

The Liquefaction of Hydrogen

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or distribution of refracting substance is similar in such lenses or combinations. And, moreover, the preceding geometrical constructions afford a ready means for effecting the transformation from any assigned type of the combinations named to the type of any other. The method is applicable to astigmatic lenses or combinations in which the curvatures are not all of the same sign.

DISCUSSION.

Prof. S. P. THOMPSON said he had never seen the treatment of an ellipsoidal lens before. Reusch had deduced the laws of crossed cylindrical lenses from the properties of the paraboloidal lens. The author's method was, so far as he knew, new, and would be very convenient to work with.

XXXV. *The Liquefaction of Hydrogen.* By MORRIS W. TRAVERS, D.Sc., Fellow of University College, London*.

[Plate IV.]

[*Note by Prof. Ramsay.*—In the course of our researches on the gases of the atmosphere, it became evident that the only means of separating neon in a state of purity from the helium with which it was mixed, was by cooling the mixture of the two gases by aid of liquid hydrogen at its boiling-point under atmospheric pressure. In order to effect this separation, Dr. Travers undertook to design and make an apparatus which would produce liquid hydrogen in quantity; and the following account of the experiments shows that his hopes have been justified.]

The Liquefaction of Hydrogen.

THE experiments described in this paper were carried out solely for the purpose indicated in Prof. Ramsay's introductory note. The liquefaction of hydrogen has already been accomplished, and my experiments differ neither in principle nor in conclusions from those of Dewar. Since,

* Read November 23, 1900.

however, they show that the production of liquid hydrogen is neither so difficult nor so costly as might have been expected, I have decided to publish an account of them.

Without touching on controversial matter, the history of the subject may be stated in a few words. In 1884 Wroblewski (*Comptes Rendus*, c. p. 979) showed that when hydrogen, compressed into a capillary glass tube cooled to the temperature of liquid oxygen, was allowed to expand from 100 atmospheres to atmospheric pressure, a sudden appearance of mist or spray in the tube indicated that partial liquefaction of the gas had taken place. In 1895 Olszewski (*Phil. Mag.* 1895 [5] xl. p. 202) confirmed these experiments by repeating them on a larger scale. Using first a glass tube of 7 mm diameter, and afterwards a steel cylinder lined with glass, from which the gas escaped through a cock, he found that the hydrogen remained in the liquid state for a sufficient time to enable him to determine its temperature by means of a platinum resistance-coil enclosed in the apparatus.

In these experiments the gas which remains in the glass tube or cylinder does work on that part of it which is escaping in overcoming the friction in the cock, the heat generated being carried away by the gas. Were the process truly adiabatic, the fall of temperature inside the apparatus might be calculated approximately from the formula

$$\frac{T_1}{T_2} = \left(\frac{p_1}{p_2} \right)^{\frac{k-1}{k}},$$

where p_1 and p_2 are the initial and final pressures, T_1 and T_2 the initial and final temperatures, and k the ratio of the specific heats. The failure to produce any quantity of liquid is chiefly to be attributed to the great difference between the thermal capacities of the gas and of the vessel into which it is compressed.

Lord Rayleigh and Kammerlingh Onnes have suggested independently that it might be possible to liquefy hydrogen by allowing the gas to do work in driving a heat-engine. The cylinder of Onnes's engine is supposed to be constructed of a non-conducting substance of low specific heat and to be enclosed in an insulated space ; a long piston-rod transmits

the energy of the system to some mechanism placed outside the apparatus. A mixture of liquid and saturated vapour would escape from the cylinder, and this alone adds to the difficulties to be overcome in constructing the machine.

Lord Rayleigh's suggestion of applying a turbine in a similar manner could be more easily realized.

By either of these processes, if conducted adiabatically, it should be possible to liquefy a *perfect* gas; and we now come to a method which can only be applied to gases which are *imperfect* and show a divergence from the simple gas law.

