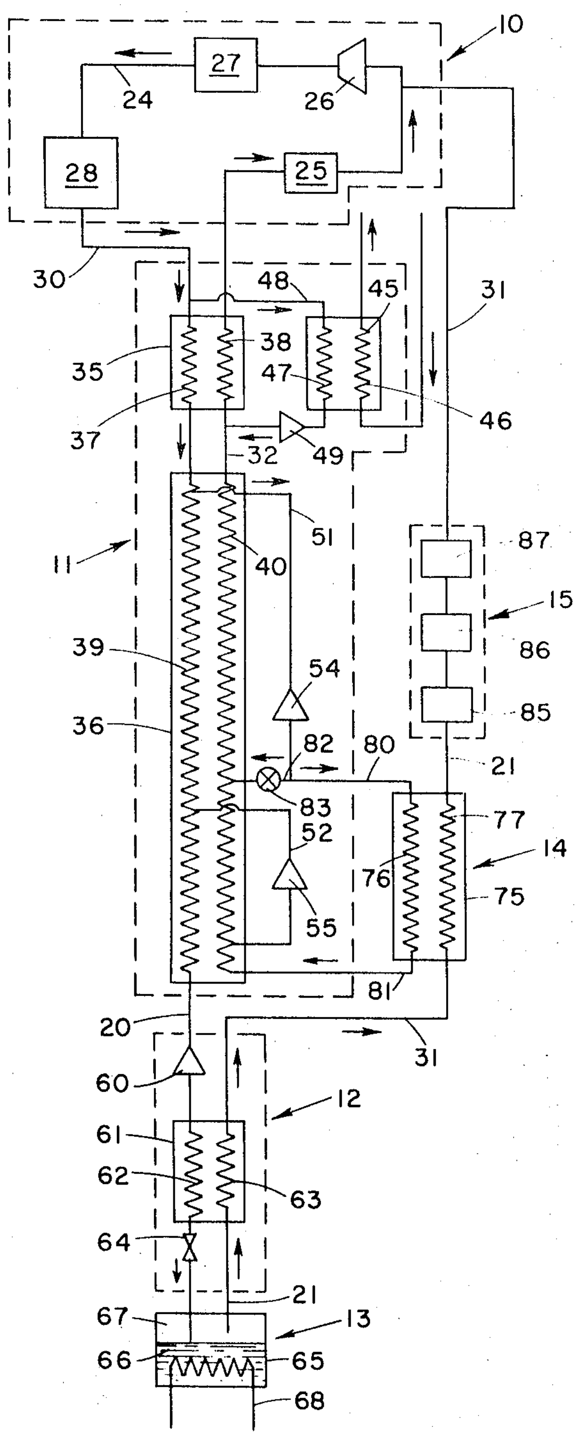

Fig. 1

INVENTOR.
Samuel C. Collins
BY Bernie A. Lepper
Attorney

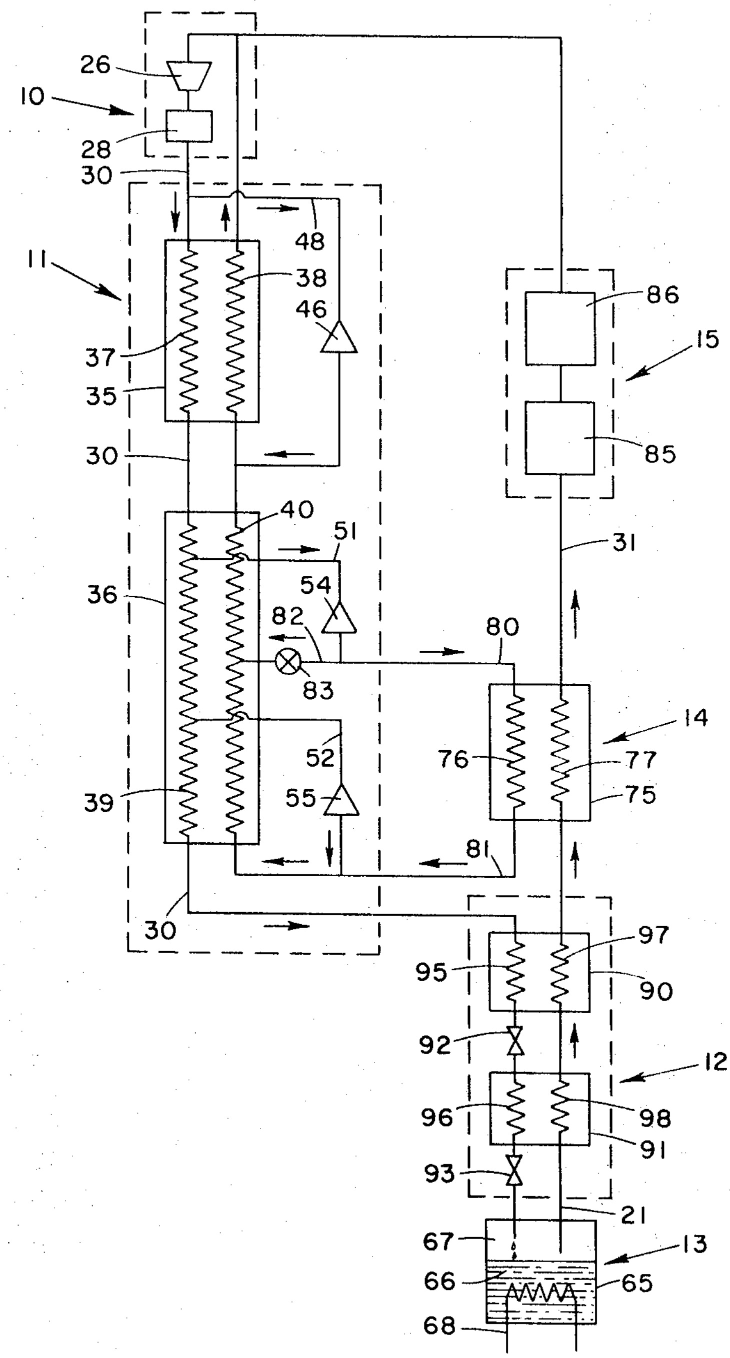

Fig. 2

INVENTOR.
Samuel C. Collins
BY
Bernie A. Lippe
Attorney

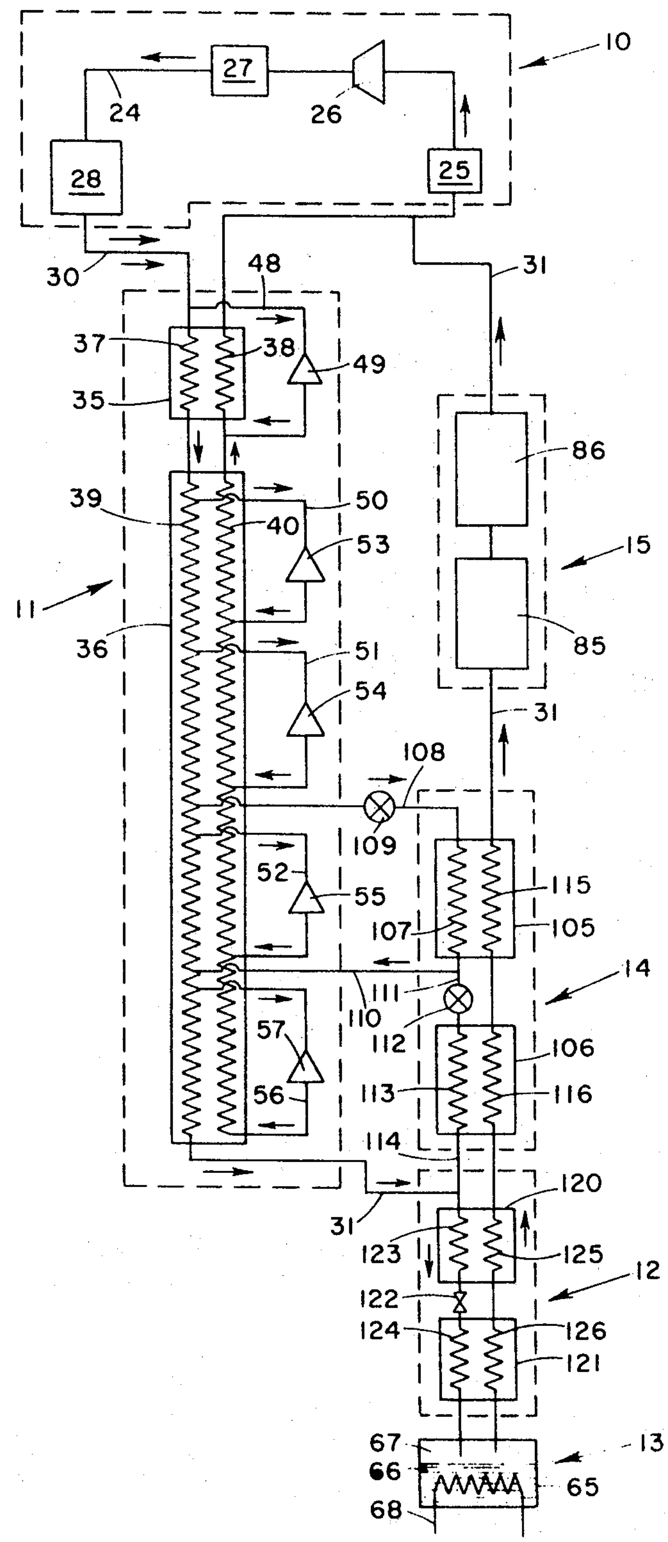

Fig. 3

INVENTOR.
Samuel C. Collins
BY Bernie A. Lepper
Attorney

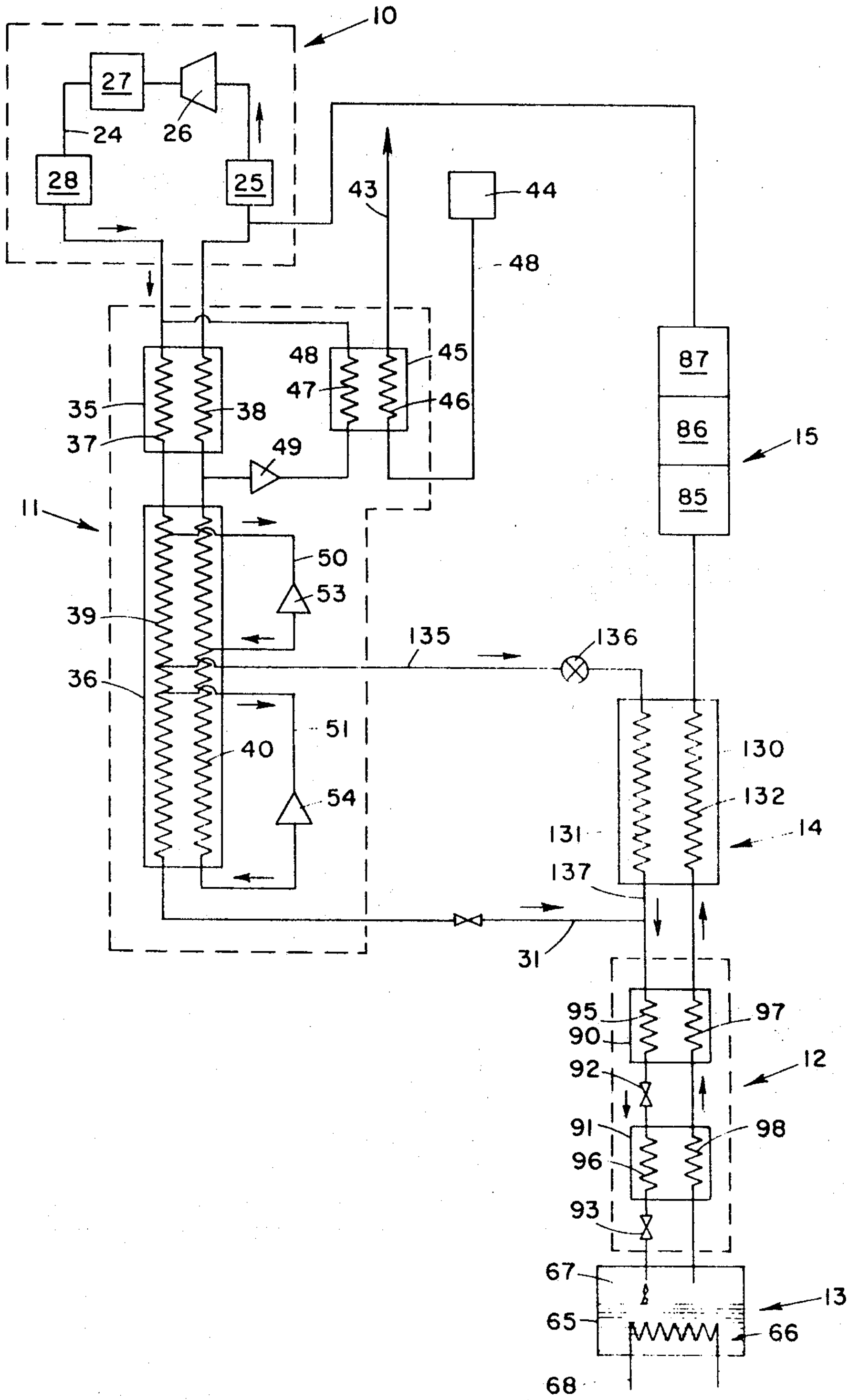

Fig. 4

INVENTOR.
Samuel C. Collins
BY
Bernie A. Lyppen
Attorney

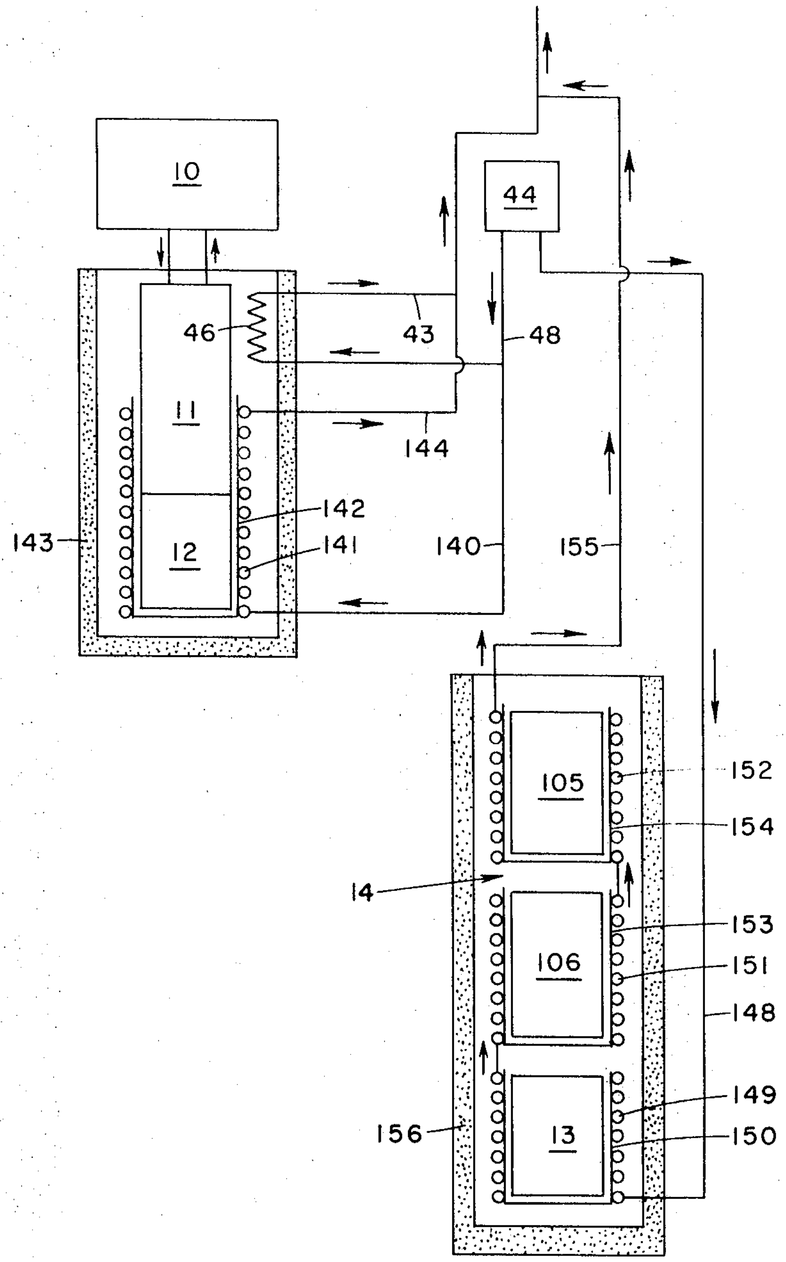

Fig. 5

INVENTOR.
Samuel C. Collins
BY
Bruce A. Lepper
Attorney

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3,613,387

METHOD AND APPARATUS FOR CONTINUOUSLY SUPPLYING REFRIGERATION BELOW 4.2° K.

Samuel C. Collins, Belmont, Mass., assignor to Cryogenic Technology, Inc., Waltham, Mass.

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U.S. Cl. 62—100 16 Claims

ABSTRACT OF THE DISCLOSURE

A cryogenic apparatus capable of continuously supplying liquid helium at a temperature below 4.2° K. by reducing the vapor pressure over liquid helium to the extent required to obtain the desired temperature. The resulting cold, subatmospheric-pressure gas is extracted and, subsequent to its use in indirectly cooling a portion of fluid circulated in an integrated cryogenic refrigerator, is compressed and returned to the system at essentially ambient temperature and pressure.

BACKGROUND OF THE INVENTION

