We gladly thank all who have assisted us in carrying out the measurements, in the first place Mr. F. M. PENNING, who was entirely responsible for the regulation and measurement of the temperatures and the calibration of the resistance thermometers, and made all the calculations involved every time; further Miss H. VAN DER HORST, who assisted in the temperature measurements and carried out and calculated the greater part of the observations with the helium thermometer; finally to Mr. G. J. FLIM, chief mechanic of the cryogenic laboratory and to Messrs. L. and A. OUWERKERK, with whom the far from simple management of the vapour cryostat was in very able hands.

Physics. — "*Methods and apparatus used in the cryogenic laboratory.* XVIII. *Improved form of a hydrogen vapour cryostat for temperatures between — 217° C. and — 253° C.*". By H. KAMERLINGH ONNES and C. A. CROMMELIN. Communication N°. 154*c* from the Physical Laboratory at Leiden. (Communicated by Prof. H. KAMERLINGH ONNES).

(Communicated at the meeting of January 29, 1921).

§ 1. *Introduction.* In a previous communication one of us has described a hydrogen vapour cryostat for temperatures between the melting point of oxygen and the boiling point of hydrogen [1]). During the preliminary determinations of the critical points of neon [2]) and of hydrogen [3]), made in this cryostat, it was found that in principle the apparatus properly performed its function, but at the same time we discovered certain faults and deficiencies. When therefore the modification, which had been foreseen all the time and by which it would become possible to take readings on a tube inside the cryostat, became necessary, we resolved with the assistance of Mr. FLIM, chief mechanic of the cryogenic laboratory, to revise the construction in all details and rather than execute the modifications as originally planned to build a new apparatus of somewhat larger dimensions. This new cryostat which in the various measurements has given almost complete satisfaction and may therefore be considered to have approached its final form, will be described in this paper.

The apparatus is shown in fig. 1, partly in section, partly in direct view, as appears easily from the different details. Moreover three sections are given at different heights, a view of the turnable drum and diagramatically the electric connections, as will be further explained later on.

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[1]) H. KAMERLINGH ONNES, these Proceedings 19, p. 1049, Leiden Comm. N°. 151*a*.

[2]) H. KAMERLINGH ONNES, C. A. CROMMELIN and P. G. CATH, these Proceedings 19, p. 1058, Leiden Comm. N°. 151*b*.

[3]) H. KAMERLINGH ONNES, C. A. CROMMELIN and P. G. CATH, these Proceedings 20, p. 178, Leiden Comm. N°. 151*c*.