In the case of a "perfect" gas we may write the equation

$$p_1 v_1 = p_2 v_2,$$

where $p v$ represents the total energy of the gas. If such a gas were allowed to expand either without doing work or in doing work in such a manner that the whole of the heat generated were absorbed by the gas, no temperature-change would take place in the system. These conditions could be partially realized by allowing the gas to enter a vacuous space through a large orifice, as in Gay-Lussac's experiment, or by forcing it through a porous plug so constructed that the velocity of the escaping gas is reduced to a minimum. The latter method was adopted by Joule and Lord Kelvin, and the results of their experiments show that for all known gases the equation must be written

$$p_1 v_1 = p_2 v_2 + Q,$$

where Q is the quantity of heat absorbed or generated in performing internal work. In these experiments the gas was compressed by a pump and escaped at constant temperature and pressure through a plug of silk fibre. Work was done on the gas by the pump, and the heat generated ($p v + Q$) was absorbed by passing it through a coil immersed in water. On its way to the plug the gas flowed in a steady stream, doing no work. In the plug, work was done against friction and the heat generated was absorbed by the gas, so that any temperature-change which occurred could be considered as consequent on the performance of internal work only. If the gas were allowed to escape at a jet, instead of passing through a plug, it is possible that, even in the case of a perfect

gas, a fall of temperature would occur close to the jet owing to the conversion of molecular energy into kinetic energy: the effect would, however, be entirely local, and would disappear as the velocity of the stream was reduced in the formation of eddies. The results of Joule and Lord Kelvin, and of others of a more recent date, show that in the case of the commoner gases a fall of temperature takes place on free expansion. With hydrogen, however, and probably with helium also, the temperature rises; these gases being, to use Regnault's expression, "*plus que parfait*."

It was first suggested by Hampson in England and Linde in Germany, that the principle of free expansion might be applied to the liquefaction of air. In the Hampson-Linde process the compressed air *flows* through a coiled copper tube, and expanding at a jet becomes cooled. The expanded gas passes back over the outside of the coil, losing any velocity it may have attained in forming eddies, so that any external work done results in the formation of heat which is absorbed directly by the gas. The effective cooling is the result of the work done against internal stresses only; and since the temperature of the expanded gas is lower than that of the coil, the latter together with the compressed gas it contains becomes cooled.

Within the last two years Dewar has shown that at a temperature close to -200° C. hydrogen also behaves as an *imperfect gas* and becomes cooled when suffered to expand freely. His experiments, which are described in the 'Chemical News' for March 1900, led him to apply this discovery to the liquefaction of hydrogen in quantity, and this he has successfully accomplished. The details of the method employed have not however been published.

Since there has been some confusion in dealing with the subject, it may be well to point out once more here that there is an essential difference between the processes employed by Olszewski and Dewar. There is no cooling of the gas *in the coil* of the Dewar apparatus owing to the performance of work; this is done entirely by the pump, and the gas merely flows along the tube in a steady stream and transmits the pressure to the jet. The cooling must be attributed entirely to the performance of internal work consequent on change of

volume only. In Olszewski's experiments the pressure in the cylinder is not maintained, and work is done by the gas which it contains.

The temperature at which the Joule-Thomson effect for hydrogen changes sign has yet to be determined; it probably lies very low.

I shall now proceed to describe my own experiments. In a preliminary experiment the gas, under a pressure of two hundred atmospheres, was cooled to -80° C. by passing through a coil immersed in a mixture of carbonic acid and alcohol, and was then allowed to expand at the jet of a Hampson air-liquefier, the coil of which had previously been cooled to the temperature of liquid air. Under these conditions it appeared that progressive cooling did not take place, and it may be concluded that at -80° C. hydrogen is still a *perfect gas*.

Four attempts were made to liquefy hydrogen before an apparatus was constructed which gave satisfactory results. These experiments, which occupied about three months, I shall not describe; it suffices to state that they served to show that hydrogen remains a *perfect gas* down to very low temperatures.

