

Nov. 15, 1966

C. L. NEWTON
REFRIGERATION METHOD

3,285,028

Filed Jan. 6, 1964

6 Sheets-Sheet 1

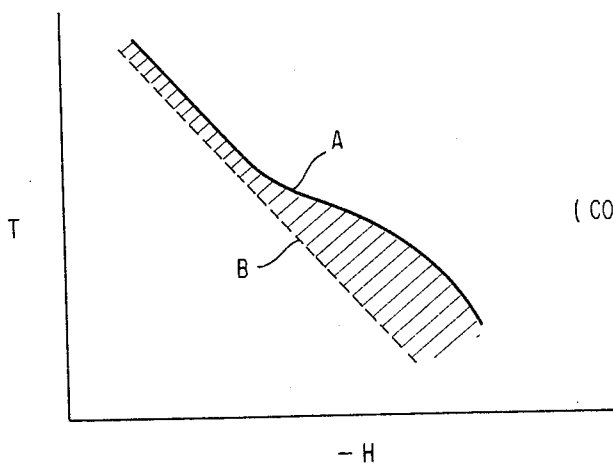


FIG. 1
(CONVENTIONAL)

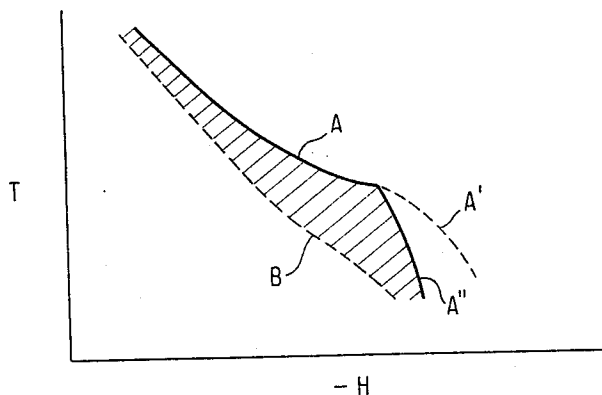


FIG. 2
(CONVENTIONAL)

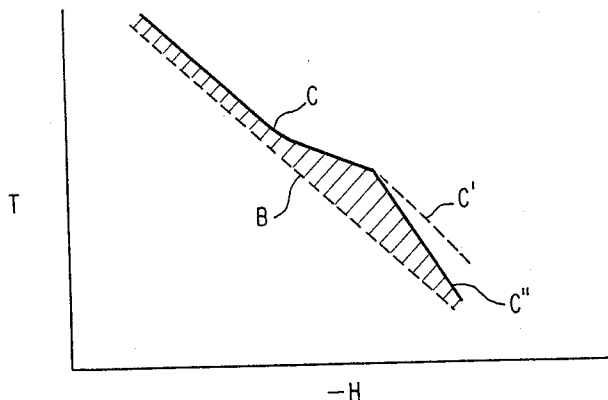


FIG. 3
(IMPROVED)

INVENTOR.
CHARLES L. NEWTON

BY *Shanley & O'Neil*
ATTORNEYS

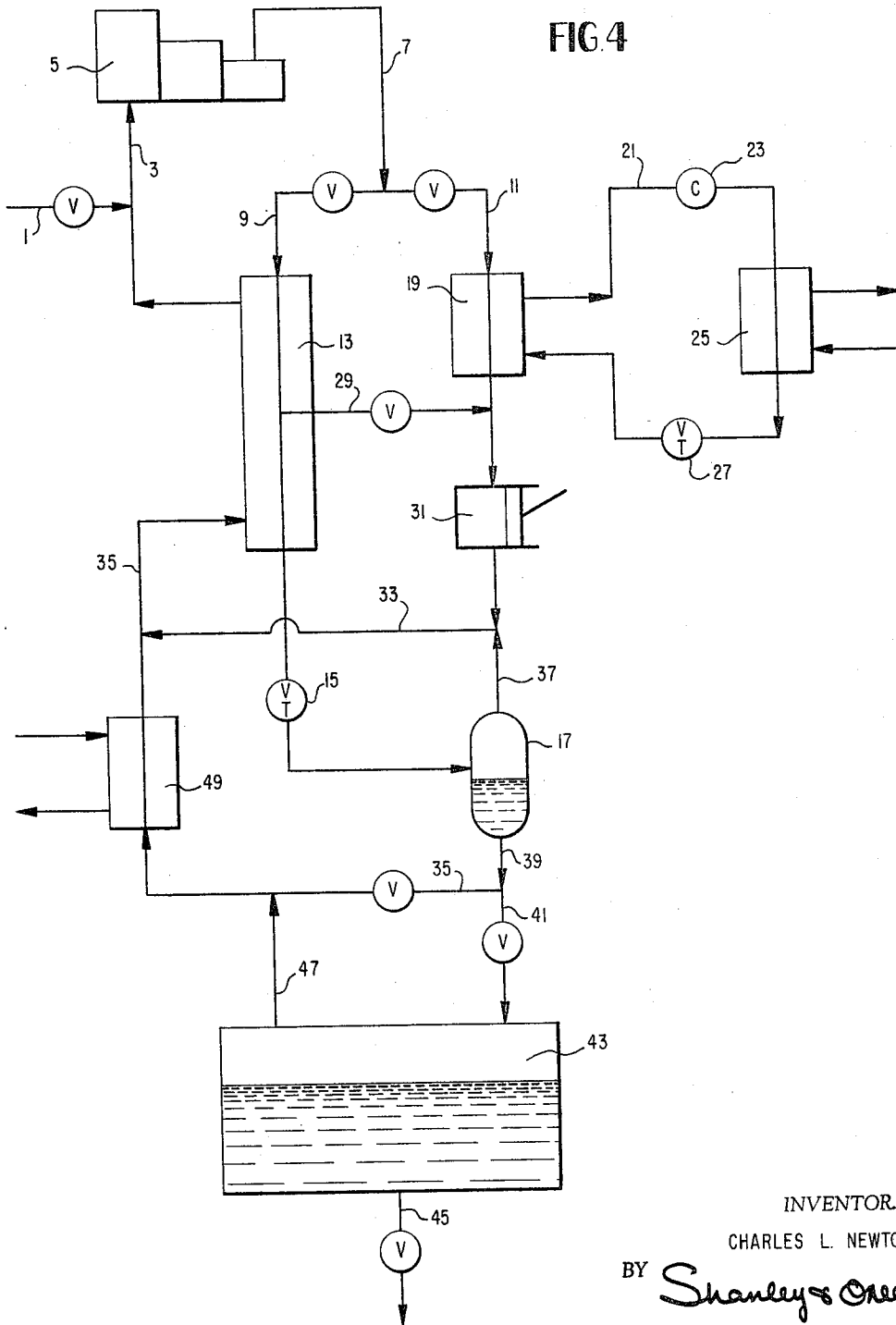
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INVENTOR
CHARLES L. NEWTON
BY *Shanley & Creel*
ATTORNEYS