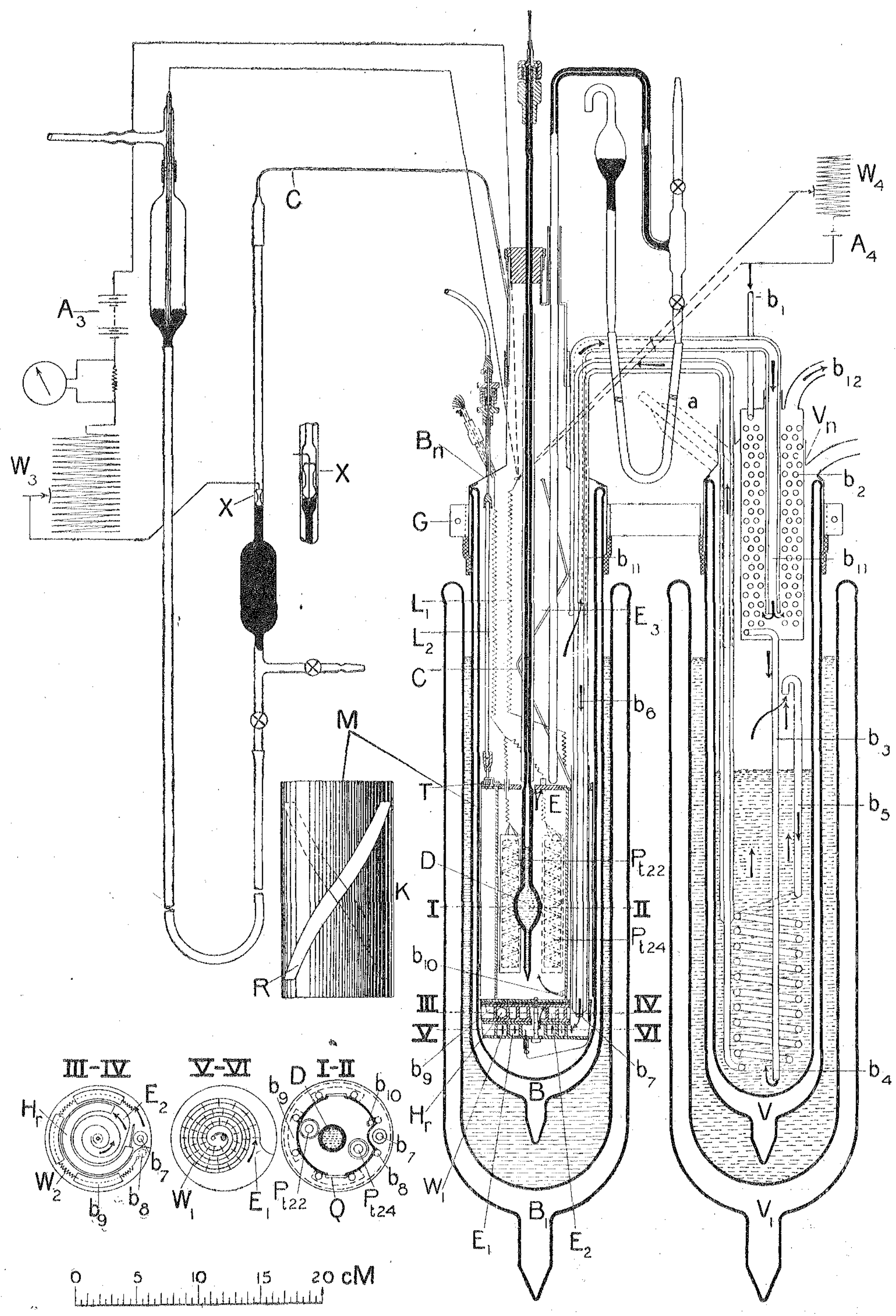

Fig. 1.

§ 2. *Description of the cryostat* [1]).

The cryostat consists of two vacuum vessels, viz. an evaporator V and cryostat B, both enclosed in vacuum vessels with liquid air V_1 and B_1 and closed by german silver lids or caps V_N and B_N.

The principle of the apparatus consists in the experimental space E being kept at constant temperature by a current of gaseous hydrogen, the temperature of which is kept at a definite value by automatic regulation of an electric current through a heating wire.

Let us follow the gaseous hydrogen on its way through the apparatus, as shown by the arrows. At b_1 it enters under small excess of pressure. For the manner in which the current is kept constant and regulated, we refer to fig. 6 of the previous paper on the vapour cryostat. It then flows through the copper spiral b_2, which is cooled, as will appear presently, by the waste hydrogen, and the tube b_3 (of german silver in order to minimize the supply of heat to the liquid hydrogen below) from which it escapes at b_4 bubbling up through the liquid hydrogen which fills the evaporator.

In this manner a fairly strong and regular evaporation of the liquid hydrogen is obtained; the hydrogen vapour passes into the tube b_5, which continues as a spiral under the liquid hydrogen, and hence into the double walled vacuum tube b_6 which carries the gas (cooled to about — 253°) to the lower end of the cryostat at b_7.

Here it enters the spiral-shaped heating space E_1 (see also section V—VI) and flows round a heating wire W_1 which heats the gas to about the desired temperature by means of an automatically regulated current. The space E_1 communicates at the centre through a hole with a second space E_2 above it. Here the gas first passes along a copper thermometer bulb H_2 (which serves for the regulation of the temperature, as will be explained further down), then along a resistance W_2 and finally rises through b_8 into a thickwalled copper tube going four times up and down, the horizontal parts of which are seen in section III—IV at b_9, the vertical soldered on the outside against the very thick copper mantle (for the purpose of a uniform temperature) of the experimental space E; this motion up and down serves to communicate the required temperature to the copper mantle. Finally the gas enters the experimental space E with the measuring instruments (in the figure a dilatometer D

