EUROPEAN STATE OF THE ART IN CRYOGENICS

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INTRODUCTION

To start with, I should like to make two remarks.

First, I have been asked to talk about the European state of the art in cryogenics. Now I certainly do not know enough about the work which is going on in the whole of Europe. I had the luck, however, to receive the invitation from your Chairman just the day before the start of the Cryogenic Engineering Conference in Brighton, England, so I used that conference to learn a bit, and an important part of what I will talk about in this lecture was told in Brighton one month ago.

Second, I may be a European, but I am also working with Philips and therefore I am not objective about the different systems. I will, therefore, devote most of my time to the work we did at Philips, and of course tell you that the Stirling system is by far the best to use for large cryogenic systems. I hope to make this clear in the next hour.

I will divide my talk into three main topics:

1) A discussion of what other firms are doing.
2) A description of the Stirling refrigerators and some low temperature systems made with it.
3) A comparison between systems and a few supplementary remarks.

CRYOGENIC INDUSTRY IN EUROPE

The title of my lecture, "European State of the Art in Cryogenics," I will primarily understand as the production of low temperatures, and, by restricting myself to the production, I can automatically restrict myself to the industrial firms in Europe and the direction in which their development and fabrication is going.

In Europe there are quite a number of firms working in this field. The most important for this talk are:

British Oxygen Company	England
Air Liquide	France
Linde	Germany
Messer	Germany
Sulzer	Switzerland
Philips	The Netherlands

There are some others such as Hymatic, Oxford Instrument Company, Petrocarbon, and Werkspoor, but these concerns are working on very small systems or in other temperature regions.

The first four of the above list are in the air separation field and mainly produce and sell industrial gases. For this activity they were obliged to fabricate air separation plants and starting from these installations they went into the low temperature region.

Sulzer was probably led into the low temperature field because of its well-known compressors and its knowledge of turbines. They have done quite a bit in deuterium separation and now also produce systems for the $4^{o}K$ region.

Philips came quite differently into this field. From research on the hot-air engine we also came with the Stirling cycle in the field of refrigeration. For a long time only small laboratory air liquefiers were made, but with a modified Stirling cycle the very low temperatures could also be reached, and we believe that with the Stirling cycle good refrigerators can be made down to very low temperatures.

I will now give you examples of the work the different European companies are doing.

BRITISH OXYGEN COMPANY

Mr. Stoll of the British Oxygen Company gave a paper in Brighton about a flexible multipurpose helium refrigerator. They have made one for the Rutherford High Energy Laboratory to operate in conjunction with a $3^{o}K$ liquid helium bubble chamber. This type of installation can produce 120 W in the 4.3 to $10^{o}K$, or 40 liters/hour of liquid helium, or 600 W at $20^{o}K$, or a combination of parts of the above-mentioned productions.

The refrigeration system is shown in Fig. 1. It makes use of precooling with liquid N_2, cooling by one or two gas-bearing expansion turbines down to $9^{o}K$, and then, of course, Joule-Thomson expansion for the lowest temperatures.

Automatic control of the installation is by three diverter valves, V_1, V_2 and V_3, controlled by temperature sensors or, in the case of V_1, by a liquid level sensor.

The system is said to be easy to operate and can run unattended for 18 hours per day. BOC hopes to have complete automatic systems in the near future.

A diagram of the complete system is given in Fig. 2.

The main compressor has a capacity of 0.34 m^3/sec (750 SCFM) with an end pressure of 8.3 atm. The turbines have a capacity of 0.225 m^3/sec (500 SCFM) at 264 000 rpm. Normally only one turbine is in operation. The second one is only used when a large load has to be cooled down.

AIR LIQUIDE

Air Liquide is working in two directions at present. For small systems they make use of our Stirling machine for precooling a Joule-Thomson system. They have, for example, made a 5 W refrigerator with a Philips A20 machine. For bigger systems they have developed a gas-bearing expansion turbine running at 200 000 rpm and with a capacity of 0.083 m^3/sec (185 SCFM).

With this turbine different systems have been developed. In Brighton, a 25 liter/hour helium liquefier was described. Figure 3 gives a diagram of this system. It uses a Claude refrigeration cycle with liquid N_2 precooling and a combined Joule-Thomson system. The compressor used is a dry Sulzer compressor with a capacity of 0.15 N m^3/sec (335 SCFM). A cylindrical cold box houses the Hampson-type heat exchangers, the turbine, Joule-Thomson valve and a liquid helium tank. This cold box has a diameter of 900 mm and is 2.3 m high. This liquefier can run continuously for 100 hours on grade A helium, then regeneration of the purifiers is needed. The production of the installation is 25 liters/hour with a power input of 95 kW and 22 liters/hour of liquid N_2. This makes a total efficiency of about 5 kW·hour/liter. The liquefier can be transformed into a refrigerator, and then produces about 130 W at 4.2°K.

A larger machine requiring about 125 liters/hour of liquid N_2, of the same type, has been made.

SULZER

Sulzer has made a number of different installations. In Brighton Mr. Pagani reported on two installations set up in the nuclear research establishment in Jülich (Germany). These were:

Installation I :	1000 W at 14.6°K + 200 W at 4.5°K
Installation II :	160 W at 4.5°K + liquefaction of helium, neon or hydrogen.

Sulzer makes use in these installations of two separate circuits, a Joule-Thomson circuit for the load at 4.5°K, and a Claude system for delivering cold at 14.6°K and precooling of the Joule-Thomson circuit.

The Claude system has two expanders in a special circuit, given in Fig. 4 (installation I). The first turbine works around 70°K and expands from 12 to 7 atm; the second works around 14°K and expands from 5.5 atm downwards. The system has been devised like this to make it possible to cool the load in the reactor with high pressure helium gas.

Sulzer dry compressors are, of course, used in the systems. The circuits are operated completely above atmospheric pressure to prevent impurities entering the circuit.

The systems can therefore run unattended for quite long periods.

Figures 5, 6 and 7 show the cold box, the control panel and the compressor station, respectively.

LINDE

Linde is making a number of different helium refrigerators and liquefiers.

The smaller ones are based on one or two Doll and Eder valveless piston expanders. These are expanders in which the piston has a very small clearance in the cylinder (average about 1.5 μ) but does not touch the cylinder due to hydrodynamic bearing operation, using the working gas. The piston itself is used to open and close the inlet and outlet ports, so that no separately actuated valves are needed. The expanders run at about 15°K, precooling at 77°K is done with liquid N_2 (Fig. 8).

The bigger systems are equipped with turbines and these do not use liquid N_2 precooling. Most often two turbines are used in a directly-coupled Claude and Joule-Thomson system. These bigger systems are tailor-made. For example, one system for

130 W at 4.7°K plus 700 W at 20°K has been made for a space research institute. Also, a 30 W, 1.8°K system has been made for a research institute in Karlsruhe.

Figures 9, 10 and 11 show the 20 liters/hour liquefier, the heat exchangers for this sytem, and the 30 W, 1.8°K system.

As you see, all these systems are quite alike. Every firm has developed a turbine expander, most often with gas bearings, and with these combined Claude and Joule-Thomson systems are made. They all have experience with heat exchangers, controls, and cold boxes from their work in the air separation field. No reason can be seen why these systems should not develop into reliable systems.

In this review I did not mention Messer because, as far as I know, they did not develop this type of system. Their work lies mainly in air separation, and at the moment also in liquid natural gas plants (together with American Messer). For helium temperatures they are interested in using Stirling machines for precooling a Joule-Thomson loop, and Messer and Philips together made a design for a 300 W, 1.8°K installation for the linac in Karlsruhe.

I will describe that design as an example of the possibilities of the Stirling system, but before I do that I will first describe briefly the Stirling cycle and the Stirling machines we make.

STIRLING SYSTEM

The Stirling cycle is performed by alternately compressing and expanding a fixed quantity of gas in a closed cycle. The compression takes place at room temperature; the expansion at a low temperature, for example 77°K. For the purpose of explanation the process may be split up into four phases; they are illustrated in Fig. 12.

This figure shows four positions of the pistons; the Roman figures indicate the four phases referred to. Cylinder I is closed by piston 2 and contains a certain amount of gas. The space is subdivided into two subspaces 4 and 5 by a second piston 3, the displacer. There is open communication between spaces 4 and 5 through an annular channel 6 wherein are located three heat exchangers: the regenerator 7, the cooler 8, and the freezer 9. In position 1 most of the gas is in space 4 at room temperature and in the first phase this gas is compressed by piston 2. In the second phase this gas is displaced by means of the displacer from space 4 to space 5, which we suppose already to be at a low temperature. During this transport the gas passes through the heat exchangers. In the cooler the heat of compression is discharged to the outside. The regenerator cools the gas nearly to the temperature prevailing in space 5; this will be discussed later on.

Phase III is the phase during which the actual cold production takes place, namely by expanding the gas by moving the displacer and piston together. Finally, by movement of the displacer, the gas is returned to space 4. When passing the freezer its cold is transferred to the outside, and in the regenerator it is reheated to nearly room temperature. The initial situation is now restored and the cycle can be repeated.

Figure 13 explains the working of the regenerator. The regenerator consists of a porous matrix with a high heat capacity. When the machine has run for a certain time, a temperature gradient will prevail in the regenerator, extending from T_1, room temperature, on the right side, to T_2, a low temperature, on the left side. During the first phase gas is forced through the regenerator from right to left. Due to the smallness of the pores in the matrix, the heat transfer from the gas to the matrix is extremely high and the gas nearly follows the temperature gradient of the matrix (along the upper dotted curve), so that it issues at the left side at nearly the temperature T_2. The heat discharged by the gas during this cool-down is temporarily stored in the matrix and due to the high heat capacity of the latter its temperature does not change very much. In the second phase the gas returns from left to right and the reverse happens; the gas temperature follows the lower dotted curve and issues at the right side at nearly room temperature. For the reheating of the gas the heat that was stored in the matrix during the first phase is used. We see that a regenerator enables us to cool and reheat matter without the need of appreciable amounts of thermal energy. The regenerators to be used in Stirling refrigerators must be of very good quality (99% or more).

THREE-SPACE STIRLING SYSTEMS

The description above gives the simple Stirling system as invented by Robert Stirling in 1816 and used by us for machines down to about 26°K. Due to the regeneration losses which increase relatively by going to lower temperatures, efficient machines for the region of 20°K can only be made when a change is introduced in the cycle, namely, the introduction of a second, intermediate, expansion space (see Fig. 14). The large amount of cold due to the higher expansion temperature can now cope with the regenerator losses of the first regenerator, and, with this system, relatively high efficiencies can be reached at lower temperatures.

