Oct. 5, 1971 J. A. O'NEIL ET AL 3,609,982

CRYOGENIC CYCLE AND APPARATUS FOR REFRIGERATING A FLUID

Filed May 18, 1970 3 Sheets-Sheet 1

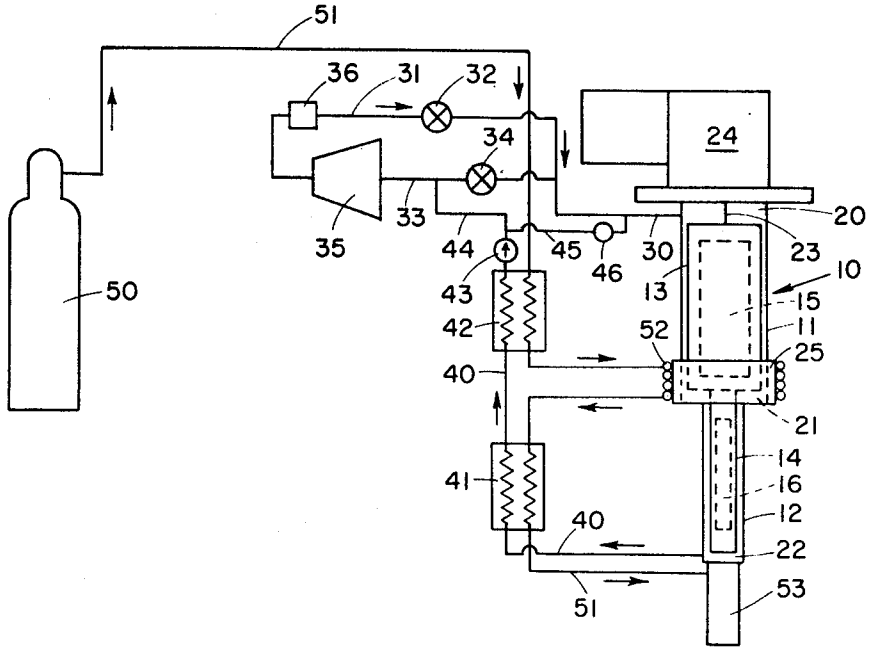


Fig. 1

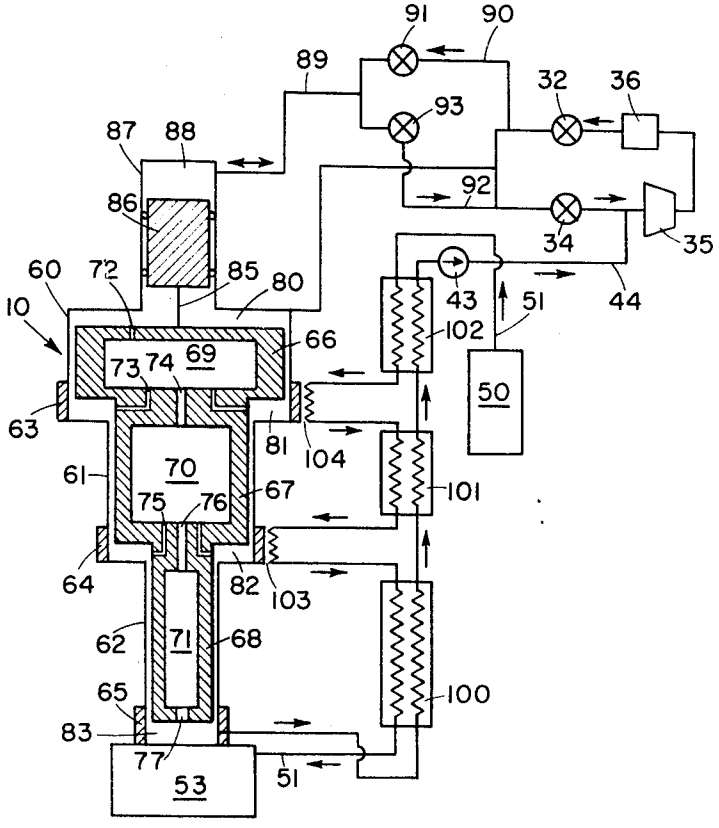


Fig. 2

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CRYOGENIC CYCLE AND APPARATUS FOR REFRIGERATING A FLUID

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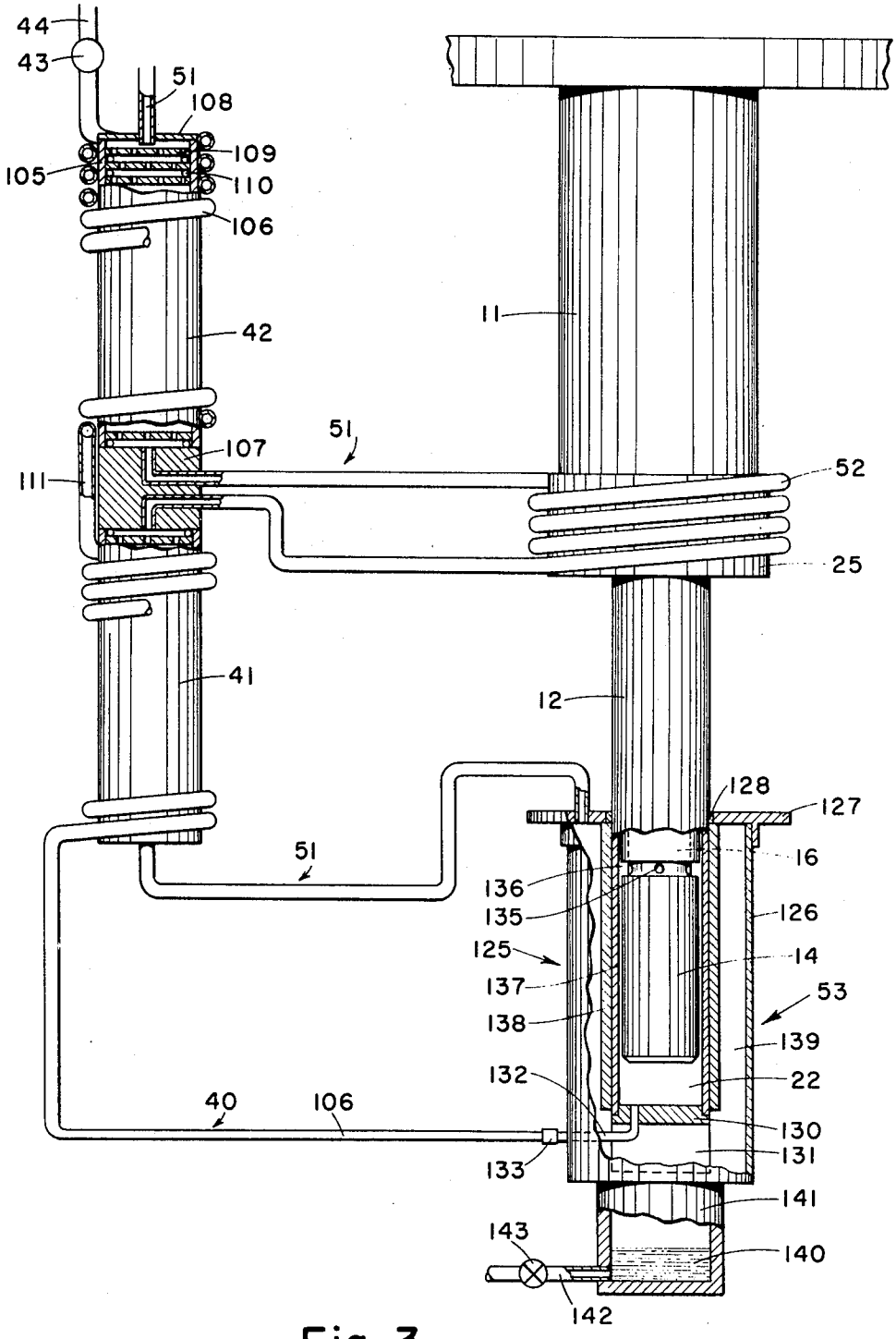


Fig. 3