Helium has a boiling point of 4.2° K. at atmospheric pressure. Liquid helium at this temperature has found a wide range of uses, including the cooling of various materials to determine their physical properties and the cooling of certain metals and intermetallic compounds to render them superconducting. Since helium has the lowest condensing point of any gas known, it is necessary to resort to systems which are capable of reducing the temperature of the liquid helium to obtain working temperatures lower than 4.2° K. It has long been known that one way of accomplishing this is to reduce the vapor pressure over the liquid helium since liquid helium (at least in this respect) behaves essentially as do other liquids, i.e., it exhibits a decrease in temperature with a decrease in pressure. Thus by reducing the pressure in a liquid helium reservoir, it is possible to reduce its temperature. For example, reducing the pressure over the liquid to 12.4 mm. reduces the liquid helium temperature to 1.8° K.; while reducing the pressure to 0.0041 mm. reduces the temperature to 0.73° K., the last being about as low as can practicably be obtained with mechanical vacuum pumps in the system.

Liquid helium at about 2.2° K. passes through a second order transition point, and below this so-called lambda point it becomes superfluid, a now well-documented property. In its superfluid state the liquid flows as if it has little, any any, viscosity; and moreover, at about 1.8° the superfluid helium exhibits its maximum thermal conductivity, making it an excellent refrigerant, particularly for refrigerating any device which is intricate in design and has a large number of very small passageways and clearances through which the refrigerant must pass to achieve the required cooling.

Two basic types of systems have been available for some time in the prior art for providing liquid helium below 4.2° K. as a refrigerant. The first of these may be referred to as an apparatus suitable for a batch process. The liquid helium is introduced into a suitably insulated fluid-tight container having therein two liquid helium reservoirs joined by a short length of a thin walled, low thermal conductivity capillary. The load to be refrigerated is affixed to the exterior of one of the liquid helium reservoirs. After precooling with liquid nitrogen the liquid helium reservoirs are filled from an outside source, and then the container is evacuated. This, of course, necessitates the periodic filling of the reservoirs with liquid helium and it is not, therefore, possible continuously to cool a load at temperatures below

4.2° K. with such apparatus. (See for example "Low Temperature Techniques" by A. C. Rose-Innes, D. Van Nostrand Company, Inc., New York, 1964.)