The details of the structure of the apparatus finally employed in liquefying hydrogen are shown in Plate IV.; text-fig. 1 indicates the general arrangement of compressor, &c.

The hydrogen from the compressor under a pressure of 200 atmospheres enters the liquefier through the tube, and passes through a coil A, which is cooled to -80° C. in a mixture of solid carbonic acid and alcohol. It then enters the coil contained in the chamber B, which is continually replenished with liquid air during an experiment. The lower portion of this coil passes into the chamber C, which is closed and communicates through the pipe *ff* with an exhaust-pump; liquid air flows continuously from B into C through a pin-valve, controlled by a lever *b*, and boiling under a pressure of 100 mm. of mercury lowers the temperature to -200° C. The gas now passes into the regenerator-coil D which is enclosed in the vacuum-vessel H, and, expanding at the valve E, passes upwards through the interstices of the coil and the annular space F, surrounding B and C, to the outlet G,

whence it can return through *w* and R and the cock *i* to the main supply-pipe N. The liquid which separates from the gas is ultimately collected in the vacuum-vessel K, which can easily be removed.

In constructing the apparatus the coil D was wound on the thin steel tube *c* which contains the valve-rod. The latter is screwed at its lower end into a perforated brass cylinder, soldered to the end of *c*, enclosing the expansion-jet. By turning the milled head *a*, the width of the annular space between the jet and the end of the valve-rod can be accurately adjusted and the flow of gas controlled. This valve was made for me by Brin's Oxygen Company after the pattern of Dr. Hampson, who first applied it in his apparatus for liquefying air. To the use of this form of valve I must attribute the success of the work, for, unlike the pinhole-valve, it does not become blocked with the impurities which separate from hydrogen obtained by treating commercial zinc with sulphuric acid. The coil itself consists of 80 feet of solid drawn copper tube of $\frac{5}{64}$ inch internal and $\frac{9}{64}$ in. external diameter; in winding it the spirals ran alternately away from and towards the central tube, and great care was taken to preserve a uniform external diameter of $2\frac{3}{4}$ inches. The coils were carefully spaced and fixed in position with solder as each layer was wound.

The length of the regenerator-coil D was 7 inches; and it must be pointed out here that in absence of all quantitative knowledge as to the behaviour of hydrogen at low temperatures, the choice of this dimension was a matter of guess-work; it was found, however, to be sufficient.

The next step in the construction of the apparatus was to fix the flanged plates *d* and *e*, which form the top and bottom of the chamber B, onto the tube *c*. The coil passes through both these plates, and *e* is also pierced for the passage of the exhaust-pipe *f* and for the liquid-air valve which is controlled by the rod *b*; the latter is screwed through a block fixed to the upper surface of *e*, so that by turning *c* the conical point closes to a greater or less extent the hole in the plate. All these junctions were made with hard solder; the tube *g*, which fits exactly over *d* and *e*, was then fixed in position with soft solder.

To allow of the escape of the hydrogen gas after its passage through the coils, a brass tube *k* of the same external diameter as the coil was fitted at the top to *g* by means of a collar soldered to both tubes, and supported by distance-pieces at the bottom. The annular space *F* so formed communicates with the escape-pipe *G*, as shown in the figure and section; the cold gas passing through *F* forms an excellent insulator for the liquid-air chambers *B* and *C*.

To support the whole apparatus, and to afford a means of securing the vacuum-vessel *H*, a collar *l* is soldered to the tube *k* and to a tube *m* 4 inches in diameter, which rests on a flange *n* in a hole in a shelf attached to the wall of the compressor room. The space between *m* and *k* is packed with animal wool, as is also the space within the containing-cylinder *Q*.

The vacuum-vessel *H* is of such a diameter that when the coil *B* and the tube *k* are covered with a single layer of flannel it exactly fits over them. To make a gas-tight junction a rubber ring, which fills the space between the vacuum-vessel and the inner wall of *m*, is pressed between a brass ring *o* and a gland *p*. The ring *o* rests on three short studs on the inside of *m*, and the gland is forced home by three nuts and screws *q q* which are fixed at their upper ends into the flange *n*.