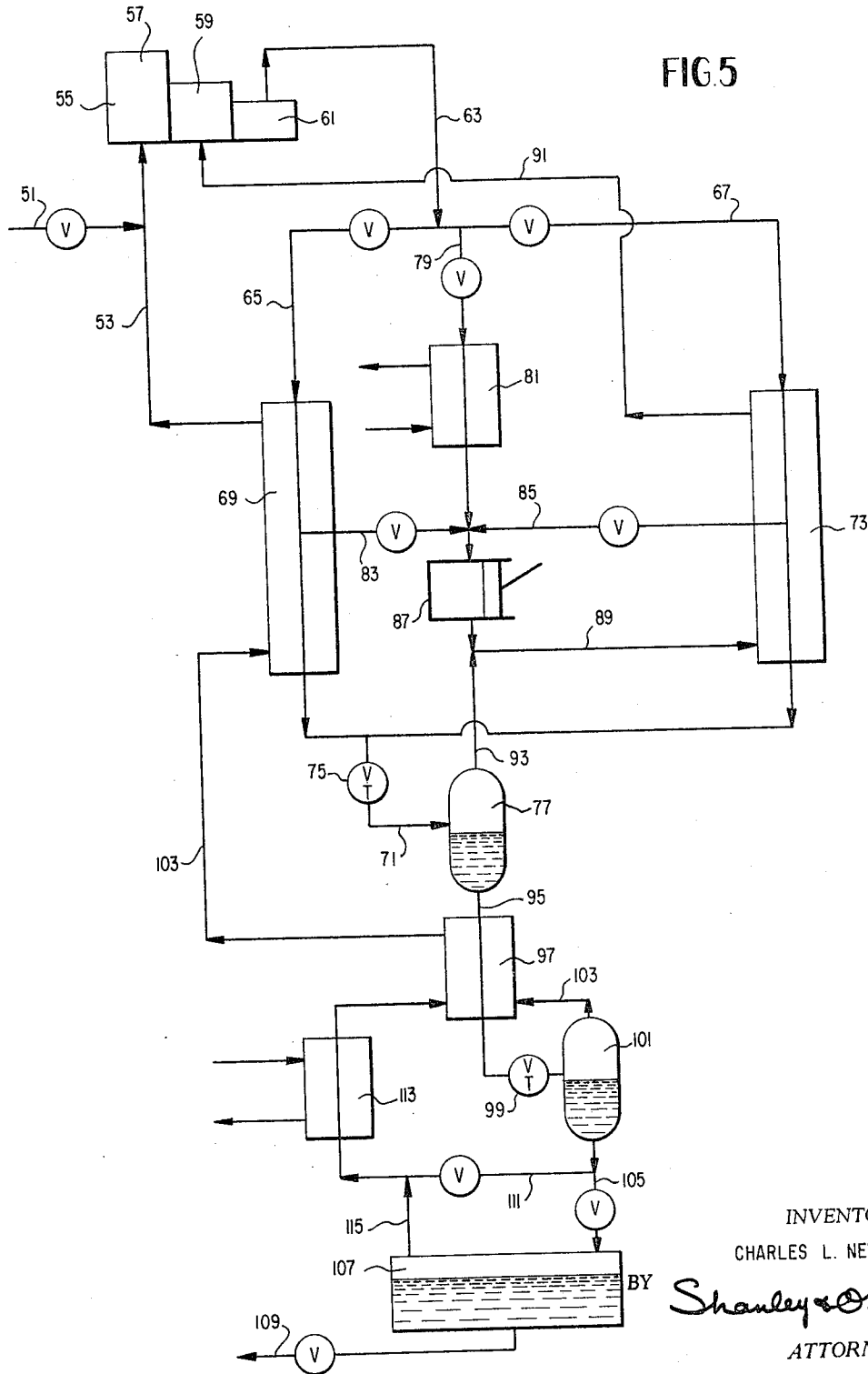
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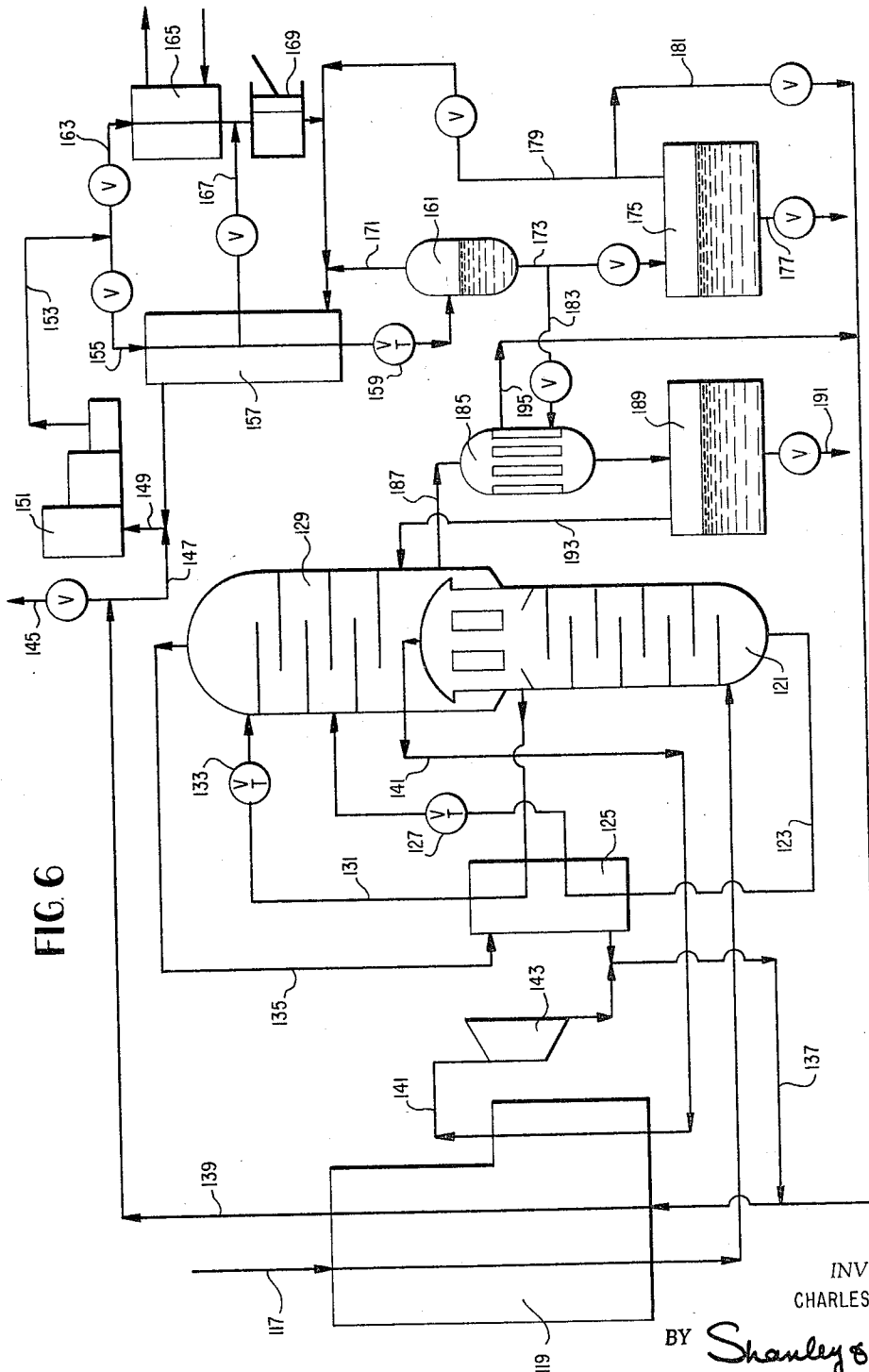
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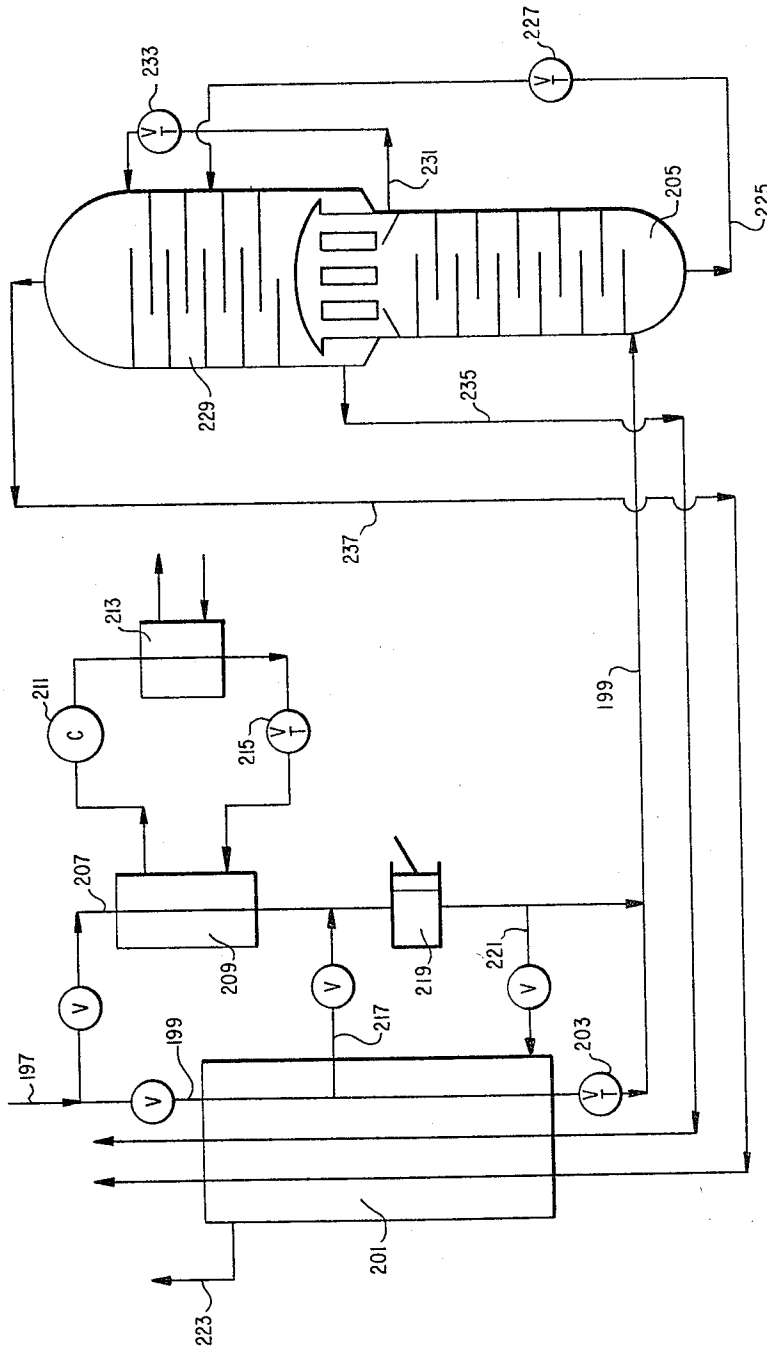