The second type of apparatus which has been in use for some time and which is designed for furnishing refrigeration below 4.2° K. to a load may be considered as a form of continuous operation, but is highly inefficient in terms of the refrigeration required. This apparatus involves a separate cryogenic liquefier designed continuously to deliver liquid helium to a reservoir in which the load is positioned and from which the helium vapor is continuously pumped by means of a suitable vacuum pump. The subatmospheric-pressure helium gas is withdrawn directly into the vacuum pump and any refrigeration which might be available from this subatmospheric-pressure helium gas is lost.

In U.S. Pat. 3,415,077, I disclosed and claimed an apparatus and method which makes it possible to continuously supply liquid helium at temperatures below 4.2° K. and at the same time to derive the maximum refrigeration from the subatmospheric helium gas pumped from the liquid helium reservoir. This apparatus and method are particularly suitable for installations where large vacuum pumps and the large-volume adjuvant heat exchanger can be employed. However, as the demand for refrigeration at temperatures below 4.2° K. increases, there arises a need for apparatus of this character which is smaller, more efficient and compact than that of U.S. Pat. 3,415,077, and which at the same time is also more flexible in its ability to be integrated into a number of different types of equipment which make up a refrigeration load. It is also desirable to have such apparatus which may deliver refrigeration over a wide load range.