This change was needed in order to reach lower temperatures, but it does more. It has the added advantage that the machine can now also be used for delivering cold at two temperatures, i.e. 80 and 18°K, which is important for a Joule-Thomson system as now the use of liquid nitrogen can be discontinued. The lowest temperature to be reached in our machines now is 12°K. In the laboratory a Stirling machine has worked down to about 8°K.

It is obvious that no Stirling refrigerator down to 4.2°K can be built as the working medium in the cycle is a gas, and no gas is available anymore below that temperature. Therefore all 4.2°K systems make use of the Stirling machines as a precooling system for a Joule-Thomson system.

As can be seen from the above, the Stirling system is a very compact system for producing refrigeration. It has a very high specific output because a high mean pressure and a high speed can be used. Furthermore, the system has very high efficiency. I will come back to this point later.

A number of different types of Stirling machines are available. Important for helium refrigeration are the three-space systems. A one-cylinder (A20) and a four-cylinder system of the same type are in production. A prototype model of the A20 is shown in Fig. 15. Figure 16 gives the production graph of this machine. The machine has two productions, Q_E at the top and Q_m at the intermediate freezer, both plotted along the vertical axis, dependent on two temperatures, T_E and T_m. T_m is plotted along the horizontal axis, and T_E is used as a parameter in the graph.

It can be seen that Q_E is only slightly dependent on T_m, which is done so as to have the machine not only useful as a pure refrigerator at, say, 20°K, but also as a precooler or liquefier where both productions are used.

Figure 17 illustrates a B20 machine. This one, of course, has four times the production of the A20. The headers can all be used separately, which means that it could be used with the eight freezers all at different temperatures.

In the near future two machines of this type will be added: the so-called X20, which has about 1/10 of the production of the A20, and a three-space version of our big industrial machine, which now produces 25 kW at 77°K. As a three-space system it will produce about 2 kW at 20°K, with an efficiency which is about 30% higher than in the A20. It will come to about 20% at 20°K (see Fig. 18).

INSTALLATIONS

To show what a helium refrigeration system will look like with these machines, I will describe two things: first the helium liquefier we have in production now, and second a design for a 300 W, 1.8°K refrigeration system. The latter we designed together with Messer (Germany) as a proposal to the Karlsruhe Nuclear Research Institute.

THE LIQUEFIER

The liquefier is a 10 liter/hour system using two of the above-mentioned refrigerators and a special compressor.

The flow diagram is given in Fig. 19. Precooling is done at about 100, 66, 26 and 16°K. This makes the system efficient and furnishes the right temperatures for purifying. The machines can run continuously for 100 hours with helium containing 2% air. Incidentally, it can handle helium containing 10% air. The helium is purified at room temperature with molecular sieves absorbing most of the water, and at 100°K, CO_2 is absorbed. At about 67°K the air is first condensed and taken off as liquid as far as possible, and then with two switching absorbers the rest of the air is taken out. These absorbers use active charcoal. At 16°K an absorber for neon and hydrogen is used.

At very low temperatures a special circuit is use with an ejector instead of the Joule-Thomson valve (see Fig. 20).

The ejector is used to improve the Joule-Thomson system. The basic idea is that in isenthalpic expansion pressure energy is transformed into kinetic energy and kinetic energy is wasted in friction. If one could use the kinetic energy this could not fail to be an improvement. In the ejector kinetic energy is used to compress gas from a second vessel at a lower pressure up to the pressure of the first vessel. By this method, say 0.4 atm absolute can be reached although the sucking pressure of the compressor is 1 atm absolute.

In the liquefier the ejector is used to compress from 1.0 to 2.5 atm absolute. This, of course, makes the return heat exchanger channel and the compressor much smaller.

The compressor used in this system is a so-called "sock compressor." In any helium system, it is an advantage to have a dry compressor. For small systems metal membrane compressors are used, but they have the disadvantage that the membranes only have a life of about 1000 hours.

We had already encountered the problem of a hermetic seal in the Stirling machines. With a normal lubricated piston, oil vapor comes into the system and freezes somewhere in the regenerator. The smaller machines have a maintenance period of about 100 hours for cleaning the regenerator. For the large industrial machine we developed the so-called "sock," a rolling rubber diaphragm between the piston and the cylinder, which is sustained by oil in a constant volume space (see Fig. 21). The average oil pressure is controlled to keep it a few atmospheres below the average gas pressure so as to keep the rubber under a constant tension.

This method is also used in the big machine I showed you (Fig. 18). These membranes can run more than a year, even with a speed of 1500 rpm.

The same system is used now for a small helium compressor used for this liquefier (see Fig. 22).

The control panel and Dewar with the Joule-Thomson system is illustrated in Fig. 23. Roughly, this same unit with two A20 machines and one compressor could be used for about 30 W at about $5^{o}K$. For use as a refrigerator the whole purifying unit can be skipped, of course, which makes the unit even more compact.

Apart from the compactness and the advantage of accepting helium with impurities, the liquefier has a high efficiency. The refrigerator and compressor together use 28 kW. For 10 liters/hour of helium this gives 2.8 kW·hours/liter. No liquid nitrogen is needed for precooling, as the intermediate freezers of the A20 machines furnish the cold needed at that temperature. I will compare this figure later with other liquefiers.

THE $1.8^{o}K$ SYSTEM

The second system I would like to mention is a design for the Karlsruhe 300 W at $1.8^{o}K$ refrigerator, which we made together with Messer.

In the design we made use of three B20 machines (a B is four A machines on one crankcase) which furnish the cold and a Joule-Kelvin system, as can be seen in Fig. 24, to transport the cold to the low temperature.

It is an advantage in this Joule-Kelvin system to have two loops, one transporting 150 W down to $5.5^{o}K$ and one going down to $1.8^{o}K$, getting 150 W enthalpy difference at 16^{o}, and the other 150 at $5.5^{o}K$. This is because one tries to have the smallest possible amount of gas in the very low pressure return flow. Therefore, if possible, all the evaporation heat of helium should be used, and this makes precooling to about $6^{o}K$ necessary. The two high pressure flows of the two loops are, of course, added here in one channel so three-channel heat exchangers can be used, and also the compressors from 2.7 to 20 atm can be combined.

Here again the ejector may be used, although the advantage is not as great as in the helium liquefier. To have always a positive temperature difference in the last heat exchanger, the high pressure helium gas has to be expanded partly in the heat exchanger. At the ejector, then, only part of the total pressure difference is available to be converted into kinetic energy. The result is that a pressure ratio of only about 1.3 can be reached in the ejector. With a pressure of 10 torr at the liquid bath, this remains, nevertheless, an important advantage for the return heat exchanger. The B20 machines are used in a special way in this circuit. In Fig. 24 it can be seen that three precooling temperatures have been used. With a B20 machine, one has eight freezers so, in principle, eight temperatures could be used. For a refrigerator such a large number is no advantage, however, and only three are used, namely 80, 26 and $16^{o}K$. Two of the four headers use one freezer at about 80 and $26^{o}K$; the other two headers only use the top freezer at $16^{o}K$. With this system the double expansion machines are used very efficiently. In practice, probably two B20 machines could do the job. Therefore, the three machines are made identical, and the system is designed so that each machine can be stopped and serviced (or replaced) while the installation remains running. This method can give the system a very long continuous running time, even though the B20 machines have to be stopped and cleaned after about 1000 hours. Also, the reliability of such a system can be made very high in this manner.

In any Joule-Thomson system the compression is a very important factor. Two types of compressors are used in the installation described. Rootes compressors are used for the low pressure region from 13 mm to about 0.2 atm. These Rootes compressors are made by Aerzener in Germany, but, for use with helium, most often delivered by Hereaus.

These Rootes compressors are made in a number of sizes, from very small to quite large, and can be made for any pressure in the vacuum region. For the higher pressures Sulzer dry piston compressors are used.

It is clear that, in cryogenics, the availability of good compressors is very important. I mentioned Aerzener and Sulzer — both have quite a lot of experience in the pumping of dry and clean gases — but there are other firms also who make this type of compressor and all cryogenic firms who make this type of compressor and all cryogenic firms who make units to $4^{O}K$ can find good dry compressors for them made in Europe.

Apart from this, progress is made in the purification of helium compressed by oil-lubricated piston compressors and that technique may also be used in Joule-Thomson systems.

EFFICIENCY COMPARISON

I have yet to make a short comparison between the efficiencies of the different systems. In most descriptions, however, no efficiency figures are given.

The only number I found was for the Air Liquide liquefier, which needed 95 kW and 22 liters/hour of liquid N_2 for a production of 25 liters/hour of helium. If we estimate the nitrogen at 1 kW·hour/liter we arrive at an efficiency of (117/25) kW·hour/liter or 4.7 kW·hour/liter. Our liquefier uses 2.8 kW·hour/liter.

From discussions with the people at Karlsruhe, we know that our proposed system had a much higher efficiency than any other system offered.

Now we have quite often discussed why the Stirling system is so different in efficiency from the Claude system (of course it must be the difference between the Claude and the Stirling systems, because the Joule-Thomson system is always roughly the same). One of the problems in this comparison is that no standard system exists and one can make systems which are extremely good on paper but never manufactured (Keesom cascade for liquid air) because they are too expensive and complicated. A number of years ago Nesselman made a comparison between calculated systems and a measured Stirling machine and found the results shown in Fig. 25. Of course, this comparison is quite old now and expanders may have been improved, but that improvement has not been very large. Also, heat exchangers may be made better than the figures he used in his calculations, but again, even with highly efficient heat exchangers, the Claude systems remain relatively low in efficiency.

The result of our investigation has been that in the Claude systems the efficiency is low due to the low efficiency of the compressors. For the compression there are some differences between Stirling and Claude systems. First the Stirling compression ratio is low (for highly efficient machines less than two) while for the Claude systems much higher ratios are used. Of course, it is possible to use smaller ratios and more compression stages, but that is never done because of the size and price of the installations. Furthermore, in the Stirling systems, the compression is not completely adiabatic as in the compressor for a Claude system. There, all the gas is first compressed and then forced through the cooler which gives quite a loss.

In the Stirling systems, the compression takes place partly in the cylinder, but also in the cooler, regenerator, and freezer. We call our system, therefore, semi-adiabatic, and believe that therein lies the main difference. A third factor is the valve loss, which does not exist in the Stirling systems.