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CRYOGENIC CYCLE AND APPARATUS FOR REFRIGERATING A FLUID

Filed May 18, 1970 3 Sheets-Sheet 3

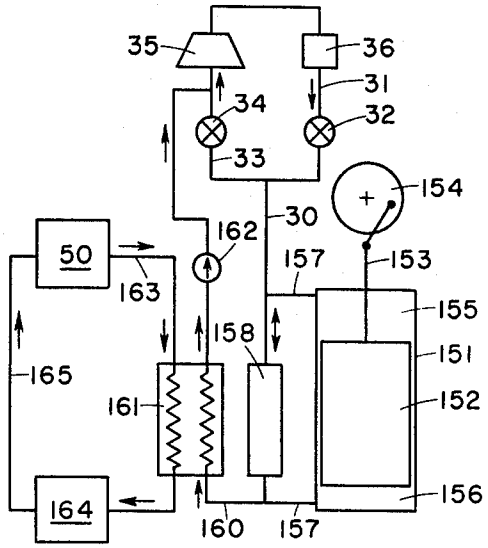


Fig. 4

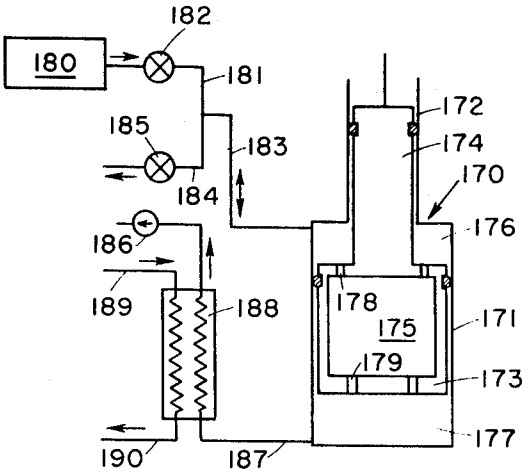


Fig. 5

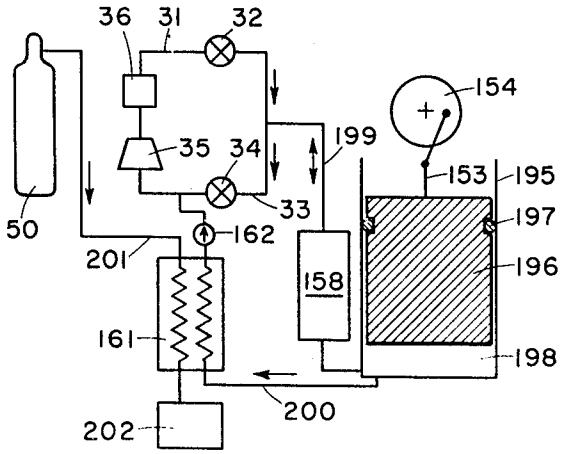


Fig. 6

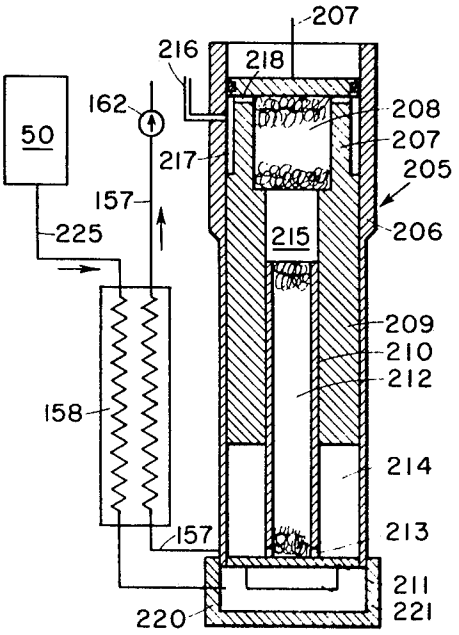


Fig. 7

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United States Patent Office 3,609,982
Patented Oct. 5, 1971