SUMMARY OF THE INVENTION

In the cryogenic apparatus of this invention cold high-pressure helium is delivered by a cryogenic refrigerator to a helium liquefying system which is adapted to deliver liquified helium to a load which may be positioned in a helium reservoir. Low-pressure helium gas is withdrawn from the load or reservoir by means of suitable vacuum pumps. A portion of the refrigeration available in the subatmospheric pressure helium withdrawn from the liquid helium reservoir is used to cool a stream of helium gas withdrawn from the cryogenic refrigerator. This stream is diverted from the high-pressure side of the heat exchanger of the refrigerator and it may, if desired, be expanded prior to its indirect heat exchange with the subatmospheric-pressure helium in an auxiliary heat exchanger. This auxiliary heat exchanger is much smaller than the adjuvant heat exchanger of U.S. Pat. 3,415,077 since its upper temperature level is intermediate between the temperature of the liquid helium and the temperature at which the low-pressure fluid is reintroduced into the system. Normally, the upper temperature of the auxiliary heat exchanger will range between 15 and 50° K., depending upon the manner in which this low-pressure gas is used for refrigeration. Thus by compressing the relatively cold helium gas it is possible to materially reduce the size and improve the efficiency of the pumps which in turn achieves an increase in the efficiency of the overall cycle.

It is, therefore, a primary object of this invention to provide an integrated cryogenic apparatus which is capable of continuously delivering refrigeration to a load at temperatures below 4.2° K. It is another object of this invention to provide apparatus of the character described which reduces the size of the heat exchanger and of the vacuum pumps and which at the same time materially increases the overall efficiency of the system. An additional object of this invention is to provide apparatus which is capable of delivering refrigeration over a predetermined range of temperatures below 4.2° K., and of being incorporated into a wide variety of equipment which in effect serves as the thermal load to be refrigerated by the apparatus of this invention.

Another primary object of this invention is to provide an improved method for continuously delivering refrigeration below 4.2° K. Other objects of the invention will in part be obvious and will in part be apparent hereinafter.

The invention accordingly comprises the several steps and the relation of one or more such steps with respect to each of the other others, and the apparatus embodying features of construction, combinations of elements and arrangement of parts which are adapted to effect such steps, all as exemplified in the following detailed disclosure, and the scope of the invention will be indicated in the claims.

For a fuller understanding of the nature and objects of the invention reference should be had to the following detailed description taken in connection with the accompanying drawings in which

FIG. 1 is a diagrammatic representation of apparatus constructed in accordance with this invention in which the subatmospheric-pressure helium is used to cool expanded helium diverted from the heat exchanger of the cryogenic refrigerator;

FIG. 2 is a diagrammatic representation of a modification of the embodiment of FIG. 1;

FIG. 3 is a diagrammatic representation of the apparatus of this invention in which the subatmospheric-pressure helium is used to cool high-pressure helium diverted from the heat exchanger of the cryogenic refrigerator;

FIG. 4 is a modification of the embodiment of FIG. 3; and

FIG. 5 is a diagrammatic representation showing the incorporation of thermal radiation means.

The device shown diagrammatically in FIG. 1 represents one embodiment of the apparatus of this invention. It is a relatively simple device and is capable of delivering refrigeration at temperatures in the range of 1.5° to 1.8° K., and of handling loads up to several thousands of watts. As will become apparent in the following description, the auxiliary heat exchanger which will typically operate to have an upper temperature level between 30–50° K. is used to cool fluid which has been diverted from the high-pressure side of the heat exchanger of the cryogenic refrigerator and then expanded. In this embodiment liquefaction of the cold high-pressure helium from the refrigerator is achieved through the use of an expansion engine and a Joule-Thomson expansion valve.

The primary components (outlined where necessary in dotted lines) of the apparatus of FIG. 1 comprise a combination high-pressure helium source and a low-pressure reservoir **10**, a cryogenic refrigerator **11**, a liquefying means **12**, a liquid helium reservoir **13**, an auxiliary heat exchanger **14**, and pumping means **15**. The gaseous helium source and low-pressure reservoir means are shown in this embodiment to be combined in a closed loop **24** which includes a low-pressure gaseous helium reservoir and surge tank **25**, a compressor **26**, a clean-up and after-cooler system **27**, and a high-pressure helium storage **28**. The primary high-pressure and low-pressure fluid flow paths, to be described in detail, are designated by reference numerals **30** and **31**, respectively; while the low-pressure flow path of the refrigerator is designated by numeral **32**.

The cryogenic refrigerator is one which is capable of delivering cold high-pressure helium at presures up to 30 atmospheres at a temperature of 30° K. or preferably lower. Typically, such a cryogenic refrigerator indicated generally by the numeral **11** will be comprised of several heat exchangers and expansion engines, and the use of liquid nitrogen to precool the high-pressure gas will normally be a part of this refrigerator. The refrigerator of

FIG. 1 has a first heat exchanger **35** and a second heat exchanger **36**. Typically, these heat exchangers are constructed to provide a helically-wound thin tubing within an annular housing for the high-pressure side, and the volume around the thin tubing as the low-pressure side. In the drawings presented herewith the high-pressure and low-pressure sides are illustrated in a conventional manner, i.e., by zig-zag lines, inasmuch as the actual heat exchanger design is not part of the present invention and any heat exchange means which can efficiently effect the indirect exchange of heat between a high-pressure gas stream and a low-pressure gas stream may be employed. Thus, heat exchanger **35** has a high-pressure side **37** and a low-pressure side **38**; while heat exchanger **36** has a high-pressure side **39** and a low-pressure side **40**. The high-pressure sides **37** and **39** of these heat exchangers are part of the high-pressure flow path **30**; and the low-pressure sides **38** and **40** are part of the low-pressure flow path **32** of the refrigerator.