The fact that the regenerator is most often better than a heat exchanger, which we thought earlier to be the main reason for the difference in efficiencies, seems to make no important contribution to this difference.

The calculation of Nesselman was based on 77°K systems. Although, as I said, I have no good figures, I believe for 15 to 20°K systems the same type of difference will be found.

SUPPLEMENTARY REMARKS

Helium^3

For the 1.8°K system we looked into the possibility of using helium^3 in the Joule-Thomson system. The difference in vapor pressure around 2°K is a factor 8 to the advantage of He^3 as against He^4. It is clear that for the heat exchangers and compressors this is quite important.

The use of He^3 has two disadvantages. The Joule-Thomson effect is smaller, so a higher mass flow has to be used (about 30% more). Moreover, in a system at 1.8°K one wants most often to make use of superfluid helium in the liquid bath, so one has to have He^4 there. This means that heat has to be transferred from the He^4 of the liquid bath to the He^3 of the refrigerator, and in this heat transfer some ΔT is involved, which means a certain loss.

These disadvantages, however, are small compared to the advantage of the higher vapor pressure. Then, of course, the price of He^3 (about $85/N liter) is a problem but even with this price a competing system could be built. The main reason which made the use of He^3 impossible was that it cannot be obtained in unlimited quantities at the moment. When it can be shown that for refrigeration around 2°K it is really worthwhile to use He^3 in large quantities, the price might go down and the availability might be improved, resulting in more economic installations in this temperature range.

The Ejector (Fig. 26)

I should like to mention some more facts about the ejector. The amount of cold which can be transferred with the ejector loop depends on the pressure ratio. With a very small amount of cold transferred a pressure ratio of 100 has been reached, meaning a temperature of 1.74°K in the second bath, while in the first vessel the temperature was 4.2°K.

This means that if the cooling function of a refrigerator is mainly to compensate for insulation losses, that is, not much dissipation is involved as is the case with a superconducting magnet, a very low temperature can be reached without seeing it on the outside of a system. If the complete magnet is surrounded by a 4.2°K shield, it is probably possible to have about 99% of the needed cold at 4.2°K and only 1% at the lower temperature. With our ejector it is then possible to reach a very low temperature indeed. I have not enough knowledge of magnets but I believe that there are some indications that superconducting magnets could behave much better below the λ point. This is not done, however, because of the added complexity in the cooling system due to the low vapor pressure above the bath. With the ejector system, however, it may be possible to do this sort of thing. Due to the added 4.2°K shield, the cryostat design may be more complicated, but the refrigerator remains simple, because no very low pressure in the return heat exchanger is needed, nor are the low pressure compression stages.

CONCLUSION

I hope I have succeeded in telling you that the cryogenics industry in Europe has the know-how and the potential to build cryogenic systems, and has, indeed, produced quite a number of installations. To reach the state where a low temperature environment can be used without any problems, however, requires more experience which can only be gotten by just doing it.

I am sorry that I could tell you only little about other firms than my own, and, therefore, had to use quite a bit of your time to tell what our group is doing. We are trying to do things a bit differently from all others, and you may have found it interesting to hear about that.

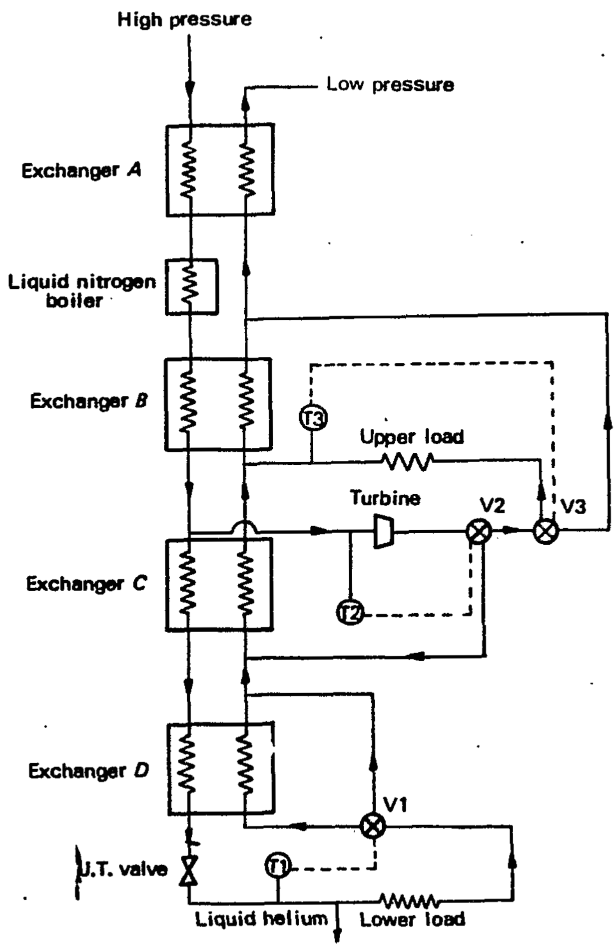

Fig. 1. Schematic layout of cold box and control system of a multipurpose helium refrigerator of the British Oxygen Company.

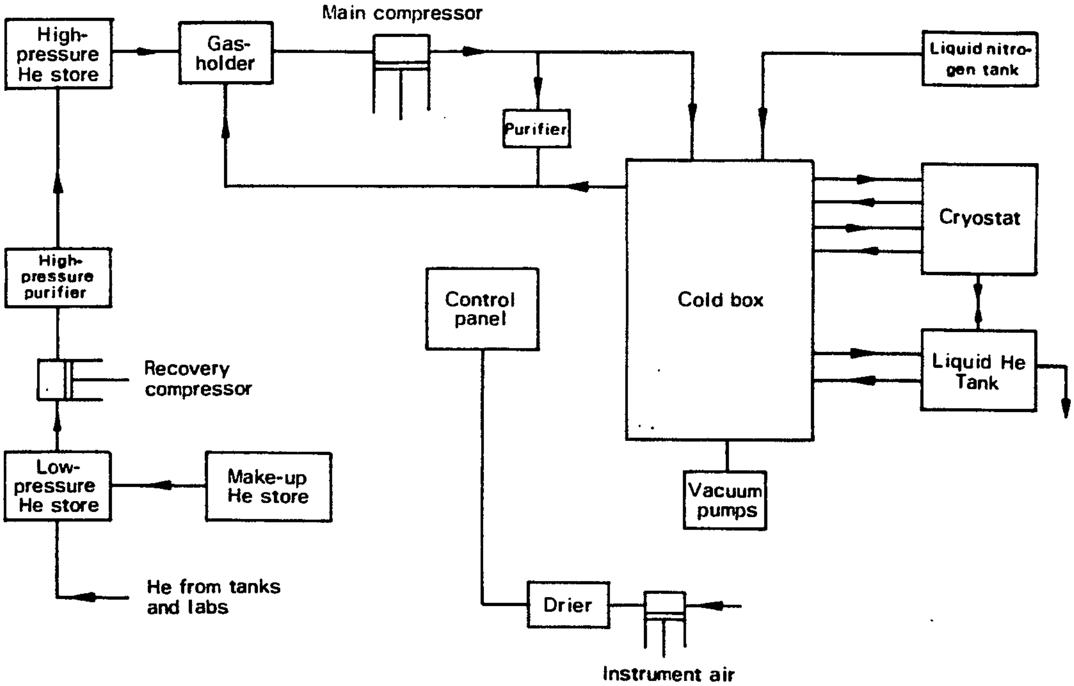

Fig. 2. General plant layout of refrigerator/liquefier system of the British Oxygen Company.

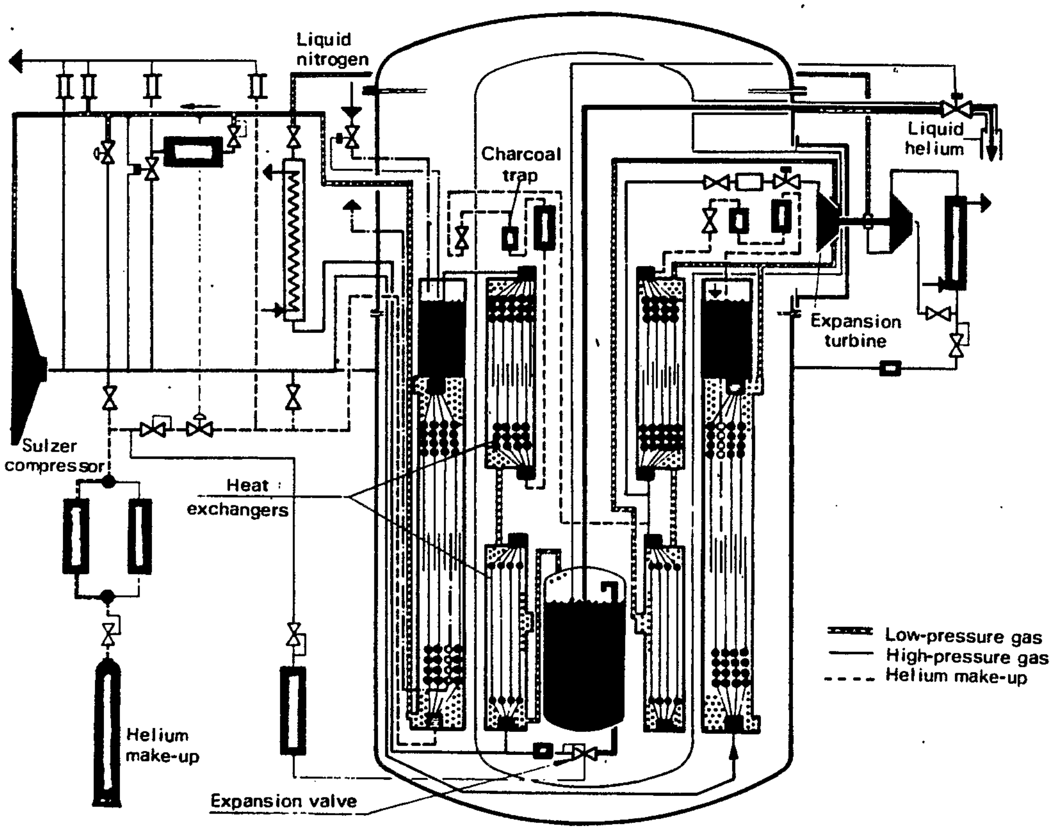

Fig. 3. Flow diagram of Air Liquide 25 liter liquefiers.