FIG. 7

INVENTOR.
CHARLES L. NEWTON

BY *Shanley & O'Neil*
ATTORNEYS

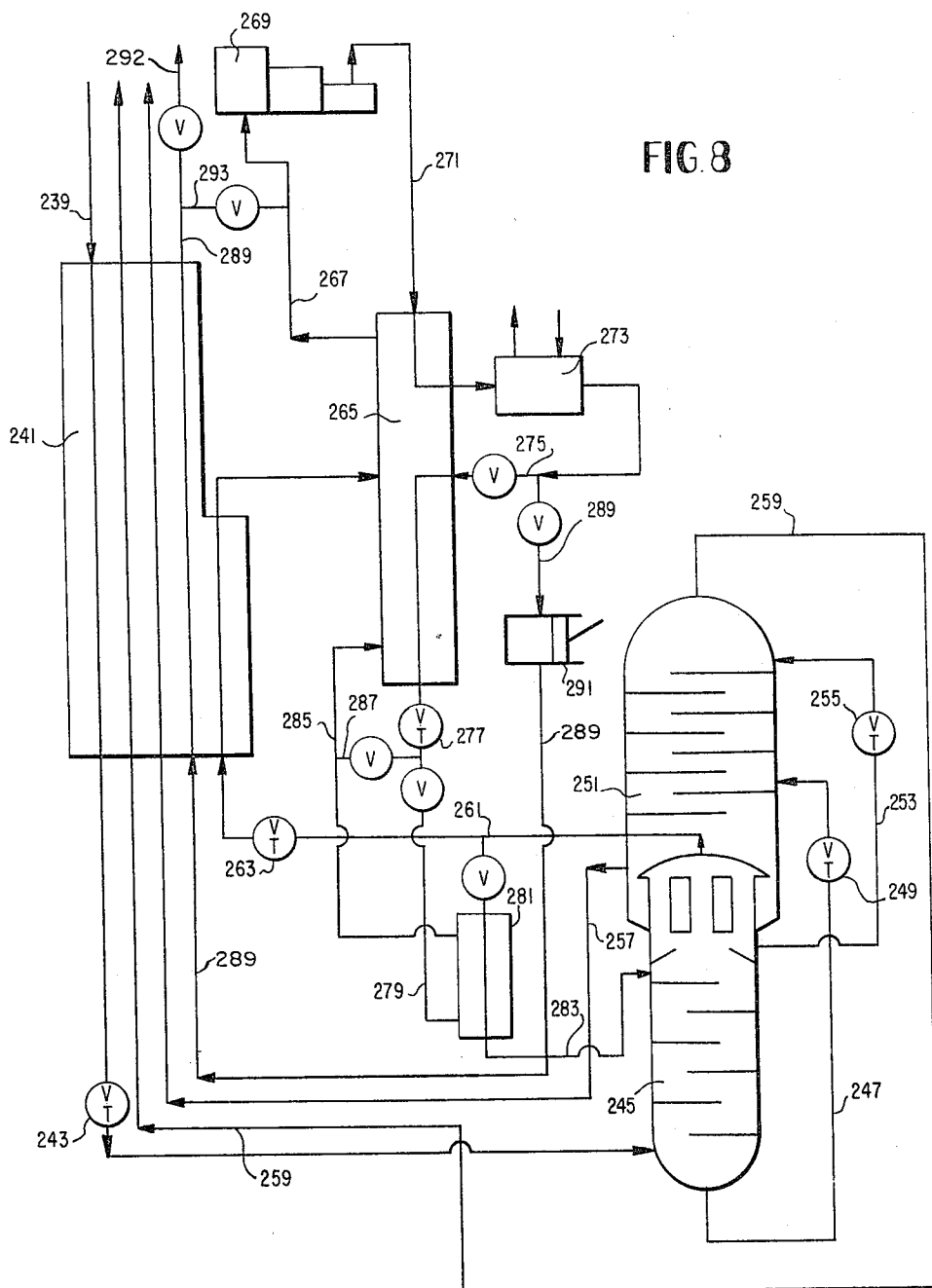
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INVENTOR.

