is probably due to the fact that these samples contained a little oxygen. While the gas was in the collecting bottle the small amount of sulphuretted hydrogen became oxidized and consequently disappeared.

According to the analysis, the spring gases at Grafarbakki contain a small percentage of carbonic acid gas, and it is not inconceivable that the presence of this gas and the larger volume of sulphuretted hydrogen in the spring gas are to some extent attributable to similar causes.

Around the hot springs at Grafarbakki a slightly larger deposit is to be seen on the stones than at Laugarás or Reykir. At Reykir the deposit is infinitesimal

That there is a greater deposit at Grafarbakki is, I think, partly due to the carbon dioxide contained in the gas; I can see no other reason why the deposits should be larger here than at the other two places mentioned.

As far as the carbon dioxide contained in the gas and the silicious sediments around the springs are concerned, the "hvers" at Grafarbakki more resemble the third type of hot springs, i. e. hot springs with considerable silicious sediments, silicious sinters. Of the hot springs I investigated in the summer of 1906, the "hvers" at Hveravellir are the most important representatives of this class. The beautiful, cream-coloured silicious sinters here form two eminences of considerable height and of great extent.

The spring gases given off by these springs are characterized by a great amount of carbon dioxide, though they contain very little sulphuretted hydrogen. As before mentioned, the carbon dioxide contained in the spring gases probably tends to the production of silicious sediments. The gas sample Reykjafoss No. 1 is of a similar composition. This spring must therefore be considered amongst the springs of this third type, in spite of its very small deposits.

The spring gas from Hveravellir contains more oxygen than that from Reykjafoss No. 1, and perhaps this has some influence on the solution of the silicious compounds in the boiling spring water, although there are probably other more decisive factors.

In this connection it is worthy of mention that the alkaline springs at Reykjafoss seem to be very changeable. A good example of this is "Litli Geysir," which was previously a ver yactive geyser, but which has now been inactive for a long time.

A similar example is to be seen in the great basin from which I collected gas samples in the summer of 1904. It was then a very energetic hot spring, but the basin is now filled with clear, tranquil water, and no gas is evolved.

The changes in the hot springs at this place seem to have been closely connected with the earthquakes which have taken place, no doubt on account of this group of hot springs being situated just on the outskirts of the district most subject to earthquakes.[1] In such districts comparatively large displacements must take

[1] In connection with the influence of earthquakes on the hot springs of Iceland, see Þ. Thoroddsen's paper in Geogr. Tidsskr. 15, 109, 1899—1909.

place during an earthquake. One has therefore good ground for supposing that the changeability of the hot springs at Reykjafoss is to some extent responsible for the insignificance of the silicious sinters around the existing springs, as the deposit of these sediments is a very slow process. The spring water must work in the same place for a long period before leaving any visible signs of its activity.

In contrast to the spring water with absorbed sulphuretted hydrogen, which in Iceland breaks down all the rocks with which it comes into contact and causes them to crumble, the alkaline spring water with absorbed carbonic acid gas seems to smooth out its course and enclose it with a crust of silicious sinter. This process possibly begins a little below the surface of the earth. If that be so, we can still better understand why the alkaline springs at Reykjafoss have such small stratifications, for by reason of the frequent changes in the course of the water, the silicious compounds dissolved in the spring water are used up in enclosing the course of the water through the crust of the earth. On the other hand, there is in the neighbourhood of Reykjafoss a large number of silicious sinters dating farther back.

A very common feature of the springs belonging to the last-mentioned type, is that most of them are periodic springs, and many of them are geysers. The same is the case with the alkaline hot springs at Reykjafoss and at Hveravellir, and very probably the thermal springs at "Stóri Geysir" are of the same kind.

There are only scattered and rather imperfect observations in existence concerning the periods of these springs, so that at present one cannot affirm more than that it is possible for springs belonging to the same group to have different periods. Many examples of this can be seen at Hveravellir. For instance Þorvaldur Thoroddsen[1] states that Nos. 15 and 16 have longer periods than the surrounding springs. According to our less studied observations, No. 12 has a period of many hours, while most of the other springs have periods of not more than a few minutes. I had no opportunity of making a closer investigation on this point. Most probably, however, the case is the same here as at the two geysers at Grafarbakki. In mentioning these geysers, Þ. Thoroddsen[2] remarks that they spout alternately, and that each eruption lasts for a minute. I made observations of the eruptions of these geysers on the 5th. August 1906. The barometer stood at 757.4 mm. and the temperature of the air was 13° Centigrade.

These observations (see Table II) show a very regular period on the part of the southern geyser. The pauses between the eruptions are very nearly equal, 60·8 seconds on the average. The measurements of the eruptions, on the other hand, seem to indicate that they have a double period lasting about 44 and 53 seconds alternately. But the measurements are too few to permit of a decision as to whether this is due to a fortuitous circumstance or not.

The figures for the northern spring do not show the same regularity, but as

[1] loc. cit.
[2] Geogr. Tidsskr. 10, 18, 1889—90.

Table II.

The Southern Geyser.

Eruption commenced	Eruption ended	Length of eruption	Pause	Period
	6 h. 37' 48" p. m.			
6 h. 38' 50" p. m.	39' 39"	49"	62"	111"
40' 42"	41' 24"	42"	63"	105"
42' 24"	43' 15"	51"	60"	111"
44' 15"	45' 00"	45"	60"	105"
45' 55"	46' 55"	60"	55"	115"
48' 00"	48' 45"	45"	65"	110"

Mean: — 109.5"

The Northern Geyser.

6 h. 39' 00" p. m.	40' 35"	95"	35"	130"
41' 10"	42' 45"	95"	70"	165"
43' 55',	45' 38"	103"	42"	145"
46' 20"	47' 48"	88"	62"	150"
48' 50"				

Mean: — 147.5"

I made the two observations simultaneously, while standing near the southern spring, I consequently paid more attention to it than to the northern spring. The irregularities observed in the periods of the latter may therefore very easily be due to inaccuracy in the observations. The possibility of inaccuracy is enhanced by the fact that the beginning and ending of the eruptions of this spring are observed with difficulty, as the eruption rises very gradually to its full height, and falls like-wise very slowly. It was therefore difficult at a distance to decide when the eruption should be considered as begun or ended. The following observations, made on the 7th. August 1906, seem to strengthen the conclusion that the irregularity is due to inaccurate observation. Barometer 754.3 mm. Temperature of the air, 16° C.

Table III.

The Northern Geyser.

Eruption commenced	Eruption ended	Length of eruption	Pause	Period
	11 h. 29' 27" a. m.		68"	
11 h. 30' 35"	33' 05"	150"	70"	220"
34' 15"	36' 48"	153"	72"	225"
38' 00"				

These measurements show that it is possible for this spring also to have eruptions with very regular periods.

From the measurements made on the 5th. August, it appears that the southern geyser has four eruptions while the northern geyser has three, for $3 \times 147.5'' = 442.5''$ and $4 \times 109.5'' = 438''$. But this is probably quite fortuitous.

Þ. Thoroddsen[1] is of the opinion that these geysers had, in 1888, periods of equal length, but my observations show that this is no longer the case.

From what is known of the nature of the geysers, it is to be expected that the weather has considerable influence on the periods of the springs. This is confirmed by people who live in the neighbourhood of the springs. They have noticed that the eruptions of "Stóri Geysir" especially are greatly dependent on the weather. In this connection I can also refer to the observations made by Gilbert Mair[2], showing that the weather has great influence on the thermal springs of New Zealand. The observations given above are an additional corroboration of changeability in the periods of the geysers, for on the 5th. August the period of the northern geyser was 147 seconds on the average, but on the 7th. it was about 222 seconds. This difference is remarkably great, especially when it is taken into account that only 41 hours elapsed between the two observations. Several hot springs in Yellowstone National Park[3] are found to have more than one distinct range of periods. Nevertheless it seems to me hardly probable that the differences I observed are due to such a cause, amongst other reasons because the transmission from one range of periods to another is usually attended by a change in the energy of the eruption, whereas, as far as I could discern, the eruptions were equally powerful at the time of both observations.

There have been several theories advanced at different times to explain the activity of the geysers. A good idea of these so-called geyser theories can be formed from Peale's treatise on "The Thermal Springs of Yellowstone National Park".[4] A. Andreae[5] also mentions several geyser theories in his treatise on geyser models.

The best known geyser theory is that of R. Bunsen[6]. As this theory, in spite of several serious objections to it, — that of H. O. Lang[7], for instance, — seems still to be the geyser theory most generally recognised, it will be made the basis of the following remarks concerning the phenomena. All the later geyser theories are to some extent based on Bunsen's theory and the materials acquired by his observations.

According to Bunsen[8], we must discern between hot springs with narrow

[1] loc. cit.

[2] New Zealand Trans. Inst. 9, pp. 22—29, 1876.

[3] Twelfth Annual Report of the U. S. Geological and Geographical Survey of the Territories. Washington, 1883. Vol. II.

[4] Twelfth Annual Report of the U. S. Geological and Geographical Survey of the Territories. Washington, 1883; p. 417.

[5] Neues Jahrbuch der Mineralogi. 1893. Vol. II, p. 1.

[6] Liebigs Ann. 62, 1. 1847.

[7] Nachrichten v. d. Königl. Gesellsch. d. Wissenschaften zu Göttingen, 1880; p. 225.

[8] loc. cit. p. 56.

channels and great heat energy supplied by hot water and steam, and hot springs with wider channels and less heat energy. The former are constantly boiling because the hot water cannot settle in the narrow channels on account of the hot vapours and water which pass through them with great force. The latter are periodic geysers. The wide and, (as at "Stóri Geysir"), perpendicular channels are filled with water which is almost stagnant. The temperature of the water at the surface is kept a little below boiling point, but the temperature increases in proportion to the depth of the water. The temperature is, however, always a little below the boiling point of water at the same pressure.

Immediately after an eruption, this difference is rather great, but it gradually lessens, until, just before the next eruption, according to measurements of the temperature made in the geyser channel itself, the difference is so small that a slight rising of the water column is sufficient to cause the water to boil.

The rising of the water is, according to BUNSEN, explained by the fact that many great basins with hot water, at "Stóri Geysir" as well as at Reykjafoss, do not give off air bubbles steadily, but periodically. Taking for granted that the same thing happens at the bottom of the geyser channel, it will then cause a periodic rising of the water, and thereby possibly an eruption.

As before stated, there are many objections to this theory. LANG[1], for instance, regards the Bunsen theory as unsatisfactory, and as conflicting with other geological theories, because it does not take into account the circulation of the water in the geyser channel caused by the hotter water lower down in the channel having less density than the colder water higher up. Neither does the Bunsen theory, in his opinion, explain the intensity and periodicity of the eruptions. In this last point I agree with LANG, though I have arrived at this conclusion on considerations somewhat different to his.

In accordance with BUNSEN's curves of the temperature in the geyser channel, a rising of the water column immediately before an eruption would only result in the temperature of the water in a small part of the channel becoming higher than the boiling point at the same pressure. Then, of course, the water in this part of the channel boils. But in ordinary circumstances this would by no means cause an eruption. If the Bunsen theory be correct there must be some particular causes at work in the geyser channel, but evidence on this point is entirely wanting.

Again, it is questionable whether Bunsen's method of dealing with the temperature measurements in the geyser channel, made by him and DESCLOIZEAUX, is absolutely correct. Of the five series of measurements they have made[2], BUNSEN only uses the 2nd., 3rd. and 4th., without giving any reason for omitting the first and the last series of observations. But these very observations omitted are of primary importance, in that they are the first measurements made after eruptions. Indeed, it seems as if the observers themselves do not have very much confidence

[1] loc. cit.
[2] Compt. Rend. 23, 934. 1847.

in these measurements, for the results of 3 out of the 7 measurements are given with a note of interrogation. But the 4 remaining measurements may safely be considered as reliable as those of the other 3 series.

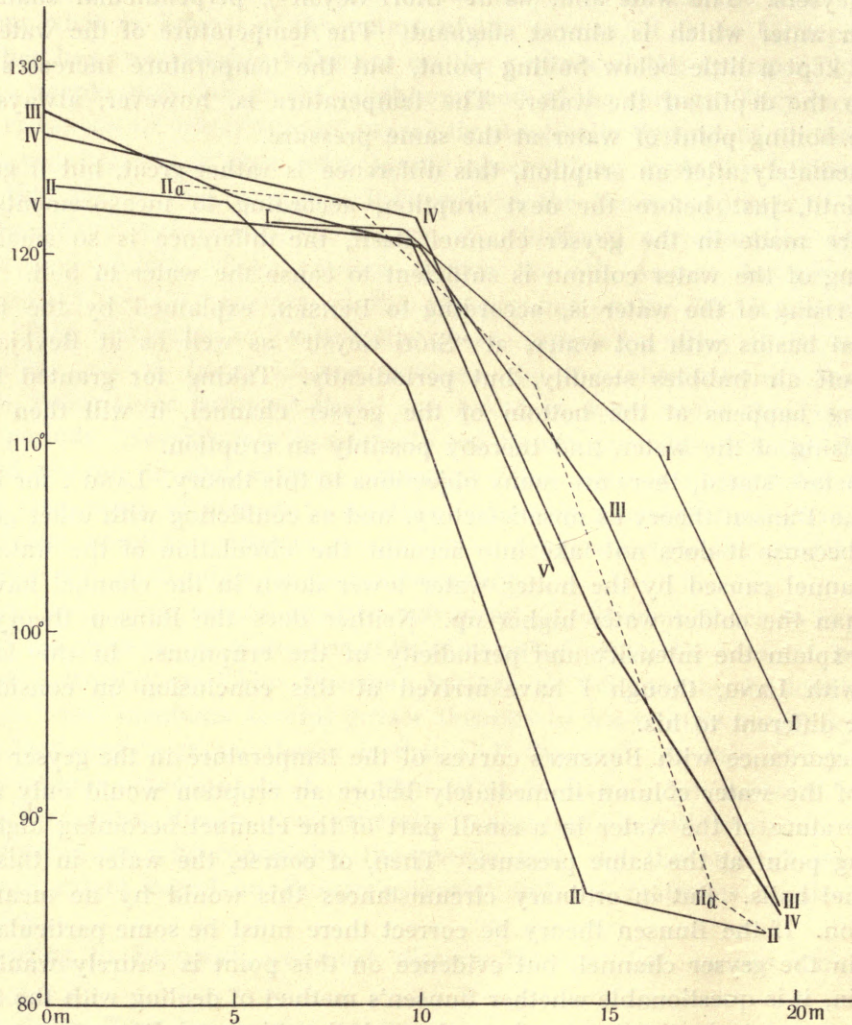I have made a graphic diagram of all the measurements, (Fig. 13), and con-

Fig. 13.

nected by means of straight lines the temperatures belonging to each series of observations. The roman figures denote the order in which the experiments succeeded each other. "I" shows the temperature immediately after a large eruption. IV shows the temperature a little before the subsequent eruption, and V the temperature after it.