3,609,982

CRYOGENIC CYCLE AND APPARATUS FOR REFRIGERATING A FLUID

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Int. Cl. F25b 9/00; F25j 1/00
U.S. Cl. 62—9 16 Claims

ABSTRACT OF THE DISCLOSURE

Method and apparatus for cooling and liquefying a refrigerated fluid such as hydrogen. A small amount of cold refrigerating fluid, bled off from a cryogenic refrigerator or liquefier, is used to cool the refrigerated fluid over a temperature range. Final cooling and liquefaction if desired is then accomplished at essentially constant temperature. The result is more efficient use of the refrigerating fluid.

This invention relates to cryogenic apparatus and more particularly to apparatus which employs a first refrigerating fluid to cool, and if desired to liquefy, by out-of-contact indirect heating exchange means a second refrigerated fluid which has a higher boiling point than the refrigerating fluid.

It is often desirable to be able to cool a fluid by indirect heat exchange with a refrigerating fluid which has a lower boiling point than the refrigerated fluid. Such cooling may be carried out to liquefy the second refrigerated fluid or to bring it to a suitable low temperature so that it may be circulated as a coolant to a remote load.

An important example of this type of refrigeration is the cooling and subsequent liquefying of hydrogen using helium in a refrigerating apparatus in which helium is controllably introduced as initially cooled high-pressure fluid into a refrigerating chamber of variable volume and then expanded and withdrawn into a low-pressure reservoir. The introduction and withdrawal of the fluid is accomplished along a fluid flow path that contains a regenerator which effects the initial cooling of the refrigerating fluid prior to its entry into the expansion chamber. Apparatus of these types, and the cycles on which they operate, are described in detail in United States Pats. 2,906,101, 2,966,034, 2,966,035, 3,188,819, 3,188,820, and 3,218,815. In using the cryogenic apparatus described in the above-noted patents to cool and liquefy hydrogen it has been customary to effect all of the indirect heat exchange between the hydrogen fluid and the refrigerating fluid at constant-temperature heat stations. Normally staged refrigerators are used making it possible to use essentially constant-temperature refrigeration at one or more essentially distinct temperature levels the lowest of which effects final cooling and liquefaction.

In the apparatus of this invention a major portion of the cooling is accomplished over a wide temperature range. A predetermined portion of the low-pressure refrigerating fluid is withdrawn from the last or coldest expansion chamber and taken along a second fluid flow path for return into the low-pressure reservoir. The fluid which is to be refrigerated, e.g., hydrogen, is in turn brought into the system through a third fluid flow path, and is cooled by means of out-of-contact indirect heat exchange with the helium being returned to the low-pressure reservoir along the second fluid flow path. Thus, by the time the hydrogen reaches the heat exchanger which is associated with the lowest temperature refrigeration chamber and which provides the refrigeration for liquefaction, a major portion of the refrigeration has already been accomplished. The advantage of this is that only the heat of liquefaction must be transferred through

a constant temperature heat station associated with the lowest-temperature expansion chamber. This energy in the case of the liquefaction of hydrogen through the use of a helium refrigerant is only about 11% of the total energy which would have to be removed from the hydrogen if the counterflow heat exchanger were not employed to take advantage of the low-pressure helium being returned to the low-pressure reservoir through the second fluid flow path.

The apparatus and cycle of this invention are also applicable to single-stage devices or to devices which have but a single refrigeration chamber available for delivering refrigeration to a refrigerated fluid. Although such modifications are normally not suitable for liquefying the lower-boiling gases, particularly hydrogen or nitrogen, they may be employed to liquefy some of the higher boiling gases such as argon or methane using hydrogen or helium as the refrigerant fluid.

It is therefore a primary object of this invention to provide an apparatus which is capable of achieving higher efficiencies in the liquefaction of the lower-boiling gases through indirect heat exchange with a refrigerating gas in a refrigerator than are now attainable. It is another object of this invention to provide an apparatus of the character described which is particularly suitable for liquefying hydrogen using helium as a refrigerant. It is yet another object of this invention to provide such apparatus which is suitable for cooling fluids for use in refrigerating loads at remote locations.

It is another principal object of this invention to provide a refrigeration cycle which incorporates both a refrigerating and a refrigerated fluid in a way to achieve maximum efficiency in refrigerating the refrigerated fluid. It is another object of this invention to provide an improved cycle for liquefying hydrogen. 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 of such steps with respect to each of the others and the apparatus embodying features of construction, combination of elements, and arrangements 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 objects of the invention, reference should be had to the following detailed description taken in connection with the accompanying drawing in which

FIG. 1 is a diagram of a complete cryogenic apparatus constructed in accordance with this invention, the refrigerator of which uses a no-work cycle as described in U.S. Pat. 2,966,035;

FIG. 2 is a modification of the cryogenic apparatus of FIG. 1 showing a three-staged refrigertor which is pneumatically driven;

FIG. 3 is a side elevational view, partly in cross section, of a cryogenic apparatus constructed in accordance with this invention and along the lines of the diagram illustrated in FIG. 1;

FIG. 4 is a diagram of another embodiment of the cryogenic apparatus of this invention using a single-stage, no-work apparatus described in U.S.P. 2,966,035;

FIG. 5 is an embodiment of the cryogenic apparatus constructed in accordance with this invention using the basic refrigerator described in U.S.P. 3,188,820;

FIG. 6 is another embodiment of the cryogenic apparatus in which the refrigerator is constructed in accordance with the teaching of U.S.P. 2,906,101; and

FIG. 7 is another embodiment of the cryogenic apparatus in which the refrigerator is an in-line staged refrigerator in which only the cold refrigeration chamber is available for delivering refrigeration.

