What the real meaning is of the often so highly differentiated organs as many extrafloral nectaries are and of the secretion of sugar which they present in most cases, can only be settled by new investigations which however will have to bear not only on the biology but also on the physiology of the plant.

Physics. — "*Methods and apparatus used in the cryogenic laboratory at Leiden. X. How to obtain baths of constant and uniform temperature by means of liquid hydrogen.*" By Prof. H. KAMERLINGH ONNES. Communication N°. 94*f* from the Physical Laboratory at Leiden.

(Communicated in the meeting of 28 May, 1906).

§ 1. *Introduction.* Communication N°. 14 of Dec. '94 treated of the results I had obtained after I had employed regenerators for the cascade method, and especially discussed the way how to obtain a permanent bath of liquid oxygen to be used in measurements at the then observed lowest temperatures. At the end of that paper I expressed the hope to be able to construct a cycle of hydrogen similar to that of oxygen. A mere continuation of the cascade method would not do. By means of liquid oxygen or nitrogen, even when they evaporate in vacuo, we practically cannot reach the critical temperature of hydrogen; for the liquefaction of this gas we had therefore to avail ourselves of cooling by adiabatic expansion.

In Comm. N°. 23 of Jan. '96 I made some remarks on what could be derived from VAN DER WAALS' law of corresponding states for the liquefaction of hydrogen following this method. I had found that an apparatus to liquefy hydrogen beginning with — 210° C. might be constructed almost after the same model as an apparatus that had proved suitable for the liquefaction of oxygen beginning with ordinary temperatures and without any further frigorific agents. My efforts, however, to obtain an apparatus for isentropic cooling by combining to a regenerator the outlet- and inflow-tubes of a small expansion motor, fed with compressed gas, had failed. Therefore I directed my attention towards the then newly published (1896) application of the JOULE-KELVIN process (LINDE's apparatus for liquefying air and DEWAR's jet of hydrogen to solidify oxygen).

Though the process of LINDE was the most promising, because he had succeeded with his apparatus to obtain liquid air statically, yet it was evident that only the principle of this method could be followed.

The cooling of an apparatus of dimensions like the first of LINDE (weight 1300 kilogrammes) by means of liquid air (oxygen) evaporating in vacuo could not be thought of. And yet, according to what has been said above, this had to be our starting point.

It rather lay to hand to magnify the spiral (enclosed in a vacuum glass) such as DEWAR had used for his jet of hydrogen to solidify oxygen, and so to get an apparatus with which air could be liquefied, and which could then serve as a pattern for an apparatus to liquefy hydrogen. It was indeed a similar construction with which in 1898 DEWAR had statically liquefied hydrogen for the first time. About the installation which apparently afterwards enabled DEWAR to collect large quantities of liquid hydrogen nothing further has come to my knowledge.

The arrangement of the Leiden hydrogen circulation is based on DEWAR's principle to place the regenerator spiral into a vacuum glass (1896). As to the regenerator spiral itself HAMPSON's apparatus for liquefying air (1896) has been followed because it appeared that the proportions of this spiral have been chosen very favourably, and with its small dimensions and small weight it is exceedingly fit, according to the thesis mentioned above, to serve as a model for a regenerator spiral to liquefy hydrogen of about — 205° at expansion from a higher to the ordinary pressure. The other physicists, who after DEWAR have occupied themselves with liquid hydrogen, — TRAVERS 1900 and 1904, OLSZEWSKI 1902, 1904 and 1905 (the latter rather with a view to obtain small quantities in a short time with simple accessories) — have also built their apparatus after this model.

The Leiden hydrogen liquefactor for constant use has enough peculiar features to occupy a position of its own as an independent construction by the side of the apparatus of TRAVERS and OLSZEWSKI, which do not satisfy the requirements for the Leiden measurements. Moreover I was the first to pronounce the principle according to which this apparatus is built and from which follows that the regenerator spiral fed with hydrogen that has been cooled by liquid oxygen (air) evaporating at a given low pressure, must lead to the goal.

The problem of making a circulation in order to maintain a bath of liquid hydrogen — and of this problem the arrangement of the liquefactor for constant use (which, tested with nitrogen, has really proved efficient) is only a part — has not yet been treated by others.

That also at Leiden we had to wait a long time for its solution cannot be wondered at when we consider the high demands which, I held, had to be satisfied by this cycle. For with a view to the intended measurements I thought it necessary to pour a bath of

1.5 liter into the cryostat (described in VIII of the series "Methods and apparatus used in the Cryogenic Laboratory" of these communications) and to keep it to within 0°.01 at a uniform and constant temperature. The requirements were therefore very much higher than they had formerly been for the bath of liquid oxygen. These requirements could by no means be fulfilled before I had the disposal of a vacuum pump (mentioned as early as Jan. '96 in Comm. N°. 23), (comp. Comm. N°. 83, March '03), suitable to evaporate in a short time large quantities of liquid air at a pressure of a few centimeters, and before I possessed compressors for constant working with extremely pure hydrogen. With the former instrument and the compressors, described in § 3, the liquefactor, described in § 2, delivers 3 à 4 liters of liquid hydrogen per hour. Thus I was able to bring to this assembly (28 May '06) 4 liters of liquid hydrogen prepared at Leiden the day before and to use it in several experiments.

Our installation proved quite satisfactory for operations with the afore mentioned cryostat. After we had succeeded in making with it some measurements in liquid hydrogen boiling under ordinary and under reduced pressure the vacuum glass of the cryostat cracked and only by mere accidence the measuring apparatus were spared. Therefore we have constructed another modified cryostat, to be described in XII, which besides insuring the safety of the measuring apparatus has the advantage of using less liquid hydrogen than the cryostat, described in VIII (Comm. N°. 94^d, June '05). This new cryostat entirely satisfies the requirements; the temperature is kept constant to within 0°,01. It is noteworthy that while the measurements are being made the cryostat shows in no way that we are working with a bath of no less than 1.5 liter of liquid hydrogen.

I wish to express thanks to Mr. G. J. FLIM, mechanist at the cryogenic laboratory, for his intelligent assistance. Under his supervision the liquefactor and cryostat, to be described in the following sections, and also other accessories have been built upon my direction in the workshop of the laboratory.

§ 2. *The hydrogen liquefactor for constant use.*

a. The apparatus does not yet entirely realize the original design [1]).