The refrigerator is also shown to have an optional precooling heat exchanger **45** designed to precool a portion of the high-pressure gas prior to its expansion and return to the low-pressure side **38** of the first heat exchanger **35**. Precooling is typically accomplished with liquid nitrogen used in any well-known heat exchanger design. In FIG. 1 the heat exchanger is illustrated diagrammatically to show the liquid nitrogram in zig-zag line **46** and the high-pressure gas in line **47**. Branch conduit **48** carries this first portion of high-pressure helium through the precooler **45** and then through an expansion engine **49** before returning the cooler low-pressure gas to the low-pressure side **38** of heat exchanger **35**.

In a similar manner, high-pressure helium is withdrawn at several temperature levels in heat exchanger **36** and returned at a colder level to the low-pressure side **40** by way of branch conduits **51** and **52** through expansion engines **54** and **55**. The expansion engines may be of any suitable type and design, for example those shown in U.S. Pat. 2,607,322 or 3,438,220.

The means provided to liquefy the cold high-pressure helium delivered by the refrigerator may take one of several well-known forms. In FIG. 1 the liquefying means **12** is shown to comprise an expansion engine **60**, a Joule-Thomson heat exchanger **61** (having a high-pressure side **62** and low-pressure side **63**) and a Joule-Thomson expansion valve **64**.

The liquid helium delivered from the liquefier **12** may be directed into a liquid helium reservoir or it may be flashed directly over the apparatus or material representing the load to be refrigerated. In the latter case the load will be contained within a suitable housing to permit the helium vapor pressure to be lowered. If a liquid helium reservoir **13** is used, it may be a closed container **65** through the walls of which the conduits forming the high- and low-pressure flow paths are passed and make fluid-tight seals. Within the container is a volume of liquid helium **66** and above it a vapor space **67**. If the load to be refrigerated (represented at **68**) is a large object, e.g., a superconducting magnet, the liquid reservoir may take the form of a large insulated vessel in which the magnet is placed.

The subatmospheric-pressure helium gas is withdrawn from the liquid reservoir **13** through the low-pressure fluid flow path which includes the auxiliary heat exchange means **14** shown in FIG. 1 as a heat exchanger **75** having a first side **76** and a second low-pressure side **77**, the latter being part of the low-pressure flow path **31**. The first side **76** is part of a fluid flow line **80** which in turn is in fluid communication through branch line **51** with the high-pressure side **39** of heat exchanger **36** of the refrigerator. Since the fluid diverted from the refrigerator is expanded and further cooled in expansion engine **54** it is returned via line **81** into the low-pressure side **40** of the refrigerator heat exchanger. If desired, a small portion of the expanded fluid may be returned directly via line **82** into the low-pressure side of the heat exchanger, the amount being controlled by valve **83**. Normally, the amount of such low-pressure fluid returned directly will be only a small percentage of that directed through heat exchanger **75**. Since the helium in side **77** is at a lower pressure than that in side **76**, it will be preferable to use a heat exchanger of a type which permits the subatmospheric-pressure helium to flow around tubing containing the helium temporarily diverted from the main heat exchanger of the refrigerator.

In the embodiment of FIG. 1 the temperature of the fluid streams at the top of auxiliary heat exchanger **75** typically will be between about 30° and 50° K. The mass flow of fluid diverted from the main heat exchanger of the refrigerator for passage through auxiliary heat exchanger **75** will preferably be about the same as the mass flow of subatmospheric-pressure helium in the low-pressure flow path. Since the specific heats of helium at the two pressure levels of the two streams are not substantially different, no marked differences in mass flow are required to be maintained.

The subatmospheric-pressure gas, at a temperature of between about 30° and 50° K. as it leaves auxiliary heat exchanger **75**, is then compressed to essentially atmospheric pressure in suitable pumping means **15** which in FIG. 1 are represented as three pumps **85**, **86** and **87**. Due to the heat of compression and pump inefficiencies the helium introduced from the low-pressure fluid flow path **31** into compressor **26** will be at approximately ambient temperature. Thus by choosing an upper temperature level for the auxiliary heat exchanger which is such that when it is compressed to essentially atmospheric pressure it has attained essentially atmospheric temperature, it is possible to materially reduce the size of the heat exchanger or heat exchangers and of the vacuum pumping means. Concurrently the efficiencies of the heat exchanger and pumping systems are increased and hence the efficiency of the overall system and cycle is improved.

In the apparatus of FIG. 1 three expansion engines **49**, **54** and **55** are used in the refrigerator to cool high-pressure fluid and return it to the heat exchangers at successively colder levels. An additional expansion engine **60** is used in the liquefier. In the apparatus of FIG. 2, wherein like numbers refer to like components in FIG. 1, three expansion engines are also used in the refrigerator, but that associated with the liquefier is eliminated, being replaced with one or more Joule-Thomson valves.

It will be noted that FIG. 2 illustrates other modifications in this embodiment, namely the use of a compressor **26** to serve in the dual role of low-pressure reservoir and high-pressure helium source and the use of two vacuum pumps **85** and **86**. The liquefying means **12** is also somewhat modified in that it comprises two Joule-Thomson heat exchangers **90** and **91** and two Joule-Thomson valves **92** and **93**. The heat exchangers have high-pressure sides **95** and **96** and low-pressure sides **97** and **98**, respectively.

The actual number of expansion engines and the combination of heat exchangers and expansion means used to liquefy the cold high-pressure helium delivered by the refrigerator may be varied, the final choice being within the competence of one skilled in the art. Thus for example, in the apparatus of FIG. 3 there are five expansion engines associated with the refrigerator **11**. These additional expansion engines **53** and **57** are located in branch lines **50** and **56**, respectively.