CHARLES L. NEWTON

BY

Shanley & Greil
ATTORNEYS

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3,285,028

REFRIGERATION METHOD

Charles L. Newton, Emmaus, Pa., assignor to Air Products and Chemicals, Inc., a corporation of Delaware
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16 Claims. (Cl. 62-87)

The present invention relates to refrigeration methods, more particularly of the type in which a normally gaseous fluid at elevated pressure is expanded to produce refrigeration, and the expanded fluid is passed in heat exchange with the higher pressure fluid so as to warm the former and cool the latter thereby to conserve refrigeration.

In general, the enthalpy of a gas varies directly as its temperature. However, the variation is not quite directly proportional. Thus, a graphical representation of temperature vs. enthalpy will be a straight line. The degree to which the relationship between temperature and enthalpy changes varies with pressure and with temperature, and also with the composition of the fluid in question. In general, the higher the normal boiling point of the fluid, the higher the temperature at which the greatest variations in the ratio of temperature to enthalpy will be observed. Also, the higher normal boiling point of the fluid in question the more marked will be those fluctuations in the ratio of temperature to enthalpy.

Let it be considered that in a given heat exchange zone, a relatively cold fluid passes in countercurrent heat exchange relationship, either simultaneously or sequentially, with a relatively warm fluid, so that the warm fluid progressively gives up its heat to the cold fluid as it traverses the length of the heat exchange zone, with the result that the cold fluid in turn progressively warms as it traverses the heat exchange zone in the opposite direction. Let it further be assumed that the fluids are at distinctively different pressures, specifically, that the relatively warm fluid is under the higher pressure and the relatively cold fluid is under the lower pressure, and that the fluids are either of the same or nearly the same composition. Such a situation might arise in the case of a closed cycle refrigeration plant in which a fluid is compressed and cooled by heat exchange with itself and then expanded to produce useful refrigeration. The situation could also arise in a similar environment in which upon expansion the fluid is liquefied and a portion of it withdrawn from the system as a liquid product. The situation could also arise in a gas separation plant, for example, for the separation of air into its components, in which a relatively warm higher pressure stream of air is heat exchanged against relatively cold separation products such as oxygen and nitrogen and then expanded prior to fractionation into the products.

In such systems as described above, the heat exchange zone, referred to can be considered to be isenthalpic, that is, it neither gives off nor absorbs heat but rather is at thermal equilibrium. This means that the change in enthalpy of one stream will equal the change in enthalpy of the counterflowing stream. But as enthalpy does not vary rectilinearly as temperature, it follows that the relationships between temperature and enthalpy of one stream at various points along the path of heat exchange will vary as compared to the corresponding points for the other stream. In other words, the T-H curves for the two streams will not be parallel.

This relationship along the course of a heat exchanger handling fluids that differ from each other either in composition or in pressure or both is set forth graphically in FIGURE 1. FIGURE 1 is a plot of temperature on the ordinate versus enthalpy on the abscissa. For convenience of reading the graph, enthalpy is given in negative units, that is, lower enthalpy is encountered to the

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right of the graph. The graph is dimensionless so as to illustrate the principle in terms of the shape of the curves and the area between them, without regard to particular data.

As is seen in FIGURE 1, a cooling curve A is shown in full line, while a warming curve B is shown in broken line. Moving from left to right, curve A shows the temperature-enthalpy relationships of a fluid undergoing cooling; while moving from right to left on the chart, the curve B shows the temperature-enthalpy relationships of a fluid undergoing warming in recuperative heat exchange with the fluid of curve A. The area between curves A and B is thus a measure of the efficiency of the heat exchange operation, and may be considered to vary directly although not rectilinearly with the work necessary to effect the operation. If that work is performed by compression of a gas such as compression of the relatively warm fluid of curve A prior to heat exchange, then the larger the area between curves A and B the greater that compression will have to be in order to reach the desired low temperature level.

On the other hand, of course, the vertical distance between curves A and B for any given enthalpy is proportional to the temperature difference or driving force for the heat exchange at that enthalpy level. The greater the distance the greater the rate of heat transfer, with the result that the less the area of heat exchange surface can be. Therefore, close convergence of curves A and B indicates that greater heat exchange surface must be provided; while a wider divergence of curves A and B indicates that a less extensive heat exchange surface can be provided.

The performance of work during the course of a refrigeration operation involves an operating expense. The extent of the heat exchange surface, however, is more in the nature of a capital expense. In determining the proper relationship between the cooling and warming curves of the fluids undergoing heat exchange, therefore, a balance must be struck between the bringing of those curves into too great registry, in which case the cost of heat exchange equipment would be prohibitive, and on the other hand permitting those curves to diverge so widely as to require the performance of excessive work during the operation.

It is evident, therefore, that to the extent that is possible great care must be exercised in the orientation relative to each other of the cooling curves of fluids that are in heat exchange relationship with each other.

Another factor that influences the preferred orientation of these curves relative to each other is the fact that the cost of the work represented by the area between the curves varies inversely as the temperature level at which that work is performed. In other words, at higher temperature levels refrigerative work costs less than at lower temperature levels. Some of the extreme examples of the operation of this principle will be illustrative when it is considered that cooling water at ambient temperature is quite cheap, while a bath of liquid helium is quite expensive to maintain. Stated graphically, for example in terms of FIGURE 1, a wider divergence between curves A and B at the upper left of FIGURE 1 is more tolerable than a wider divergence between curves A and B at the lower right of FIGURE 1.

However, it will be seen that the curves of FIGURE 1 are oriented in just the reverse relationship of the optimum described above. In other words, the distance between the curves and hence the area between the curves that represents increased work consumption is greatest toward the lower right of the figure and least toward the upper left of the figure. This means not only that the work necessary to effect the refrigeration operation of which FIGURE 1 represents the initial and final condi-

tions of the fluid will be greater than is necessary, but also that work must be performed at the least desirable, i.e. the lowest, temperature level.

FIGURE 1 represents, by way of example, the cooling curve A of nitrogen at a pressure above its critical pressure, and the warming curve B of nitrogen at a pressure only a little above atmospheric. The fact that curve A has no horizontal plateau intermediate its length is of course due to the fact that a fluid above its critical pressure never develops a vapor-liquid two-phase system at any temperature. Curve A is typical of the cooling curves of normally gaseous fluids above their critical pressure. In the case of fluids boiling higher than nitrogen, such as methane, the flex point where curve A changes from upwardly concave to downwardly concave would be located at a higher temperature, while for fluids boiling below nitrogen, such as hydrogen or helium, the flex point would be located at a lower temperature. Also, the sinuosity of curve A would be greater for higher boiling fluids and less for lower boiling fluids.

In the past, measures have been taken to remedy the undesirable situation represented by the relationship to each other of curves such as A and B in FIGURE 1. One of these measures has been to decrease the quantity of the higher pressure fluid in the colder portion of the heat exchange zone. One way to do this has been by withdrawing from intermediate the length of the heat exchange zone a quantity of the higher pressure fluid and expanding it with the production of external work to reduce its temperature while at the same time reducing its enthalpy. The effect on the T-H diagram of such a prior art practice is shown in FIGURE 2, in which the cooling curve A-A' is the same as the curve A in FIGURE 1, the condition of the fluid undergoing cooling being shown in actuality by the new curve A-A''. The section A'' of the modified cooling curve represents the temperature-enthalpy conditions of that portion of the higher pressure fluid which remains in the heat exchange zone after withdrawal of a side stream. Curve A'' is more steeply inclined than curve A', because the quantity of the stream has been reduced, with the result that a decrease in temperature of the remaining stream is accompanied by less decrease in enthalpy. This is reflected by the fact that the projection of A'' on the abscissa is correspondingly shorter than the projection of A' on the abscissa, the relative lengths of these projections being about proportional to the original and reduced volumes of the stream in the colder portion of the heat exchange zone.