[1]) It might be improved by dividing the regenerator spiral in several successive coils, each opening into the next with its own expansion-cock, where the pressures are regulated according to the temperatures. Compare the theory of cooling with the JOULE-KELVIN process and the liquefying by means of the LINDE process given by VAN DER WAALS in the meeting of Jan. 1900.

The latter is represented schematically by fig. 1 on Pl. I and hardly requires further explanation. The compressed hydrogen goes successively through the regenerator coils $D_4, D_3, D_2, D_1, C, B, A$. B is immersed partially in a bath of liquid air which, being admitted through P, evaporates at a very low pressure; D_4, D_2, C and A are surrounded by hydrogen expanding at the cock M, and D_1 and D_3 by the vapours from the airbath in F. As, however, we can dispose of more liquid air than we want for a sufficient cooling of the admitted hydrogen, and the vacuum pump (comp. Comm. N°. 83, March '03) has a greater capacity than is required to draw off the evaporating air[1]) at reduced pressure, even when we sacrifice the regenerator working of the spirals D_1, D_2, D_3 and D_4, we have for simplicity not yet added the double forecooling regenerator D, by means of which a large quantity of liquid air will be economized, and hence the apparatus consists only of one forecooling regenerator C, the refrigerator F with cooling spiral B and the principal regenerator A in the vacuum glass E with a collecting vessel L, placed in the case V, which forms one complete whole with the case U.

b. The principal regenerator, Pl. I fig. 2, consists of 4 windings of copper tubing, 2.4 m.m. in internal diameter and 3.8 m.m. in external diameter, wound close to each other and then pushed together, indicated by A_1, A_2, A_3 and A_4, (number of layers 81; length of each tube 20 M.). As in the ethylene regenerator (Comm. N°. 14, Dec. '94, and description of MATHIAS [2]), fig. 1F) and in the methyl chloride regenerator (Comm. N°. 87, March '04, Pl. I) the windings are wound from the centre of the cylinder to the circumference and again from the circumference to the centre round the cock-carrying tube M_4, and are enveloped together in flannel and fit the vacuum glass E_0 (the inner and outer walls are marked with E_{01} and E_{02}). Thence the liquid hydrogen flows at E_1 into the collecting vessel L_0. At M_{00} the four coils are united to one channel which (comp. cock T in fig. 3 of MATHIAS' description l.c.) is shut by the pivot point M_{11} moved by the handle M_{21}. The packing M_3 hermetically closes the tube M_4 at the top, where it is not exposed to cooling (comp. MATHIAS' description l.c.). The hydrogen escapes at the side exactly as at the ethylene cock L, fig. 2 in MATHIAS' description l.c., through 6 openings M_{01} and is prevented from rising or circulating by the screens M_{02} and M_{03}.

c. The new-silver refrigerator case F_1 is suspended in the new-

[1]) When using oxygen we might avail ourselves of cooling down to a lower temperature, which then must be carried out in two steps (comp. § 4*b*).

[2]) Le laboratoire cryogène de Leyde, Rev. Gen. d. Sc. Avril 1896.

silver case U_1, from which it is insulated by flannel U_{64}. A float F_{31} indicates the level of the liquid air, of which the inflow is regulated through the cock P_{01} with pivot P_{11} and packing P_3 identical with the cock mentioned above, except that the glass tube with cock is replaced by a new-silver one P_4.

The evaporated air is drawn off through a stout copper tube F_2 (comp. § 4*b*). The 2 outlet tubes B_{12} and B_{22} of the spiral B_{11} and B_{21} (each 23 windings, internal diameter of tube 3.6 m.m., external diameter 5,8 m.m., length of each 6 M.) are soldered in the bottom. The two inflow tubes B_{10} and B_{20} are soldered in the new-silver cover, on which the glass tube F_4 covering the index F_{32} of the cork float F_{31} are fastened with sealing wax (comp. for nitrogen Comm. N°. 83 IV, March '03, Pl. VII).

d. The forecooling regenerator spiral C_1, C_2, C_3, and C_4 is wound in 4 windings like A, wrapped in flannel and enclosed in the cylinder of the new-silver case U_2. The four windings (internal diam. of the tubing 2.4 m.m., external diam. 3.8 m.m., number of layers 81, length of each tube 20 M.) branch off at the soldered piece C_{01} from the tube C_{00}, soldered in the cover of U_2. They unite to the two tubes C_7a and C_7b through which the hydrogen is led to the refrigerator. The axis of this spiral is a thin-walled new-silver tube C_6 shut at the top.

The hydrogen blown off is expelled through the tube U_5.

e. The liquid hydrogen is collected in a new-silver reservoir L_1, fitting the vacuum glass L_0, which by means of a little wooden block V_7 rests on the wood-covered bottom of the insulated case V_1, which is coated internally with paper V_{64} and capoc V_{63}. Thanks to L_1 the danger of bursting for the vacuum glass is less than when the hydrogen should flow directly from E_1 into the glass L_{02}. This beaker moreover prevents rapid evaporation in case the glass should burst (comp. § 1).

The level of the liquid hydrogen is indicated by a float L_{200}, which by means of a silk cord L_{21}, slung over the pulleys L_{22} and L_{23} is balanced by an iron weight L_{24}, moving in a glass tube V_{31}, which can also be pulled up and down with a magnet from outside. The float is a box L_{00} of very thin new-silver, the hook L_{201} is a bent capillary tube open at both ends and soldered in the cover. The glass V_{31} fits by means of india rubber on the cylinder V_{32}, which is connected with the case by means of a thin-walled new-silver tube V_{30}.

The hydrogen is drawn off through the new-silver siphon tube N_{01}, which is continued as the double-walled tube N_{51} N_{501}, leading

towards the delivery cock N_{01}. Here, as at the ethylene cock (description of MATHIAS l. c. fig. 2), the packing N_3 and the screw-thread are in the portion that is not cooled. The pin N_1, made of a new-silver tube, passes through the cock-carrying tube N_4. Both the outlet tube N_0 and the delivery cock N_4 are surrounded by a portion of the cold hydrogen vapours, which to this end are forced to escape between the double wall of the tube through N_{504} and along *Kha* (*Kd* on Pl. II). The outer wall N_{501}, N_{502} of the double-walled tube is insulated from the side tube V_{21} at the case V_{20} by means of wool.