From this diagram it is evident that the temperature measurements of the two experiments omitted by BUNSEN are in fair agreement with the other measurements. Two measurements in the first experiment, however, seem to be a good deal too high, but both these measurements are given with a mark of interrogation, and may therefore be regarded as uncertain. A glance at the diagram also shows that the measurements of the second experiment, (line 4 in BUNSEN's paper), does not agree with the other measurements. This would lead one to suppose that an inaccuracy has crept into this experiment. This suspicion is strengthened by the fact that if these measurements are correct, the temperature of the water must have risen about 2° C. from 19.2 m. to 14.4 m., and 17° C. from 14.4 m. to 9.6 m., which seems in the highest degree improbable. Such abnormities are not to be found in the other experiments. This disagreement is readily explained by supposing that the thermometer measuring the temperature at 14.4 m. remained higher up the channel, at about 17.8 m., and as all the thermometers were hanging on the same string, the result would be that the thermometers which were farther down the channel measured the temperature 3.4 m. higher up than was assumed by BUNSEN and DESCLOIZEAUX. The dotted line, constructed on the basis of this supposition, now shows a fair consistence to the other lines. But the lines in this instance have a vastly different significance to that which BUNSEN assigned to them. In the first place, we observe that the lines form a well-marked angle at about 9 m. In this respect they resemble the temperature curves of Strokkur[1]. The significance of this is evident enough. The heat supply is brought into the geyser channel in the neighbourhood of the spot corresponding to the angle in the temperature curve, i. e. about 9 m. from the bottom. Thus the temperature measurements are brought into harmony with direct observations by BRYSON[2]. He has found that at a depth of 45 feet from the surface, there is a projecting rim in the geyser channel, and that very hot water and steam flow into the channel immediately beneath this rim. As it is known that Strokkur also has side channels, the manner in which the temperature in the channel of this spring varies with the depth must naturally be explained in the same way. BUNSEN's supposition that the lower part of Strokkur's channel must be full of steam, is therefore incorrect. It must be filled, as in the case of "Stóri Geysir", with stagnant or almost stagnant hot water.

BUNSEN reports several peculiarities in the eruptions of "Stóri Geysir", which in his opinion indicate the existence of fissures in the sides of the geyser channel supplying the channel with hot water and steam during the eruptions. But he considers this to be of secondary importance. But it is, however, of great importance in considering BUNSEN's objections against MACKENZIE's theory. BUNSEN proved, by actual experiment, that a thermograph could lie unmoved and unharmed at the bottom of the channel during an eruption of "Stóri Geysir". This, he contended,

[1] Liebigs Ann. **62**, 39, 1847.
[2] Frost and Fire. Vol. II, p. 417.

would not be possible if hot water and steam, according to MACKENZIE's theory, rushed into the channel with great violence. This objection cannot now be maintained, as we know that the inlet to the geyser channel is situated 9– 10 m. from the bottom.

My explanation of the measurements of BUNSEN and DESCLOIZEAUX also shows that BUNSEN's theory that the temperature at a given spot in the channel continually increases from one eruption to another, can no longer be held in its entirety. For if we replace line II by the dotted line, then lines I to IV show that the temperature at a given point in the geyser channel does not rise appreciably from the cessation of one eruption to the commencement of the next.

The chief cause of the eruption is, therefore, to be sought outside the geyser channel. Of course the energy accumulated in the channel will increase the power of the eruption, but the calculations made by BUNSEN to show that the water in the channel is possessed of sufficient energy to sustain the eruption, do not, however, appear to me to be conclusive.

It is very difficult to form even an approximate estimate of the amount of energy required for an eruption, and besides this, the calculations do not provide for the diminution of the available energy, produced by the intermixture of hotter and colder water.

PEALE[1], who inclines perhaps most to BUNSEN's theory, supposes, however, that subterranean channels and cavities are of considerable significance in regard to the geyser phenomena.

BUNSEN himself inclines to the opinion that in the case of Strokkur, — which, as already pointed out, resembles "Stóri Geysir" in many particulars, — the motive power of the eruption is outside the channel. He has come to this conclusion through the following observations. One can cause Strokkur to spout by stopping up its channel with sods. This makes the jet of water at first discoloured, on account of the dirt the water in the channel has received from the stoppage. But after a short time the water becomes clear as a fresh supply of water flows into the channel from other channels deeper down.

In other respects BUNSEN has been quite clear on the point that the typical geyser channel is not the sole cause of the periodic eruptions. For instance, he remarks in describing "Litli Geysir", that the eruptions of this spring are not due to the same causes as those of "Stóri Geysir". He seems to incline to the opinion that the eruptions of "Litli Geysir" are most satisfactorily explained by MACKENZIE's theory.

MACKENZIE's theory is illustrated by Fig. 14. The cavity A is supplied with water (of atmospheric origin) through fissures in the walls of the cavity. The water in A receives heat partly conducted from the volcanic surroundings, and partly by a supply of highly heated steam. At last the temperature in A becomes so high

[1] Twelfth Annual Report of the U. S. Geological and Geographical Survey of the Territories. Washington, 1883, p. 421.

that the pressure of the steam can withstand the pressure of the water column in the channel. A sudden increase of the heat supply will then give rise to an eruption.

The principal fault of MACKENZIE's theory is that it does not explain the intermittence and periodicity of the geysers, which are the most characteristic features of the geyser phenomena.

Amendments of this theory, proposed by later scientists, have not, as far as I know, overcome these difficulties in a satisfactory manner.

In order to see in what way the existing theories need to be amended in order to agree with the existing facts, it will be very instructive to make a closer examination of an eruption of one of the small geysers in its different phases. I select as an example the southern geyser at Grafarbakki.
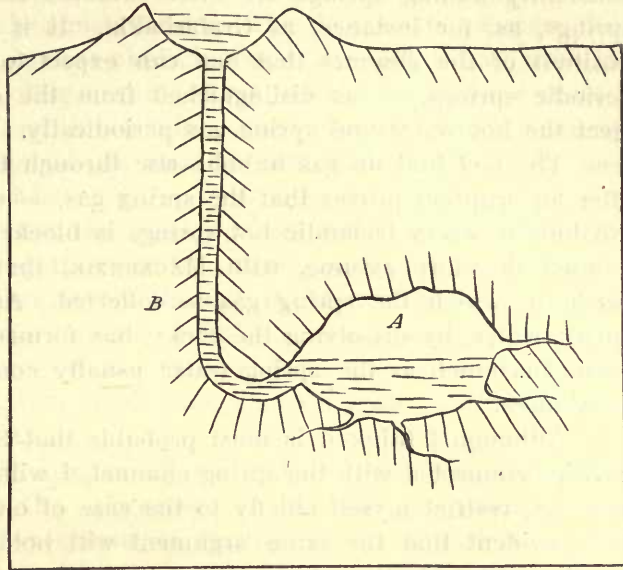

Fig. 14.

Immediately after an eruption the small shallow basin is quite empty. The dampness of the stones at the bottom of the basin is the only visible sign that boiling water has recently filled the basin. But the water soon begins to show itself between the stones at the bottom of the basin, and it rises steadily and rapidly. At last it fills the whole basin and begins to overflow the brim. Shortly after, the spring enters upon its next phase, when air bubbles commence rising through the water from the bottom of the basin. The water is not boiling, for real ebullition very seldom takes place in the Icelandic springs. The water is agitated by bubbles of spring gas, which, saturated with vapour, force their way up through the water. At first these bubbles are neither large nor numerous, but they increase rapidly until at last they rise with such violence that the water is thrown up a little into the air. The eruption has commenced.

At the height of the eruption the water column is fairly constant, but it sometimes happens towards the end, when the energy of the eruption is declining, that two or three water jets suddenly rise far above the others. It looks as if the motive energy pulls itself together for a last effort. At the close of the eruption the water in the basin sinks down again into the earth, preparatory to the next eruption.

The main points of the mechanism of the periodic eruptions seem to be included in the foregoing. I assume the supply of hot water, steam and spring gas from the interior of the earth to the lowest part of the spring channel, to be con-

stant in all the hot springs, whether they be periodic or in a constant state of ebullition. For I am not aware of any reason why this supply should be periodic, and this assumption is rendered more plausible by the fact that both periodic and constantly boiling springs are often situated side by side in the same group of springs, as, for instance, at Grafarbakki. It is therefore only in the shape and position of the channel that one can expect to find the factors which cause the periodic springs, — as distinguished from the constantly ebullient springs, — to eject the hot water and spring gas periodically.

The fact that no gas bubbles rise through the water in the basin immediately after an eruption proves that the spring gas, — which appears to be an inseparable attribute of every Icelandic hot spring, is blocked up down in the spring channel. I must therefore assume, with MACKENZIE, that there are cavities down in the earth, in which the spring gas is collected. And it is highly probable that the spring water, by dissolving the rocks, has formed many such cavities down in the earth, inasmuch as the spring water usually contains great quantities of dissolved substances.

Although I think it is most probable that the majority of geysers have several cavities connected with the spring channel, I will, in order to simplify the following remarks, restrict myself chiefly to the case of only one cavity, as shown in Fig. 14. It is evident that the same argument will hold good when the spring has many cavities, although the whole subject then becomes more complicated. The water in the bend of the channel B cuts off from the atmosphere the spring gas accumulating in A. But as fresh spring gas is constantly coming from below, the gas accumulated in A is constantly expanding. Again, the loss of heat in the spring being comparatively small while the channel is stopped up, and the supply of heat to A being constant, the temperature in it must consequently increase. This causes an increase in the volume of the gas in A, on account of the expansion of the gas itself, and the augmentation of the steam pressure through the increasing temperature. This increase in the gas volume in A is at first counteracted by the increasing pressure produced by the rising of the water in the channel B. At last the volume of the gas in A increases so much that bubbles of spring gas, saturated with vapour, begin to force their way through the channel B. The volume of the first bubbles is, however, very much diminished on the way up, on account of the condensation of a great deal of the vapour through contact with the colder water in the channel. A considerable difference is possible in the temperature of the water in different parts of the channel, especially when the channel is so narrow that the water cannot circulate freely enough to distribute evenly the loss of heat in the spring water which takes place in the upper part of the channel, through the lower temperature of the surroundings. The condensation of the vapours from the gas bubbles increases the temperature of the water, so that subsequent bubbles are not so much diminished.

In ordinary circumstances a state of equilibrium will eventually ensue, in

which the bubbles will force their way up through the water in the channel of the spring without producing any disturbance in the pressure in the channel. This is the case with the continually ebullient springs. But if the channel is at any point so narrow that the gas bubbles can fill it entirely, then the water column resting on the gas volumes below becomes shorter. The decrease of pressure thus produced will give rise to a more intense ebullition and emission of gas from the cavities and adjacent side channels. The current of gas bubbles through the channel becomes therefore more intense, and increasingly displaces the water from the channel. Consequently the emission of gas and the ebullition increase still more, as the pressure of the water diminishes.

At last the water columns barring the passage of the gas bubbles through the channel become so few and so small, that the steam pressure from below can easily overcome them. They are then forced through the channel with great speed, and thrown to a considerable height when expelled. The eruption of the spring is then in full activity. The length of the interval from the moment when the first bubbles appear, until the eruption takes place, is to a great extent dependent on the shape of the spring channel.

In springs with a simple form of channel, the eruption may commence suddenly, almost simultaneously with the appearance of the first gas bubbles. This is most readily explained by the experiment of forcing air up a narrow perpendicular glass tube filled with water. The air pushes the water column before it up the tube, and expels the water almost all at once. On the other hand, where the spring channel is irregular, being in some parts very wide and in others very narrow, some time may elapse before the water is thrown so high above the basin that a real eruption may be said to have begun.

The length and character of the eruptions also depend very much on the shape of the channel, but in this respect the conditions under which evaporation and ebullition take place down in the cavities is also of great importance. In the interval between the eruptions, during which the spring is at rest, a large supply of energy, in the form of highly heated water, is accumulated down in the cavities. The duration of the eruptions seems to indicate that this reserve energy of the spring has some resistance to overcome before it can properly develop itself. Of course, some of the hot water is accumulated in recesses and side channels leading to the principal cavities, and can only take effect gradually during the eruption, because very probably it has first to pass through narrow channels into the principal cavities.

During the eruption itself it is possible that the passage of the spring exhalations through the principal spring channel may frequently be hindered by small water columns, formed in the bends or narrow passages of the channel by the water which the vapour carries from below, or which is conveyed to the principal channel from the side channels.

While the eruption is at its height these stoppages only last a very short

time, because the pressure of the steam from below drives them along as soon as they are formed, but they are, however, of sufficient duration to account for the intermittent character of the eruptions.

When the eruption is on the decline and the evolution of steam decreases, the water barricades can remain in the channel a little longer. The spring must have time to gain strength to expel them, but when at last it is able to master them, it will eject them from the channel with great velocity. This will doubtless account for the extraordinarily high water jets which we noticed so often at the end of the eruptions of the two geysers at Grafarbakki.

During the eruption the great water pressure usually prevailing in the spring cavities becomes almost nil. The accumulated energy of the spring is therefore liberated. But when this is exhausted, and the steam evolution is only sustained by the heat energy continually supplied from beneath, the steam current through the channel is so much weakened that it is not able to keep the passage through the channel free.

The barriers of water formed as described, in bends and narrow passages of the principal spring channel, can then remain stationary, as long as there is a perceptible stoppage of the steam current through the channel. But as soon as the steam current is stopped, the water will also fill other parts of the channel, from which water has previously been excluded by the steam. The increase of the water pressure then becomes greater than the increase of the steam pressure from below. As a result the water column recedes downwards through the channel, enters the cavities of the spring, and fills up the whole of the space formerly occupied by the steam. The steam is unable to resist, on account of the pressure of water being so great and the tension of the vapour becoming less through the decrease in temperature caused by the entrance of colder water from above into the cavities. The eruption is now ended, which event is marked by the water from the basin rushing down into the channel.

We have noticed that the spring gas, saturated with steam, which is continually supplied to the spring from below, cannot force its way in the form of bubbles through the water in the spring channel, without producing a decrease in the pressure of the water, and thus causing an eruption. In exactly the same way, the eruption is brought to a close through the steam current kept up by the constant supply of energy to the spring becoming insufficient to keep the spring free of water stoppages, which block the passage of the steam current through the channel.

This is, in my opinion, the principal cause of the periodic eruptions of the thermal springs. Of course, very hot water, by suddenly boiling, may also cause an eruption, as many of the geyser models show, but it occurs very seldom in nature. On the whole, it is hardly probably that the spring water can be superheated to any extent, because it is, in almost every case, impregnated with spring gas. In those cases where hot springs are found with a temperature a little higher than

the boiling point at that elevation, it is more probably due to the substances dissolved in the spring water and too strong a heat supply from heated steam, than to the tendency of the spring water to become superheated.

That the channels be crooked, can no longer be regarded as a necessary condition of the intermittance or periodicity of the springs, for the latter, as already mentioned, could easily be in a constant state of ebullition, even though their channels are crooked. On the other hand the irregularity of the channels may in several different ways influence the progress and character of the eruptions of the periodic springs; they tend especially to shorten the eruption, as the water is collected in the bends, and forms stoppages to the steam current through the channel.

It is evident that special circumstances in the individual springs may greatly influence the character and period of the eruptions. In most of the springs there is a cup-shaped hollow at the place where the spring channel reaches the surface. Owing to the rapid loss of heat at the surface, the spring water gathering in this hollow is kept considerably cooler than the water deeper down in the channel. The rapidity of the loss of heat at the surface is evidenced by the temperature measurements made by BUNSEN and DESCLOIZEAUX at "Stóri Geysir" and Strokkur. This is also borne out by our measurements of the temperature of the water at the surface and at the bottom of Básahver and Vaðmálahver at Grafarbakki.

During the eruption, the steam current from the orifices in the bottom of the basin is generally so strong that the channel below is kept free from the cold surface water in the basin, but if the steam current is stopped for a moment, or weakened to any extent, the surface water runs down into the channel.

In many cases this will result in the entire cessation of the eruption, because the pressure produced by the water is increased, at the same time as the tension of the vapour is decreased on account of the temperature in the channel being lowered by the cold water.

At Grafarbakki and, generally speaking, in most of the spring groups that contain periodic geysers, there are constantly boiling springs and periodic geysers side by side. Hence it is evident that two entirely independent channels are often found side by side in the earth. It is therefore quite possible that two or more really independent channels may be united to one channel beneath the surface of the earth. Only one of these channels being capable of causing periodic eruptions, suffices to render the spring itself periodic.