In the apparatus embodiments of FIGS. 3 and 4, in which like components are identified by the same reference numerals used in FIGS. 1 and 2, the high-pressure helium diverted from the cryogenic refrigerator for passage through the auxiliary heat exchanger is not expanded prior to its passage therethrough. In the apparatus of FIG. 3 the auxiliary heat exchange means are modified to provide for adjustments in mass flow due to the much greater difference in the pressures of the two fluid streams in the auxiliary heat exchanger. This modification takes the form of two heat exchangers **105** and **106**. High-pressure, partially cooled helium gas is diverted from the high-pressure side **39** of the main heat exchanger into the high-pressure side **107** of heat exchanger **105** through line **108**, the fluid flow in which is controlled by valve **109**. A portion of the further cooled high-pressure fluid leaving heat exchanger **105** is returned via line **110** to the high-pressure side of the main heat exchanger at an appropriate temperature level; while the remainder is directed by line **111**, the flow in which is controlled by valve **112**, into the high-pressure side **113** of heat exchanger **106**. The high-pressure fluid leaving heat exchanger **106** is at a sufficiently low temperature, e.g., below 30° K. (typically about 10° K.) to permit it to be introduced by line **114** into the cold high-pressure fluid in the high-pressure fluid flow path **31** so that the mixed streams can be directed into the liquefying means **12**.

At the fluid stream temperatures which prevail in heat exchanger **105**, e.g., from 20° to 50° K., the specific heat of helium is essentially independent of pressure, a fact which permits a large mass flow of helium in the high-pressure side of that heat exchanger. However, at lower temperatures such as those which prevail in heat exchanger **106**, this is no longer true for at these temperatures, e.g., below about 16° K. the specific heat of high-pressure helium is much greater than that of the low-pressure helium. Thus some adjustment of mass flow is necessary and this is accomplished through the use of valve **112** which restricts the mass flow of high-pressure fluid into heat exchanger **106** and returns a predetermined portion to the high-pressure side of the main heat exchanger. The ratio of the amount of high-pressure helium introduced into heat exchanger **106** to the amount returned to the main heat exchanger can readily be determined through thermodynamical calculations for any given set of pressure-temperature conditions.

The liquefying means of the apparatus of FIG. 3 comprises two Joule-Thomson heat exchangers **120** and **121** with an optional Joule-Thomson valve **122** interposed between. As in the case of FIG. 2, these heat exchangers have high-pressure sides **123** and **124** and low-pressure sides **125** and **126**, the latter making up a portion of the low-pressure fluid flow path **31** which also includes low-pressure sides **116** and **1115** of heat exchangers **106** and **105** as well as the compressors **85** and **86**.

The apparatus illustrated in FIG. 4, in which like components have like numbers in the preceding drawings, is a modification of the embodiment of FIG. 3, the fluid diverted from the main heat exchanger being from the high-pressure side. In place of the five expansion engines in the refrigerator of FIG. 3, the refrigerator of FIG. 4 has only three expansion engines and the gas diverted from the main heat exchanger to the single auxiliary heat exchanger **130** is at a lower temperature than in the apparatus of FIG. 3. Cold high-pressure helium is passed through the high-pressure side **131** to be further cooled by the subatmospheric-pressure gas in the low-pressure side **132**. The amount of high-pressure gas entering heat exchanger **130** through line **135** is adjusted by valve **136** to maintain the required mass flow ratio of the two gas streams in the two sides **131** and **132** of the auxiliary heat exchanger. The high-pressure gas from auxiliary heat exchanger **130** is then delivered by line **137** into the high-pressure flow path prior to the introduction of the cold high-pressure helium into the liquefying means **12** which is shown as the same as that in the apparatus of FIG. 2.

The refrigerator of FIG. 4 has a precooling heat exchanger **45**, the coolant for which (e.g., liquid nitrogen) is supplied from source **44** through line **48** and discharged through line **43**. FIG. 5 illustrates diagrammatically how an external coolant such as liquid nitrogen is also used along with suitable insulating means to thermally protect various apparatus components. In addition to providing precooling of a portion of the high-pressure helium in the main heat exchange of the refrigerator, as explained above, the liquid nitrogen is delivered by line **140** to coils **141** which are wrapped about a radiation shielding **142** which in turn encases the colder end of the refrigerator **11** and the liquefier **12**. These components are in turn maintained in a suitably insulated housing **143**, e.g., in an evacuated fluid-tight structure. The nitrogen is withdrawn from coils **141** through a discharge line **144**.

In a similar manner, liquid nitrogen is delivered through line **148** to coils **149** which are in heat exchange contact with radiation shielding **150** around the liquid helium reservoir **13**. The cold nitrogen is then conducted to coils **151** and **152** around radiation shieldings **153** and **154** which are associated with the two auxiliary heat exchangers **106** and **105**. The nitrogen gas is then discharged through line **155**. The auxiliary heat exchangers and the liquid helium reservoir are also thermally protected by suitable insulating means such as an evacuated housing **156**. It will be appreciated that many different insulating systems are available and that those described are illustrative only.

The cryogenic apparatus of this invention and its various embodiments and modifications may be constructed to deliver refrigeration below 4.2° K. over a wide load range. It lends itself to incorporation in many types of equipment requiring such refrigeration.