The glass L is covered with a felt cover L_3, fitted at the bottom with a sheet of nickel-paper to prevent radiation towards the liquid hydrogen. This cover fits tightly on the lower end E_2 of E and rests on the tube N_{501} and the pulley-case L_{22}.

f. We still have to describe the various safety arrangements to prevent the apparatus from bursting when the cock M should suddenly admit too much gas, as might occur when the opening has been blocked by frozen impurities in the gas, which suddenly let loose or when one of the tubes breaks down owing to the same blocking or an other cause.

For this purpose serves in the first place the wide glass tube W_1, which ends below mercury. The quantity of gas which of a sudden escapes, and the great force with which the mercury is sometimes flung away rendered it necessary to make a case W_{30} with several screens W_{31} all of varnished card-board to collect the mercury and to reconduct it into the glass W_2 (where a sufficient quantity of it must be present for filling the tube during the exhaustion).

If the pressure in the reservoir rises higher than that for which the safety tube is designed, the thin-walled india rubber tube V_{42}, which is drawn over the perforated brass cylinder wall V_{41} (separated from it by a thin sheet of tissue-paper), breaks. The safety apparatus is connected with the case V_1 by a wide new-silver tube V_{40}.

In order to avoid impurities in the hydrogen in the liquefactor through diffusion of air the india rubber cylinder V_{432} that is drawn over the rings V_{431} and V_{430} after being exhausted is filled through the cock V_{44} with hydrogen under excess of pressure; during the exhaust the india rubber cylinder V_{432} is pressed against the india rubber wall V_{42}.

An arrangement of an entirely identical construction protects the case U_1, which encloses the principal regenerator, and the case U_2 which encloses the forecooling regenerator C.

As to the protection against pressure which may occur in consequence of evaporation of air, it was sufficient to protect the refri-

gerator space F by means of the tube Y opening below mercury.

g. In protecting the different parts against heat from the surrounding atmosphere, care has been taken that those surfaces of which the temperature might fall below the boiling point of air and which are not sufficiently protected by the conduction from less cooled parts, should not come into contact with air but only with hydrogen. The refrigerator vessel F, for instance, is surrounded with the hydrogen which fills the cases U and V; hydrogen is also to be found in the space between the vacuum glass L and the wall of the case V; and lastly a side tube V_{20} and V_{21} branches off from the case V in order to surround with hydrogen the double-walled siphon tube N_{51}, N_{501} and the double walled cock N_4, N_{501}.

The new-silver case V, from which the vacuum glass L is insulated by layers of paper V_{64} and the refrigerator vessel F by a layer of flannel, and in the same way the new-silver case U, are further protected from conduction of heat from outside by separate wrappings of capoc V_{81}, packed within a card-board cover V_{82} pasted together. To prevent condensation of water vapour, the air in this enclosed space communicates with the atmosphere by means of a drying tube *t.dr* filled with pieces of sodium hydroxide, as in the ethylene- and methyl chloride regenerators (comp. above sub *b*).

The air-tight connection between the case U and the case V is effected by the india rubber ring *Ua*, which fits on the glass and on the strengthened rims U_{50} and V_{50} of the new-silver cases. India rubber of somewhat larger dimensions can only be used for tightening purposes when it is not cooled. In this case the conduction along the new-silver wall, which is insulated from the vacuum glass by layers of paper, is so slight that the ring-shaped strengthened rims remain at the ordinary temperature and the closure can be effected by a stout stretched india rubber ring. When the india rubber is only pressed on the glass this closure is not perfectly tight; therefore the whole connection is surrounded with an atmosphere of almost pure hydrogen, which is obtained and maintained by the india rubber ring *Uc*, which fits tightly on U_1 and V_1 and which is filled with hydrogen under excess of pressure through the cock *Ud*. Thanks to the small conduction of heat of new-silver no cooling is to be feared for the connections of V_{42} and U_{42} no more than for the packings of the cocks M_3 and N_3.

h. The cases V and U are joined and form one firm whole by the three rods *Ub* with the screw-fastenings U_{51} and V_{51}. The vacuum glass E_0, held by the india rubber ring *Ua*, rests with a wooden ring E_1 and a new-silver cylinder U_{31} against the refrigerator vessel F.

The whole construction can stand exhaustion, which is necessary to fill the apparatus with pure hydrogen. After the case U, of which the parts U_1 and U_2 are connected together by beams, and the case V are mounted separately, the vacuum glass E is placed in position and the case V is connected with the case U. The entire liquefactor is suspended from the ceiling by means of some rods and is particularly supported by the stout outlet tube F_2 for air and the outlet tube U_5 for hydrogen.

Plate II represents the circulation schematically: the pieces of apparatus in their true proportions, the connections only schematically. The liquefactor is designated by the letters ℒq. The compressed hydrogen is admitted through Kc, the hydrogen blown off is let out through Khd or Khc.

i. Before the apparatus is set working it is filled with pure hydrogen (the cock M being open) by means of exhaustion and admission of pure hydrogen along Kc. In the drying tubes $\mathfrak{D}a$ and $\mathfrak{D}b$ the pure hydrogen is freed from any traces of moisture which it might have absorbed.

§ 3. *The compressors and the gasometers.*

a. The hydrogen is put under high pressure by means of two compressors in each of which the compression is brought about in two steps.

While other physicists use compressors with water injection running at great speed of the same kind as I have formerly arranged for operations with pure gas (comp. Comm. N°. 14 of Dec. '94, § 10, and N°. 51, Sept. '99, § 3), I have used for the hydrogen circulation slowly running compressors (see Pl. II ☾ at 110 and ♄ at 80 revolutions per minute) which are lubricated with oil. To enable constant working with hydrogen the highest degree of purity of the gas is required. For if air is mixed with the gas it is deposited in the regenerator spiral and when some quantity of it is collected there it will freeze and melt alternately through the unavoidable variations of temperature in different parts of the spiral, so that even small quantities, taking into consideration that the melted air flows downward, necessarily must cause blocking. And such small quantities of air may easily come in through the large quantity of injection water which is necessary for the above mentioned compressors with water injection or may penetrate into the pieces of apparatus which are required when the same injection water is repeatedly used. Lastly the chance of losing gas is much smaller with the last mentioned compressors

and the manipulation much easier. These compressors are made very carefully by the BURCKHARDT company at Basel.