In the case of several geysers, the eruption takes place in all the channels at once, for as soon as the eruption in one of the channels has relieved the pressure due to the water column in the common channel, the decrease of the pressure will give rise to an eruption in the other channels. With other geysers the decrease of the pressure is not sufficient to cause an eruption in the remaining channels, and as an interesting medium between these two extremities, we have geysers where the eruption in the remaining channels only takes place when the eruption

in the first channel is extraordinarily intense, while they remain passive when the eruption is less intense. This is undoubtedly the case with many geysers which have two kinds of eruptions. They must be provided with two or more channels beneath the surface of the earth.

Another reason for two different kinds of eruptions taking place in the same geyser will be mentioned later, in the dissertation on the eruptions of "Stóri Geysir."

Where violent eruptions take place the spring gas and the vapour in the channels are subjected to great pressure previous to the eruption. The walls of the channels must therefore be very strong, in order to sustain this great pressure. Where the soil is loose and disintegrated, the spring gas makes new passages as soon as the old ones are stopped up. In these localities therefore no great eruption can take place. This is evidently the principal reason for the scarcity of geysers where the spring gas contains large quantities of sulphuretted hydrogen. For the soil surrounding the sulphurous springs is always disintegrated.

In some geysers, Grýla for instance, the real eruption is succeeded by a steam jet period. This is most readily explained by assuming that the form of the spring channel is comparatively regular, so that the steam can easily drive the whole of the water out of the channel. Besides this, the supply of hot water which produces the steam cannot enter into the channel during the eruption. When the spring has spent its accumulated energy, and the steam power is consequently on the decrease, the vapours in the channel become condensed and stop the flow of steam out of the geyser.

Finally, I will mention somewhat more exhaustively a particular type of periodic spring, namely, the great hot water basins, which evolve gas periodically. The periodicity of these springs is not easily apparent on the surface. The steam and gas bubbles which are periodically ejected from the small holes at the bottom of the basin, diminish very rapidly as soon as they come into contact with the water in the basin, which is kept cooler on account of the evaporation from its large exposed surface.

These eruptions may therefore appropriately be termed subterranean eruptions, inasmuch as their energy is exhausted before they reach the surface.

The periodicity of these springs is easily explained in the same way as in the previous instance. The steam flow is not strong enough to keep the water in the basin out of the channels, and by the time the water has entered the channels and hindered or completely stopped the outflow of spring gas, the spring has accumulated sufficient energy to expel it again.

This class of hot spring claims more attention, inasmuch as "Stóri Geysir" must be considered as belonging to it. For besides its characteristic large eruptions, "Stóri Geysir" has also small eruptions with regular periods. These small, or as BUNSEN has called them, unsuccessful eruptions, are, like the larger eruptions, accompanied by subterranean detonations. Water and spring gases flow with such

velocity through the geyser channel, that it causes the water to rise in the shape of a cone on the surface. These small eruptions are called "flóðs" in Icelandic, owing to the increase in the amount of water flowing away. These "flóðs" are subterranean eruptions, only much more powerful than similar eruptions in the large hot water basins. The geyser channel, with its large funnel-shaped basin, plays a similar part to the water basins in choking the eruptions. The circulation of the water in the geyser channel is generally able to keep the temperature sufficiently low, so that the bubbles of steam condense on coming from the side channels. Occasionally, however, either on account of the subterranean eruptions being more powerful, or because the loss of heat is less than usual, the steam bubbles are able to fill up the whole width of the channel and raise the entire water column, thus occasioning a large eruption.

The pressure of the water column in the geyser channel is for the most part suspended during the larger eruptions. The energy accumulated in the side channels has then more freedom to spend its strength than in the smaller eruptions ("flóðs"), where the subterranean forces have to work under the pressure of the water in the channel.

One can now understand that the period of inaction after a large eruption is about twice as long as after a small one.[1] For, after a long eruption, a far greater supply of energy and spring gas must be conveyed to the side channels and their cavities in order to enable them to produce a new eruption, than after a small one.

At Öskurhóll we noticed that the steam emissions varied in strength. We could not make a closer investigation of the periodicity of the steam emissions, but there is little doubt that Öskurhóll must be reckoned amongst the periodic springs. Small subterranean eruptions, either in the principal channel or, more probably, in one of the side channels, would be sufficient to account for the periodicity of the steam emissions. But it is nevertheless not impossible that Öskurhóll is in communication with one of the adjacent geysers, so that the variations in the steam emissions might be due to influences from another spring.

Many attempts have been made to construct models to show in miniature the mechanism of the geyser phenomena.[2] It seems to me, however, hardly probable that we can with these apparatuses make even an approach to the actual conditions. In my opinion, the only thing which the geyser models have proved with sufficient clearness, is that the relation of the width of the channel to the steam evolution on the one hand, and the loss of heat in the channel on the other, is one of the chief causes of the intermittence or periodicity. But as to the part the spring gases play in the eruption, very little information is to be gathered from the geyser models. However, as stated, the relation between the spring gases and the width of the channel is evidently the chief cause of the periodicity.

[1] DESCLOIZEAUX: Ann. d. Chem. 3rd. Series, 19, 456, 1847.
[2] Full details of previous papers on Geyser Models are to be found in a paper by J. A. ANDREAE in "Neues Jahrbuch der Mineralogi", 1893, Vol. II, p. 1. Many models are described in this paper.

On the basis of the preceding remarks we can sum up the conditions of the periodic eruptions as follows.

A mixture of hot water and spring gases saturated with vapour is conveyed through the spring channel, which we must assume to be situated in solid strata, and to be well defined, at least in the upper part, i. e. near the surface of the earth.

If the gas bubbles, while a state of equilibrium rules, do not cause the water pressure to decrease on their way up the channel, we have then a continually ebullient spring.

If, on the other hand, the gas bubbles, while the spring is in a state of equilibrium, would produce a decrease in the pressure, especially by filling out parts of the channel, the spring is periodic.

In the latter instance, the surface tension, and adhesion, will be of considerable consequence, especially in regard to the size of the gas bubbles.

The constantly boiling springs are therefore hot springs with a fixed equilibrium, while the periodic springs have no fixed equilibrium. I understand that a spring has attained its state of equilibrium, when the flow of water, steam and spring gases, passing through the channels of the spring, becomes constant, and the temperature in all parts of the channels has also become constant.

We have assumed that water is conveyed through the spring channels, for that is a necessary condition of the periodic springs. Where no water is to be found in the spring channel, an eruption can hardly take place. But it is sufficient if there is water in the upper part of the spring channel. In this connection it matters little if there is only steam farther down the channel, for the cause of the eruption is only to be sought in the parts of the channel where there is water.

In the theory of the periodicity of the hot springs, it is immaterial whether we assume that the heat energy is supplied by steam or by highly heated water which, on account of the great pressure to which it is subjected, cannot boil and evaporate. But, in my opinion, the heat energy is most probably supplied by highly heated steam and spring gas. Direct proofs of this are not forthcoming, but there are many things that seem to indicate that it is correct: amongst others, that I have never been able to detect any radium worth mentioning in the sediments or mud of the springs; and since radium emanation is always found in the exhalations of the springs, either the spring water or the steam must have been in contact with radium. If it were the spring water, it would dissolve a little radium, and carry it in this manner up to the earth's surface, where it ought to be found in the deposits of the springs, as is the case with many springs in Italy and France.

But this is not the case with any of the hot springs I have investigated in Iceland. This is most probably on account of the spring water having, somewhere down under the earth's surface, passed into a state of vapour, and thus being hindered from conveying any radium. On the other hand the vapour must con-

dense again at a considerable depth, for otherwise the spring water would hardly be able to convey such large quantities of dissolved substances as it actually does.

The surface temperature of the spring water is dependent on several different factors. Some of these are of a more individual character, in that they are controlled by the form and nature of the spring. The loss of heat to the surroundings, — whether it is produced by heat conduction from the spring channel or by evaporation from the surface of the water, can be considered among these. The differences in the temperature of springs situated in the same group are chiefly due to these circumstances. There are two other factors likely to be of importance with regard to the temperature of the spring water, which may be supposed to be almost identical in springs belonging to the same group. These factors are the heat supply from below and the loss of heat caused by boiling.

At Reykir in Skagafjörður the first of these is the most important factor. The intensity of the heat supply is evidently much less there than at the other places explored. As the highest temperature measured at Reykir was only 68° C., the water in the depth of the earth cannot possibly have as high a temperature as at the other places.

At the other places investigated, the temperature down in the earth is undoubtedly considerably higher than 100° C. We know that the temperature in the depth of the earth must be over 100° C., otherwise the steam in these springs would not possess sufficient power to consummate an eruption. The highest temperature measured by BUNSEN and DESCLOIZEAUX at the bottom of a geyser channel was 127° C.

When the temperature of the spring water is nearly at boiling point, which is the case at most of the places we explored, the surface temperature is very little influenced by variations in the supply of heat energy. In such cases, the circumstances of cooling, and, foremost among these, the ebullition, are of the greatest importance with regard to the temperature of the spring.

The ebullition of the springs is dependent on the standing of the barometer, on the amount of substances dissolved in the spring water and on the volume of the spring gases. The dissolved substances raise the boiling point of the water. It cannot yet be decided how much this amounts to in the case of spring water, as no measurements to this end are available, but probably it only amounts to a small fraction of a degree. Setting this aside, we calculate, in the fourth column of Table I, the boiling point of distilled water, corresponding to the respective height of the barometer. It appears from this table that the boiling point thus calculated is higher throughout than the temperature of the spring.

The bubbles rising up through the water are not filled only with vapour, as by ordinary boiling, but with a mixture of vapour and spring gas, and it is the combined pressure of the vapour and the spring gases that withstands the atmospheric pressure. Assuming that the bubbles are saturated with vapour having the same temperature as the spring, the relation between the spring gases and the

vapour can easily be calculated, provided that the height of the barometer and the temperature of the water are known. Hence it follows that, in the case of two springs with the same temperature and at the same pressure of the atmosphere, the spring that evolves the greater volume of gas in proportion to the volume of water, will lose the greater amount of heat by ebullition. For in this case the evaporation is proportional to the volume of the spring gases.

As a rule, the spring gas augments the evaporation of the spring water, and thus contributes to keep its temperature below boiling point. The loss of heat consequent on boiling is therefore greater in springs evolving much gas than in springs with slight gas evolution.

A glance at the temperature of the hot springs investigated, shows that springs in the same locality have practically the same temperature. In most cases where considerable divergencies from this rule occur, a direct observation of the springs on the spot will show that these divergencies are due to some special peculiarities in regard to the process of cooling.

Springs in the same locality not only resemble each other as regards their temperature, but in the composition of their spring gases, as Table I shows. The same may be said in regard to the amount of emanation contained in the gas.

All this seems to indicate that springs in the same locality have a common source, or at least originate under similar conditions. The well-known fact, that the hot springs are always found in fissures in the earth's crust confirms this. At Reykir, (Plate II b), at Grafarbakki, (Plate VII b), and at Reykjafoss, (Plate IX a), it is noticeable that the principal springs are situated almost in a straight line, showing the direction of the fissures. Where the surface of the earth is much disintegrated, as it is around the solfataras, it is not so noticeable that the hot springs are confined to fissures. Every visible sign of the fissures is destroyed by the disintegration of the surface, and the hot springs find their outlets at the lowest places possible.

Our knowledge of the processes taking place in the depth of the earth, where the real source of the energy of the springs is situated, is very slight, and the available methods of investigation very limited, in that we are almost exclusively confined to the study of the exhalations of the springs, viz. the steam, the spring gases and the radioactive emanations.

As far as I know, no analyses of spring gases from the places I investigated have been made, except BUNSEN's[1] and O. T. CHRISTENSEN's[2] analyses of spring gases from the hot springs in the vicinity of Mývatn. I have already pointed out that many hot springs have changed in the course of time. The mention of these changes served particularly to illustrate the action of the hot springs on the outer crust of the earth, and the influence of meteorological conditions and earthquakes on the thermal activity of the springs.

The matter has another aspect, if one considers the change in the composition

[1] Pogg. Ann. 83; p. 238. 1851.
[2] Tidsskrift for Physik og Chemie. 10, p. 225. 1889.

of the gases from the same spring. If the composition of the spring gases is changed in the course of time, then we have reason to suppose that a corresponding change has taken place in the depth of the earth, where the spring has its origin.

For the purpose of comparison, I quote here CHRISTENSEN's analyses of samples of spring gases collected by JOHNSTRUP at Krafla in the summer of 1871.

Table IV.

	I	II	III
SH_2 %	5.89	13.94	14.55
CO_2 %	68.80	63.52	71.99
H_2 %	15.59	11.71	9.30
N_2 %	9.72	10.83	4.16

We see at once that the last of JOHNSTRUP's gas samples, (III), has almost exactly the same composition as one of mine. The other two have a somewhat more divergent composition, which is chiefly due to a comparatively large increase in the amount of nitrogen. This suggests that these samples originate from springs where the soil is particularly porous, and that a little atmospheric air has therefore mingled with the spring gas.

Unfortunately, however, there is no detailed description of the springs from which the gas samples originate, in JOHNSTRUP's and CHRISTENSEN's papers. Any conclusions drawn from a comparison of my analyses with those of CHRISTENSEN may therefore be to some extent uncertain. My two samples of gas show a considerable divergence in their composition, although they originate from two very similar hot springs, the distance between them being only about 20 m. Nevertheless it is confirmed with sufficient accuracy by the analyses quoted, that the spring gases at Krafla have undergone very little change, if any, in the period 1871—1906.

We might expect that the gases evolved by the hot springs at Námafjall, situated about 10 km. south of Krafla, would very closely resemble the gases evolved by the hot springs at Krafla. The outward appearance of the springs is in many respects similar, and the geological conditions indicate that the springs originate from the same source.

It was during the long period of volcanic eruptions 1722—1729, when Helvíti was a very active ash-crater, and when the great line of craters at Leirhnjúkur, a short distance west of Helvíti, emerged and threw up an immense quantity of lava, that the active craters in Bjarnarflag, west of Námafjall, also came into existence, (see Fig. 2).

All this seems to indicate that the hot springs at Krafla and at Námafjall must be in connection with each other. Nevertheless the composition of the spring gases at Námafjall differs essentially from that of the spring gases at Krafla. The great amount of hydrogen in the former is especially conspicuous.

These gases have also some interest in other respects.

In the following table I have collected the analyses within my knowledge of spring gases from Námafjall.

Table V.

	BUNSEN	CHRISTENSEN				TH. THORKELSSON	
		1.	2.	3.	4.	1.	2.
	(1845)	(1876)	(1871)	(1871)	(1876)	(1906)	(1906)
H_2S %	24.12	26.32	15.78	19.26	21.75	2.2	18.4
CO_2 %	50.00	59.24	44.97	52.00	48.25	37.5	30.0
H_2 %	25.14	7.94	25.49	27.02	28.03	54.4	49.0
N_2 %	0.72	6.50	13.76	1.72	1.97	5.9	2.6

It appears from this table that a slight change in the composition of the gas took place between 1845 and 1871, the amount of hydrogen becoming a little greater. This change seems to have developed along the same lines with surprising rapidity during the years 1871 and 1906. My gas samples from Námafjall show the greatest amount of hydrogen that has been found in gases evolved by the hot springs of Iceland. As already emphasized, one must exercise great care in drawing conclusions from changes in the composition of the spring gases, but as the mud pools at Námafjall are grouped together within three well-defined areas, one of which it is not possible to approach, and the spring gases in each of these three groups of springs have in all essentials the same composition, we shall not be far wrong in assuming that the alterations in the composition of the spring gases, shown in the above table, correspond fairly well to the actual conditions.