That portion of the apparatus in which the refrigerating fluid circulates may be defined as one which is comprised of a fluid-tight enclosure, a body movable within the enclosure to define at least one expansion chamber of variable volume, a source of a first high-pressure refrigerating fluid and a low-pressure fluid reservoir, both of which are external of the enclosure, and a fluid flow path which provides fluid communication between the high-pressure fluid source and the low-pressure fluid reservoir and the chamber of variable volume. Located within the fluid flow path is a heat storage means which effects the necessary initial cooling of the high-pressure fluid introduced into the expansion chamber through refrigeration stored therein and derived from the low-pressure fluid as it is returned to the low-pressure reservoir. Basic refrigerators of this general type are the subject of U.S. Pats. 2,906,101, 2,966,035, and 3,188,819 and 3,188,830.

In the cryogenic apparatus of this invention, second and third fluid flow paths are provided in addition to the first fluid flow path which is associated with the refrigerator. The second of the fluid flow paths is one which provides fluid communication between the coldest expansion chamber in the refrigerator and low-pressure fluid reservoir which is external of the refrigerator housing. In some modifications of the refrigerator, the second flow path may optionally also be connected directly with the refrigerator. Associated with this second fluid flow path is a metering valve which controls the amount of refrigerating fluid that is returned through an out-of-contact heat exchanger incorporated in the second fluid flow path. The fluid flow metering valve controls the amount of fluid that is allowed to return through the second fluid flow path. The actual quantity is determined by the amount of cooling required and the temperatures involved. It is of course necessary that the major portion of the fluid in the refrigerator be returned through the first fluid flow path in order to cool the regenerator material so that the high-pressure fluid entering the refrigerator in the next cycle is initially cooled prior to its entrance into the expansion chamber.

The third fluid flow path is that through which the fluid to be refrigerated is introduced into the system and directed to its predetermined destination. Thus, for example in the case of the liquefaction of hydrogen, this third fluid flow path will extend from a source of hydrogen gas to a reservoir adapted to contain liquid hydrogen. Normally this reservoir will be in heat transfer relationship with the coldest of the exansion chambers of the refrigerator. Alternatively the fluid in the third fluid flow path may be recirculated and used to cool a remote thermal load.

Apparatus constructed in accordance with this invention and suitable for liquefying hydrogen is shown in diagrammatic form in FIG. 1. The refrigerator **10** is constructed in accordance with the teaching and operates on the cycle shown in U.S.P. 2,966,035. It will be noted that a two-stage refrigerator is formed of an upper or warmer stage **11** and lower or colder stage **12**. (It will be appreciated that the terms "warmer" and "colder" and "upper" and "lower" are used in a relative sense and that the refrigeration apparatus may be operated at different temperature levels and oriented in any manner.) Within the enclosure which defines the refrigerator **10** is a displacer comprising an upper section **13** and a lower section **14**. Within the upper section of the displacer is a regenerator **15** and within the lower section is a regenerator **16**, these regenerators being connected with each other and in fluid communication with the various refrigeration chambers by means illustrated for example in U.S.P. 3,218,815 (see in particular FIG. 6 of that patent which details a preferred arrangement of displacers and design of the flow path within the enclosure defining the refrigerator).

Within the refrigerator housing enclosure are an upper warm chamber **20**, an intermediate-temperature chamber **21** and a lowest-temperature chamber **22**. All of these chambers are of variable volume defined by the motion of the displacer, this motion being effected through a displacer rod **23** which is mechanically linked to a suitable driving device (not shown) located in the crosshead **24**. This crosshead may be constructed in accordance with the teaching of U.S.P. 3,312,239. A suitable heat station **25** is associated with the intermediate-temperature volume **21** and is designed to provide refrigeration at relatively constant temperature to a load. This heat station may be constructed in any known way, a preferable construction being described in a co-pending application Ser. No. 807,606 filed Mar. 17, 1969, in the names of Fred F. Chellis and James A. O'Neil and assigned to the same assignee as the present application.

Refrigerating fluid is introduced into and is withdrawn from the refrigerator through line **30** which in turn is in fluid communication with a high-pressure line **31**, the flow of fluid in which is controlled by a valve **32**. Likewise, a low-pressure fluid line **33**, having fluid flow control valve **34**, is also in communication with line **30**. Interposed between the high-pressure line **31** and the low-pressure line **33** is a compressor **35** which in this case serves as both the source of the high-pressure fluid and the low-pressure reservoir required in the operation of the refrigerator. It is, course, also within the scope of this invention to include such auxiliary equipment as aftercooler **36** and any suitable clean-up system. The use of these is well known to those skilled in the art.

In the embodiment of FIG. 1 the first fluid flow path is comprised of the compressor **35** (serving as the source of high-pressure fluid), the high-pressure line **31**, valve **32**, inlet **30**, the warm chamber **20**, regenerator **15**, intermediate-temperature chamber **21**, regenerator **16** and low-temperature chamber **22**. Also included are low-pressure line **33**, its associated valve **34**, and the compressor **35** serving in the role of the low-pressure reservoir.

The second fluid flow path, which provides direct fluid communication between the lowest-temperature chamber **22** and the low-pressure reservoir **35**, comprises the conduit **40** which will be seen to pass through indirect countercurrent heat exchangers **41** and **42** and to have associated with it a metering valve **43** and a branch line **44** which communicates with low-pressure line **33**. Branch line **45** which joins conduit **40** with line **30** is optional and fluid flow through this line directly into the refrigerator chamber **20** may be permitted or not by actuation of valve **46**. Metering valve **43** may be located anywhere along conduit **40**.