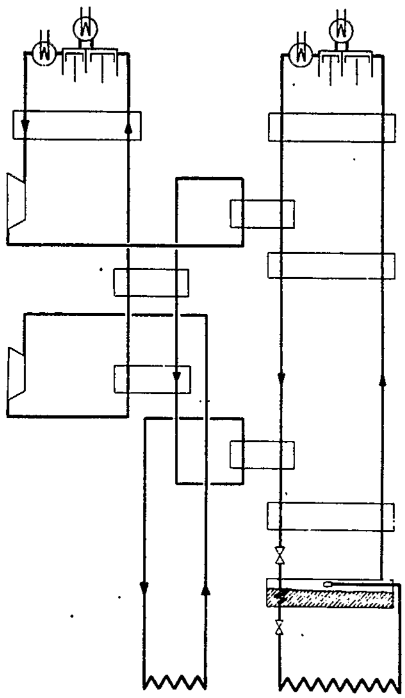

Fig. 4.   Flow diagram of Jülich I refrigerator (Sulzer).

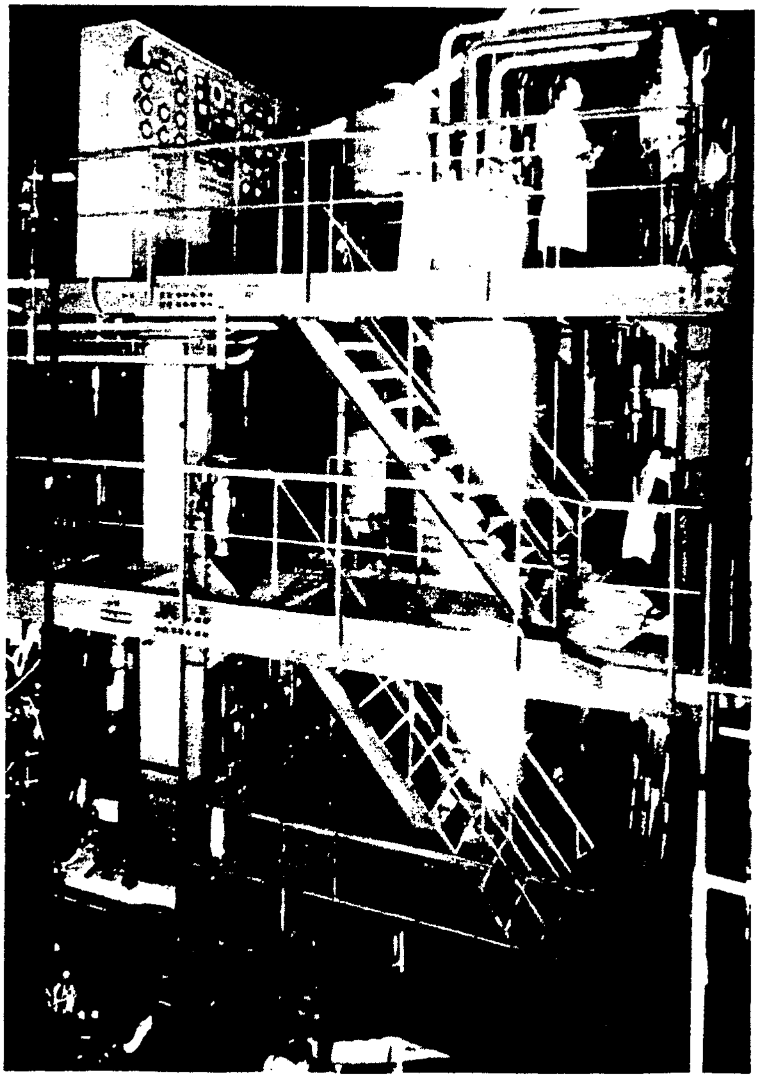

Fig. 5.   Cold box of Jülich refrigerator.

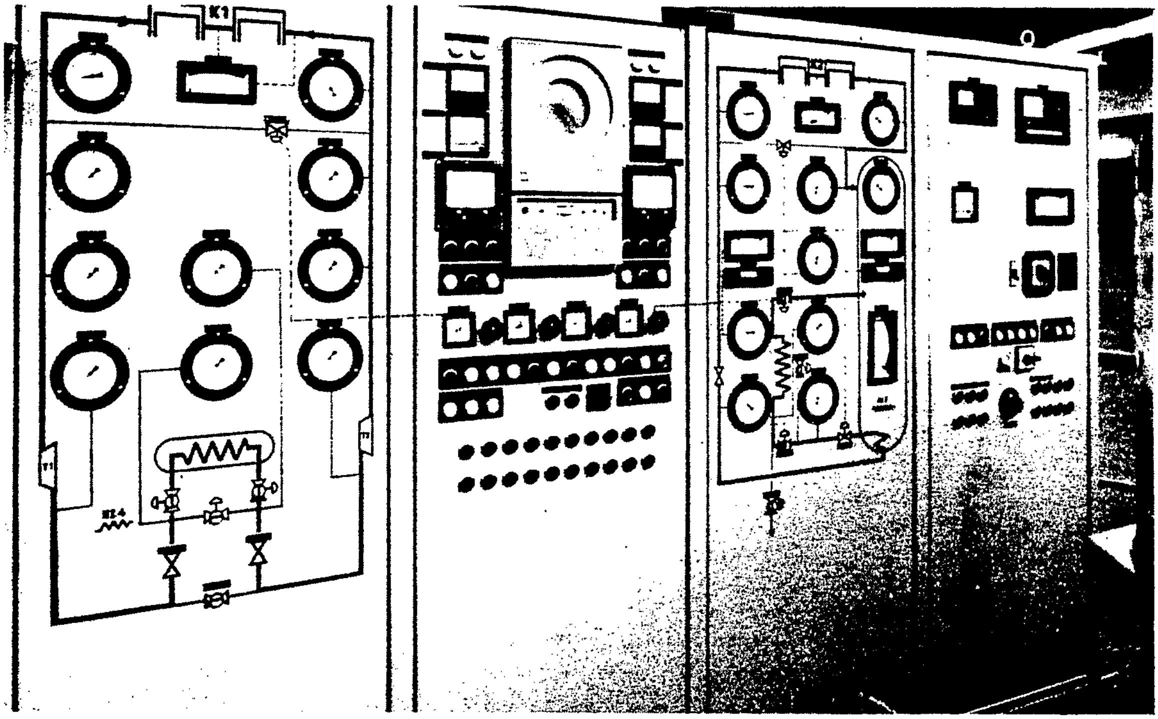

Fig. 6. Control panel of Jülich refrigerator.

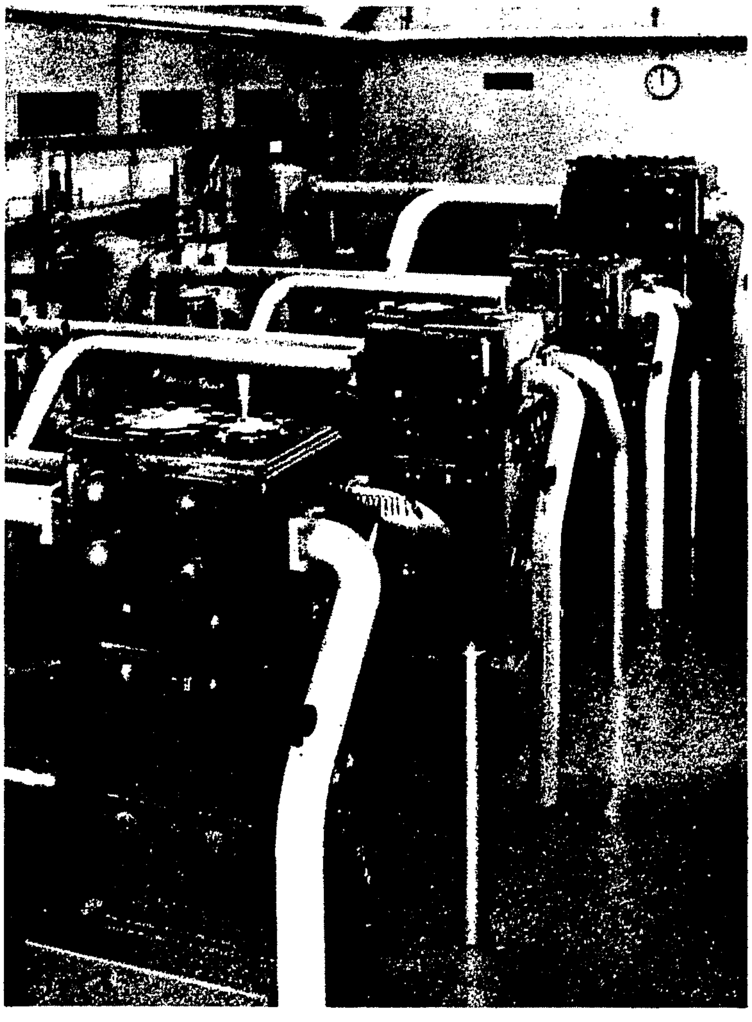

Fig. 7. Compressor room of Jülich refrigerator.