Of course the few results given cannot help us to determine whether the alterations have taken place suddenly or as the result of a gradual process.

Assuming that BUNSEN's theory regarding the process of the formation of hydrogen and sulphuretted hydrogen in the springs is correct, CHRISTENSEN[1] expresses his opinion that the increase of hydrogen must be regarded as a sign that the spring gases have been highly heated. If this be so, we must suppose that the terrestrial heat at Námafjall is on the increase. However, comparing my observations of the terrestrial heat at Námafjall with previous descriptions of the locality, I have been unable to find the least sign of such an increase in the thermal activity on the earth's surface.[2]

With regard to their composition, the spring gases from Kerlingarfjöll and Hengill most closely resemble the gases evolved by the hot springs at Mývatn, especially on account of the large quantities of hydrogen. The analyses of the gases from the hot springs at Kerlingarfjöll and Hengill harmonize very closely

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[1] loc. cit. p. 242.

[2] I have since learnt that the inhabitants of the district at Mývatn are of the opinion that the thermal activity really is increasing.

with each other, having on an average a volume of about 71 %/o of carbon dioxide and 26 %/o of sulphuretted hydrogen plus hydrogen gas. One of the gas samples from Hengill has a slightly greater percentage of carbon dioxide but the spring from which this sample was taken differed in other respects also from the surrounding springs. The gas sample Krafla No. 2 is also consistent with spring gases of this type, and as one of CHRISTENSEN's gas samples is of a similar composition, one has reason to suppose that spring gases with about 71 %/o of carbon dioxide and about 26 %/o of sulphuretted hydrogen plus hydrogen gas, are common among the Icelandic solfataras and mud pools.

In spring gases of this type, the amount of sulphuretted hydrogen and of hydrogen gas, taken separately, may each vary considerably, but taken as a whole, the percentage of the volume of these two gases is fairly constant. In his remarks on the spring gases from Krafla, CHRISTENSEN mentions that an increase in the amount of sulphuretted hydrogen is attended by a decrease of the amount of hydrogen gas. It appears thererefore that the sulphuretted hydrogen and the hydrogen are closely related to each other in the spring gases. CHRISTENSEN is of the opinion that an easy explanation of this is found in BUNSEN's theory of the process of formation of hydrogen and sulphuretted hydrogen in the hot springs, viz. that the sulphuretted hydrogen originally formed disunites according to the formula $SH_2 = H_2 + S$. Thus, a molecule of hydrogen gas is formed by the decomposition of every molecule of sulphuretted hydrogen.

The hydrogen liberated by the decomposition of the sulphuretted hydrogen does not therefore combine with other substances. As the relation between the volume of the carbon dioxide and the sum of the volumes of hydrogen gas and sulphuretted hydrogen is practically constant in this kind of spring gases, it appears probable from the above that there is a certain connection between the carbon dioxide and the sulphuretted hydrogen before its dissociation.

Taking into account the laws of chemical equilibrium, we perceive that the cause of the relation which exists between the two gases is either that they are produced in the same place, and consequently under the same chemical and physical conditions, or else that the one gas has liberated the other by acting on its chemical compounds. For it is highly improbable that two gases produced independently in two different places should be found mixed in the same proportion in several separate localities. The possibility that sulphuretted hydrogen, more or less dissociated, should always liberate carbon dioxide in the same proportion to the sum of the volumes of hydrogen gas and sulphuretted hydrogen, can hardly be considered, as it does not harmonize with the laws of chemical equilibrium.

In my opinion, the foregoing experimental data seem to indicate that the three gases, carbon dioxide, hydrogen and sulphuretted hydrogen, are produced at the same time and by the same physical and chemical processes.

The conditions of the production of these gases must consequently be the same over vast stretches of Iceland. Most probably the source of gas evolution is

to be found in the flowing mass, the fluid lava or magma in the interior of the earth, the gas evolution being either the result of the action of the mass on the solid crust of the earth, or else being produced through the gases originally absorbed in the mass being released as the pressure lessens.

It is evident that when the conditions of the gas evolution are fixed, the gases evolved must have a fixed proportion to each other. At the moment of production, the carbon dioxide, the hydrogen and the sulphuretted hydrogen appear to be in the proportion 71 : 11.5 : 14.5. As these three gases are very liable to combine with other substances, it is not surprising that the proportion between them is not very constant at the earth's surface. Sulphuretted hydrogen particularly is a very unstable gas, and this is doubtless the reason why the volume of this gas is more liable to variation than that of the two other gases, (carbon dioxide and hydrogen).

In this class of spring gases carbon dioxide, hydrogen gas and sulphuretted hydrogen constitute nearly 97 % of the whole volume. Hence it follows that a decrease in one of these gases must be attended by a corresponding increase in the combined volume of the other two.

The remainder of the spring gas, amounting to 3 % of the entire volume, consists chiefly of nitrogen, and is undoubtedly mostly due to the intermixture of foreign gases of atmospheric origin. The real spring gases in the solfataras and similar hot springs, i. e. the spring gases of which the production is so closely connected with the thermal activity of these springs, are therefore almost exclusively composed of hydrogen gas, carbon dioxide and sulphuretted hydrogen, the remaining gases being treated as a negligible quantity, their percentage being so small. A rise in the percentage of one of these three gases is therefore not so much due to an absolute increase of the gas in question, as to a decrease in the other two gases on account of destruction and absorption.

The analyses of the spring gases from Kerlingarfjöll and Hengill show that these gases contain some traces of methane, and differ in this respect from the spring gases at Mývatn, which contain no hydrocarbon. The gas samples from Hveravellir, Grafarbakki, Laugarás and Reykjafoss also contain a little methane.

According to my analyses methane must be a rather common constituent of the Icelandic spring gases, although it is nowhere found in large quantities. This does not, however, agree with the results obtained by other analysts. BUNSEN in particular states emphatically that he has not been able to find hydrocarbon in any of the spring gases, although he considers that with his instruments he would have been able to detect even a tenth per cent of methane, had it been in any of the samples. The apparatus I used for the analysis being provided with stop cocks, it was not absolutely impossible that the methane came from the grease used for lubricating. I therefore made, in the middle of my analysis work, some experiments with atmospheric air, treating it in the same way as the gas samples under investigation. But in this case no methane could be traced. Another proof experiment was carried out in the following manner. After having proved that a

gas sample from Laugarás only contained nitrogen, inert gases and methane, I mixed a known volume of the same gas sample with a little atmospheric air and a suitable amount of oxygen and hydrogen in chemically equivalent proportions and then exploded the gas mixture. A subsequent examination of the gas remaining from the explosion showed the same result as regards the methane. Immediately after this I treated an equal volume of atmospheric air in exactly the same manner, without detecting the slightest trace of methane. The view that the methane found in the spring gas samples is not entirely due to erroneous methods in the analysis work is further confirmed by the fact that the investigation of the gas samples containing methane was twice interrupted by the examination of the gas samples from Reykir. In these samples I could never find any traces of methane. The gas samples from the hot springs at Mývatn, on the other hand, were examined in the beginning of the analysis work. When one considers that several of the gas samples investigated were proved to contain no methane, it can hardly be contended that the methane found in the remaining samples is due to awkwardness in collecting the gas, or in fusing the collecting bottle.

On the other hand, the method I employed is under a disadvantage, as compared with that used by BUNSEN, in that the gas under investigation often comes into contact with organic substances, the indiarubber tubing, and the grease on the stop-cocks. It is therefore, in my opinion, more probable that where very small quantities of methane are found, — i. e. only a few thousandths of the entire volume of the gas examined, — it is on account of erroneous treatment of the gas sample, rather than that methane is really a constituent of the original spring gas. But where methane is found in larger quantities as, for instance, in the gas samples from Hveravellir, I consider it quite impossible that this should be due exclusively to errors in analysis. In these cases methane is really contained in the spring gases.

The existence of methane may be explained as follows. The spring water, or at least a part of it, comes from swampy ground, and it is a well-known fact that methane is produced in such places by fermentative processes in organic matter. In this way the water conveys the methane to the interior of the earth, where it is mingled with the other spring gases.

Three of the gas samples from Reykjafoss are, as regards their composition, most closely allied to the class of spring gases represented by the gas samples from Hengill, Kerlingarfjöll and Krafla. But this might have been expected, for the hot springs at Reykjafoss and Hengill may really be considered as one group of hot springs, which stretches from Reykjafoss right through to Hengill. The small quantity of nitrogen found in the spring gases from Reykjafoss indicates that they are only slightly mixed with atmospheric nitrogen and other gases of atmospheric origin. The amount of hydrogen gas and, to some extent, of sulphuretted hydrogen, is less than at Hengill, while the percentage of carbon

dioxide naturally becomes greater. This has probably some relation to the fact that the thermal activity at Reykjafoss is not so intense as at Hengill.

The gas sample Reykjafoss No. 1 is quite different to the three others, and shows clearly that the spring gas in question is mixed with atmospheric air. Calculating how much air is mingled with the original spring gas, we find that about $2^1/_2$ volumes of air are mixed with one volume of the original spring gas. In this calculation I have assumed that the spring gas has originally had the same composition as the three other gas samples from Reykjafoss, and also that no carbon dioxide has been lost by intermixture or on its way to the surface of the earth. One observes that the proportion between the nitrogen and the oxygen is very different from that in the atmosphere, in that the greater part of the oxygen in the spring gas has disappeared, i. e. entered into chemical combinations in the interior of the earth.

As the spring from which the gas sample Reykjafoss No. 1 comes is also a periodic alkaline spring, it is very probable that the intermixture of atmospheric air with the spring gases has some connection with the periodicity of the hot springs. The spring gases from Hveravellir supply evidence to confirm this. For one is doubt-less quite safe in concluding that the oxygen and the comparatively large amount of nitrogen in these spring gases are of atmospheric origin, while the carbon dioxide and the small quantities of sulphuretted hydrogen and hydrogen gas may be regarded as remnants of the original spring gas, which has probably had a similar composition to the spring gases from Kerlingarfjöll and Hengill.

According to the analyses before us, the spring gases from Hveravellir may be divided into two groups.

One is represented by the two gas samples: Hveravellir Nos. 2 and 25, which come from hot springs apparently not periodic, situated in the north-west part of the spring district. The three other samples, i. e. Nos. 10, 27 and 16 belong to the second group, all coming from periodic springs.

These gas samples are distinguished from the two first mentioned by the great amount of nitrogen they contain in comparison with carbon dioxide and by a considerable quantity of oxygen. Taking it for granted that the oxygen and the nitrogen are of atmospheric origin, this shows that the spring gas in periodic springs has received a greater contribution of air than that in the non-periodic springs. The connection between the periodicity of the springs and the amount of atmospheric gases in the spring gas is here shown very clearly. It is most prob-able that the periodicity of the springs is a direct cause of the intermixture of air with spring gases.

The hot spring No. 12 at Hveravellir will perhaps be the means of throwing considerable light on this subject. When Þ. Thoroddsen visited Hveravellir in the summer of 1884, this spring was found to be periodic. In the summer of 1906 the basin was occasionally filled with tranquil water, but generally it was quite dry, and showed no signs of activity. As far as I know, this spring did not once spout

during our stay at Hveravellir. If this be so, the spring water must have found another outlet. The water standing in the old channel would then rise or sink according to the pressure prevailing in the water in the earth below. It is quite possible that similar channels are found in many places in the neighbourhood of the periodic springs, although they are not yet discovered, as the water in such channels does not necessarily reach up to the surface of the earth.

It is not difficult to perceive that a natural channel of a similar form to that shown in Fig. 15 may suffice to explain how the air is mixed with the spring gases, provided that the channel has suitable dimensions.

We may assume that the channel b is at the beginning entirely filled with water. When the pressure down in the earth is reduced, the water recedes down the channel, and as soon as the surface of the water has fallen as low as the bend, the atmospheric air, forcing its way through the water, enters the reservoir B, where it is stored up, and also in the upper part of the channel c. When the pressure below increases again, the water rises in the channels b and c, and expels the air from them; but the air remains in the reservoir B. By the subsequent reduction of the pressure in d, the air in B is forced down the channel c by the pressure of the water column in the channel b. Supposing d to be in communication with the channel of a geyser, the periodic variations of the pressure in the geyser channel will be sufficient

Fig. 15.

to produce the required variations in the pressure in the channel d.

Inasmuch as channels similar to that shown in Fig. 15 are undoubtedly very common, especially in periodic springs, one can readily understand that when such a channel falls into inactivity on account of the spring water finding an outlet on a lower level, it is very likely that the vacant channel serves as a kind of pumping
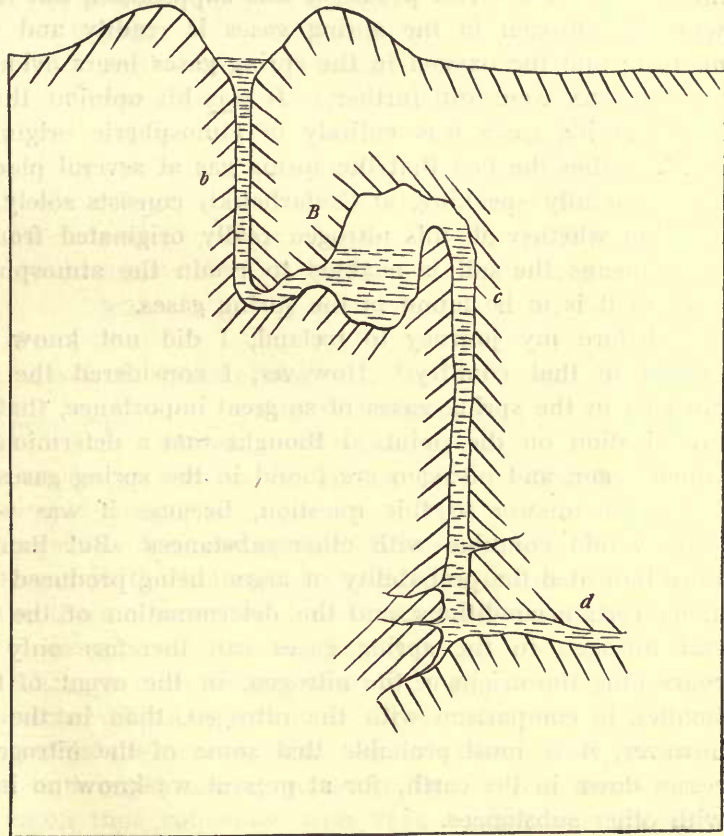
apparatus to pump the air down into the subterranean cavities, where it mixes with the original spring gases.

The air decomposes the sulphuretted hydrogen in the spring gases, and thus prevents the destructive effect of this gas on the rocks. In this way the intermixture of the air with the spring gases perhaps serves to uphold the periodicity of the springs. On the other hand, the oxygen will doubtless affect the solubility of the rocks in spring water containing carbonic acid. The characteristic deposits of silica at Hveravellir have possibly some connection with the comparatively large quantity of oxygen in the spring gases there.

I have assumed that the relatively large amount of nitrogen in the spring gases from Hveravellir and in Reykjafoss No. 1 is of atmospheric origin. I cannot, however, adduce direct proofs of this supposition, but it seems to me that the presence of nitrogen in the spring gases is readily and naturally explained in this manner; and the oxygen in the spring gases bears evidence to the same effect.

BUNSEN went still further.[1] It was his opinion that the nitrogen in the Icelandic spring gases was entirely of atmospheric origin. But when we take into consideration the fact that the spring gas at several places, (at Reykir, at Laugarás and, generally speaking, at Grafarbakki) consists solely of nitrogen, it is open to question whether all this nitrogen really originated from the asmosphere, and by what means the soil is enabled to retain the atmospheric oxygen so that not a trace of it is to be found in the spring gases.