[1]) We here refer to Leiden Comm. N°. 151*a* (these Proceedings 19, p. 1049) where many constructional details are mentioned and the principle of the apparatus is explained; at the same time the present description is so arranged, that it may be read and understood by itself.

and two platinum resistance thermometers Pt_{22} and Pt_{24} as used for the determination of the diameter of hydrogen [1]) passes through it and by the holes in the lid E enters the space E_2 above; it is then carried through the vacuum tube b_{11} into the space surrounding the spiral b_2, by which the gas inside acquires a preliminary cooling, and finally escapes by b_{12} to a gasometer.

The half *automatic regulation of the temperature* is very simple in principle. By the resistance W_1 the gas is heated to the desired temperature, the current being furnished by the accumulators A_3 (36 volts) and adjusted by the regulating resistance W_3. The gas-thermometer H_r already referred to, which is connected with the manometer through the capillary C, provides for the automatic closing and opening of the current, in a manner easily understood from the figure. As long as the temperature is too low, the manometer being properly adjusted, there is electric contact at D; when the temperature rises above the desired value, the contact is broken. When the cryostat is in action and everything properly regulated, the automatic arrangement is continually in action and the current is opened and closed at regular intervals (of say 10 or 20 seconds).

When this arrangement was tested, it appeared from the readings of the platinum resistance thermometers that owing to some inertia in the automatic action small fluctuations of the temperature in the experimental space of ·02° to ·03° were still present. With a view to a still finer regulation the resistance W_2 was then introduced in the space E_2.

The current through this small resistance is furnished by an accumulator A_4 and is regulated by hand by the observer at the galvanometer by means of the regulating resistance W_4. The deflection of the galvanometer shows the small variations of temperature much more quickly than the automatic regulator can act and the observer is able by a change of W_4 at once to bring back the temperature to the desired value. In this manner it is possible to keep the temperature constant to .01°, sometimes during hours.

The connecting wires of the various resistances are only shown diagrammatically in the figure. Thus L_1 represents the 4 wires of the automatic regulator and the resistance W_4, L_2 the eight wires of two platinum resistance thermometers Pt_{22} and Pt_{24}.

One of the principal desiderata in the previous simpler cryostat was the possibility to make visual observations in the space E. The apertures which had originally been made in the copper mantle for

[1]) E. Mathias, C. A. Crommelin and H. Kamerlingh Onnes, these Proceedings 23, p. 1175, Leiden. Comm. N°. 154*b*.

this purpose had afterwards been closed again by copper plates for safety, in order to avoid fluctuations of the temperature in consequence of the presence of these apertures in connection with the small heat-capacity of the gaseous hydrogen. On the latter account the vapour cryostat requires much greater precautions than an ordinary liquid cryostat and for this reason in our first trials all superfluous complications were avoided. The difficulty which was then feared (correctly, as we found later on) is met in the present model by providing the copper mantle with two diametrically opposite narrow glass windows and surrounding the mantle with a second one M of german silver (also shown separately in the figure). In this mantle two screw shaped slits have been cut. Thus a field K is left clear for illumination from behind and observation from the front.

The mantle M may be turned by means of a glass rod G and the cogwheel T which works in a rack fitted on the outside of the mantle at the top: by this means K may be moved vertically up or down. An experimental tube mounted axially in the space E may thus successively be observed from the bottom to the top. The resistance thermometers which do not need to be seen may be mounted excentrally.

In this manner the aperture for visual observation which might produce fluctuations of the temperature by radiation is reduced to a minimum, and moreover the mantle can be closed by turning far enough as soon as an observation is finished.

We have systematically investigated whether the opening did still cause any change of temperature and for this purpose have tried various sources of light, for instance a metal wire lamp with or without alum filter, diffuse daylight, etc. A lamp without a filter immediately produces a rise in the temperature of a few hundredths of a degree. When a heat filter (alum solution) was placed between the lamp and the cryostat, and the light was used with caution, no changes of the temperature of as much as .01° could be observed.