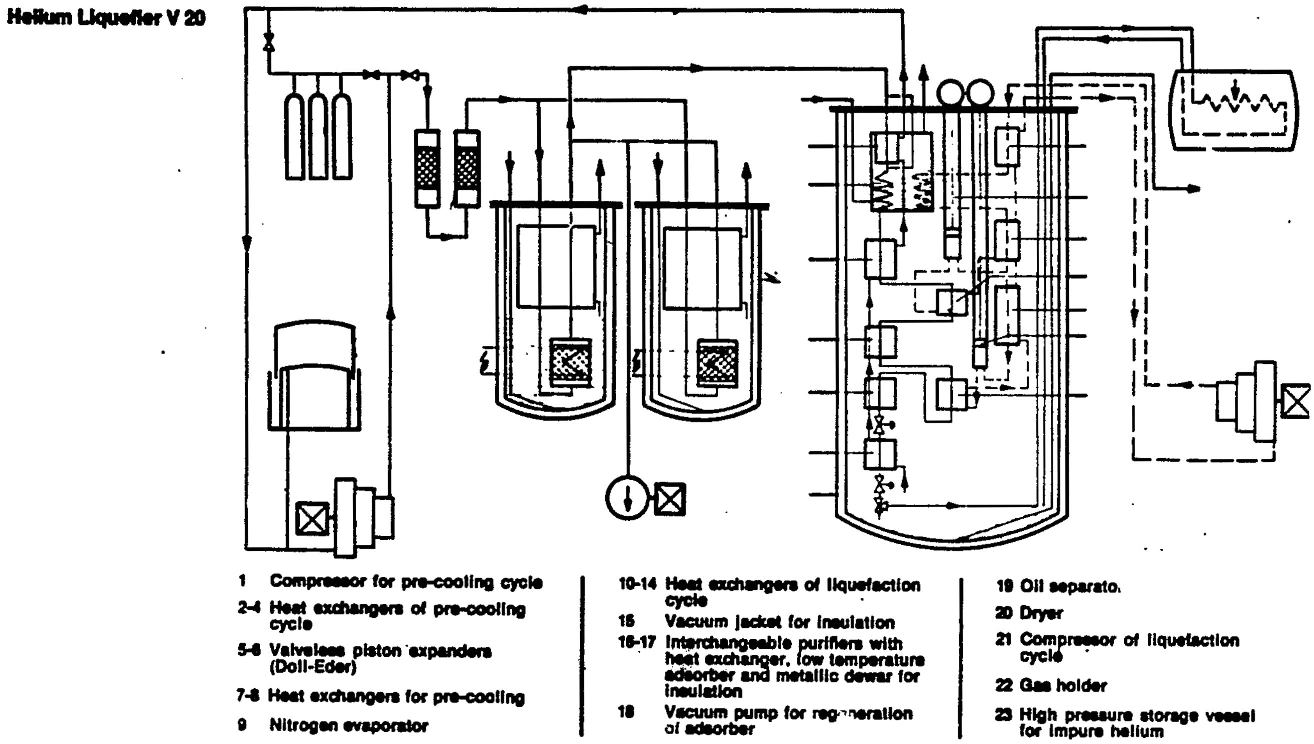

Fig. 8. Flow diagram of Linde V liquefier.

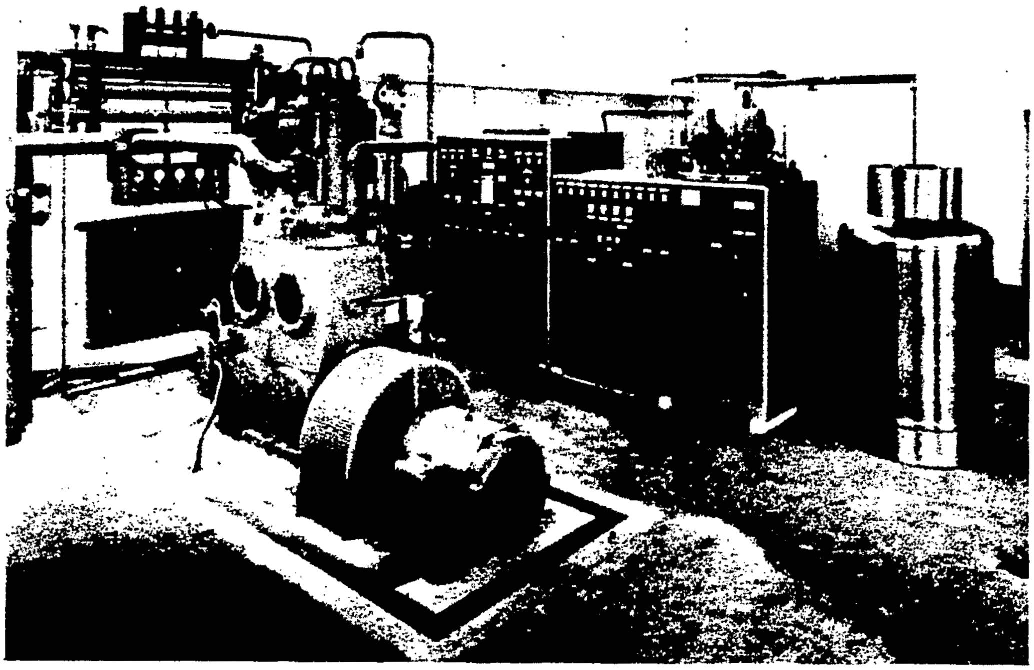

Fig. 9. Linde V20 liquefier.

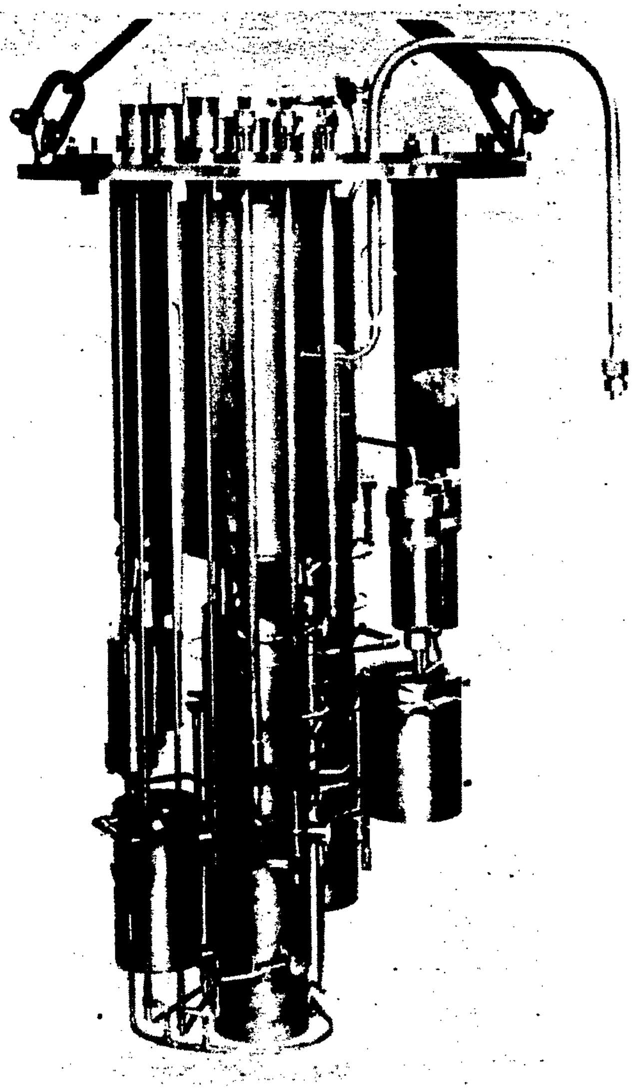

Fig. 10. Heat exchangers of V20 liquefier.

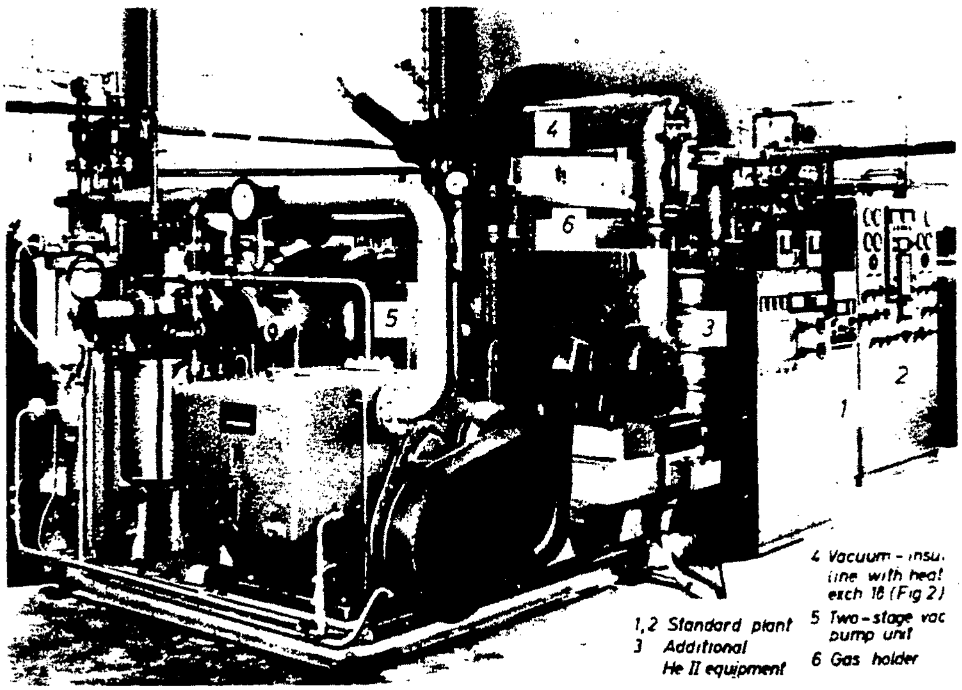

Fig. 11. Helium II refrigerator (Linde).

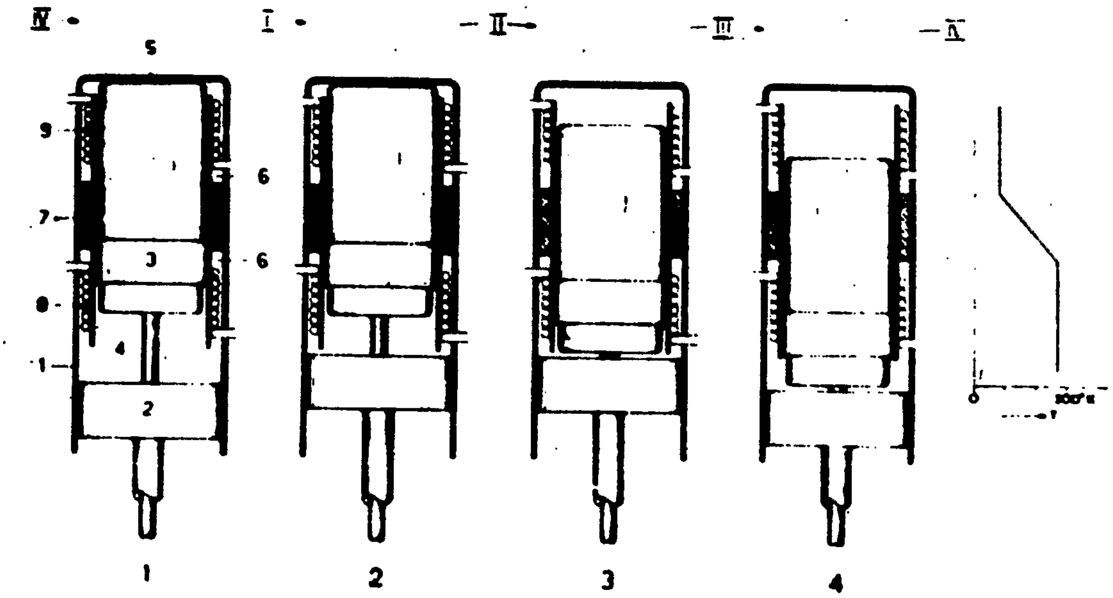

Fig. 12. Schematic phases of Stirling process.