Before my journey to Iceland, I did not know that such nitrous springs existed in that country.[2] However, I considered the question of the origin of nitrogen in the spring gases of so great importance, that I decided to make a closer investigation on the point. I thought that a determination of the proportions in which argon and nitrogen are found in the spring gases would most probably give a decisive answer to this question, because it was very improbable that these gases would combine with other substances. But Ramsay's[3] investigations have since indicated the probability of argon being produced by radio active substances under certain conditions, and the determination of the proportion between argon and nitrogen in the spring gases can therefore only give reliable information concerning the origin of the nitrogen, in the event of the amount of argon being smaller, in comparison with the nitrogen, than in the atmosphere. In this case, however, it is most probable that some of the nitrogen is due to chemical processes down in the earth, for at present we know no instance of argon combining with other substances.

[1] Liebigs Ann. 62, 5. 1847.

[2] I have since noticed that BUNSEN, (Gasometrische Methoden, 2. Aufl. 1877, p. 78), has made an analysis of an Icelandic spring gas which consists chiefly of nitrogen, (99·48 % nitrogen, 0·52 % hydrogen). As this spring gas is stated to have come from a small group of hot springs to the north of "Mælifell", it probably originates from the spring group "Reykir in Skagafjörður".

[3] Nature. 1907. p. 269.

In the following table, the volume of the argon in some spring gases is referred to in the second column in the percentage of the entire volume of nitrogen plus argon. In the 3rd. and 4th. columns the percentage of helium plus neon is given respectively in proportion to the nitrogen plus argon and to the argon plus helium.

Table VI.

Gas sample	Argon, in percentage of Nitrogen + Argon	Helium, in percentage of Nitrogen + Argon	Helium, in percentage of Argon + Helium
Reykir No. 1	1·50 %	0·0132 %	0·88 %
Reykir No. 2	1·63 -	0·0140 -	0·87 -
Reykir No. 5	1·64 -	0·0146 -	0·97 -
Hveravellir No. 2 ...	1·75 -	0·0298 -	1·67 -
Hveravellir No. 25 ..	2·10 -	0·0302 -	1·42 -
Grafarbakki No. 1 ..	1·83 -	0·0114 -	0·62 -
Grafarbakki No. 2 ..	2·30 -	0·0110 -	0·48 -
Laugarás No. 1	1·94 -	0·0105 -	0·55 -
Laugarás No. 3	2·11 -	—	—
Reykjafoss No. 1 ...	1·96 -	0·0148 -	0·75 -
Hengill No. 1	0·63 -	0·0326 -	4·76 -
Hengill No. 3	2·21 -	0·0511 -	2·31 -

As could be expected, this table throws little light on the origin of nitrogen in the spring gases. The proportion $\dfrac{\text{volume of argon}}{\text{volume of nitrogen} + \text{argon}}$ is, as the table shows, with one exception always greater in the spring gases examined than in the atmosphere. The gas sample Hengill No. 1 proved to have only half as much argon in proportion to nitrogen as the atmosphere. From this fact one deduces that a great deal of the nitrogen in the hot spring in question originates from the soil, or from the seat of the thermal activity of the spring. Another gas sample from the same district, i. e. Hengill No. 3, shows, however, quite a different proportion between argon and nitrogen. But unfortunately this gas sample was mixed with the atmosphere. I corrected the final result by determining the amount of oxygen in the gas sample used in the investigation, and calculated from this how much atmospheric nitrogen and argon corresponded to the oxygen found. The volumes of nitrogen and argon thus calculated were then subtracted from those directly measured by the experiment, in order to find the volumes of argon and nitrogen originally in the spring gases. Of course all this tended to make the final determination of the volume of argon in this sample rather uncertain. I therefore attach less weight to this result, especially as it is not in harmony with the measurements of the gas sample Hengill No. 1, which are, in my opinion, quite trustworthy.

In other respects the measurements of argon and helium-neon show considerable harmony in gas samples from the same spring group, and this may be considered as a guarantee of the accuracy of the methods employed.

Table VI shows that the relation between the argon and the nitrogen contained in the spring gases is fairly constant in the samples from Reykir, Laugarás, Grafarbakki and Hveravellir, and in the sample Reykjafoss No. 1, being in each case a little greater than in the atmosphere.

I have already shown that it is probable that the nitrogen contained in the gas samples from Hveravellir and Reykjafoss No. 1 is of atmospheric origin; one is, therefore, well within the bounds of reason in concluding that in the spring gases from Reykir, Grafarbakki and Laugarás it is also of atmospheric origin. The surplus of argon in the spring gases may therefore be ascribed partly to the greater absorption of argon in water, and partly to the destruction of nitrogen in the soil.

The fluctuations in the amount of helium-neon in the spring gases are much less than I had expected. One can hardly form a true conception of the amount of helium in the spring gases from the table, for the proportion between the helium and neon varies considerably. For instance, the spectroscopic examination of the helium-neon mixtures from Reykir, Laugarás and Grafarbakki showed a fairly intense spectrum of neon as compared with the spectrum due to helium, while no lines due to neon were visible in the spectrum of Hengill No. 1. The fluctuations in the amount of helium are doubtless much greater, therefore, than Table VI shows. On the other hand the measurements do not indicate any parallel between the amount of radium emanation and helium.

I have also endeavoured to trace xenon and krypton in argon gas from the spring gases. For this purpose I used the same apparatus as for the separation of the helium-neon from the argon, but in this case I cooled the charcoal to $-80°$ C. by means of liquid carbon dioxide. As VALENTINER and SCHMIDT[1] have shown, it is possible in this way to detect xenon and krypton in argon, the xenon and krypton being retained by the cold charcoal, while the argon is removed by means of the pump. As I expected to find only minute quantities of these gases, I mixed together all the argon that originated from the same spring group, before examining it. But I was unable to detect any trace of these rare gases. I then mixed the last distillates of the argon gases from Reykir, Laugarás and Grafarbakki, and examined this gas mixture in the above-described manner for xenon and krypton, but without success. If, therefore, the spring gases contain any xenon or krypton, it must be in very small quantities.

Thus the study of the rare inert gases has not given a decisive answer as to the origin of nitrogen in the Icelandic spring gases, but it is most probable that the nitrogen found in springs such as those at Reykir, Laugarás and Grafarbakki, which are rich in nitrogen, is chiefly of atmospheric origin; while the small quan-

[1] Ann. d. Phys. IV Folge. 18, 187. 1905.

tities found in the solfataras at Hengill and Kerlingarfjöll are partly due to chemical processes in the interior of the earth.

The exhalations from Bjarnarflagshraun, (the lava field east of Mývatn), and the northern part of Kjalhraun, (south of Hveravellir), differ from those of the other hot springs in that they contain little or no radium emanation. The composition of the outflowing gases coincides closely with that of the atmosphere, so that there is no doubt whatever that it is atmospheric air that we have to deal with. Similar exhalations of warm, damp air are fairly common in the hot lava fields of Iceland.

In 1846 BUNSEN[1] collected some gases exhaling from the crater of Hecla and the surrounding lava, the latter having been produced by the eruption of 1845, and having not then become cold. These gases proved to be of similar composition to the atmosphere. JOHNSTRUP[2] collected a similar gas sample in some lava in Mývatnsöræfi, east of Mývatn, which had been ejected about a year previously. CHRISTENSEN[3] also finds that the gases emanating from a fumarole at Krisuvík have the same composition as the atmosphere, and he explains the presence of air in these exhalations on the hypothesis that the steam, rushing out through the spring channel, sucks the air into the channel through the side walls. He considers the feasibility of this much increased by the fact that lava and other volcanic rocks are exceedingly porous. I think it more probable, however, that the atmospheric air and water are in such a case in actual circulation, similar to the circulation of water in hot water pipes. The air and the water ooze down, in cooler parts, through small channels and fissures in the soil. In the heated interior of the earth the air becomes hot and the water evaporates, and their density consequently decreases. They now rise again up to the earth's surface through channels which are kept hot by the current of hot air and steam.

A most interesting point in connection with these atmospheric exhalations is that they do not appear to come into contact with the real seat of thermal activity, for this would at once be marked by a change in the composition of the spring gases. The heat energy necessary to maintain these exhalations must be conveyed to them in a special manner. The exhalations studied by BUNSEN and JOHNSTRUP, from Hecla and Mývatnsöræfi respectively, provide a ready explanation of the heat energy. The lava from recent eruptions had not become cold throughout, and although the surface was cold, there was sufficient heat in its depths to produce the circulation of air and water as above described. The same explanation is not, however, applicable to the exhalations we investigated from Bjarnarflagshraun and Kjalhraun. Bjarnarflagshraun was formed by the volcanic eruptions which took place during the years 1724—1729, and is thus about 180 years old. Kjalhraun is, however, older than the settlement of Iceland, i. e. at least 1100 years old. These stretches of lava would doubtless therefore have become cold throughout, if

[1] Pogg. Ann. **83,** 242. 1851.
[2] Festskrift, p. 180; or Tidsskrift for Physik og Chemie, **10,** 232. 1889.
[3] loc. cit. p. 233.

particular causes had not been at work to keep the bulk of the lava hot. Bearing in mind that there are hot springs in the immediate neighbourhood of the atmospheric exhalations both in Bjarnarflagshraun and in Kjalhraun, it is very probable that the high temperature of the lava is maintained by heat conduction from hot springs beneath the lava. They have not been able to break through the hard crust at the bottom of the lava, but have been compelled to find an outlet at the edge of the lava field. The atmospheric exhalations ·may therefore be correctly characterized as secondary hot springs, as distinct from the real hot springs, in that they derive their heat energy from the latter.

The exhalations from the above-mentioned secondary hot springs contained very little radio active emanation. It was therefore out of the question to determine the character of the emanation. But the ionizing effect of the radio active emanations from the other hot springs was so great as to render this possible. As to the methods employed, I refer to page 35. The investigations showed that the ionisation in the ionisation chamber increased immediately after the introduction of the spring gases, in such a way as might be expected if the gases contained no other emanations than radium emanation.

The coefficient of transformation calculated from the experiment, and referred to in Table I under the head of a' is of the same magnitude as the coefficient of transformation for radium emanation (2.16×10^{-6}) found by Rutherford. The divergences seldom exceeded probable experimental errors, the latter of course being rather great owing to the difficult conditions under which the experiments were carried out.

Taken as a whole, the divergences of a' for spring gases from the same group appear to be to some extent of a systematic nature, in that a' for the same group is generally either too great or too small. But bearing in mind that the ionisation in the ionisation chamber apparently made the same progress whether the spring gas was examined immediately after the gas was collected, or after it had stood three or four days in the collecting bottles before it was investigated for radio-activity, it seems rather improbable that these small divergences, even though they are systematic, should be due to different radio active emanations. They are more likely to be due to small systematic errors in the treatment and investigation of the gases. The Icelandic spring gases may therefore for the present be regarded as not containing any slowly decaying radio active emanation except radium emanation.

Rapidly changing radio active emanations such as, for instance, thorium and actinium emanation, cannot of course be examined in the same way. I therefore endeavoured to examine them in the following manner.

Fig. 16.

The spring gases were conducted from the collecting funnel, which was placed in the spring, through the tube a (Fig. 16) into the tin vessel B. From B the spring gases were passed
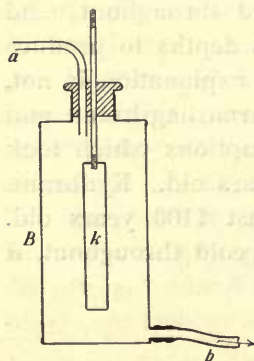
through the tube *b*, about 1 m. in length, out into the atmosphere. The cylinder *k* is, as the illustration shows, placed in the middle of the vessel *B*. The whole was arranged so that the gases evolved by the spring were spontaneously and without supervision passed through the vessel in the manner described. The apparatus thus arranged was left untouched for about 12 hours, when the cylinder *k* was brought to the tent, where its ionizing effect was measured in the ionisation chamber. The rate of decay of the induced activity was then investigated.

In these experiments the induced activity due to Ra-emanation was so predominant, that I was not able in the time at my disposal, and with the apparatus I used, to decide with certainty whether other kinds of emanation might not be present in the spring gases.

If, therefore, the Icelandic spring gases contain thorium emanation or other similar rapidly decaying emanations, they must be present only in very small quantities in comparison with the radium emanation. In support of this view, I will mention that we were unable to trace radio active substances in the sediments or mud of any of the springs. For if the spring gases contained a large amount of rapidly decaying emanations, one would reasonably expect to find in the spring water the radio active substances responsible for these emanations, and therefore also in the sediments and mud of the springs, and it is hardly possible that we should have failed to detect them.

The amount of radium emanation in the spring gases varied greatly in the different groups of springs. The greatest amount of emanation in the gas samples from Kerlingarfjöll, was about 43 times as large as in one of the gas samples at Reykir, although the secondary exhalations from the lava fields of Bjarnarflagshraun and Kjalhraun gave quite an insignificant amount of emanation compared with the above-mentioned gas samples from Reykir.

In springs belonging to the same group one also meets with considerable variations in the amount of emanation, but these variations are, however, much less than those between one spring group and another. We observe particularly that when the springs in a group are similar in other respects, the variations in emanation are also comparatively small. When, therefore, BOLTWOOD[1] on the occasion of his investigations of some hot springs in America states that the amount of emanation in a spring cannot be deduced from the emanation in a neighbouring spring, this only holds good, in the case of many Icelandic spring groups, with regard to the smaller variations. As a rule, the amount of emanation in the springs of a group is known approximately when one has determined the amount of emanation in one of the springs.

On the other hand, in the case of springs in the same group belonging to different types, the variations in the emanation may be comparatively large. This is the case with the hot springs at Hveravellir and at Reykjafoss. Acetous, sul-

[1] Americ. Journ. Sc. **20**, 128. 1905.

phurous springs and alkaline springs containing free oxygen are found at each of these places.

The measurements of the emanation in the spring gases apparently contribute very little to an elucidation of the nature of the hot springs. The comparatively large variations in the emanations indicate that the emanation is affected by several factors which have little importance in connection with other properties of the springs. In this regard it is certainly very important to note that the emanation is distinguished from the other gases evolved by the springs, on account of its gradual decay. In two spring gases, originally of the same composition and undergoing similar treatment on their way to the earth's surface, there will be less emanation in that which has been longer on the way, owing to the decay of the emanation. This latter factor will therefore doubtless contribute to increase the difference between the amounts of emanation contained in the gases.

The emanation in springs situated on the same fissure in the earth's crust often increases the nearer one comes to one end of the fissure. This is the case with the three hot springs at Reykir, (Reykir Nos. 1, 2 and 3), the springs at Grafarbakki and those at Hengill. At the first-named place the springs with the greatest emanation are situated at the south end of the fissure, and in the two other places at the north-east and north ends respectively. The decay of the emanation will possibly account for this, as the spring gases take less time to reach the surface at the end of the fissure where the emanation is greater. This may either be because the subterranean seat of the spring is nearer this end of the fissure, or because the gases, for some unknown reasons, pass more rapidly through the subterranean channels. The great variation in the amount of emanation from the alkaline springs at Hveravellir is probably to a great extent due to similar causes, in that the spring gases often stand for a considerable time in the subterranean cavities which, according to the geyser theory I have advanced, are to be found in this locality. The fact that the whole of the emanation does not come from the subterranean seat of the spring would have considerable bearing on the variations in the amounts of emanation. A considerable part of the emanation from the springs is often due to radium contained in the superficial strata. The atmospheric water, sinking through the ground, receives a great deal of the emanation produced in these strata, and conveys it to the spring channel. A comparison of the radio activity of the alkaline and acetous springs at Reykjafoss and at Hveravellir seems to confirm this. The acetous springs at these places are in my opinion more closely connected with the real subterranean seat of these spring groups than the alkaline springs, which contain gases of atmospheric origin and consequently also atmospheric water in considerable quantities. But the alkaline springs are nevertheless often more radio active than the acetous springs, which is certainly to be regarded as a proof that atmospheric water and air supply the springs with radium emanation from the strata the water has passed through. It is possible that this could be demonstrated experimentally, for there is good reason to suppose

that, provided the water which rushes into the upper part of the spring channel carries with it an appreciable amount of emanation, a parallel could be shown between the quantity of emanation and the amount of water in the springs. An exhaustive investigation of the amount of water and of the emanation would therefore doubtless give a decisive answer to this question. On our journey, we were so much occupied with other investigations, that time did not permit of our measuring the volume of the water, but our observations on the spot indicate that an increase in the volume of water is generally attended by a corresponding increase in the radio activity. Mud pools with little water, as for instance those at Hveravellir and at Reykjafoss, often seemed to exhibit a surprisingly slight radio activity in comparison with the other springs of the same group.