In the first compressor (℔ Pl. II, displacing 20 M³ per hour) the gas is raised in the first cylinder (double-acting with slide) from 1 to 5 and in the second cylinder (plunger and valves) from 5 to 25 atmospheres; in the second compressor ♄ (plunger and valves) in the first cylinder from 25 to 50 and in the second from 50 to 250 atmospheres. After each compression the gas is led through a cooling spiral. With the two first cooling spirals (those of ℔ Pl. II) an oil-separator is connected.

Safety-valves lead from each reservoir back to the delivery, moreover the packings are shut off with oil-holders (Comm. N°. 14 '94 and N°. 83, Pl. VIII). The hydrogen that might escape from the packing at ♄ is collected.

b. The high pressure compressor forces the hydrogen through two steel drying tubes 𝔇*a* and 𝔇*b* filled with pieces of sodium hydroxide (comp. § 2, *i*, and Pl. II), of which the first also acts like an air-chamber for the regenerator spiral. As in all the operations the gas (comp. *c*) originally is almost dry and comes only into contact with oil, we need only now and then run off a small quantity of concentrated sodium hydroxide solution.

c. For the usual working the compressors suck the gas from gasometers. If these should float on water the separation of the water vapour, which is inevitably taken along by the large quantities of gas displaced, which constantly come into contact with water, would give rise to great difficulties in the compression. Therefore we have used for this purpose two zinced gasometers, *Gaz a* and *Gaz b*, Pl. II, with tinned welds (holding each 1 M.³) floating upon oil [1]), which formerly (comp. Comm. N°. 14, Dec. '94) have been arranged for collecting ethylene [2]).

The cock *Kpa* (*Kpb*) is immersed in oil; likewise the connection of the glass tube, through which the oil of the gasholder can be visibly sucked up till it is above the cock, with the cover are immersed in oil. The india rubber outlet tube and the connection with the

[1]) The drawing sufficiently represents the construction which has been followed for economizing oil. The gasometers can be placed outside the laboratory and therefore they are protected by a cover of galvanized iron and curtains of tarred canvas, which can be drawn round them.

[2]) Formerly it was of the utmost importance that ethylene could be kept pure and dry in the gasometers. But now the purifying of ethylene through freezing in liquid air (comp. Comm. N°. 94*e* IX § 1) has become a very simple operation and weldless reservoirs for the storage of the compressed gas are obtainable in all dimensions.

copper exhaust tube are surrounded by a second india rubber tube filled with glycerine. From the cock onward the conduction can be exhausted; to prevent the tube from collapsing during the exhaust a steel spiral has been placed in it. A float with valve *Kph* (*Kpi*) prevents the oil from being drawn over into the apparatus.

Besides these gasometers we dispose of two other gasometers holding 5 M^3 each to collect hydrogen of a less degree of purity. They are built following the same system as the zinced gasometers for the economizing of liquid, carefully riveted and caulked and float on a solution of calcium chloride. The oil-gasholders serve only for the storage of very pure hydrogen and this only while the apparatus is working.

During the rest of the time the pure hydrogen is kept in the known steel bottles shown on Pl. II at $\mathfrak{R}ha$. When we wish to liquefy hydrogen, this is blown off into the gasometer through *Kg* (*Khe*, *Kpe* and *Kpb* for instance to *Gaz b*), after this gasometer, which has been left standing filled with hydrogen, is washed out on purpose with pure hydrogen. When we stop working the hydrogen by means of ☉ and ☽ is repumped along *Kpf* and *Kpc* through *Ka* and *Kf* into the reservoirs $\mathfrak{R}ha$.

The gasometers may be connected with the pumps or the liquefactor either separately or together. The former is especially required when the cryostat is worked (comp. XII) and for the purification of hydrogen (comp. XIV).

§ 4. *The cooling by means of liquid air.*

a. The liquid air is sucked into the refrigerator vessel *F* (Pl. I), which by *Ks* (Pl. II) is coupled to the vacuumpump $\mathfrak{F}$, along the tube *Pb* connected with the siphon of a vacuum bottle $\mathfrak{A}a$ containing liquid air.

This has been filled by catching the jet of liquid air from the apparatus (Pl. IV, fig. 2) in which it is prepared (comp. XIII), into the open glass (see the annexed fig. 1) and is kept, covered with a loose felt stopper *m* (fig. 1). To siphon the liquid air into the apparatus, where it is to be used, the stopper is replaced by a cap *h* (fig. 1) with 3 tubes; one of these *d* is designed to raise the pressure in the bottle with a small handpump, the other *c* is connected to a small mercury manometer, and the third *b* reaches down to the bottom, so that the liquid gas can be let out. (When the bottle is used for other liquid gases, *d* is used for the outlet of the vapours and *c* for the admission of the liquid gas). One of the first two tubes reaches as far as the neck. It may also be used

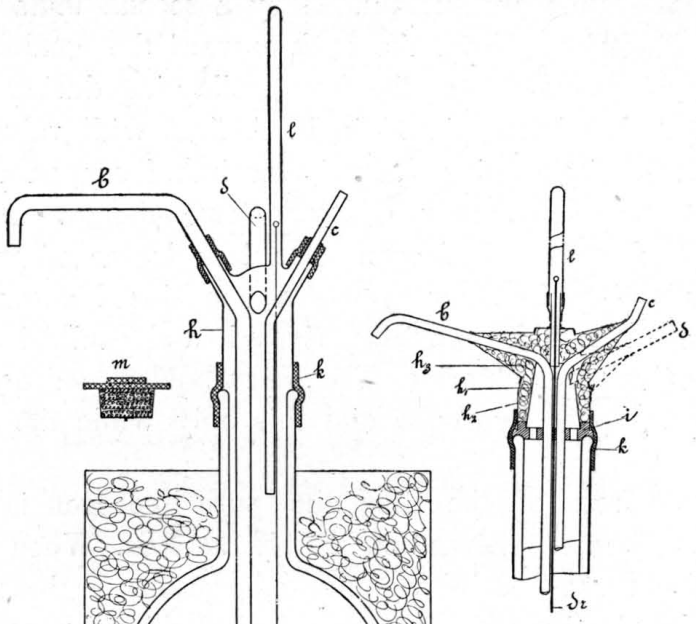


Fig. 2.

Fig. 1

to conduct liquid air from a larger stock into the bottle. With the cap a closed glass tube b is connected, in which an index of a cork float dr indicates the height of the liquid.