Although the withdrawal of a side stream was a useful step in bringing the cooling and warming curves of fluids at distinctively different pressures into a desirable orientation relative to each other, it was nevertheless not a complete solution to the problem. For many purposes, the curve A'' in FIGURE 2 would be too steeply inclined and curve A in FIGURE 2 not sufficiently steeply inclined, relative to the warming curve B. In other words, where the economic balance favored increasing the heat exchange area to reduce the cost of the work of compression, the relationship represented by FIGURE 2 was still unsatisfactory.

Accordingly, it is an object of the present invention to provide refrigeration methods characterized by heat exchange relationships of sufficient flexibility to permit a closer approach to optimum relationship between the temperature-enthalpy conditions of fluid streams in heat exchange with each other throughout the region of heat exchange.

Another object of the present invention is the provision of methods for bringing the temperature-enthalpy relationships of a fluid stream more nearly into coincidence with the temperature-enthalpy relationship of another fluid stream with which it is in heat exchange relationship.

Still another object of the present invention is the provision of refrigeration methods designed to reduce the in-

efficiency of heat exchange between two fluids at distinctively different pressures.

It is also an object of the present invention to improve the efficiency of heat exchange between two fluids one of which is above its critical pressure and the other of which is below its critical pressure.

The invention also contemplates the provision of refrigeration methods designed to improve the efficiency of heat exchange between two portions of the same fluid, or between two fluids, in which the portions of the fluids are at least principally nitrogen.

Another object of the present invention is the provision of refrigeration methods having provision for recovery of refrigeration through heat exchange between fluids the improvement between the temperature-enthalpy relationships of which is represented by a comparison of FIGURE 3 with FIGURE 2 in the accompanying drawings.

Finally, it is an object of the present invention to provide refrigeration methods that will be relatively simple and inexpensive to practice and that will give uniformly predictable and desired results.

Other objects and advantages of the present invention will become apparent from a consideration of the following description, taken in connection with the accompanying drawings, in which:

FIGURE 1, as previously explained, is a graphical representation of the temperature-enthalpy conditions of a relatively compressed stream being cooled in heat exchange with a relatively uncompressed stream, according to the prior art;

FIGURE 2, as also previously explained, is a graphical representation similar to FIGURE 1 but corresponding to a modification of improved efficiency, according to the prior art;

FIGURE 3 is a view similar to FIGURES 1 and 2 but showing relationships obtainable by the practice of the present invention;

FIGURE 4 is a schematic diagram of a refrigeration or liquefaction cycle according to the present invention;

FIGURE 5 is a schematic diagram of another form or refrigeration or liquefaction cycle according to the present invention;

FIGURE 6 is a schematic diagram of an air separation plant including a refrigeration or liquefaction cycle according to the present invention;

FIGURE 7 is a schematic view of another embodiment of air separation plant embodying a refrigeration cycle according to the present invention; and

FIGURE 8 is a schematic diagram of still another air separation plant embodying a refrigeration cycle according to the present invention.

Broadly stated, the invention comprises passing a normally gaseous fluid through a pair of heat exchange zones, cooling each of the zones by heat exchange with a different fluid, adiabatically expanding the fluid from one of the zones, expanding at least a portion of the fluid from the other zone with the production of work, and recovering refrigeration from at least the adiabatically expanded fluid in the heat exchange zone from which it has emerged. The fluid from which the refrigeration is recovered may be either the same fluid that was expanded, as in the case of a liquefaction or refrigeration plant, or it may be one or more components of that liquid, as in the case of a gas separation plant. In either case, refrigeration is recovered from the expanded fluid, although the fluid may not be in the same form as when expanded.

Referring now to the drawings in greater detail, the significance of FIGURES 1-3 was explained above. FIGURE 4 shows one of the many embodiments in which the present invention may be practiced. Specifically, FIGURE 4 shows a liquefaction or refrigeration system including a valved inlet conduit 1 through which a normally gaseous fluid is introduced. Conduit 1 empties into a conduit 3, which in turn feeds to the low pressure stage of a compressor 5. Material compressed in com-

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pressor 5 emerges from the high pressure stage of the compressor and passes through a conduit 7. From conduit 7, the material is divided and a portion is passed through each of valved conduits 9 and 11 in parallel. The material in conduit 9 passes through a counter-
current heat exchanger 13 of the recuperative type. The cooled material emerging from the cold end of exchanger 13 is then flashed through a throttle valve 15 to a lower pressure. The mixed vapor and liquid thus produced is then fed into a phase separator 17.

In the other of the parallel conduits, conduit 11, the material passes through a second heat exchanger 19 which is cooled by a separate external refrigeration system comprising a conduit 21 in fluid communication with a compressor 23 having an aftercooler 25 to cool the compressed fluid circulating through conduit 21. A throttle valve 27 expands the compressed and cooled material in the closed circuit to lower temperature and pressure, whereupon the material enters the cold end of exchanger 19 to cool the material in conduit 11.

A side stream from conduit 9 is withdrawn through valve controlled conduit 29 intermediate the length of exchanger 13, and this side stream is merged with the material in conduit 11 emerging from exchanger 19. The merged stream is then isentropically expanded, that is, expanded with the production of external work, in a reciprocating expansion engine 31. The isentropically expanded material passes then through a conduit 33 and into a conduit 35, whence it enters the cold end of exchanger 13 in indirect heat exchange relationship with the material in conduit 9. Emerging from the warm end of exchanger 13, the material which enters through conduit 35 passes through conduit 3 to the high pressure stage of compressor 5 for recycle.

The vapor flashed through throttle valve 15 separates out in phase separator 17 and passes through an overhead conduit 37 into conduit 33 and thence through conduits 35 and 3 to recycle. The liquid that collects in phase separator 17, which is saturated, that is, at its boiling point, is removed through conduit 39 and through valved conduit 41 and is collected in storage tank 43. Liquid in storage tank 43 may be removed through a valved conduit 45 as desired for use as liquefied gas. The material that evaporates from the liquid in storage tank 43 is removed through conduit 47 and thence through conduit 35 to recycle.

Alternatively, instead of feeding the liquid from separator 17 to storage tank 43, it can be used as a source of refrigeration in a heat exchanger 49 for the purpose of cooling some other fluid in any of a variety of environments. In that case, the liquid in conduit 35 would largely evaporate in exchanger 49, which would be used as a source of refrigeration.

Another embodiment of the present invention is shown in FIGURE 5, in which the normally gaseous feed material enters through valved conduit 51 and proceeds thence through conduit 53 to a compressor 55 of which it enters the low pressure stage 57. The material passes through intermediate pressure stage 59 and high pressure stage 61 of compressor 55 and emerges from the high pressure stage through a conduit 63. From conduit 63, the flow of compressed material is divided, one branch passing through valved conduit 65 and the other branch passing through valved conduit 67. The material in conduit 65 is cooled in a countercurrent recuperative heat exchanger 69 and emerges from the cold end of exchanger 69 and enters a conduit 71. The material in conduit 67 is cooled in a countercurrent recuperative heat exchanger 73 and emerges from the cold end of exchanger 73 and is merged with the material in conduit 71. This merged material is then expanded adiabatically through a throttle valve 75, whereupon it becomes part liquid and part vapor and is fed in that mixed phase condition to a phase separator 77.