Of course these experiments throw no light on the question as to what extent the radio activity of the springs is due to emanation conveyed by atmospheric water into the upper part of the channel. But there is no doubt that a great deal of the emanation in the springs must come with the other exhalations from the interior, where all the springs in the same group have a common channel, or perhaps even all the way from the seat of the heat energy of the springs, for otherwise it is difficult to understand why the amount of emanation in proportion to the other gases is usually of the same magnitude in the same group.

I have already shown, (page 63) that spring channels may often extend deep down into the earth before joining the main channel of the group. Even two springs situated side by side may have channels independent of each other deep down in the earth. But it is evident that the longer the individual channels are, and the deeper they extend down in the earth, the more probable it is that the decay of the emanation and the supply of fresh emanation from the side channels will cause the amounts of emanation from the two springs, originally equal, to be finally quite different. When, therefore, we find that the three springs Námafjall Nos. 1, 2 and 3 have practically an equal radio activity, it must undoubtedly be attributed to the group in question having a common channel which divides into three not far from the surface.

The same is probably the case with the two hot springs in Vestur-Hveradalir, i. e. Kerlingarfjöll Nos. 1 and 2.

Inasmuch as the Icelandic hot springs are all radio active, and as radium spontaneously produces heat, it seemed quite reasonable to conclude that the heat energy of the springs is due to radium. I therefore expected that my measurements of the radio activity of the hot springs would render valuable information on this point. But this has not been the case. There are no definite proofs that the heat energy of the springs is directly connected with their radio activity. The fact that the nitrous springs at Reykir are both colder and less radio active than similar springs at Laugarás and Grafarbakki, is probably due to other causes. And on the other hand, although they are apparently quite as vigorous, the hot springs at Hengill are less radio active than those at Hveravellir and Kerlingarfjöll.

The radio activity is therefore more likely to be dependent on other properties of the springs, and curiously enough, it seems to increase with the height of the springs above sea-level.

Again, if the heat energy of the springs is produced by radium accumulated around the subterranean seat of the springs, a greater amount of emanation would probably be found in the spring gases than is the case. Of course, the emanation takes a considerable time to pass through the channels of the spring from the interior of the earth up to the surface, so that it is difficult to calculate how great a fraction of the original emanation reaches the surface without being transformed.

The radio activity of the German and Austrian mineral springs[1] seems to be about the same as of the Icelandic springs. A few, for instance Grabenbächer-quelle, which contains emanation amounting to $564 \times 10^{-3} ESE = 267$ per gram of uranium per second, are even more radio active than the Icelandic springs. This is generally the case in springs containing appreciable quantities of radio-active substances in the spring water or in the sediments. It does not, however, preclude the possibility of radium being an indirect cause of the thermal activity of the hot springs. STRUTT's[2] researches have rendered it probable that the internal heat of the earth is sustained by the radium contained in common rocks. It is true that no measurements have yet been made of the radium contained in the Icelandic rocks, but there is no reason to doubt that they are similar in this respect to the same sort of rocks in other lands.

We examined the water from two cold springs in the neighbourhood of Akureyri for radio activity. They turned out to be more radio active than the tap water in Copenhagen. This example shows that the superficial rocks of Iceland may contain radium, but our measurements of the emanation in the hot springs may also be considered as a proof of the presence of radium in the Icelandic rocks. I have already pointed out that the radium contained in the superficial rocks may have considerable bearing on the radio activity of the hot springs. But the radium in the lower strata has also considerable significance, in that some of the emanation evolved in these rocks is carried by water, steam and other spring exhalations to the main channel of the spring group. This has no little influence on the activity of all the springs in the group, for the average radio activity of a spring group depends on the amount of emanation supplied to the spring channel deep down in the earth where the springs of the group have all a common channel, or where the different spring channels are so near to each other that they are subject to the same influences. The emanation thus received by the channels originates chiefly in the surrounding rocks, which are of course very deep down, although some of it may be carried by the water all the way from the superficial strata.

[1] See, for instance, H. MACHE u. ST. MEYER: Phys. Zeitschr. 6, 693. 1905; and H. W. SCHMIDT u. K. KURZ: Phys. Zeitschr. 7, 209. 1906.

[2] Proc. Roy. Soc. 77, 472. 1906.

When one considers that the supply of the emanation is thus evolved from rocks ranging over a large area, one can readily understand that the amount of emanation contained in the spring gases is not dependent solely on the amount of radium contained in the rocks, but also on the facility with which these rocks give off the emanation. As already mentioned, the decay of the emanation will also tend to increase the uncertainty of deducing from the emanation contained in the spring gases the amount of radium in the rocks, for it is difficult to say how much time has elapsed since the gases were in contact with the rocks producing the emanation.

A peculiarity of the hot springs is that they are generally found gathered in groups, being of course confined to fissures in the crust of the earth, (see p. 68). The reason for this is, that it is only where fissures are found in the crust that water can penetrate sufficiently deep down into the earth to become hot. In my opinion, one has no ground for expecting to find any special agents which produce the heat necessary for the thermal activity of the springs, inasmuch as this activity is undoubtedly occasioned by the fact that the heat present in the interior of the earth can be transmitted without difficulty to the earth's surface at the places where the hot springs are situated.

But the transmission of heat from the interior of the earth takes place almost exclusively by means of convection of hot water and steam through fissures in the crust of the earth.

It will readily be seen that, at the places where the thermal springs are, the earth must suffer an extraordinary loss of heat. An estimate of this loss of heat can be obtained by means of a simple calculation. The temperature gradient of the earth is generally estimated at $0.000304°$ per cm., and the earth's coefficient of heat conductivity at 0.0041. Hence we get the loss of heat through each square cm. of the earth's surface per second as 0.0000125 gram calories, or through a square km. 12500 gram calories. It is sufficiently accurate to reckon the mean temperature of Iceland at $0°$ C., and assuming that the thermal activity of the springs will raise the temperature of 1 litre of water to $100°$ C. in one second, the heat consumption amounts to 100000 gram calories, which, according to the above calculation, corresponds to the loss of heat from 8 square km. of the earth's surface. But in reality the loss of heat from the spring groups explored by us is undoubtedly much greater. For these spring groups deliver on an average more than 1 litre of water at $100°$ C. per second, and the spring water has already lost a great deal of its heat energy on its way up to the earth's surface, partly from heat conduction from the spring channel to the surroundings, and partly on account of evaporation. I presume therefore that the loss of heat on the part of the earth through the thermal activity of the springs is not exaggerated when we reckon it, at each of the spring groups we investigated, at from 5 to 10 times as great as calculated above, or as great as the loss of heat due to conduction from about 60 square km. of the earth's surface.

Apart from the possibility of the loss of heat occasioned by the thermal activity of the springs being compensated for by heat produced by special agents or reactions on the spot, such an extraordinary loss of heat within such a limited area must apparently lead to extraordinary temperature gradients in the surroundings, if the heat energy is only supplied by means of conduction. The consequent gradual cooling of the surrounding strata would probably, after a short time, be attended by a corresponding decline in the activity of the springs. In my opinion, however, the thermal activity of the springs does not decrease as rapidly as the above might lead one to expect, whence it follows that special causes must be present, and the prominent cause is that the heat supplied to the hot springs is chiefly by means of convection and not by conduction.

Sulphurous springs usually come into existence immediately after volcanic eruptions, and on this account it is probable that their channels extend deep down into the earth; I have already adduced reasons which seem to indicate that these springs are directly connected with the fluid interior of the earth (magma). In this case there seems to be no reason why the heat should not be transmitted by convection, by means of the spring exhalations coming from the fluid magma up to the surface. Through the circulation of the fluid magma, the loss of heat is distributed over a wide area.

In the secondary hot springs in the lava fields, the heat is conveyed by the exhalations from the bottom of the lava up to the surface. But from the fluid magma up to the bottom of the lava the heat is undoubtedly conveyed through the lower spring channels.

The nitrous hot springs apparently do not communicate directly with the fluid magma, for, as I have already pointed out, it is highly probable that the nitrogen and argon contained in their exhalations are of atmospheric origin. It is therefore obvious that they belong to a kind of secondary hot spring similar to the lava exhalations, only with this difference, that their channels go much deeper down than those of the lava exhalations. In both cases atmospheric water and air are caused to circulate in the channels by means of the heat energy supplied to the bottom of the channels. In the case of the nitrous springs it is not very likely that the heat energy is conveyed through other channels from the magma up to the actual spring channels. One has more reason for assuming that the channels of these springs go down so deep that the necessary heat energy is easily supplied to them by conduction from the lower strata of magma. It is not altogether impossible that these springs may to some extent communicate with the magma. The small quantities of sulphuretted hydrogen (and carbon dioxide) found in the spring gases from Laugarás and Grafarbakki might perhaps be looked upon as the last remnants of sulphurous exhalations from the interior of the earth.

Corrigenda.

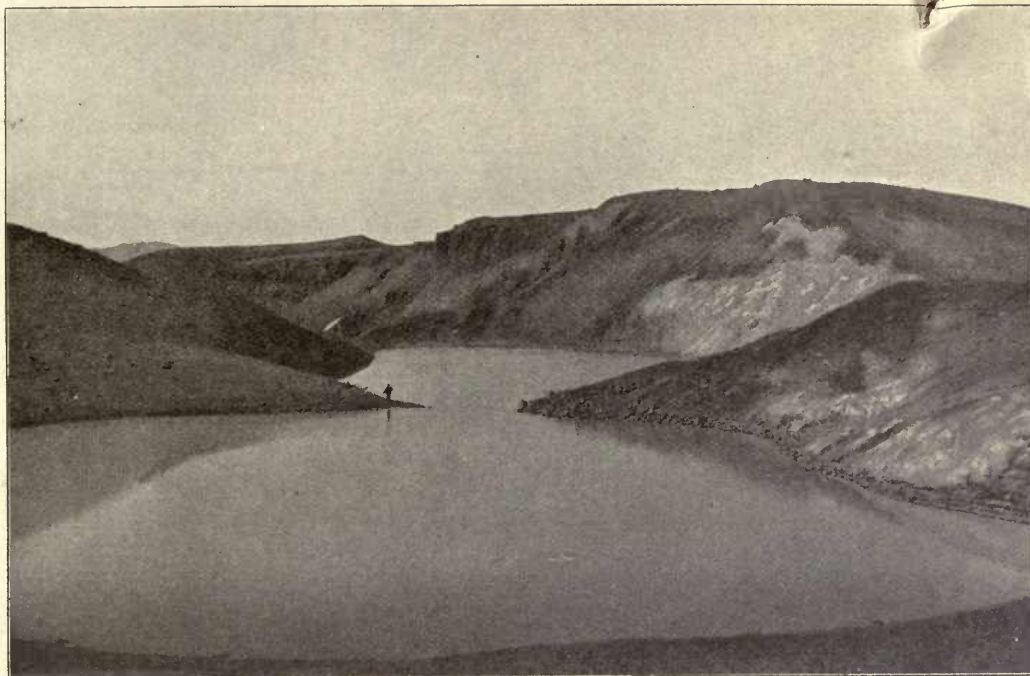Page 18, line 31, for spouting-spring read spouting spring.
— 24, — 34, for is altered read is then altered.
— 26, — 29, for ganged read gauged.
— 30, — 11, for used by unit is read unit is used by.
— 38, — 1, omit from.
— 49. In Table I against Námafjall No. 1 in column H_2 49,0 % should be 5 4,4 %, and against Námafjall No. 4 in the same column should stand 4 9,0 %.

Corrigenda.

Page 15, line 31, for *spouting spring*, read *spouting spring*.

" 24, for *is altered* read *is then altered*.

" 27, for *passed* read *pushed*.

" 11, the word *by* unit is read until is used by.

Note. Table I against Formula No. 4 in column B ... should be in M... and Table Formula No. 4 in the same column should read 41·4.