It will thus be seen that the objects set forth above, among those made apparent from the preceding description, are efficiently attained, and since certain changes may be made in carrying out the above method and in the constructions set forth without departing from the scope of the invention, it is intended that all matter contained in the above description or shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

I claim:

1. An apparatus for continuously providing liquid helium at a temperature below 4.2° K., comprising in combination

(a) high-pressure helium source means;
(b) low-pressure helium reservoir means;
(c) vacuum pump means;
(d) cryogenic refrigerator means, including heat exchange means with high-pressure and low-pressure sides in indirect heat exchange relationship and fluid expansion means, said refrigerator means being adapted to deliver gaseous helium at an elevated pressure up to about 30 atmospheres and at a temperature below 30° K.;
(e) auxiliary indirect heat exchange means including means to define first and second sides and being adapted to effect indirect heat transfer between a first fluid stream diverted from the high-pressure side of said heat exchange means of said cryogenic refrigerator flowing in said first side and a second low-pressure stream flowing countercurrently in said second side;
(f) conduit means providing direct fluid communication between said high-pressure side of said heat exchange means of said cryogenic refrigerator means and said first side of said auxiliary heat exchange means thereby providing said first fluid stream in said auxiliary heat exchange means;
(g) helium liquefying means including heat exchange means arranged to effect heat transfer between two fluid streams and fluid expansion means, said liquefying means being adapted to liquefy cold high-pressure helium supplied by said refrigerator and to deliver liquefied helium to a load;
(h) a primary high-pressure helium flow path extending between said high-pressure helium source means and said helium liquefying means and incorporating the high-pressure side of said heat exchange means of said cryogenic refrigerator means; and
(i) a low-pressure helium flow path extending from a vapor volume associated with said load to said low-pressure helium reservoir means and incorporating in order one of said fluid streams of said helium liquefying means, said second low-pressure stream of said auxiliary indirect exchange means and said vacuum pump means.

2. An apparatus in accordance with claim **1** wherein said high-pressure helium source means and said low-pressure helium reservoir means comprise a fluid compressor.

3. An apparatus in accordance with claim **1** wherein said cryogenic refrigerator means has at least two expansion engines as said fluid expansion means, each of said expansion engines being located in a branch fluid flow path joining said high-pressure side of said heat exchange means of said cryogenic refrigerator means at a predetermined temperature level with said low-pressure side at a lower temperature level.

4. An apparatus in accordance with claim **3** wherein external cooling means are provided to cool the fluid prior to expansion in the warmest of said branch fluid flow paths.

5. An apparatus in accordance with claim **1** including means associated with said conduit means to expand said first fluid stream prior to delivery into said first side of said auxiliary heat exchange means and conduit means to return the expanded fluid from said first side of said auxiliary heat exchange means to said low-pressure side of said heat exchange means of said refrigerator.

6. An apparatus in accordance with claim **1** wherein said conduit means are adapted to deliver said first fluid stream to said auxiliary heat exchange means as high-pressure fluid, and including additional conduit means adapted to deliver at least a portion of said high-pressure fluid discharged from said auxiliary heat exchange means to said helium liquefying means.

7. An apparatus in accordance with claim **6** including means to return a portion of said fluid discharged from said auxiliary heat exchange means to the high-pressure side of said heat exchange means of said refrigerator at a temperature level below that at which it was withdrawn.

8. An apparatus in accordance with claim **1** wherein said fluid expansion means of said helium liquefying means comprises at least one expansion engine.

9. An apparatus in accordance with claim **1** wherein said fluid expansion means of said helium liquefying means comprises at least one Joule-Thomson expansion valve.

10. An apparatus in accordance with claim **1** including liquefied helium reservoir means.

11. An apparatus in accordance with claim **10** wherein said liquefied helium reservoir means is adapted to deliver refrigeration to a load.

12. An apparatus in accordance with claim **1** including radiation shield means to protect said load, said cryogenic refrigerator means, said auxiliary indirect heat exchange means and said helium liquefying means, and means to cool said radiation shield means.

13. A method of continuously delivering refrigeration to a load at a temperature below 4.2° K., comprising

(a) effecting indirect heat exchange in a refrigerator between a high-pressure stream of helium and a first cold low-pressure stream of helium thereby to provide helium at an elevated pressure and a temperature below 30° K.;
(b) liquefying the high-pressure cold helium;
(c) employing the resulting liquefied helium to refrigerate a load;
(d) reducing the vapor pressure above the liquefied helium and pumping out the cold, subatmospheric-pressure helium gas thereby to provide a second cold low-pressure stream of helium; and
(e) diverting a portion of said high-pressure stream in said refrigerator for indirect heat exchange with said second cold low-pressure stream of helium, thereby

to derive auxiliary refrigeration from said second low-pressure stream prior to its being compressed and raised to essentially ambient temperature, the temperature of said second cold low-pressure stream of helium being not above about 50° K. after effecting said indirect heat exchange with said diverted portion of said high-pressure stream.

14. A method in accordance with claim **13** including the steps of expanding said diverted portion of said high-pressure stream prior to indirect heat exchange with said second cold low-pressure stream and of subsequently returning the resulting expanded fluid to said first low-pressure stream.

15. A method in accordance with claim **13** wherein said diverted portion of said high-pressure stream is refrigerated as high-pressure fluid and including the step of mixing at least a portion of the resulting refrigerated high-

pressure fluid with high-pressure helium from said refrigerator just prior to said liquefying.

16. A method in accordance with claim **15** including the step of returning a portion of the resulting refrigerated high-pressure fluid to said high-pressure stream in said refrigerator.

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WILLIAM F. O'DEA, Primary Examiner

P. D. FERGUSON, Assistant Examiner

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62—9, 38, 39, 115, 513, 514