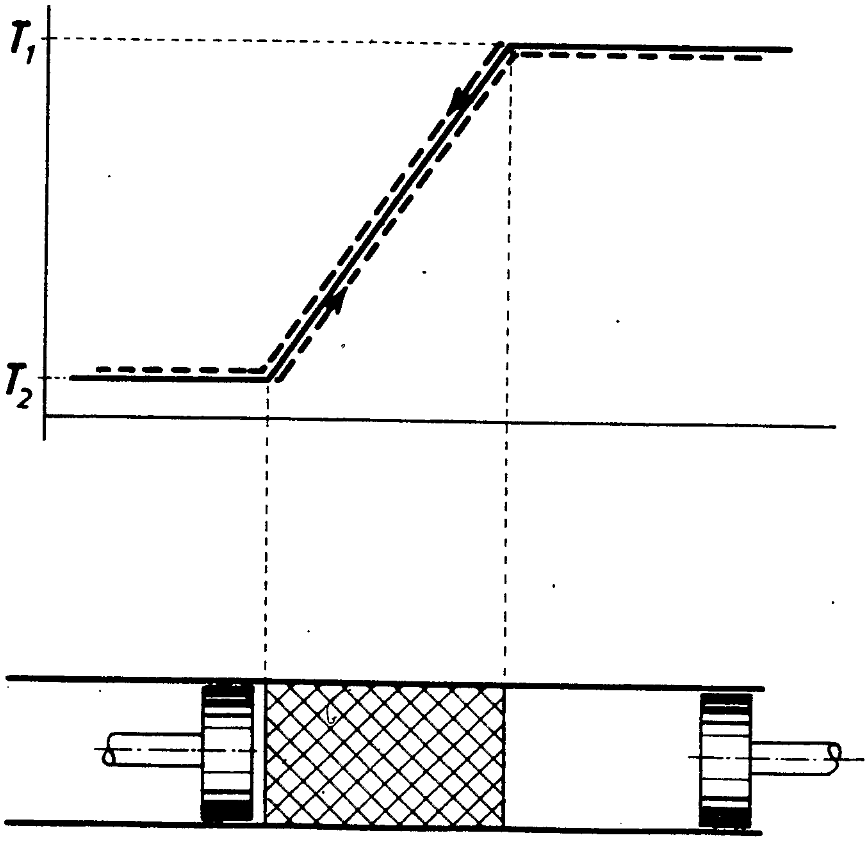

Fig. 13. Regenerator temperatures in Stirling process.

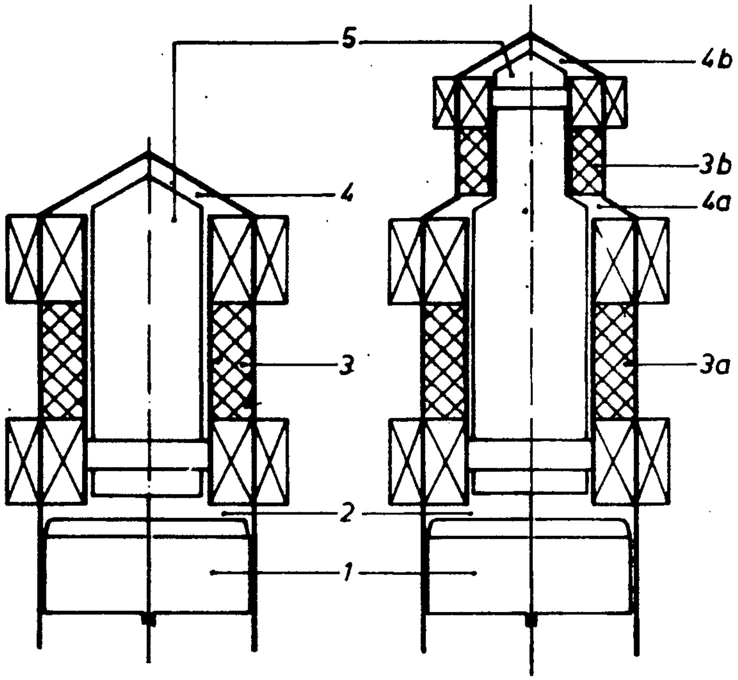

Fig. 14. Two- and three-phase Stirling process.

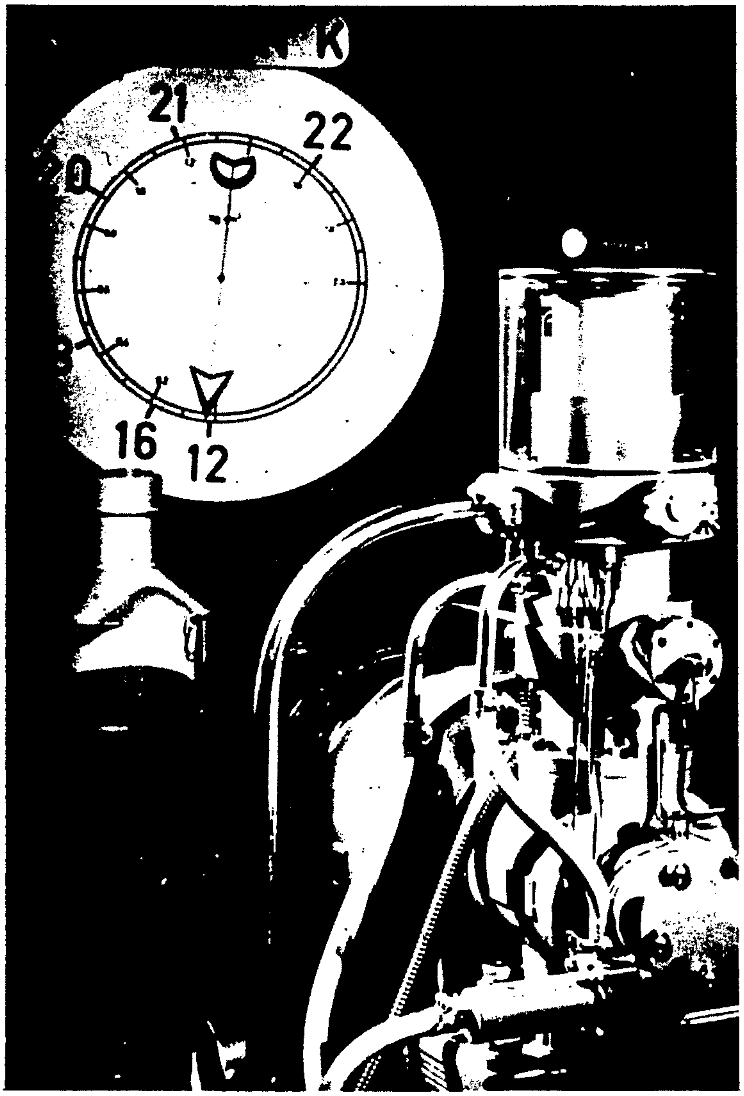

Fig. 15. Prototype A20 Stirling machine, with bar magnet floating above superconducting plate.

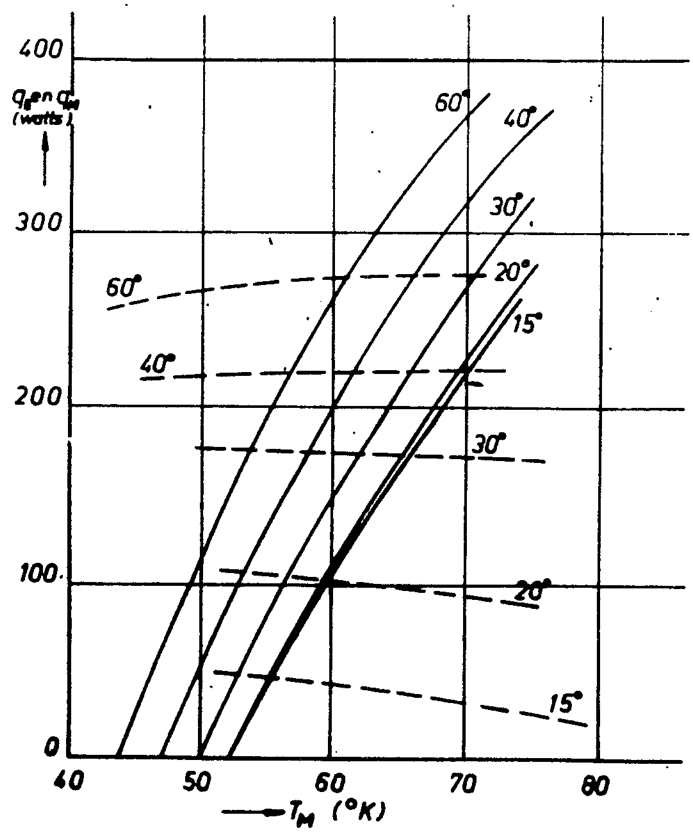

Fig. 16. Cold productions of prototype A20 Stirling refrigerator.

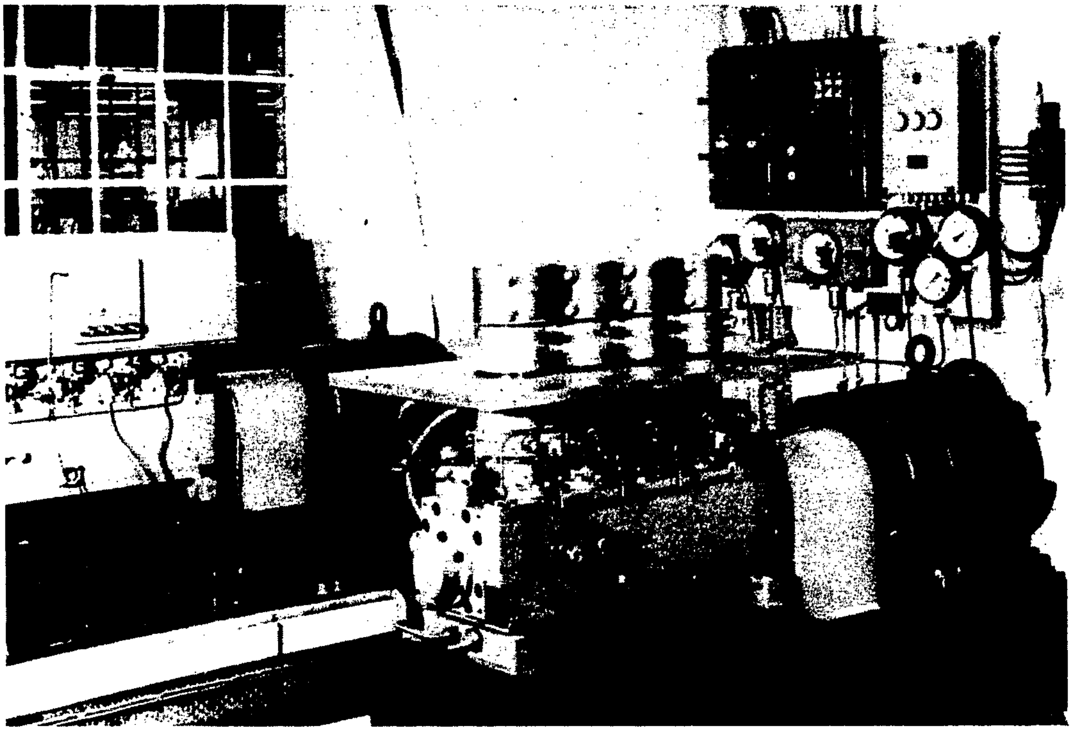

Fig. 17. Four-cylinder Stirling refrigerator.