a. The twin lakes on the western slope of Krafla, looking north.　The solfataras are seen in the light-coloured sections on the north-eastern slopes of the two lakes.　A man is standing at the spot where the two lakes join.
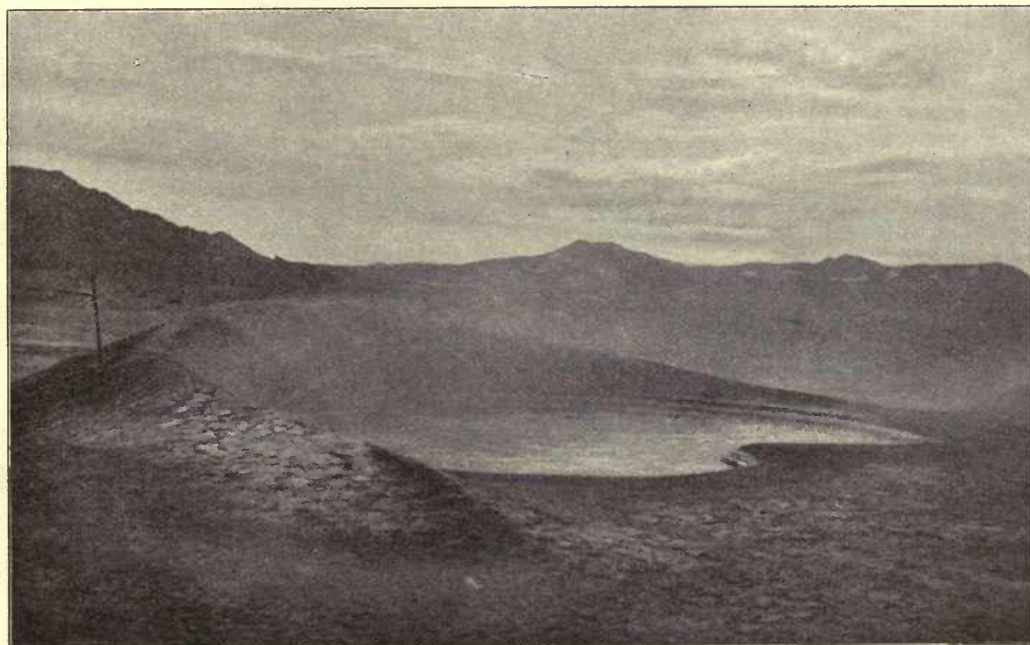
b. The hot springs at Námafjall, looking north.　Gas sample No. 1 originates from the slough seen in the foreground.　The rod standing to the left of the slough is about 1 m. high.　Krafla is seen in the background, near the centre.
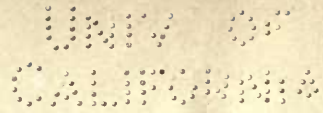
a. Bjarnarflagshraun and Jarðbaðshólar. The hill in the background (to the east), is Jarðbaðshólar. In the foreground (to the west), a small part of Bjarnarflagshraun with a row of three craters is seen.
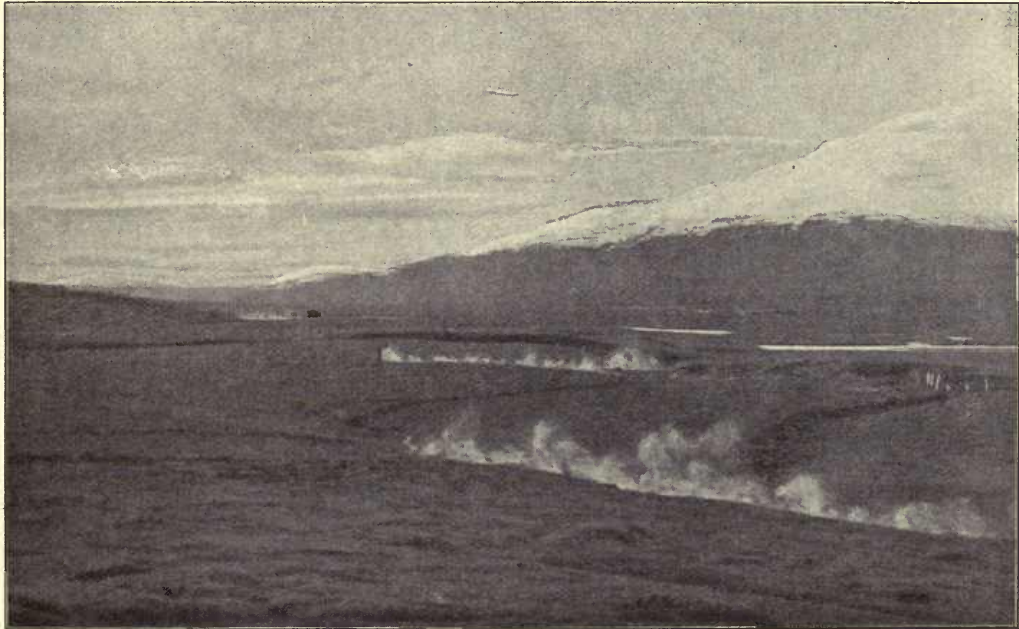
b. Reykjalaugar. At the "Sundlaug", which is farthest away, a small black house is visible. A man is standing at the middle spring, Hornahver.
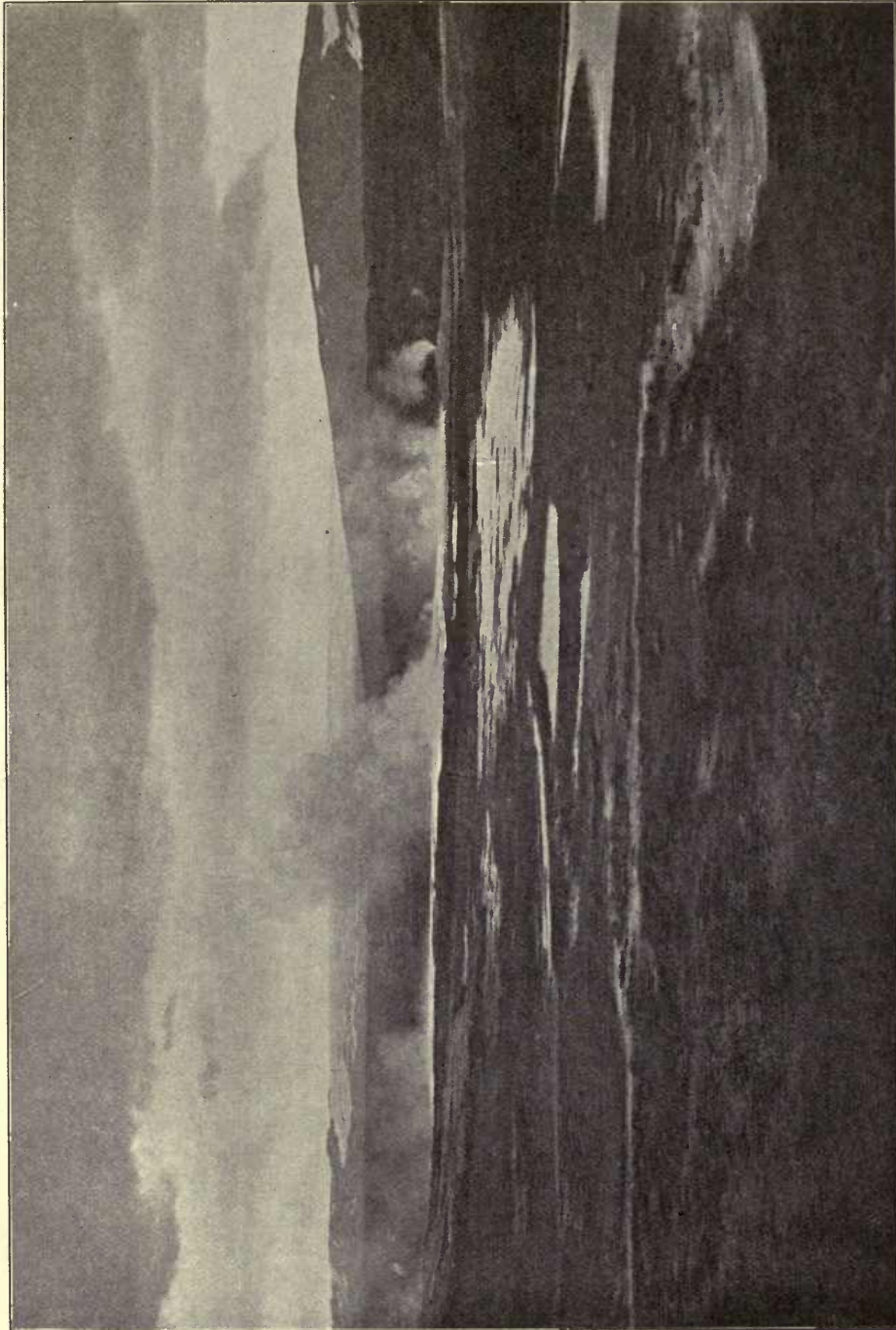
Hveravellir, looking east. The isolated spring to the right (south) is Öskurhóll. In the right background is the mountain Dúfufell, and farther to the left is the glacier Hofsjökull.
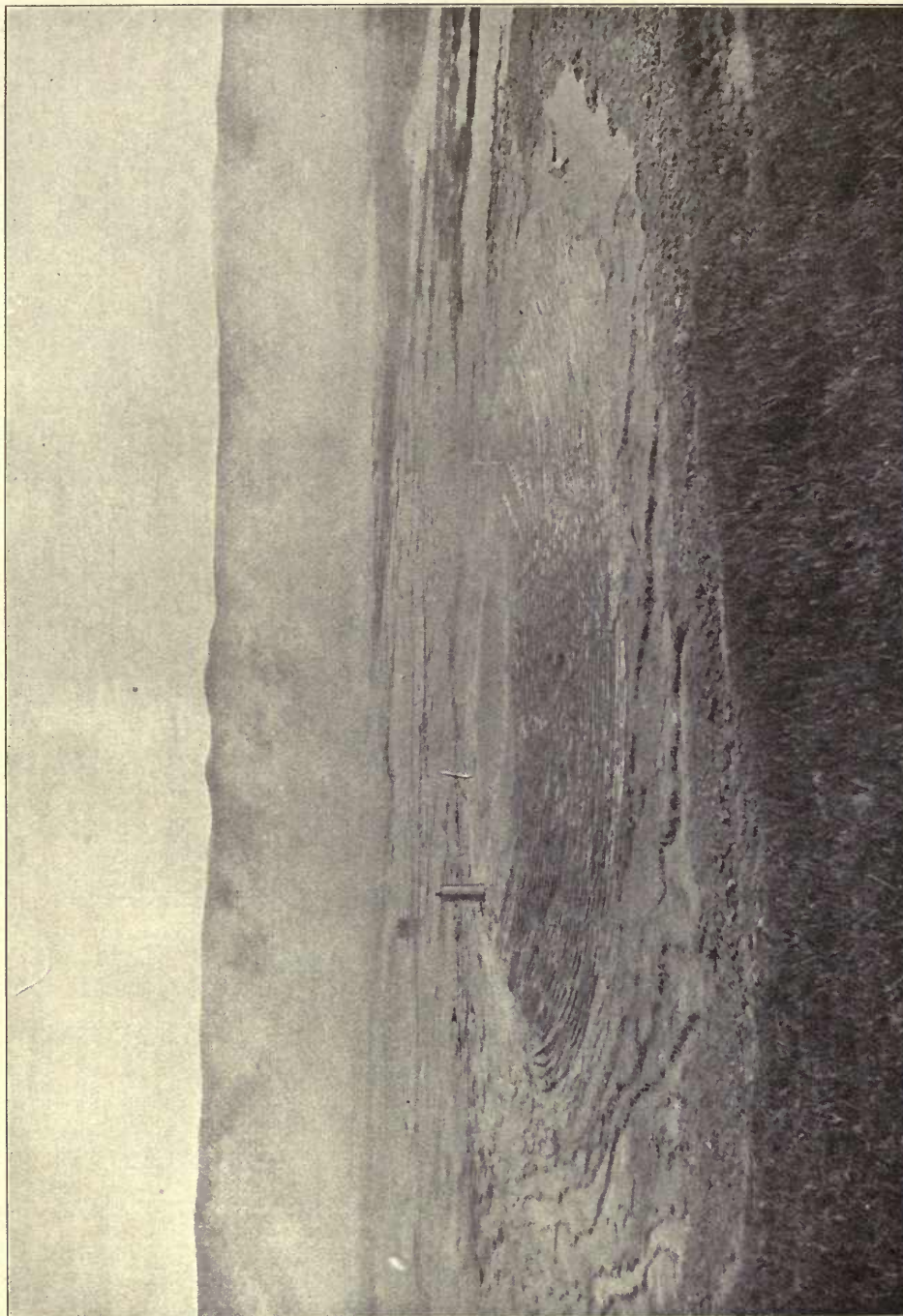
Fagrihver.   The tin standing on the brink of the spring is 20 cm. high.
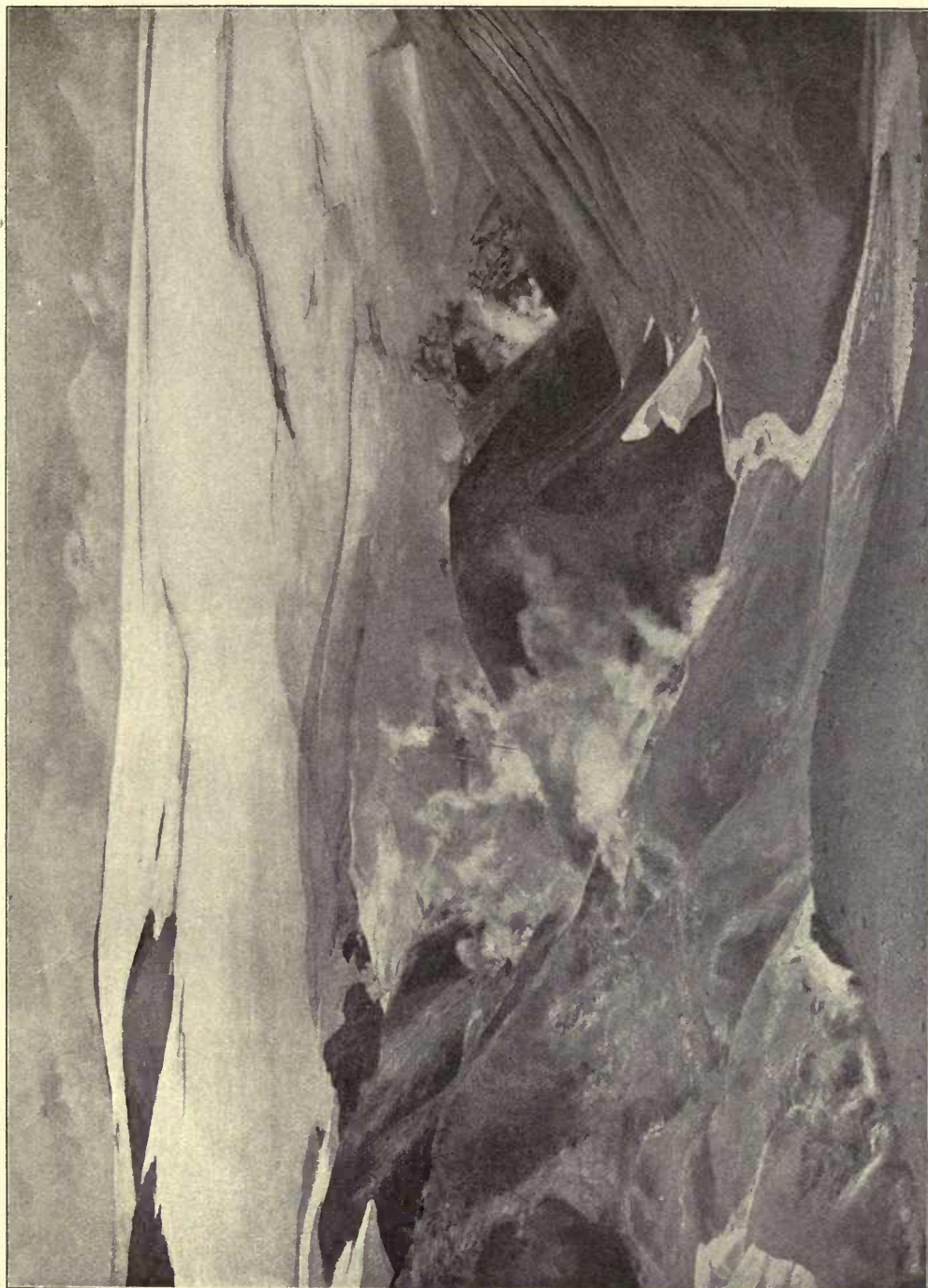
Vestur-Hveradalir, Kerlingarfjöll. The illustration shows two ravines in the western slope of the main valley. The two gas samples Kerlingarfjöll No. 1 og No. 2 were collected in the ravine to the left. There are several hot springs in this ravine, the mist produced by them almost hiding it from view. Higher up, the slope is covered with snow, which is in many places undermined by the action of the hot springs.