The caps, as shown in fig. 1, were formerly blown of glass and the three tubes were fastened into it by means of india rubber. Afterwards the cap h_1, as shown in fig. 2, with the three tubes and with a double wall h_2 of very thin new-silver have been soldered to form one whole, which is fastened on the bottle with an india rubber ring k. The space between the walls is filled with capoc h_3 and the whole piece rests on the neck of the bottle by means of a wooden block i. After it is placed on the bottle the cap is wrapped round with wool.

With a view to the transport the vacuum glass is placed in a card-board box with fibre packing.

When the siphon is not used it is closed with a piece of india rubber tubing, fitted with a small stopper. When we wish to

siphon over, this stopper is removed and the inflow tube *Pb* (Pl. I) is connected with the siphon-tube *b* (fig. 2) with a piece of india rubber tubing. To prevent breaking of the india rubber, which through the cold has become brittle, the new-silver tubes are arranged so that they fit into each other, hence the india rubber is not strained so much.

The admission of liquid air into the refrigerator vessel is further regulated with the cock *P*, Pl. I. When the float indicates that the reservoir is almost empty, another reservoir is put in its place.

The cock *Ks* is regulated according to the readings on the mercury manometer tube *Y*.

b. The air is caused to evaporate at a pressure of 15 mm., which is possible because a BURCKHARDT-WEISS-pump ℑ Pl. II is used as vacuumpump.

The vacuumpump is the same as that used in measurements with the cryostat containing a bath at —217° (comp. Comm. No. 94*d* June '05) and has been arranged to this end as described in Comm. No. 83 V. March '03. The letters at ℑ on Pl. II have the same meaning as on Pl. VIII of Comm. N°. 83. As has been described in Comm. No. 94*d* VIII, June '05, this vacuumpump ℑ, displacing 360 M³ per hour, is exhausted by a small vacuumpump, displacing 20 M³ per hour[1]) (indicated by ℜ on Pl. II).

§ 5. *How the liquefactor is set working.*

a. When the apparatus is filled with pure hydrogen, as described in § 2, and when air evaporating under low pressure is let into the refrigerator, for convenience the hydrogen, admitted through ℭ and ℌ Pl. II along *Kc*, is caused to stream through during some time with wide open cock *M*, Pl. I, for the forecooling of the whole apparatus. Then the cock *M* is regulated so that the pressure in the regenerator spiral rises slowly. It is quite possible for the apparatus to deliver liquid hydrogen at 100 atm., it has done so at 70 atm. As a rule, however, the pressure is kept between 180 and 200 atm. because then the efficiency is some times larger [2]). The liquefactor then delivers about 4 liters liquid hydrogen per hour. Part of the hydrogen is allowed to escape along *Kha* Pl. I fig. 2 (*Kd* Pl. II) for the forecooling of the siphon N_{61} Pl. I and the cock *N*.

As soon as liquid hydrogen begins to separate we perceive that the

[1]) When we use oxygen (comp. § 2 note 2), and a pressure as low as a few mm should be required, forecooling is required in the second refrigerator like *F*, where oxygen evaporates under low pressure, for instance towards ℜ.

[2]) v. D. WAALS has shown the way how to compute this (comp. note 1 § 2).

cock M must be tightened a little more in order to keep the pressure within the same limits.

When liquid hydrogen collects in L rime is seen on the tube N_{503}, Pl. I, fig. 2 near the cock N.

b. The gaseous hydrogen escapes along *Khd* (Pl. II) to ⑤ and to one or to both gasholders. When liquid hydrogen separates, the compressor ⑤ receives, besides the hydrogen escaping from the liquefactor, a quantity of hydrogen from the gasholders along *Kpa* and *Kpb*. New pure hydrogen is then admitted from ℜ*ha*, Pl. II, along *Kg*.

c. The float (L_{200} Pl. I) does not begin to indicate until a fairly large quantity of liquid hydrogen is collected.

§ 6. *The siphoning of liquid hydrogen and the demonstration of liquid and solid hydrogen.*

a. When the float L_{200}, Pl. I, shows that the glass is filled to the top (this usually happens an hour after the liquefactor is set working) the hydrogen is siphoned into the vacuum glasses *Hydr a*, *Hydr b* etc., Pl. II, which are connected behind each other so that the cold hydrogen vapour, which is led through them, cools them successively before they are filled. When one is full the next is moved one place further.

They are fitted with caps of the same description as the bottles for siphoning liquid air, figs. 1 and 2 in the text of § 4. Pl. III represents on a larger scale 2 bottles coupled behind each other and a third which has been filled, all as on Pl. II, in side- and top-elevation. The evaporated hydrogen escapes along d'_3 and d''_3 and further along K_o (see Pl. II) to the gasholder. The letters of the figures have the same meaning as in fig. 2; for the explanation I refer to the description of that figure in § 4.

The conduction of heat in the thin new-silver is so little that the new-silver tubes can be soldered in the caps h_2 and that they are sufficiently protected by a double wall h_{11} of new-silver with a layer of capoc between, which is again thickly enveloped in wool.

It has occurred that the india rubber ring k' has burst through the great fall of temperature, but in general the use of india rubber has afforded no difficulties, and hence the somewhat less simple construction, which would lie to hand, and through which we avoid cooling of the india rubber at the place where it must fit, has not yet been made.

b. If we desire to see the jet of liquid hydrogen flowing from

the cock N, Pl. I, we connect with the tube N_0 and the india rubber tube d_2, instead of the silvered flasks of Pl. II and Pl. III, a transparent vacuum cylinder fig. 3*a*, closed by an india rubber ring with a new-silver cap with inlet tube. After the cock is opened the india rubber outflow tube d_3 covers with rime and becomes as hard as glass; soon the first drops in spheroidal state are seen splashing on the bottom of the glass and the lively liquid fills the glass. If, as shown by fig. 3*b*, a glass cover is placed on the top, the glass may be left standing in the open air without the air condensing into it, which would hasten the evaporation. In the same manner I have sometimes filled non-silvered vacuum flasks holding 1 liter, where the liquid hydrogen boils vividly just as in the glass mentioned before. The evaporation is of course much less and the rising of the bubbles stops when the vacuum glass or the vacuum flask is placed in liquid air.