Inasmuch as the apparatus of FIG. 1 is designed to liquefy hydrogen it is necessary to provide a source of hydrogen gas such as cylinder **50**. The third fluid flow path in which the hydrogen flow is designated by conduit or line **51** which, it will be seen, forms the other side of the indirect heat exchanges **42** and **41** in a way so that the hydrogen flowing therein is in heat exchange relationship with the cold, low-pressure helium which is bled from the chamber **22**. The third fluid flow path carrying the hydrogen also leads through a heat exchanger **52** which is in heat exchange relationship with heat station **25** associated with the intermediate-temperature chamber **21**. Finally, the third fluid flow path carrying the hydrogen terminates in a hydrogen discharge vessel **53** which is adapted to effect final heat transfer between the hydrogen and the helium in the coldest-temperature chamber **22** prior to the collection of the liquid hydrogen in the discharge vessel **53**. Heat exchanger **52** serves to overcome the heat exchange loss of heat exchanger **42** and it must transfer only a small portion of energy through a constant-temperautre heat station in contrast with the heat transfer which would be required if the counterflow heat exchanger **42** were not used.

The cycle on which the refrigerator **10** operates is described in detail in U.S. Pat. 2,966,035 and need not be described here. Suffice it is to say that expansion and final cooling occur when the high-pressure valve **32** is closed and the low-pressure valve **34** is open to permit discharge

of helium back through the flow path into the compressor. If metering valve **43** is a simple flow restriction, then cool helium will flow through conduit **40** principally during the pressurizing portion of the refrigerator cycle. As a result, this cool helium will be at the average temperature of the cold end of the regenerator **16**. If metering valve **43** is controlled by fluid pressure in line **30**, then it will only open during the time when the exhaust valve **34** is open, a situation which is advantageous because this "exhaust" gas entering line **30** through branch line **45** and opened valve **46** will be colder than the cold end of the regenerator **16**. Maximum fluid flow through conduit **40** will in this arrangement be determined by the ease of the cold helium to pass through line **40** relative to the ease of its ability to pass through regenerators **16** and **15**. Thus the system, regardless of the path or paths by which the small amount of helium is directed through the second flow path, is essentially self-regulating. By permitting the check valve **43** to open only during that time when the exhaust valve **34** is open it is possible to obtain even greater efficiency in the cycle. As pointed out previously only a small portion of the cold helium can be permitted to go by way of the second fluid flow path for this indirect heat exchange. However, this portion of the helium is sufficient to effect as much as 89% of the refrigeration of the hydrogen prior to its final cooling and liquefaction by heat exchange with the heat station associated with the final cold expansion chamber **22**. This will be described in more detail in the description of a typical apparatus shown in FIG. 3.

In the embodiment of FIG. 2 a three-stage refrigerator is used and it is shown to be pneumatically driven rather than mechanically driven such as is illustrated in the apparatus of FIG. 1. Thus, this refrigerator **10** is constructed in accordance with the teachings of U.S. Pat. 3,188,819 and reference should be had to that patent for a detailed discussion of the apparatus as well as the cycle on which the refrigerator **10** operates. In FIG. 2, in which like numerals refer to like components of FIG. 1, the refrigerator is formed of stages **60**, **61**, and **62**, each of these having an associated heat station **63**, **64** and **65**, respectively. The displacer is likewise formed of three stages namely **66**, **67**, and **68** which have a series of regenerators **69**, **70** and **71** connected by passages **72**, **73**, **74**, **75**, **76** and **77**. The chambers, regenerators and passages form the first fluid flow path. This staged displacer in its operation within the staged cylindrical housing defines a warm or upper chamber **80**, two intermediate-temperature chambers **81** and **82** and the coldest-temperature refrigeration chamber **83**. Typically, in a refrigerator which uses helium as a refrigerant, the temperatures of the helium will be about 60° K. in chamber **81**, 30° K. in chamber **82** and 10 to 20° K. in chamber **83**.

Attached to the displacer by means of a mechanical link **85** is a piston section **86** which has suitable sealing means associated with it and which operates in a vertical motion within a piston section housing **87** integral with the refrigerator housing. The piston **86** in its motion defines within the housing **87** a driving chamber **88** of variable volume into which high-pressure fluid is introduced and low-pressure fluid withdrawn for imparting the necessary motion to the displacer. As shown in FIG. 2 the chamber **87** has an inlet **89** which is in fluid communication with a high-pressure line **90** incorporating a fluid flow control valve **91**, and in fluid communication with a low-pressure line **92** incorporating a fluid flow control valve **93**. Thus, in the arrangement of FIG. 2 the same fluid which is used as the refrigerant in the refrigerator is also used as the driving fluid in the driving chamber **88**. It is, of course, within the scope of this invention to use a separate driving fluid with separate source and reservoir means and sepaarte auxiliary equipment.

The refrigerating fluid, helium, is cycled from the compressor by way of aftercooler **36** into the system and withdrawn in the manner described previously for the fluid circulating in the refrigerator of FIG. 1. Likewise, the fluid to be refrigerated, i.e., hydrogen, is withdrawn from a suitable source **50** and conducted through the third fluid flow path which in this case includes three heat exchangers, namely **100**, **101**, and **102** which are adapted for indirect heat exchange with the helium bled off from chamber **83**, and two heat exchangers **103** and **104** which are adapted to cool the hydrogen by refrigeration delivered from the heat stations **64** and **63**, respectively.