Plate VI
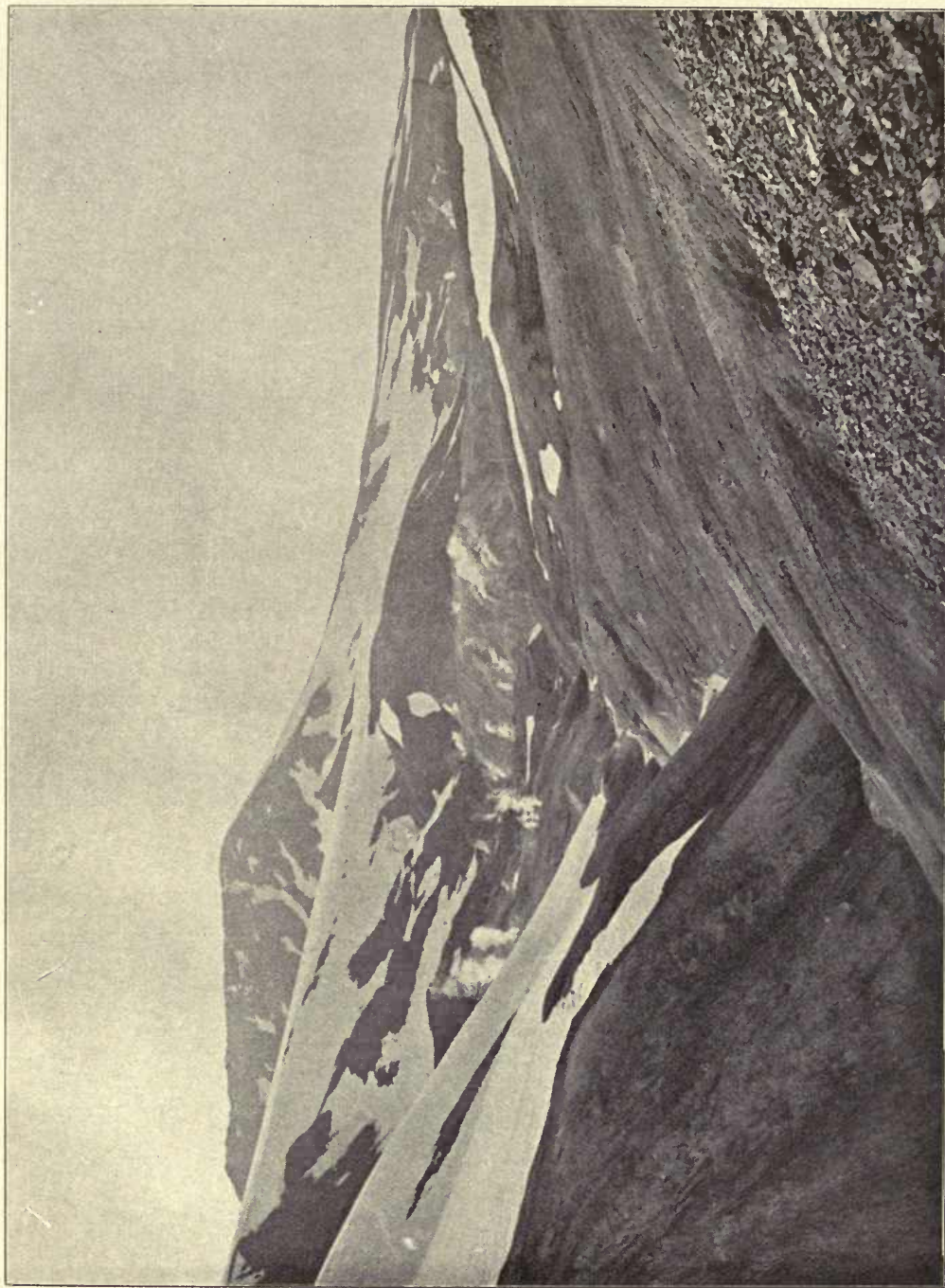
Mið-Hveradalir, Kerlingarfjöll. The photograph is taken from Austur-Hveradalir, looking west. The hot springs (in the centre of the illustration) are distinguished by the white columns of mist rising from them.
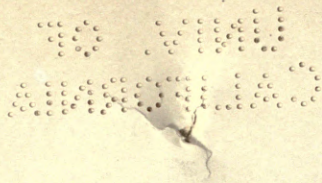
a. Austur-Hveradalir, Kerlingarfjöll, looking east. The steam from Öskrandi and another steam vent fills the valley with a thick mist. Most of the solfataras in Austur-Hveradalir are situated in ravines to the left (north) of the main valley shown in this illustration.
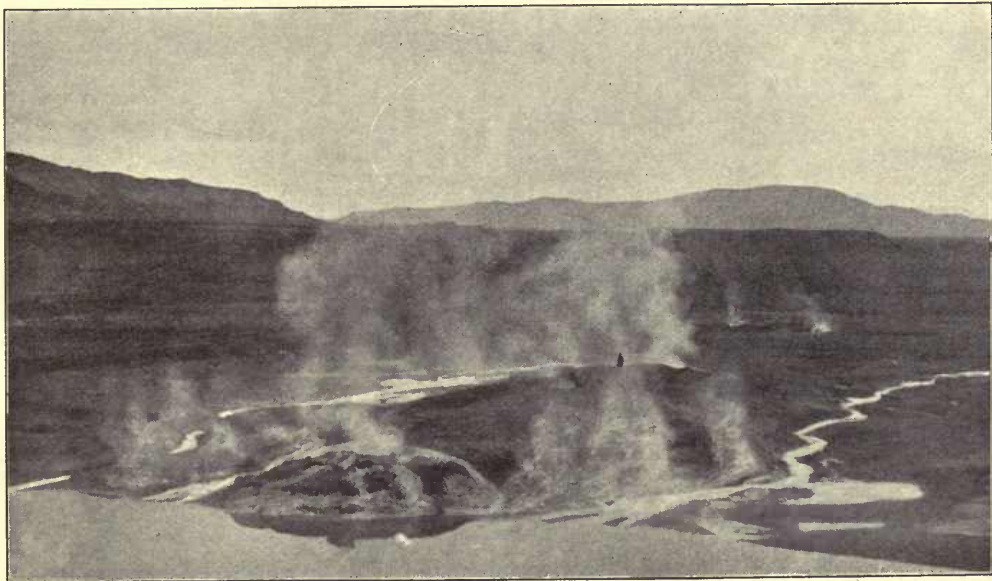
b. Grafarbakkahverir, with the river Litla Laxá in the foreground. Vaðmálahver is nearest the river; the reflection of the little dome-shaped eminence around the spring may be seen in the sheet of water. A man is standing in the immediate neighbourhood of the larger geyser.

Plate VIII
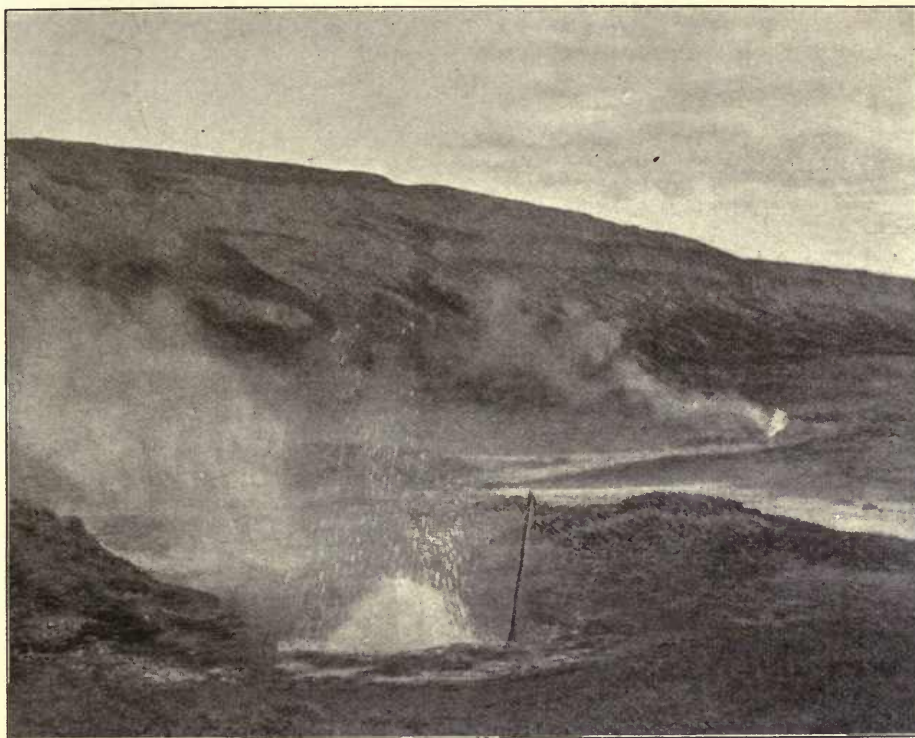
a. The geysers at Grafarbakki. The rod standing by the southern geyser is nearly 1 m. high.

b. Grýla, showing the steam period of the spring.

a. Hveragerði at Reykjafoss, looking north.   Only the alkaline springs in the northern part of Hveragerði are visible.

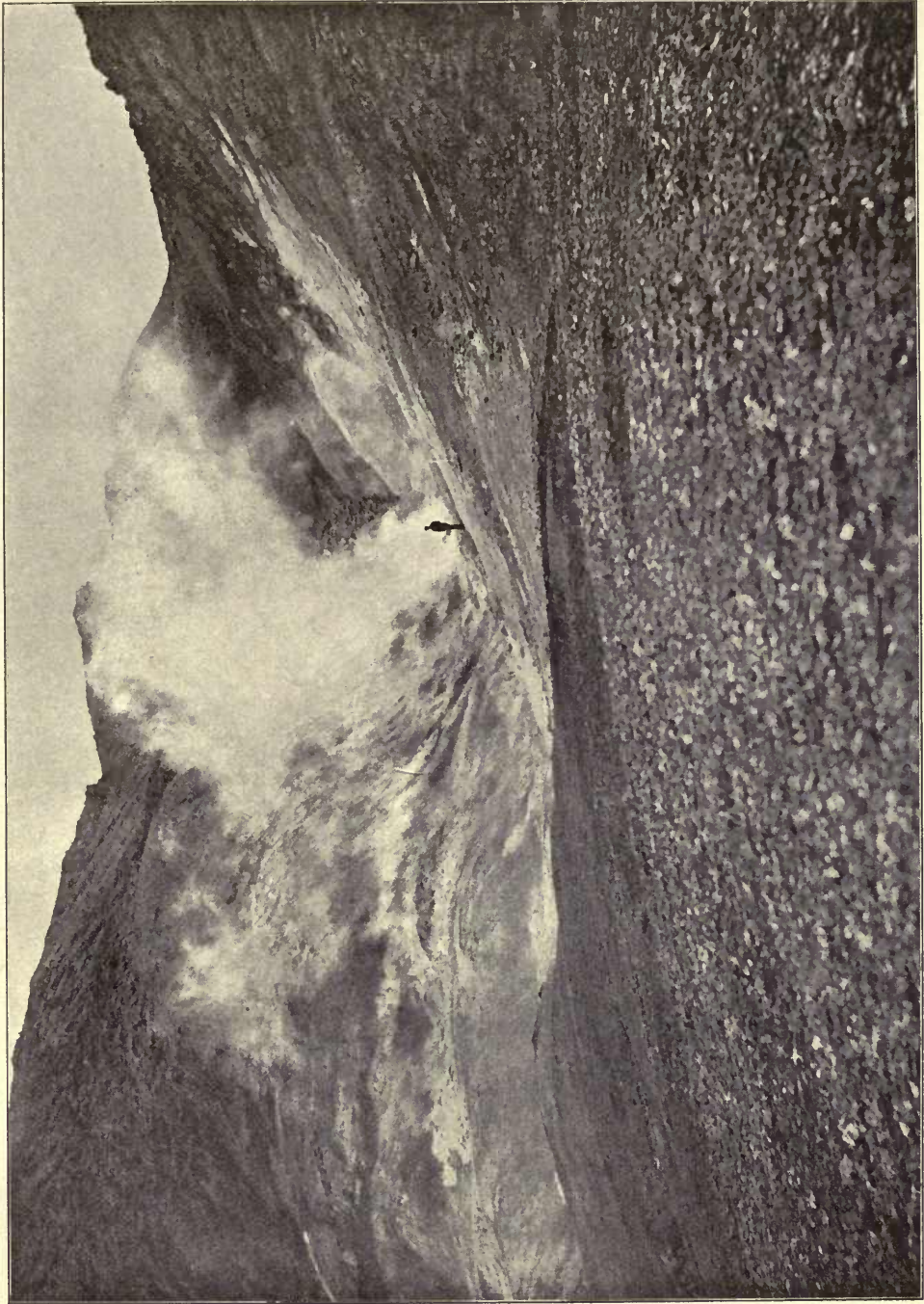*b.* A mud volcano at Hengill.   The rod shown is about 1 m. high.

The eastern slope of the mountain Hengill, with two groups of hot springs. A man is standing on the ridge to the left (south) of the lower group.
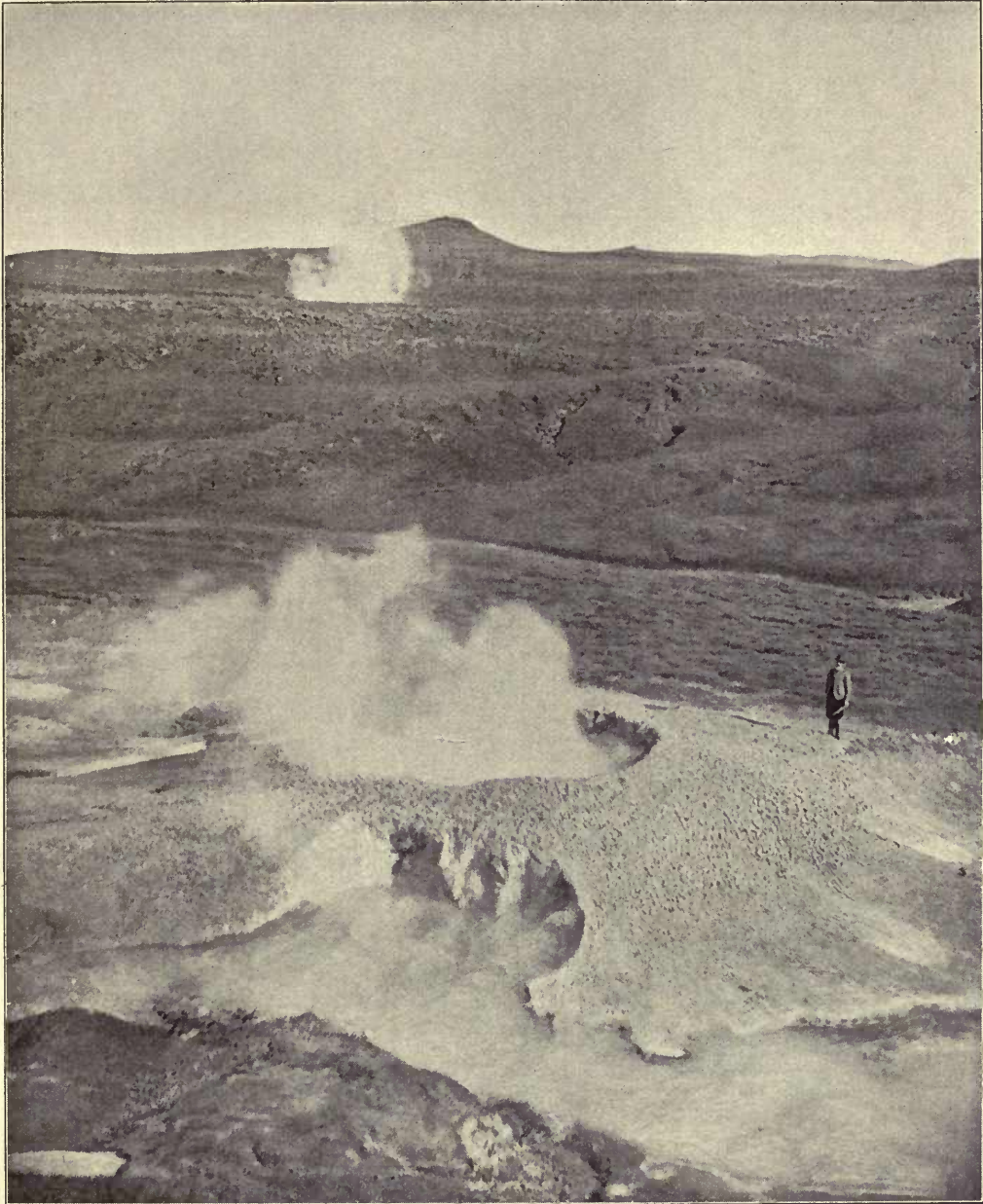
A group of solfataras in a hollow on the eastern slope of Hengill.

Plate XII

A large isolated mud volcano at Hengill. The column of white mist in the background indicates a group of hot springs to the south-east of the mud volcano.

A fuming mud cone at Hengill.   A traveller is standing to the left
of the spring.

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