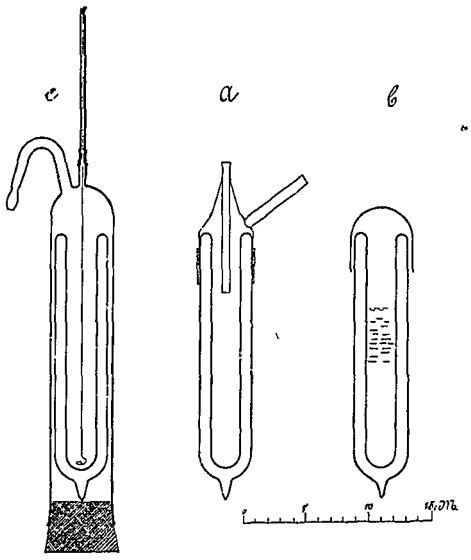


Fig. 3

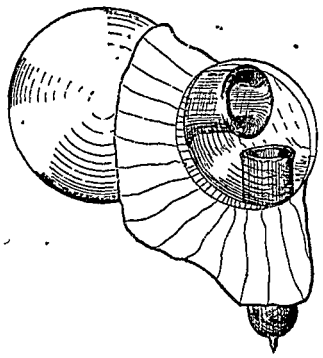


Fig. 4

To demonstrate the pouring of hydrogen from one open vessel into the other, I use a glass, cap round which a collar of thin india rubber sheet is bound (comp. the accompanying fig. 4). The flask from which and the glass into which we want to pour, the latter after being filled with liquid air and quickly turned down and up again (if this is not done quickly a blue deposit of H_2O from the air will come in), are placed under the cap, which fills with hydrogen and hence remains transparent, then with the india rubber round the neck of the bottle and round the glass we take hold of the two, each in one hand. Through the cap we can observe the pouring. The escaping hydrogen rises in the air as clouds.

In order to keep the half filled glass clear it is covered, under the pouring off cap, with a glass cap, and so it can be taken away from the pouring off cap.

c. It is very instructive to see what happens when we proceed to remove this cap and the glass is tilted over a little. Above the level of the liquid hydrogen thick snowy clouds of solid air are formed, the minute solid particles drop on the bottom through the extremely light hydrogen (specific weight $^1/_{14}$), there they collect to a white pulver which, when the hydrogen is shaken, behaves as heavy sand would behave in water. When the hydrogen is evaporated that sand soon melts down to liquid air [1]).

d. Solid hydrogen may be easily demonstrated when we place the glass, fig. 3*a*, under a bell as fig. 3*c* in which a wire can be moved up and down (for instance by fastening it into an india rubber tube) and connect the bell with the airpump. A starch-like white cake is soon formed, which can be moved up and down with the wire.

e. To fill a vacuum flask as shown on Pl. III we first cool it by washing it out with liquid air. The connection at N_0, Pl. I fig. 2 and Pl. III, is brought about simply by drawing a piece of india rubber tubing N_{81} over the new-silver tubes N_0 and C_0 fitting into each other, round which flannel is swaddled. This again is enveloped in loose wool. When some bottles are connected they are filled with pure hydrogen through the tube b_0 of *Hydr. a* after repeated exhaustion and care is also taken that each newly connected bottle is filled with pure hydrogen and that no air can enter the apparatus while the connections are being made.

When from the indications of the float L_{200} (Pl. I, fig. 2) we conclude that a bottle is full, it is disconnected, but as long as the liquid hydrogen is kept in this glass the evaporating hydrogen is allowed to escape into the gasholder, as is represented by Pl. III for *Hydr. c.* The disconnection at N_0 is simply effected by taking off the flannel band C_2, heating the piece of india rubber tubing N_{81} (unvolcanized) with one's fingers (or with a pair of pinchers arranged to this end) till it becomes soft again and can be shoved from the tube N_0.

§ 7. *Transport to the cryostat, closure of the cycle.*

a. The vacuum glasses filled with liquid hydrogen (see *Hydr. d* on Pl. II) are transported to the room where the cryostat $\mathfrak{C}r$ is mounted

[1]) All this has been demonstrated by me at the meeting of 28 May. To show the small specific weight of hydrogen I held a very thin-walled glass bulb, which sinks only a little in ether (as a massive glass ball in mercury), suspended by a thin thread in the glass with liquid hydrogen, where it fell like a massive glass ball in water and tapped on the bottom.

H. KAMERLINGH ONNES. Methods and apparatus used in the cryogenic laboratory at Leiden. X. How to obtain baths of constant and uniform temperature by means of liquid hydrogen. Pl. I.