The remainder of the stream from conduit 63 proceeds

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through valved conduit 79 and thence through heat exchanger 81, in which it is cooled by countercurrent heat exchange with a closed cycle refrigerant as also in the case of exchanger 19 in the embodiment of FIGURE 4. As also in the embodiment of FIGURE 4, there is side stream withdrawal from exchanger 69, and also from exchanger 73. Specifically, a valved conduit 83 withdraws a portion of the material from conduit 65 at a point intermediate the ends of heat exchanger 69, while a valved conduit 85 performs the same function with regard to exchanger 73. The streams in conduits 79, 83 and 85 are merged and then proceed through conduit 79 to a reciprocating expansion engine 87 in which they are expanded with the production of external work. The output of expansion engine 87 proceeds through a conduit 89 into the cold end of exchanger 73 and leaves the warm end of exchanger 73 through a conduit 91 after having cooled the stream flowing through conduit 67 in exchanger 73. The material in conduit 91 is then introduced into intermediate pressure stage 59 of compressor 55 for re-compression and recycle.

The overhead from phase separator 77 is withdrawn through a conduit 93 and merged with material in conduit 89 to cool exchanger 73. The bottoms from phase separator 77 are removed through a conduit 95 as a saturated liquid and are subcooled in a heat exchanger 97. Emerging from heat exchanger 97 in a subcooled condition, the liquid is then flashed through a throttle valve 99 into a phase separator 101, so that a vapor is separated from the remaining liquid. The vapor emerging from phase separator 101 leaves through a conduit 103 and passes from the cold end to the warm end of heat exchanger 97 in heat exchange relationship with material in conduit 95 prior to expansion of the latter material in throttle valve 99. The material in conduit 103 then enters the cold end of exchanger 69 and passes in countercurrent heat exchange with the material in conduit 65, and proceeds thence through conduit 53 to low pressure stage 57 of compressor 55 for recycle.

The liquid that collects in phase separator 101 is saturated and is removed through a valved conduit 105 to a storage tank 107 whence it may be removed as desired through a valved conduit 109. Alternatively, the liquid from phase separator 101 can be removed through a valved conduit 111 and passed through a heat exchanger 113, in which it provides low temperature level refrigeration for a material to be cooled. From exchanger 113, the material then passes from the cold end to the warm end of exchanger 97 and leaves through conduits 103 and 53. Vapor from storage tank 107 is removed through a conduit 115 to conduit 111 and thence to recycle.

Another of the many embodiments in which the present invention may be utilized is in connection with a fractionating operation. FIGURE 6 shows such an embodiment. Specifically, FIGURE 6 is a diagrammatic representation of an air separation plant designed to produce a liquid oxygen product. Ordinarily, in a low temperature plant for the separation of a gaseous mixture such as air or natural gas, one or more of the products of separation is passed in heat exchange relation with the entering feed, so as to conserve refrigeration. Refrigeration is ordinarily provided by compressing the feed and then expanding it stepwise to produce successively lower levels of cooling as required. In order to avoid excessive compression of the feed, as much refrigeration as possible is recovered from the cold products, at least in part by heat exchanging them against feed. However, when one or both of the products is removed at least partly in liquid phase, a certain amount of refrigeration, so as to speak, is withdrawn from the cycle. If this refrigeration is to be replaced solely by compression of the feed, then it becomes necessary to compress a great quantity of feed to a relatively high pressure. This is wasteful of work and therefore uneconomical. Accordingly, another use of the present invention is to

enable the retention of a desirably low pressure for the feed and at the same time to permit the withdrawal of a liquid product, with a substantial saving of work and hence lower expense as compared to a plant in which a liquid is withdrawn and the refrigeration loss is made up by compression of the feed.

To this end, therefore, as shown in FIGURE 6, a relatively low pressure feed stream of air is introduced through a conduit 117 into a main heat exchanger 119 and in that cooled condition is introduced into the bottom of the relatively high pressure stage 121 of a two-stage air separation column. A crude oxygen liquid product leaves the bottom of high pressure stage 121 through a conduit 123 and is subcooled in the warm end of a heat exchanger 125. This crude liquid oxygen is then expanded through a throttle valve 127 and a vapor is flashed from it. The mixed liquid and vapor are introduced into the relatively low pressure stage 129 of the air separation plant at the appropriate composition level, it being understood of course that both of stages 121 and 129 are provided with the usual fractionation trays so that both a temperature gradient and a composition gradient obtains from top to bottom of each stage, as is conventional in gas separation plants of this type.

The usual condenser interconnects stages 121 and 129 in heat exchange relationship with each other, and liquid nitrogen falling from the condenser is withdrawn from high pressure stage 121 through a conduit 131 and is passed through the cold end of heat exchanger 125 to subcool it, after which it is throttled through a valve 133 and introduced in mixed liquid and vapor phase into the upper end of low pressure stage 129. The liquid entering through conduit 131 is essentially nitrogen and provides reflux for low pressure stage 129. The vapor emerging from the top of low pressure stage 129 is withdrawn through conduit 135 and is used as the cooling fluid in heat exchanger 125, in which it passes in countercurrent relationship with the liquid in conduits 123 and 131. The superheated nitrogen vapor is then passed through a conduit 137 and a conduit 139, in which it flows in countercurrent heat exchange relationship with the feed in main exchanger 119.

High pressure nitrogen in vapor phase is withdrawn from the condenser of high pressure stage 121 through conduit 141 and passed through the cold end of main exchanger 119, and is then expanded with the production of external work through an expansion turbine 143. The vapor in conduit 141 is superheated during passage through exchanger 119 and accordingly no liquid is formed in turbine 143. The work expanded fluid is then introduced into conduit 137 and joins the other gas in conduit 139. A valved withdrawal conduit 145 is provided downstream of conduit 139 for removing excessive nitrogen vapor from the cycle.

The nitrogen vapor that is not removed through valved conduit 145 passes through conduit 147 and then through conduit 149 to the intake of the low pressure stage of a compressor 151. In compressor 151 it is compressed to relatively high pressure, preferably above its critical pressure, and leaves through a conduit 153. It is then divided into two parts and one part passes through a valved conduit 155 and thence through a heat exchanger 157. The vapor cooled in exchanger 157 is then flashed through a throttle valve 159 to below its critical pressure, so that it forms a liquid and a vapor phase which are both introduced into a phase separator 161.

The compressed vapor that does not pass through conduit 155 passes instead through a valved conduit 163 and thence through a heat exchanger 165 which is cooled by an external refrigeration source such as Freon or the like flowing in a closed circuit (not shown). Further material for the stream in conduit 163 is withdrawn through a valved conduit 167 from conduit 155 at a point intermediate the length and hence intermediate the temperature gradient of heat exchanger 157. This material

in conduit 167 is merged with the material in conduit 163 and the merged stream is then expanded with external work through a reciprocating expansion engine 169. The vapor overhead from phase separator 161 is withdrawn through conduit 171 and is merged with the efflux from expansion engine 169, and the merged stream is introduced into the cold end of exchanger 157, withdrawn from the warm end of exchanger 157, and merged with the stream in conduit 157 that enters the inlet of the low pressure stage of compressor 151 through conduit 149.