FIG. 3 is a side elevational view, partly in cross section, of a refrigerator constructed in accordance with the diagram of FIG. 1; and in this FIG. 3 like reference numerals are used to refer to like elements in FIG. 1. It will be seen in FIG. 3 that the heat exchangers **41** and **42** take the form of a cylindrical tube **105** having a small-diameter tubing **106** helically wound around it and bonded to the outer wall thereof in heat exchange relationship such that heat transfer may be effected between fluids flowing in tube **105** and tubing **106**. The two heat exchangers **41** and **42** are joined by a cylindrical block **107** formed of a material such as stainless steel and they are closed at their nonjoining ends with end members **108**. Within each cylindrical tube **105** are a plurality of stacked foraminous disks **109** (typically photoetched copper) held in spaced relationship, by stainless steel wires serving as spacers **110**. Hydrogen, or other fluid to be cooled, is brought into the heat exchanger through conduit **51** and passes down through the foraminous disks. From heat exchanger **42** it is taken through tubing **52** which is bonded to the heat station **25** and is then taken into heat exchanger **41** from where it is delivered to the hydrogen discharge vessel **53** for liquefaction.

The bleed-off cold helium line **40** takes the form of the tubing **106** wound around the tubes **105**. The metering valve **43** is shown to be located where tubing **40** joins branch conduit **44** which communicates with the low-pressure side of the refrigerator. Although this is the most convenient location for metering valve **43**, it may equally well be placed in tubing **40** between the expansion chamber **22** and heat exchanger **41** or in that section **111** of tubing **40** which extends between heat exchangers **41** and **42**.

The precooled hydrogen having heat exchanger **41** is discharged into a liquefaction chamber **125** which is defined by a cylindrical wall **126** and a cover member **127** which permits the lower stage cylindrical housing **12** of the refrigerator to pass down into and extend throughout a major portion of the length of the liquefaction chamber. A suitable seal **128** is provided between the housing wall and the liquefaction chamber cover member. The refrigerator terminates in a heavy copper plate **130** serving as a part of the heat station associated with the refrigeration chamber **22**. To this copper plate heat station are attached a number of thin copper fins **131** for enhancement of heat transfer to the hydrogen contained within the liquefaction chamber **125**. A small-diameter tubing **132** carries the bled-off cold helium from chamber **22** to tubing **106** of the heat exchanger **41** and is joined thereto through a connector **133**.

FIG. 3 illustrates a preferred embodiment of the displacer and fluid flow path within the refrigerator. Thus the helium gas after leaving regenerator **16** (indicated by the dotted lines) passes out through radial passages **135** into a grooved passage **136** and then into an annular passage **137** which is defined between the lower displacer wall and the internal wall of the refrigerator housing **12**. Extending down essentially the entire length and in thermal contact with the lower end of the lower stage housing is a cover sleeve **138** which is in effect also a heat station designed to deliver refrigeration at essentially constant temperature from the fluid in annular passage **137**. This arrangement provides the maximum amount of heat transfer from the cold helium to the precooled hydrogen in order to effect liquefaction of the hydrogen within the volume **139** of the liquefaction cham-

ber. Finally the liquid hydrogen **140** is collected in a liquid hydrogen reservoir **141**. It may be withdrawn through a suitable line **142** controlled by valve **143**.

FIG. 4 is a diagrammatic illustration of a cryogenic apparatus constructed in accordance with this invention in which the refrigerator used is that which is described in U.S.P. 2,966,035. In FIG. 4, like reference numerals are used in identify like elements of the apparatus as in FIGS. 1 and 2. The refrigerator through which the refrigerant is cycled is shown as a cylindrical enclosure **151** having movable therein a displacer **152** which is driven by any suitable means such as mechanically through rod **153** and driving mechanism **154**. In its motion the displacer **152** defines a warm chamber **155** and a cold refrigeration chamber **156**. Inasmuch as the regenerator in the embodiment shown in FIG. 4 is located external of the refrigerator the first flow path is also external of the refrigerator and comprises the line **157** and the regenerator **158**. It will be seen that this line communicates with the refrigeration chamber **156** as well as with the inlet line **30** through which high-pressure fluid is introduced and low-pressure fluid withdrawn to the low-pressure reservoir.

The second fluid flow path **160** comprises a conduit which passes up through the indirect, out-of-contact heat exchanger **161**. The flow of the bled-off fluid from refrigerator chamber **156** is controlled through the check valve **162**. The third fluid flow path in this case is shown to be one which is completely closed in that the fluid to be refrigerated is withdrawn from a source **50**, taken through line **163** which incorporates heat exchanger **161**, delivered as cool refrigerating gas to a load **164**, and then returned by line **165** to the original source.

FIG. 5 illustrates two additional modifications in the apparatus constructed in accordance with this invention. First, the refrigerator in which the refrigeration is developed is of a type such as disclosed in U.S.P. 3,188,820. In this case the refrigerator **170** is constructed of a main housing **171** and an auxiliary housing **172** attached or integral therewith. The body movable within the housing is comprised of a displacer portion **173** and a piston portion **174**. In its movement the body defines a warm or upper chamber of variable volume **176** and a lower refrigeration chamber of variable volume **177**. These volumes are connected through a regenerator **175** located in the displacer portion **173** of the body. Suitable passages such as those shown at **178** and **179** are provided to form the necessary first fluid flow path within the refrigerator.

FIG. 5 shows another modification in that the apparatus is of an open-cycle type. The high-pressure fluid required as the refrigerant in the refrigerator **170** is provided from the fluid source **180** and is introduced into the refrigerator through high-pressure line **181**, valve **182** and conduit **183** which communicates with the warm chamber **176**. In like manner there are provided a low-pressure line **184** and valve **185** in communication with conduit **183**. Low-pressure line **184** is open to the atmosphere and thus the refrigerator of FIG. 5 would be suitable for operating on compressed air or perhaps compressed nitrogen. The second fluid flow path required, in which the fluid within the refrigerator is bled off for heat exchange with the refrigerated fluid, comprises the line **187**, heat exchanger **188** and metering valve **186**. This portion of the refrigerant is also discharged into the atmosphere. In like manner the third fluid flow path comprises conduit **189** which is in communication with a source (not shown) of fluid to be refrigerated and a conduit **190** which may lead to a load which is to be refrigerated at a point remote from the development of the refrigeration.