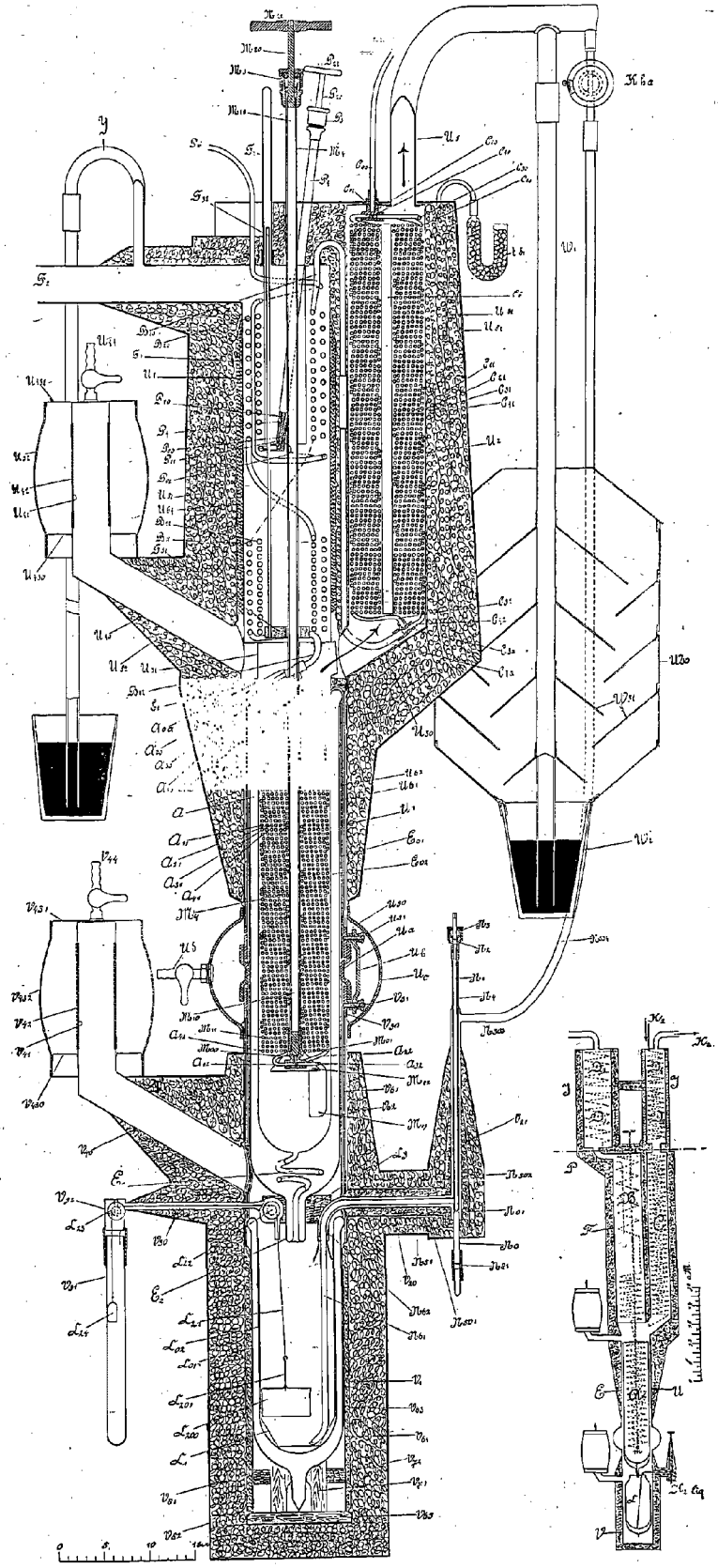
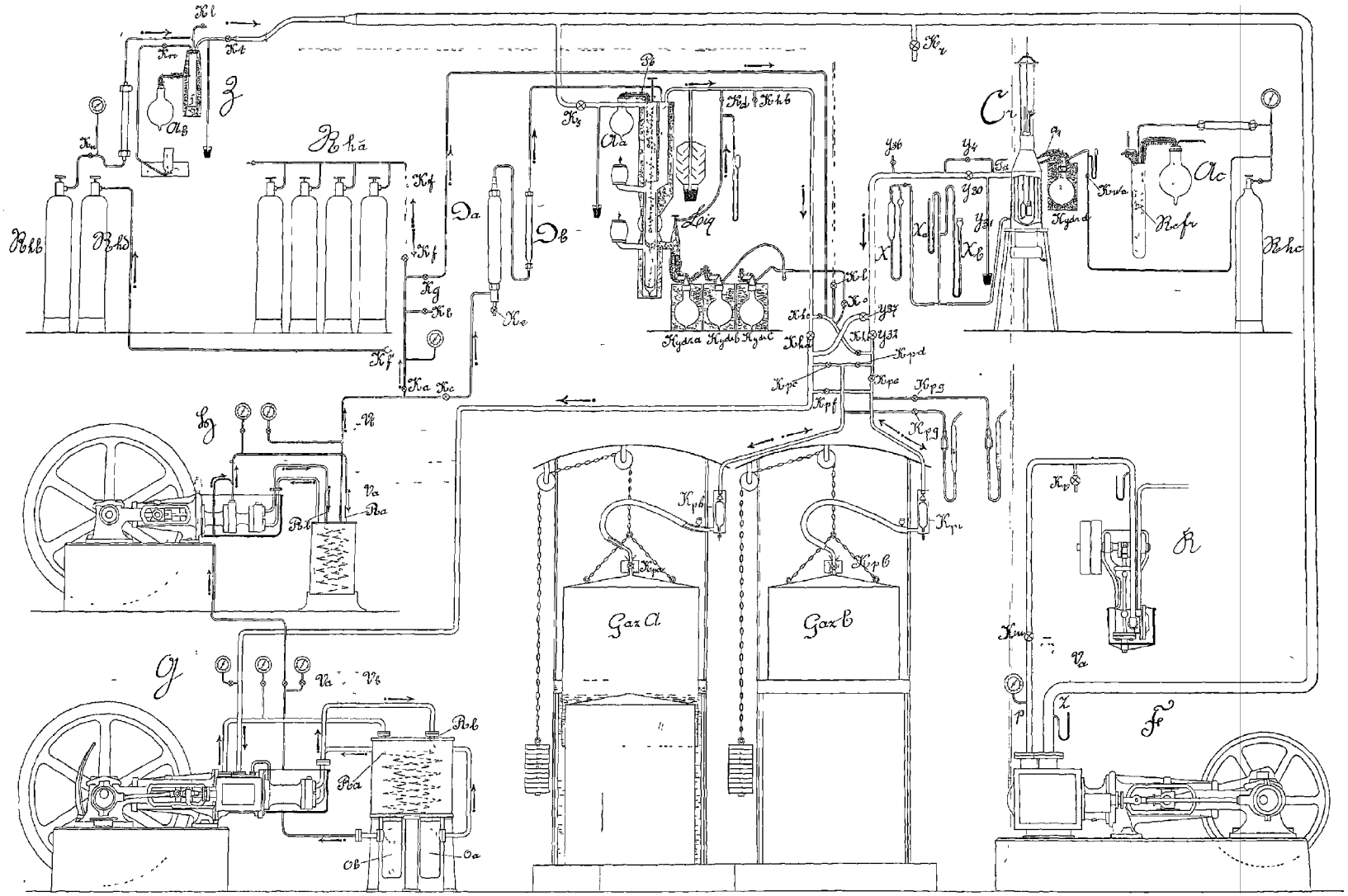


Fig 2.

Fig. 1.