When the gland is in position the only means by which gas or liquid can escape from the apparatus is by the tube *G*, or through the opening at the bottom of the vacuum-vessel *H*. It is, of course, intended to draw off the liquid at the latter opening, and as it is quite impossible to employ a stopcock for the purpose, the following arrangement has been adopted. The vacuum-vessels *H* and *K* are both enclosed in a glass tube *LL*, which is closed at the bottom and is connected at the top by a rubber sleeve *s* to a brass tube *h* which forms part of the gland *p*; a short copper tube is soldered into *s* and terminates in a stopcock *r*. When *r* is closed any liquid formed at the valve *E* is retained in *H*; but when *r* is opened the liquid can flow into *K*, as the gas produced by its evaporation can then escape. The lower part of the tube *L* is enclosed in a large vacuum-vessel *M*, which contains a small quantity of liquid air during the experiment; it serves rather to

prevent the frosting of the outside of *L* than to exclude heat.

The hydrogen escaping from *G* passes through the rubber tube *w* into the tube *R*, which communicates directly with the cylinder *P* (text-fig.) and through the stopcock *i* with the main supply-pipe *N* connecting the gasometer and the compressor. The cylinder *P* is of sheet zinc, and is soldered to the three brass tubes *R*, *S*, and *T*. The tube *S*, which is lined with glass and has a window in front and behind, contains the nozzle of the tube leading from the cylinder μ in which the water used to lubricate the cylinder of the compressor is separated; this arrangement prevents the loss of the gas which escapes each time the water is discharged. The tube *T* reaches to the bottom of a deep vessel (fig. 1, ϵ) filled with water; it serves also as an escape for the gas issuing from *G* before the cock *i* is opened.

The tube *f* communicates with an exhaust-pump which is not shown in either figure. It is a simple double-action pump with a single cylinder of 3-inch bore and 6-inch stroke, and, driven by a half-horse-power gas-engine, maintains a vacuum of 100 mm. of mercury in the chamber *C*. The barrel and plug of the stopcock *t* are bored so that *C* can be cut off from the pump and opened to the air; through the stopcock *v* the pipe *G* can be placed in communication with the pump.

It is now convenient to call attention to the general system of heat-insulation in the apparatus. The coil *A* is surrounded with solid carbonic acid and alcohol, contained in an earthenware battery-jar which is unprotected; the tube between *A* and *B* is surrounded with a wrapping of animal wool and covered with baize. *B* and *C* are protected by the cold gas returning through the annular space *F* after passing through the regenerator-coil *D*; additional protection is afforded by the layer of animal wool inside the cylinder *Q*. The increasing steepness of the temperature-gradient at *C* is compensated for by the protecting influence of the upper part of the vacuum-vessel *H*; the vacuum-vessel *M*, which contains liquid air, serves as a protection to *K* and the lower part of the regenerator-coil *D*; it also prevents deposition of moisture on the tube *L*. The method of supporting the apparatus by the

tube *m* answers admirably, for as the space between *m* and *n* is packed with wool, the gland *p* only becomes frosted over when the experiment is at an end, showing that the influx of heat in this direction is inconsiderable.

The hydrogen gas was obtained by the action of dilute sulphuric acid on commercial granulated zinc, and was stored in a gasometer over water. The gasometer consists of a cylinder of sheet iron (No. 16 gauge), 6 feet in height and 5 feet 6 inches in diameter, inverted in a cylindrical tank which was filled with water. The gas enters and escapes through a 2-inch iron pipe, passing through the bottom of the tank and terminating inside a small dome 6 inches in diameter on top of the inner cylinder. This arrangement makes it possible to expel the whole of the gas from the gasometer without danger of introducing water into the supply-pipe. Before filling the gasometer the water in the tank is saturated with hydrogen by passing a stream of the gas through a tube reaching to the bottom. This operation occupies about five days.