The apparatus shown diagrammatically in FIG. 6 illustrates the employment of a single-stage refrigerator, the apparatus and cycle of which are described in U.S. Pat. 2,906,101. In FIG. 6 like reference numerals are used to identify like components shown in FIG. 4. The refrigerator of the apparatus of FIG. 6, which has but one refrigeration chamber is comprised of a cylindrical enclosure housing **195** having movable therein a piston **196** having sealing means **197** to isolate the expansion chamber **198**. The first fluid flow path is designated by the numeral **199** and it will be seen that it extends from the high-pressure fluid source (compressor **35**) and the low-pressure reservoir (also compressor **35**) and to expansion chamber **198** and incorporates regenerator **158** which is located external of the housing. The second fluid flow path is designated by the numeral **200** and is seen to connect the expansion chamber **198** with the low-pressure line **33**, passing through the indirect heat exchanger **161**. Lastly, the third fluid flow path is designated by the number **201** and it communicates between the source **50** of the fluid to be refrigerated and a reservoir **202** for collecting either cold low-pressure fluid or liquefied gas.

Finally, the apparatus of FIG. 7 embodies a refrigerator which is staged, but which conveniently has only one heat station for delivery of refrigeration to a fluid. The refrigerator **205** operates on the cycle described in U.S. Pat. 2,906,101. This form of refrigerator may also be constructed to operate on the cycle described in 2,966,035. The construction of the refrigerator is described in detail in a co-pending patent application Ser. No. 867,661 filed Oct. 20, 1969, in the name of James A. O'Neil for "Temperature Staged Cryogenic Apparatus" and assigned to the same assignee as the present application. Briefly, it is an in-line, staged refrigerator which comprises a cylindrical housing **206** having movable therein (through the action of a suitable driving means represented by driving rod **207**) a displacer which comprises upper or solid section **207** having a regenerator **208** and a lower or annular section **209**. The annular section **209** of the displacer is designed to make a fluid-tight fit and move slidably over a central tubing member **210** which is connected to the bottom **211** of the refrigerator housing. The tubing **210** contains therein a regenerator **212** and has suitable openings such as ports **213** which permit the regenerator to be in fluid communication with the lower-temperature expansion chamber **214**, which in this case is in an annular form. The intermediate-temperature chamber **215** is defined within the displacer between the regenerator **208** and the top of the tubing **210**. Fluid is introduced into the system through a suitable line **216** and passes through an annular passage **217** and radial passages **218** into regenerator **208**. Affixed to the bottom end of the refrigerator is a liquid reservoir **220** into the volume of which copper fins **221** extend from the bottom **211** of the refrigerator.

The second fluid flow path comprises the same components as shown in FIG. 4, i.e., a conduit **157**, heat exchanger **158** and metering valve **162**. The third fluid flow path comprises conduit **225** which communicates between the source of fluid **50** and the liquid reservoir **220** by way of heat exchanger **158**. The remaining components are the same as described above. Since the fluid in chamber **214** is colder than in chamber **156** of FIG. 4, chamber **177** of FIG. 5 or chamber **198** of FIG. 6 (by virtue of its being the second stage of a two-staged refrigerator) it is possible in some cases to use the cryogenic apparatus of FIG. 7 to liquefy some higher-boiling gases.

It will of course be apparent that many other modifications of the cryogenic apparatus of this invention are possible. For example, any or all of the refrigerators may be pneumatically driven, they may be open or closed cycles, and may employ a wide range of regenerator and heat exchanger designs.

By using a portion of the refrigerating fluid in an indirect heat exchanger over essentially the entire temperature range from the coldest temperature attainable to ambient temperature, it is possible to remove a large portion of the energy from the refrigerated gas before it

is finally cooled by constant-temperature refrigeration at the final heat station of the refrigerator.

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.

We claim:

1. In a cryogenic apparatus in which a refrigerator is used to provide refrigeration by indirect heat exchange with a circulating fluid and in which said refrigerator comprises an enclosure, a body movable within said enclosure defining in its motion at least one expansion chamber of variable volume, an external source of high-pressure fluid, an external low-pressure fluid reservoir, a refrigerator fluid flow path incorporating heat storage means connecting said expansion chamber with said high-pressure source and said low-pressure reservoir, fluid flow control means and means to move said body, the improvement which comprises:

(a) a second fluid flow path providing direct fluid communication between said expansion chamber of said refrigerator and said low-pressure reservoir;

(b) one-way fluid flow control means adapted to meter a predetermined amount of fluid from said refrigerator into said second fluid flow path when fluid is being discharged from said refrigerator through the flow path associated therewith;

(c) a source of a fluid to be refrigerated;

(d) discharge means adapted to receive said refrigerated fluid;

(e) a third fluid flow path joining said source of fluid to be refrigerated and said discharge means; and

(f) heat exchange means incorporated in said second and third fluid flow paths adapted to effect indirect heat exchange between said fluid to be refrigerated in said third fluid flow path and refrigerating fluid in said second fluid flow path.

2. A cryogenic apparatus in accordance with claim **1** wherein said discharge means is a reservoir adapted to contain said fluid to be refrigerated in liquefied form.

3. A cryogenic apparatus in accordance with claim **1** wherein said discharge means comprises means to convey said refrigerated fluid to a load remote from said apparatus.