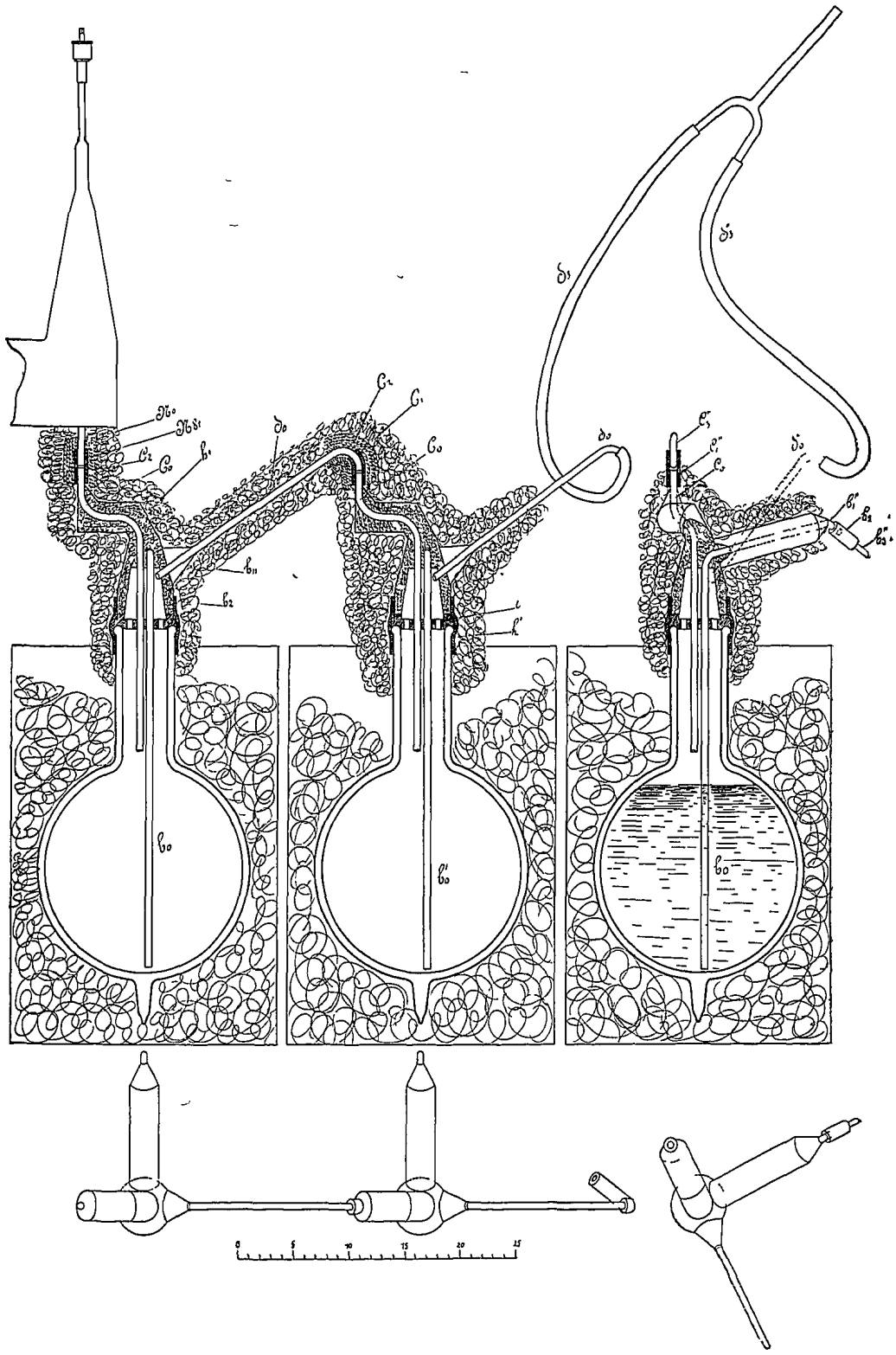
H. KAMERLINGH ONNES. Methods and apparatus used in the cryogenic laboratory at Leiden. X. How to obtain baths of constant and uniform temperature by means of liquid hydrogen.

Pl. II.



H. KAMERLINGH ONNES. Methods and apparatus used in the cryogenic laboratory at Leiden. X. How to obtain baths of constant and uniform temperature by means of liquid hydrogen.

Pl. III.



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into which the hydrogen is siphoned. To this end the tube b''_1 of Pl. III is connected (again by a piece of india rubber tubing, enveloped in flannel and wool) to the inflow tube a_1 of the cryostat and the tube d_0 to an inflow tube of pure hydrogen under pressure, which is admitted from $\mathfrak{R}hc$, Pl. II, along *Kwa*. With all these connections and disconnections care must be taken that there should always be an excess of pressure in the tubes that are to be connected, that the disconnected tubes should be immediately closed with stoppers but that first the apparatus after having been exhausted should preliminarily be filled with pure hydrogen. The liquid hydrogen is not admitted into the cryostat $\mathfrak{C}r$ until the latter has been cooled — coupled in another way (see the dotted line on Pl. II) — by means of pure hydrogen which has been led from $\mathfrak{R}hc$ through a cooling tube immersed in liquid air. This refrigerator is of a similar construction as the nitrogen condenser Pl. VII of Comm. N°. 83 (March '03). Instead of *Nliq* should be read H_2 and instead of *Ox liq*, *Aër liq*, which is siphoned from the vacuum flask $\mathfrak{A}c$. (comp. § 6).

During the siphoning of the liquid hydrogen into $\mathfrak{C}r$ the rapidity of the influx is regulated after a mercury manometer, which is connected with the tube *c* on the cap *h*, Pl. III (comp. fig. 2 of § 4).

b. From the cryostat the evaporated hydrogen escapes along Y_{37} into the compressor $\mathfrak{S}$, Pl. II, which can also serve as vacuumpump and which precautiously through $\mathfrak{P}$ and *Kf* at the dotted connection *Kf* stores the gas, which might contain minute impurities, in the separate reservoir $\mathfrak{R}hd$; or it escapes along Y_{32} and *Kpe* or *Kpd* into the gasholders *Gaz a* or *Gaz b*.

XI. *The purification of hydrogen for the cycle.*

a. This subject has been treated in Comm. N°. 94*d* IX. To be able always to obtain pure hydrogen, to make up for inevitable losses, and lastly to be freed from the fear of losing pure hydrogen, which perhaps might deter us from undertaking some experiments, a permanent arrangement for the purification has been made after the principle laid down in IX. The apparatus for the purification is represented on Pl. IV and is also to be found on Pl. II at $\mathfrak{Z}$.

The impure hydrogen from $\mathfrak{R}hb$ is admitted through *Kn* and along a drying tube into a regenerator tube (see Pl. IV) consisting of two tubes enclosing each other concentrically, of which the outer *a* serves for the inflow, the inner *b* for the outlet. Outside the apparatus *a* and *b* are separated as a_0 and b_0, within the apparatus from the point *c* downwards *a* is continued as a_1 and subsequently as the spiral