The saturated liquid withdrawn from phase separator 161 leaves through a valved conduit 173 and is introduced into a storage tank 175, from which liquid nitrogen may be withdrawn as desired through a valved conduit 177. The vapor emerging from storage tank 175 is withdrawn through a valved conduit 179 and joins the vapor in conduits 163 and 171 that is introduced into the cold end of exchanger 157 for recycle through compressor 151. Alternatively, the vapor emerging from storage tank 175 can be withdrawn through a valved conduit 181 and its refrigeration used in main exchanger 119 instead of in exchanger 157, to which end the vapor in conduit 181 is merged with that in conduit 139 for passage through main exchanger 119.

Alternatively to the introduction of the liquid from phase separator 161 into storage tank 175, this liquid can be withdrawn through a valved conduit 183 and passed into the cold end of a condenser 185. Relatively pure oxygen product in vapor phase can be withdrawn from immediately above the liquid oxygen product sump at the bottom of low pressure stage 129 through a conduit 187 and passed from the warm end to the cold end of condenser 185, in which it is completely condensed to saturated oxygen and is introduced into a liquid oxygen storage tank 189 from which it can be removed as desired in liquid pulse through a valved conduit 191. The oxygen in vapor phase that emerges from storage tank 189 can be reintroduced through conduit 193 into the bottom of low pressure stage 129. The evaporated liquid nitrogen that emerges from the warm end of condenser 185 can be withdrawn through a conduit 195 and introduced into conduit 181, in which its refrigeration is recaptured upon passage through main exchanger 119 on the way to recycle through compressor 151.

Still another embodiment of the present invention is illustrated in FIGURE 7. FIGURE 7 shows that the gas to which the present invention is applied can be a mixture of gases such as air, as well as a single gas such as nitrogen. FIGURE 7 also shows that the gases flowing in the countercurrent heat exchange streams of the present invention can be different gases, such as air and the components of air, e.g., oxygen and nitrogen.

In the cycle shown diagrammatically in FIGURE 7, air under relatively high pressure enters through a conduit 197 and is divided into two portions. One portion flows through a valved conduit 199 and thence through a main heat exchanger 201, in which it is cooled. The air is preferably above its critical pressure, so that no liquid forms in exchanger 201. Instead, the cooled and compressed air is expanded through a throttle valve 203 and the expanded material is fed into the relatively high pressure stage 205 of a two-stage air separation column.

The other air feed stream flows through a valved conduit 207 and thence through an auxiliary heat exchanger 209 which is cooled by a separate refrigeration cycle including a compressor 211, an aftercooler 213, and a throttle valve 215, which auxiliary cycle performs the same function as in the auxiliary cycle shown in FIGURE 4.

Air from conduit 199 is withdrawn at a point intermediate the length of main exchanger 201, through a valved conduit 217 and is merged with the cooled air in conduit 207, the merged stream being then fed through a reciprocating expansion engine 219, in which it is expanded with the production of external work. The work-expanded material is then merged with the material in con-

duit 199 for introduction into the high pressure stage 205 of the air separation column, except for a portion that is diverted through a valved conduit 221 and introduced into the cold end of main exchanger 201 on the shell side thereof. The material introduced through conduit 221 is withdrawn from the warm end of exchanger 201 through a conduit 223 and can be either vented or recycled with the main air feed, as desired.

The crude liquid oxygen that collects in the bottom of high pressure stage 205 is withdrawn through a conduit 225, flashed through a throttle valve 227, and introduced partly in liquid and partly in vapor phase into the relatively low pressure stage 229 of the oxygen plant. Liquid nitrogen falling from the interstage condenser is collected on the usual shell and withdrawn through a conduit 231 and flashed through a throttle valve 233 and introduced into the upper end of low pressure stage 229, in which the liquid component from conduit 231 refluxes the low pressure stage. Oxygen product in vapor phase is withdrawn from adjacent the lower end of low pressure stage 229 through a conduit 235 and is passed through main exchanger 201 in countercurrent heat exchange relationship with the air feed. Gaseous nitrogen from the top of low pressure stage 229 is withdrawn through a conduit 237 and also introduced into the cold end of main exchanger 201 in countercurrent heat exchange relationship with the air feed, so that the refrigeration of both of the products of the air separation is recovered.

Still another embodiment of the present invention is shown in FIGURE 8, in the environment of an air separation cycle. In the embodiment of FIGURE 8, air at relatively low pressure is introduced through a conduit 239 into the main exchanger 241, after which it is expanded through a throttle valve 243 and fed into the relatively high pressure stage 245 of a two-stage air fractionating column. Crude liquid oxygen is withdrawn from the bottom of high pressure stage 245 through a conduit 247 and is throttled through a throttle valve 249 and introduced at its appropriate composition level into a relatively low pressure stage 251 of the air separation column. Liquid nitrogen is withdrawn from relatively high pressure stage 245 through a conduit 253 and is expanded adiabatically through a throttle valve 255 and introduced into the top of relatively low pressure stage 251. The liquid thus introduced into the top of stage 251 refluxes stage 251.

Gaseous oxygen product is withdrawn from the bottom of low pressure stage 251 through a conduit 257 and introduced into the warm end of main exchanger 241. Gaseous nitrogen is withdrawn from the top of low pressure stage 251 through a conduit 259 and is introduced into the warm end of main exchanger 241. High pressure nitrogen is withdrawn from the interstage condenser in vapor phase through conduit 261 and is expanded adiabatically through throttle valve 263 and passed through the cold end of main exchanger 241 and introduced into a heat exchanger 265 intermediate the length of the shell side of exchanger 265. The nitrogen from the shell side of exchanger 265 is withdrawn from the warm end thereof through a conduit 267 and is introduced into the low pressure stage of a compressor 269. The compressed nitrogen emerging from the high pressure stage of compressor 269 is withdrawn through a conduit 271 and introduced into the warm end of exchanger 265.

The cooled material in conduit 271 is withdrawn from an intermediate point in exchanger 265 and is all passed through an exchanger 273 cooled by an external refrigeration cycle (not shown) like that in FIGURE 4. The material emerging from exchanger 273 is then divided, and a portion is passed through a valved conduit 275 through the remainder, that is, the cold end, of exchanger 265. This material in conduit 275 is throttled through a throttle valve 277 and passes through a conduit 279 and is introduced into the cold end of the shell side of an exchanger 281, in which it cools and condenses nitrogen withdrawn

from conduit 261 through a valved conduit 283 by which the condensed nitrogen is introduced into the top of the high pressure stage as reflux. The warmed nitrogen from the warm end of exchanger 281 passes through conduit 285 into and through exchanger 265 for recycle through compressor 269.

A by-pass conduit 287 permits regulation of the amount of liquid nitrogen reflux production.

The remainder of the material emerging from exchanger 273 passes through valved branch conduit 289 and is expanded with the production of external work through a reciprocating expansion engine 291. The work-expanded material in conduit 289 is then passed through main exchanger 241 from the cold to the warm end thereof. The material conduit 289 may be withdrawn from the cycle through a valved conduit 292, but at least a portion is preferably passed through a valved conduit 293 back to conduit 267 for recycle to the low pressure stage of compressor 269.