The main bulk of the hydrogen is generated in the following manner. About 40 lb. of zinc are placed in a beer-cask fitted with a tap-funnel, a delivery-tube, and an escape-pipe, which passes into a vessel filled with water and so acts as a safety-valve; there is also a stoneware cock at the bottom for drawing off spent acid. When all the air has been expelled from the cask the gas, after passing through a wash-bottle filled with a solution of potassium permanganate, is allowed to enter the gasometer. The latter is thoroughly *washed out* with hydrogen before the main quantity is collected. The preparation of the hydrogen occupies five hours.

The general arrangement of the plant for the compression of the hydrogen, which is carried through the pipe NN to the cock and temporary communication made by means of a lead pipe σ with two screw-unions, is shown in text-fig. 1. The hydrogen, or air when the latter is to be liquefied, is first of all taken into the low-pressure cylinder β of the compressor, which is driven by a 5-horse-power motor, and passes thence through the coil, kept cool by a current of water which circulates through the tanks surrounding the cylinders and coils, and enters the high-pressure cylinder through the

tube δ under a pressure of about 16 atmospheres. A small quantity of a mixture of glycerol and water containing 5 per cent. of caustic soda is taken into the low-pressure cylinder together with the gas. The mixture is contained in the vessel η , and the flow is controlled by the glass stopcock and arrangement shown in the figure. In the second cylinder θ the pressure is raised to about 200 atmospheres, and the gas, after passing through the coil ω , enters the cylinder μ , in which the water used in lubricating the cylinders is separated and expelled through the cock κ . This water, together with a little gas, passes along the tube u and enters the cylinder P: the water flows into the tank ϵ , and the gas, during the compression of the hydrogen, is allowed to return to the gasometer through the cock i . The details of this apparatus have already been given.

The gas from μ passes into the cylinder λ , which contains lumps of solid caustic potash to remove traces of moisture or of other impurities. This cylinder is employed in compressing both air and hydrogen, and can be connected by the tube τ either with a Hampson air-liquefier or, as in the figure, with the coil A of the liquid-hydrogen apparatus. The tube τ also communicates with a gauge and with a cock, through which, if the pressure becomes too high, the excess of gas may be allowed to escape into the pipe NN connecting the gasometer and the compressor. The liquefier, of which the detail has already been given, does not require further description. It is sufficient to state that the gas, after passing through the coils enclosed in Q and L, expands at a valve within L controlled by the milled nut a , and finally returns by the tubes G, w , and R and the stopcock i to the tube N.

The loss of gas during each experiment amounts to about 10 per cent. of the whole; and since air and other gases of higher boiling-point separate as solids in the vacuum-vessel H, the gas becomes purer each time it is used.

During the two or three days immediately preceding an experiment, the compressor is employed in producing liquid air. For this purpose we use a Hampson liquefier, which is capable of yielding about 1.25 litres of the liquid per hour. The liquid air is stored in vacuum-vessels capable of holding altogether about 8 litres; comparatively little loss occurs

through evaporation, and the vessels are usually filled up on the last morning. After preparing the liquid air it is advisable to take the compressor to pieces and carefully inspect the valves, springs, and fibre packings. In the meantime the Hampson machine is removed, the connexions are made between the potash cylinder and the hydrogen liquefier, and the lead pipe connecting the supply-pipe NN with the intake of the compressor is placed in position.

The actual experiment requires four persons. One controls the valves *a* and *b*; the second attends to the compressor, regulates the escape of the water from the cylinder μ , and opens or closes the cock *x* as the pressure rises or falls; the third sees that the vessel in which the coil A is immersed contains sufficient solid carbon dioxide; the fourth hands the vacuum-vessels of liquid air as they are required.