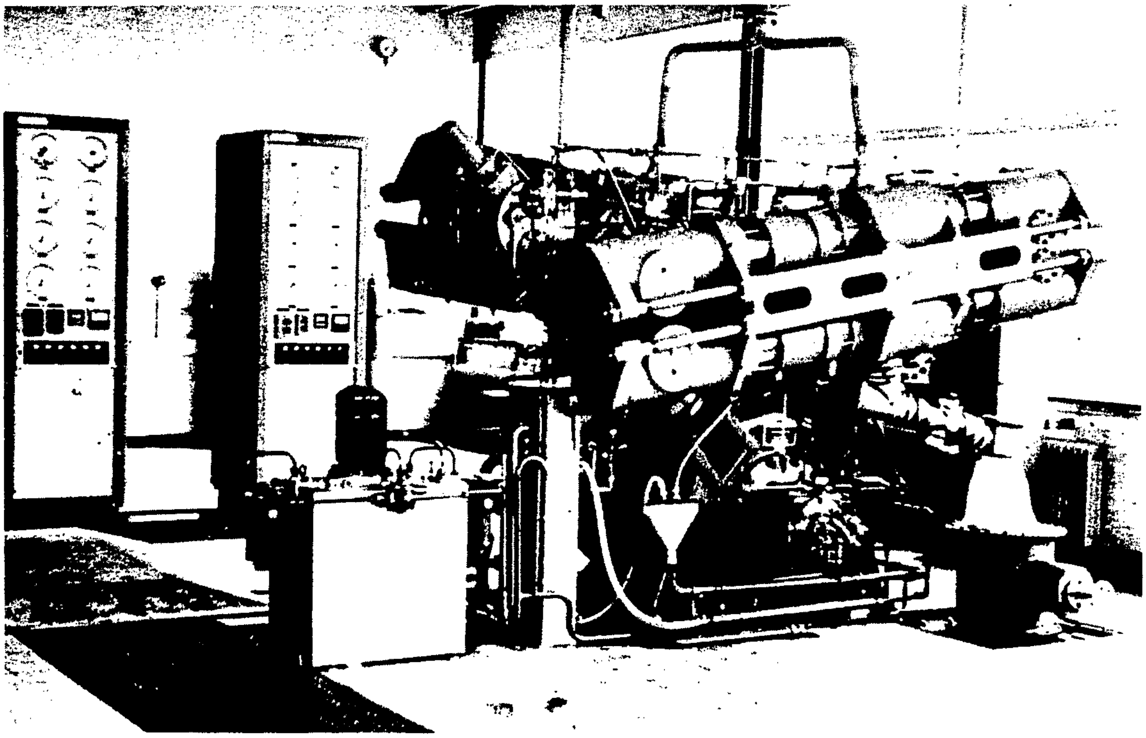

Fig. 18. Stirling refrigerator for 25 kW at $77^{o}K$.

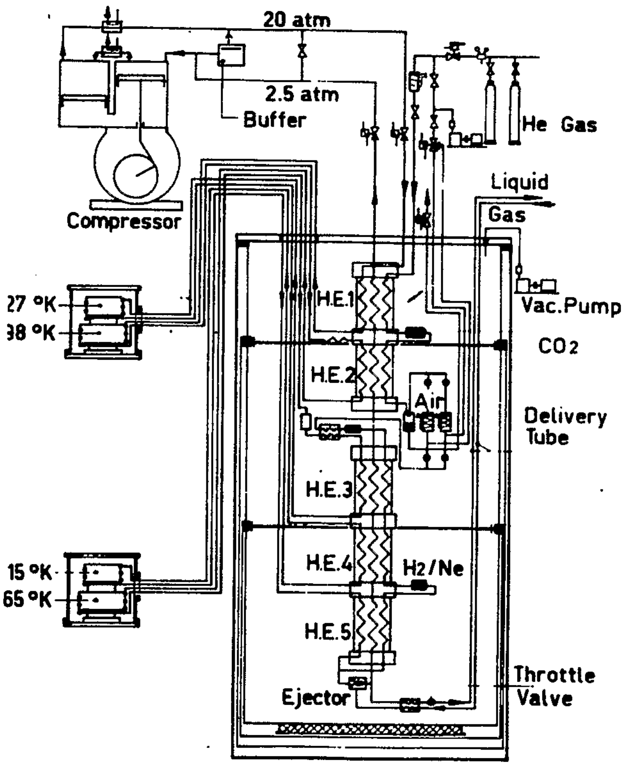

Fig. 19. Flow diagram of Philips helium liquefier.

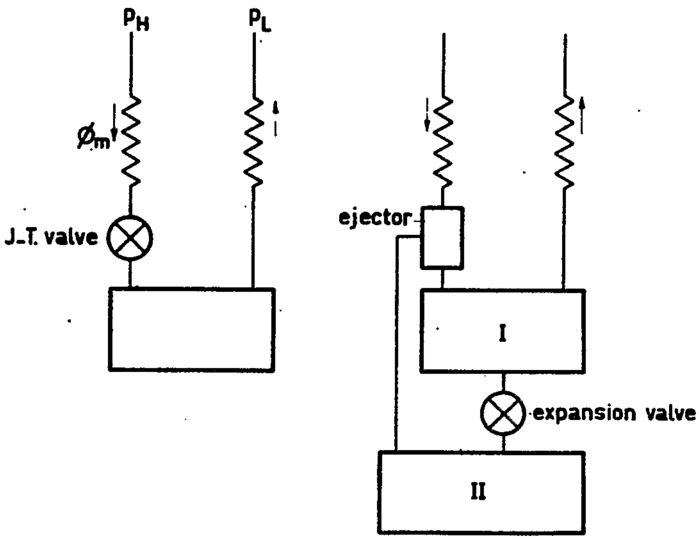

Fig. 20. Ejector system in Joule-Kelvin process.

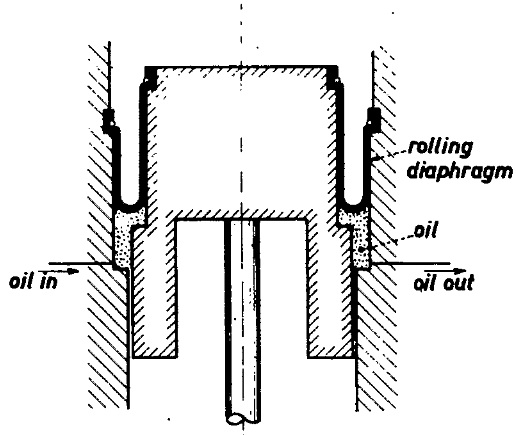

Fig. 21. Schematic of oil-supported rolling diaphragm.

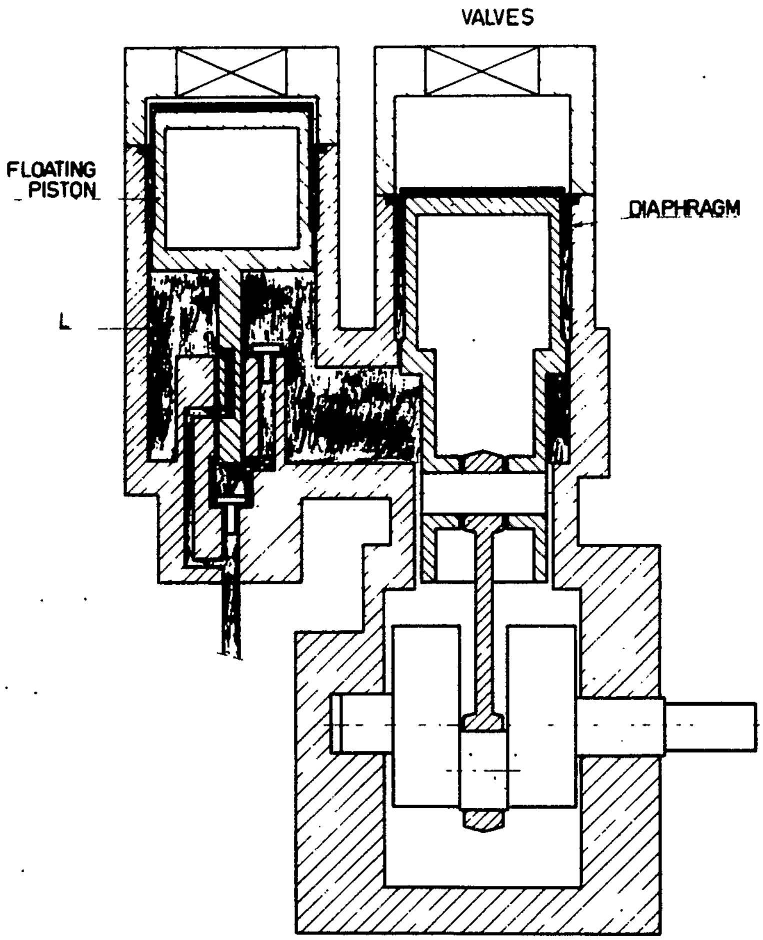

Fig. 22. Oil-free compressor with rolling diaphragms.