In the silver coating of the vessels B and B_1 narrow slots have naturally also been left open, and similarly in the coating of vessel V_1 in order that the evaporation of the liquid hydrogen may be followed. V is for the greater part unsilvered.

The construction of these vessels, which was particularly difficult in the case of the large outer ones, we thank to the exceptional ability of the chief glassblower Mr. O. Kesselring. It seems as if with these largest vessels the limit of what can be done with cylindrical vessels has almost been reached. They have to be treated with the utmost care and have to be very slowly cooled, at least for half an hour, before liquid air may be poured in. Even then it has happened repeatedly that a vessel of this kind burst, specially during the addition of liquid air in the narrow space between the vessels.

To begin with we feared that the very low temperatures near the boiling point of hydrogen would give difficulties and might

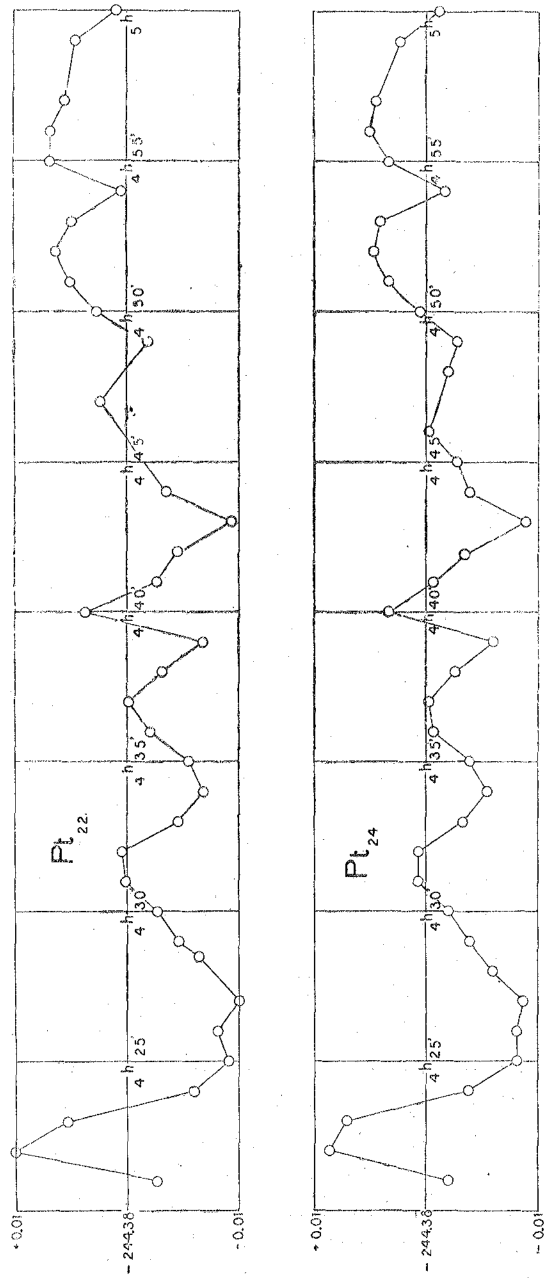

Fig. 2.

possibly not be attainable at all[1]). This fear turned out to be unfounded. Temperatures of — 250° and — 251° do not procure any special difficulties.

It was mentioned above, that the temperature in the experimental space could be kept constant to .01 of a degree during a long time. In confirmation of this we here reproduce two curves drawn according to the galvanometer-deflections of the two thermometers Pt_{22} and Pt_{21}, representing the deviations of the temperature as a function of the time. They refer to an observation at — 244.°38. It must be mentioned, however, that the management of the cryostat is far from easy or simple. A great deal of routine and experience is required to work the cryostat in such a way that the above constancy of the temperature is attained, and it is only after repeated vain efforts that even our highly trained technical staff has now learned to make the apparatus answer to the slightest hint.

Much is due to Mr. G. J. Flim, chief mechanic of the cryogenic laboratory, under whose able guidance the apparatus was designed and constructed, and further to Messrs. L. and A. Ouwerkerk both attendants 1st class, under whose supervision the apparatus now works so excellently.

[1]) Comp. Leiden Comm. No. 151*a* p. 4 note 1.