The first step in the operation is to cool the liquefier to the temperature of liquid air. Liquid air is first poured into the chamber B, and thence flows into C by connecting it with the exhaust-pump through the cock *t* and turning the valve *b*; when C is partially filled and the vacuum-gauge indicates that the liquid air is not evaporating at a great rate, the valve *b* is closed and the cock *t* is turned so as to cut off the exhaust and leave the chamber open to the atmosphere (p. 565).

The vacuum-vessel M and the tube L with the vacuum-vessel it contains are removed by rolling up the rubber sleeve *s* on to the tube *h* and lowering the cradle in which M is suspended. The rubber cap carrying the tap *v* is then fitted to the nozzle of H and connected with a rubber tube dipping into a vacuum-vessel filled with liquid air.

The escape-pipe G, from which the rubber tube has already been removed and replaced by a rubber cork, is now connected with the exhaust-pump through the cock *v*. Liquid air is drawn into the vacuum-vessel H, and on closing the stopcock V boils under reduced pressure, cooling the regenerator-coil to below -200° C. By closing the cock *v*, removing the rubber cork, and opening the stopcock V, the liquid air flows out of H. The rubber cap securing V is now removed, the tube L and the vacuum-vessels M and K are replaced in position, and the rubber sleeve *s* is secured to L with a single turn of copper wire.

Meanwhile the assistant in charge of the compressor has

removed all air from the compression-apparatus by opening the cock α (text-fig. 1), allowing the compressor to make a few revolutions and then stopping it and opening the cock ρ . This operation is repeated three or four times; the pressure is then allowed to rise, the valve a being closed, and the gas is allowed to escape, if necessary, through the cock x into the pipe N. The arrangements are made so that the pressure is raised to 200 atmospheres by the time the liquefier has been cooled and the vacuum-vessels K, &c., replaced.

The remaining operations may be shortly described:—

Communication is once more established between the chamber C and the exhaust-pump, and the valve b is carefully regulated so that the liquid air does not enter too fast; a too rapid flow is at once indicated by a fall of the mercury in the vacuum-gauge. The expansion-valve is then opened by turning the milled nut d , and the gas, passing upwards through the coils, through the annular space F, through the tubes G, w , and R, finds its way into P, and is allowed for a few moments, in order to remove air from the apparatus, to escape through the water in the tank ϵ . The cock i is then opened, and the gas is allowed to circulate through the system. The chamber B and the vessel containing the coil A are continually replenished with liquid air and solid carbonic acid respectively.

The whole difficulty in this part of the experiment lies in properly regulating the escape of the hydrogen. The rate of flow of the gas is roughly indicated by the height of the glycerol in the gauge z , which shows the pressure in the interior of the apparatus caused by the friction of the gas in the tubes G, w , and R. It is intended in future experiments to introduce in place of w a coil of lead pipe, and to connect the top of the glycerol gauge with a tube leading into the cylinder P, as it will then give an absolute reading of the rate of flow of the gas.

The reasons for which it is necessary to carefully regulate the valve are twofold. Firstly, the hydrogen must not pass too quickly through the refrigerating-coils else the gas is insufficiently cooled; secondly, since liquid hydrogen has a very low specific gravity, the gas and liquid do not separate readily at the jet, and much of the latter is lost. Further,

since the efficiency of the regenerator-coil is dependent on the rate of transmission of heat through its walls—and this is proportional to their superficial area—the maximum effect is attained with a limited quantity of gas.

To guard against blocking of the valve by the deposition of solid impurities, the milled nut *a* is turned slowly backwards and forwards during the whole experiment. In the valve E the screw fits so tightly into the brass cylinder containing the jet that no gas can escape from the liquefier through the steel tube *c*, and it is necessary at times to apply some force to *a*. In constructing another machine I should either place the screw on the valve-rod in the tube *c* about two inches above the valve, or I should ease the screw in its socket and place a gland round the valve-rod at the top of the steel tube *c*.