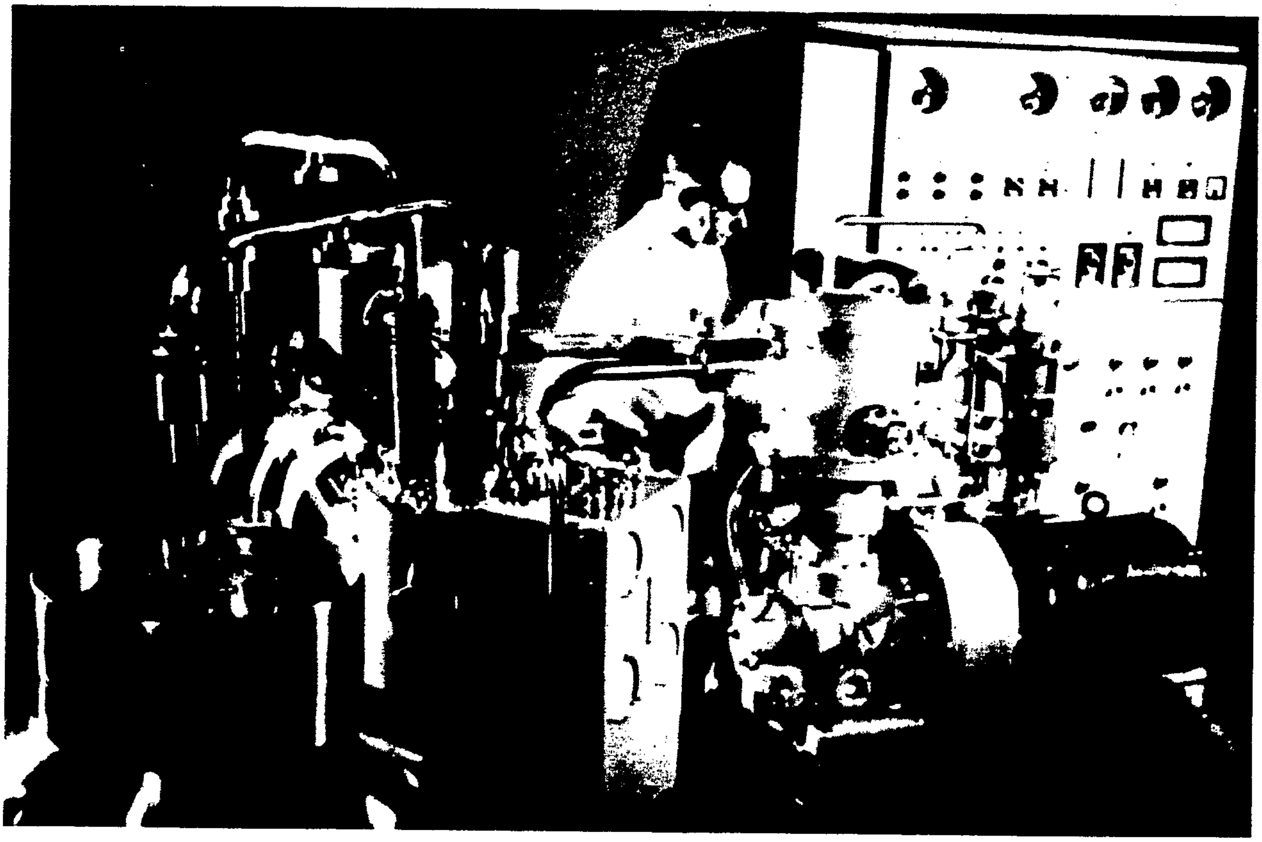

Fig. 23. Philips helium liquefier.

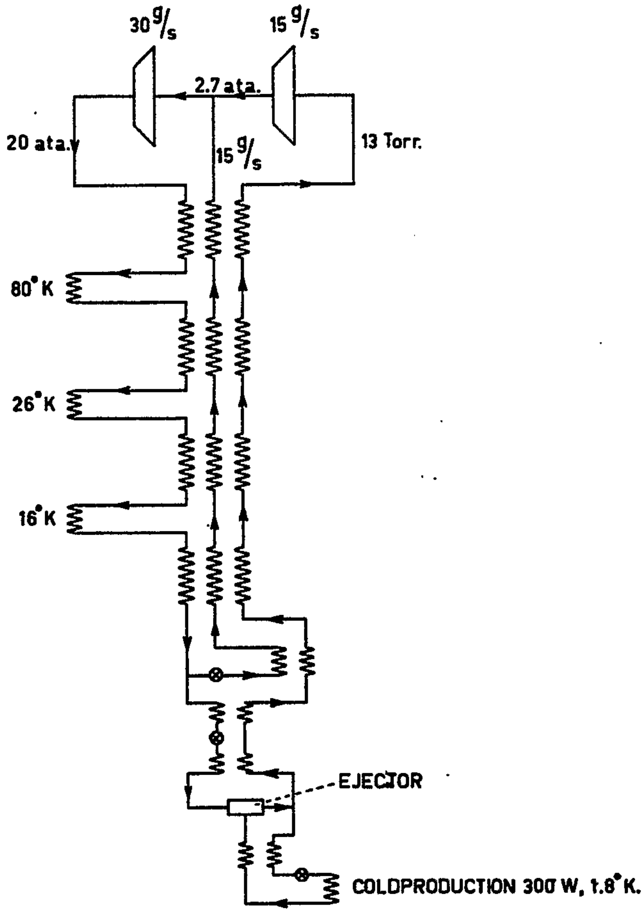

Fig. 24. Flow diagram of proposed 300 W, 1.8^{O}K system.

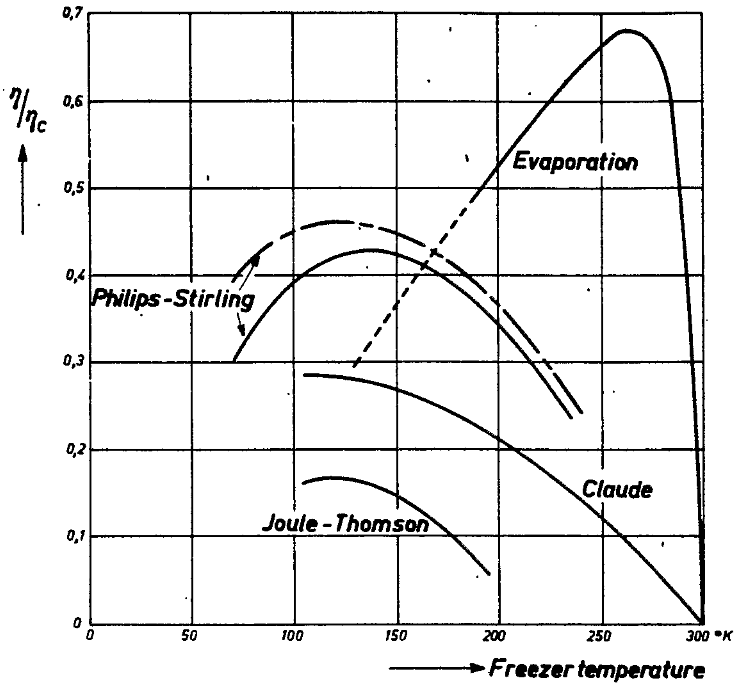

Fig. 25. Comparison of efficiencies of different systems.

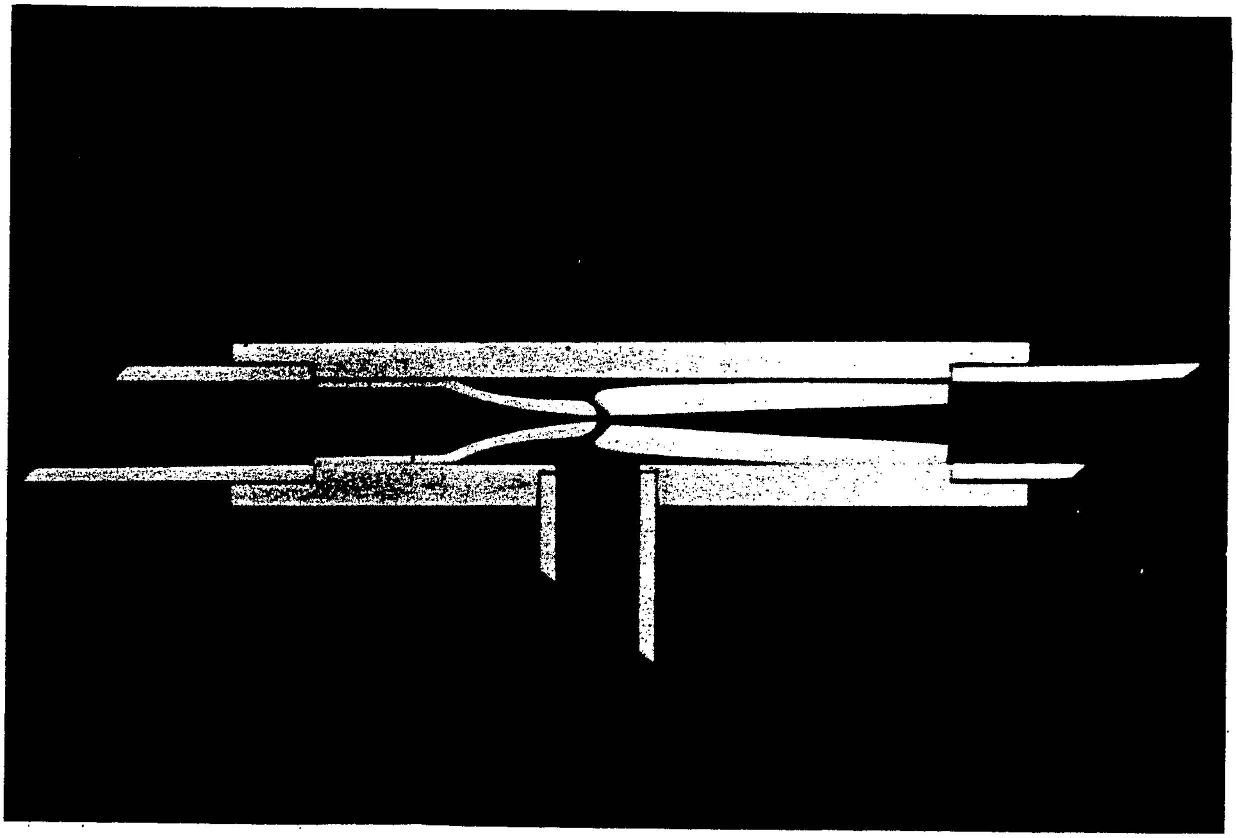

Fig. 26. Ejector.