4. A cryogenic apparatus in accordance with claim **1** including heat station means associated with said expansion chamber of said refrigerator and being connected to said discharge means in heat transfer relationship.

5. A cryogenir apparatus in which a refrigerated fluid is cooled through indirect heat exchange with a refrigeration fluid, comprising in combination:

(a) a refrigerator, comprising in combination:

(1) cylindrical fluid enclosure means;

(2) a body movable within said enclosure means which in its motion defines at least one chamber of variable volume in said enclosure means;

(3) a source of a first high-pressure refrigerating fluid external of said enclosure means;

(4) a low-pressure fluid reservoir for said first refrigerating fluid external of said enclosure means;

(5) a first fluid flow path, including high-pressure and low-pressure fluid flow control means, extending from said source of said first high-pressure refrigerating fluid and said low-pressure fluid reservoir and said chamber of variable volume;

(6) heat storage means located in said first fluid flow path;

(b) a second fluid flow path providing direct fluid communication between said chamber and said low-pressure reservoir;

(c) one-way fluid flow control means adapted to meter a predetermined amount of said first refrigerating fluid from said chamber into said second fluid flow path;

(d) a source of a second fluid to be refrigerated;

(e) discharge means adapted to receive said second refrigerated fluid;

(f) a third fluid flow path providing fluid communication between said source of said second fluid and said discharge means; and

(g) indirect heat exchange means incorporated in said second and third fluid flow paths and adapted to effect refrigeration of said second fluid in said third fluid flow path through indirect heat exchange with said first refrigerating fluid in said second fluid flow path.

6. A cryogenic apparatus in accordance with claim **5** wherein said body within said refrigerator also defines at least one intermediate-temperature chamber of variable volume and said third fluid flow path includes heat exchange means adapted to effect indirect heat exchange between the fluid in said intermediate-temperature chamber and fluid in said third fluid flow path.

7. A cryogenic apparatus in accordance with claim **5** wherein said source of high-pressure fluid and said low-pressure reservoir are combined in the form of a fluid compressor.

8. A cryogenic apparatus in accordance with claim **5** wherein said body within said refrigerator also defines a warm chamber of variable volume.

9. A cryogenic apparatus in accordance with claim **8** including conduit means joining said second fluid flow path with said warm chamber of variable volume.

10. An apparatus for liquefying a gas, comprising in combination

(a) a refrigerator, comprising in combination:

(1) fluid enclosure means;

(2) a body movable within said enclosure means which in its motion defines a plurality of chambers of variable volume adapted for fluid expansion to provide refrigeration at successively lower temperatures;

(3) a source of a first high-pressure refrigerating fluid external of said enclosure means;

(4) a low-pressure fluid reservoir for said first refrigerating fluid external of said enclosure means;

(5) a first fluid path, including high-pressure and low-pressure fluid flow control means, extending between said source of said first high-pressure refrigerating fluid and said low-pressure fluid reservoir and said chambers of variable volume;

(6) a plurality of heat storage means located in said first fluid flow path;

(7) heat station means associated with said chambers and adapted to provide essentially constant-temperature refrigeration to a load from the fluid within said chambers;

(b) a second fluid flow path providing direct fluid communication between the coldest of said chambers and said low-pressure reservoir;

(c) one-way fluid flow control means adapted to meter a predetermined amount of said first refrigerating fluid from said coldest chamber into said second fluid path;

(d) a source of a second fluid to be liquefied;

(e) a fluid reservoir in heat transfer relationship with the heat station means associated with said coldest chamber and adapted to contain said liquefied gas;

(f) a third fluid flow path extending from said source of said second fluid to said fluid reservoir;

(g) first indirect heat exchange means incorporating said second and third fluid flow paths and adapted to effect refrigeration of said second fluid in said third fluid flow path through indirect heat exchange with said first refrigerating fluid in said second fluid flow path; and

(h) second indirect heat exchange means incorporated in said third fluid flow path in heat exchange relationship with said heat station means associated with all but said coldest chamber whereby fluid in said third fluid flow path is said load refrigerated by the fluid in said chambers.

11. An apparatus in accordance with claim **10** wherein said body within said refrigerator also defines a warm chamber of variable volume.

12. An apparatus in accordance with claim **11** including conduit means joining said second fluid flow path with said warm chamber of variable volume.

13. An apparatus in accordance with claim **10** wherein said liquid reservoir surrounds said coldest chamber and said heat station associated with said coldest chamber comprises a sleeve around said refrigerator end and fins attached to the end of said refrigerator, said sleeve and said fins being formed of a metal having high heat conductivity at the temperature of said liquefied gas.

14. A method of refrigerating a fluid through indirect heat exchange with a refrigerating fluid which is supplied from an external source as high-pressure initially cooled fluid along a flow path into an expansible volume, expanded to effect final cooling and then withdrawn along said flow path to a low-pressure region, comprising the steps of:

(a) returning a portion of the expanded, finally-cooled refrigerating fluid directly along a second fluid flow path into said low-pressure region simultaneously with the withdrawing of said refrigerating fluid to said low-pressure region;

(b) transferring a fluid to be refrigerated along a third fluid flow path; and

(c) effecting indirect heat exchange between the fluids in said second and third fluid flow paths.

15. A method in accordance with claim **14** wherein said refrigerating fluid is finally cooled to successively colder temperature levels in a plurality of expansible volumes and the fluid in said third fluid flow path is brought into indirect heat exchange relationship with the fluid in said expansible volumes.

16. A method in accordance with claim **15** wherein said refrigerating fluid is helium, said refrigerated fluid is hydrogen and said hydrogen is refrigerated in said third fluid flow path to the extent that only the latent heat of liquefaction must be removed by indirect heat exchange with the fluid in the coldest of said expansible volumes.

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