There appears to be no danger of the coil becoming blocked through the deposition of solid matter inside it, even though the hydrogen contains two or three *per cent.* of air and perhaps traces of arseniuretted hydrogen, hydrocarbons, &c. It must be remembered that within the regenerator-coil, even very close to the jet, the temperature of the gas does not fall below its critical point or the coil would become filled with liquid, and it appears that this is not the case. Under these conditions a gas is capable of holding a considerable quantity of solids *in solution*, a phenomenon which has not been fully explained; this may account for the fact mentioned above. Solid impurities do, however, separate from the liquid in the vacuum-vessel H, but as the liquid on its way to the vessel K is obliged to pass through a piece of baize pressed down into the bottom of H by a spring, it can be collected perfectly clear.

Almost immediately the valve E is opened the inside of the vacuum-vessel H becomes coated with a layer of white matter, which is probably solid air; and shortly after, placing a light behind the lower part of the apparatus and opening the cock *r*, liquid is seen running in a fairly rapid stream from the nozzle of H and collecting in K. The flow of the gas from the jet E can then be checked, the tubes M and L lowered, and the vacuum-vessel K, which is attached to a wire, withdrawn and

placed in another vessel containing a little liquid air. It would then be possible to place another vacuum-vessel in L, to restore L and M to their original positions, and to prepare a further quantity of liquid hydrogen ; this has not, however, been attempted.

The apparatus which I have described, with the exception of the compressor, motor, and Hampson air-liquefier, which together cost about £200, is comparatively inexpensive. The gasometer cost £15, the material used in making the liquefier amounted to about £5, and possibly £30 was spent in the experiments in addition to the sum named. Each time liquid hydrogen is made 5 kilos of solid carbonic acid and 8 litres of liquid air are used ; this involves a further cost of about £1. These figures indicate that the cost of liquid hydrogen is not excessive.

I am much indebted to Mr. Holding, lecture-assistant in the department, for assistance in constructing the liquefier and in carrying out the experiments. I also wish to express my most cordial thanks to Dr. W. Hampson for his valuable advice and for the assistance which he has so willingly rendered.

University College, London.

DISCUSSION.

Dr. HAMPSON said he would like to offer a correction. Dr. Travers had said that he (Dr. Hampson) was the first to liquefy air by the application of the counter current process to the Joule-Thomson effect. Although he was the first to make the proposal, he was not the first to apply it. Dr. Travers had referred at length to a valve which he (Dr. Hampson) had devised, but as it was straightforward common sense he did not wish to accept any credit for the use it had been to the author in his experiments. He would like to call attention to the remarkable features of the work in two respects :—The economy of means and the magnitude of results. By means of liquid hydrogen Prof. Ramsay and Dr. Travers had succeeded in obtaining the physical and other properties of some of the rarer gases.

Prof. S. P. THOMPSON said the author had asserted that the Joule-Thomson effect for hydrogen changes in sign at some temperatures, and expressed his interest in the fact that it was possible to get a cooling effect by allowing hydrogen to expand.

Mr. BOYS asked if it was necessary or desirable to allow the hydrogen to expand to atmospheric pressure.

Dr. TRAVERS said the mechanical advantages of this were great.

Dr. LEHFELDT asked if there had been any attempt to determine the temperature of the liquid, and, secondly, if the apparatus could be employed to determine the magnitude of the Joule-Thomson effect.

Dr. HARKER asked if the temperature at which the Joule-Thomson effect changes sign was known.

Dr. DONNAN said that the effect changed sign at the temperature at which " pv " was a minimum.

Dr. TRAVERS, in reply to Dr. Lehfeltdt, said he had not determined the temperature of the liquid, and the apparatus was not suitable for measuring the Joule-Thomson effect. He should say that the change of sign occurred about -150°C . It was Daniel Berthelot who first pointed out that the change of sign corresponded with the minimum value of " pv ." In the experiments of Amagat the gas was obtained by heating potassium formate and probably contained as much as 30 per cent. of carbon monoxide; the results were not sufficiently accurate to give the temperature.