FIGURE 8 thus illustrates that the present invention in its broadest aspects includes embodiments in which the material passed through the auxiliary heat exchange may include all the feed, and may comprise the withdrawn side stream. FIGURE 8 also illustrates that the work-expanded material need not be returned through the heat exchanger through which the side stream is withdrawn, but may be returned through a separate heat exchanger.

In order to enable those skilled in this art to practice the present invention, the following illustrative example is given in connection with the embodiment of FIGURE 5:

In connection with the cycle of FIGURE 5, let it be assumed that 12.164 mols per hour of nitrogen per ton of refrigeration leaves high pressure stage 61 of compressor 55. This material is at 100° F. and at 3,025 p.s.i.a., and is divided into three streams, comprising 4.863 mols per hour in conduit 65, 2.749 mols per hour in conduit 79, and 4.552 mols per hour in conduit 67.

The material in conduit 65 is cooled to -270° F. by the time it reaches the cold end of exchanger 69. The material in conduit 67 is cooled to -256° F. by the time it reaches the cold end of exchanger 73. Side stream withdrawal conduit 83 withdraws 1.453 mols per hour, while side stream withdrawal conduit 85 withdraws 1.090 mols per hour from the streams in conduits 65 and 67, respectively. This material, along with material cooled in exchanger 81, totals 5.292 mols per hour and enters expander 87 at a temperature of -53° F. It is expanded isentropically to a pressure of 160 p.s.i.a.

The remaining material in conduits 65 and 67, which emerges from the cold ends of exchangers 69 and 73, respectively is expanded to 150 p.s.i.a. to throttle valve 75 and has a total volume of 6.872 mols per hour. It separates into 0.589 mol per hour of vapor and 6.283 mols per hour of liquid. The vapor leaves through conduit 93 and joins the work-expanded vapor in conduit 89, in which it has a flow rate of 5.881 mols per hour and a temperature of -261° F. The cold end temperature differential in exchanger 73 is thus 5° F., while the warm end temperature differential is 15° F., so that the warming fluid leaves exchanger 73 through conduit 91 at a temperature of 85° F. and goes to the intermediate pressure stage 59 of compressor 55.

The liquid from phase separator 77 is withdrawn, sub-cooled, and throttled through valve 99 to a pressure of 63 p.s.i.a. and a temperature of -294° F. This latter temperature is the refrigeration and storage temperature for the cycle. The material returning through conduit 103 to the cold end of exchanger 69 has a temperature of -275° F., so that there is a cold end temperature differential of 5° F. in exchanger 69. The warm end temperature differential of exchanger 69 is 15° F., so that the warmed recycled material in conduit 53 has a temperature of 85° F. and a mol quantity of 6.283 mols per hour. The conditions described in this example assume

that valved conduit 51 is closed so that there is no makeup.

Under the conditions described, the compressor power requirement is 26.887 B.H.P. per ton; the Freon power requirement for exchanger 81 is 1.349 B.H.P. per ton; the expander power recovery by causing expander 87 to operate a generator is 1.664 B.H.P. per ton, so that the net power requirement is 26.572 B.H.P. per ton. The Carnot efficiency factor, which is actual work divided by Carnot work, is 2.374.

From the above and similar examples, it has been found that the process of the present invention is particularly well adapted for providing refrigeration in the temperature range of -260 to -320° F. The cycles of the present invention are particularly well adapted to operation in which the relatively high pressure gas is at a pressure at least about 1500 p.s.i.a. For temperatures above about -290° F., a single flash type cycle is preferable, while for achieving refrigeration temperatures below about -300° F., the double flash process is preferable. For the double flash process, the intermediate pressure gas should be at about 100–200 p.s.i.a. Also, for the double flash process, it is preferable to use a subcooler such as subcooler 97.

From a consideration of the foregoing disclosure, it will be evident that all of the initially recited objects of the present invention have been achieved. Specifically, it will be understood that why cooling curves resembling those of FIGURE 3 are achieved: the curve C in FIGURE 3 is swung closer to the curve B because there is an overall reduction in the quantity of fluid represented by curve C, that is, the quantity of fluid being cooled through any one heat exchanger. At the same time, the angle between curves C and C' adjacent the point of side stream withdrawal is greater in FIGURE 3 than in FIGURE 2 because the quantity of side stream withdrawal in FIGURE 3 is less than in FIGURE 2 by virtue of the fact that a large part of what otherwise would have been withdrawn as a side stream has already been cooled in the parallel separately refrigerated branch of the feed.

Although the present invention has been described and illustrated in connection with preferred embodiments, it is to be understood that modifications and variations may be resorted to without departing from the spirit of the invention, as those skilled in this art will readily understand. Such modifications and variations are considered to be within the purview and scope of the present invention as defined by the appended claims.

What is claimed is:

1. Refrigeration method comprising passing compressed normally gaseous fluid through a first heat exchange zone and a second heat exchange zone, cooling said first heat exchange zone and said second heat exchange zone by heat exchange with relatively cold different fluids, adiabatically expanding said compressed normally gaseous fluid from the first heat exchange zone, expanding with the production of work at least a portion of said compressed normally gaseous fluid from the second heat exchange zone, and recovering refrigeration from said work expanded fluid in the first heat exchange zone.

2. Refrigeration method as claimed in claim 1, and recovering refrigeration from at least a portion of said adiabatically expanded fluid in the first heat exchange zone.

3. Refrigeration method as claimed in claim 1, and cooling said other second heat exchange zone by means of a refrigerant circulating in a closed refrigeration circuit.

4. Refrigeration method as claimed in claim 1, in which said normally gaseous fluid is at least principally nitrogen,

5. Refrigeration method as claimed in claim 1, in which said normally gaseous fluid consists essentially of nitrogen.

6. Refrigeration method as claimed in claim 1 in which the compressed normally gaseous fluid flows in parallel relation through said first and second heat exchange zones.

7. Refrigeration method as claimed in claim 1, in which the compressed normally gaseous material flows in series through said first and said second heat exchange zones.

8. Refrigeration method comprising passing a normally gaseous fluid in two streams through a pair of heat exchange zones in parallel, withdrawing a portion of the normally gaseous fluid from an intermediate point along the length of one of said heat exchange zones and merging it with normally gaseous fluid emerging from the other of the heat exchange zones, expanding the merged fluids with the production of work, and recovering refrigeration from at least a portion of the work-expanded fluid in one of said heat exchange zones.

9. Refrigeration method as claimed in claim 8, in which refrigeration from the work-expanded fluid is recovered in said one heat exchange zone.

10. Refrigeration method as claimed in claim 8, and adiabatically expanding the remainder of the fluid emerging from said one heat exchange zone, and recovering refrigeration from at least a portion of the adiabatically expanded fluid in said one heat exchange zone.

11. Refrigeration method as claimed in claim 8, and cooling said other heat exchange zone by heat exchange with a fluid other than a fluid passing through said one heat exchange zone.

12. Refrigeration method as claimed in claim 8, and cooling said other heat exchange zone by means of a refrigerant circulating in a closed refrigeration circuit.

13. Refrigeration method as claimed in claim 8, in which said normally gaseous fluid is at least principally nitrogen.

14. Refrigeration method as claimed in claim 8, in which said normally gaseous fluid consists essentially of nitrogen.

15. Refrigeration method as claimed in claim 8, in which said one heat exchange zone is comprised of two portions in parallel, expanding the fluid from said one zone to two distinctively different pressures, cooling one portion of said one heat exchange zone with expanded fluid at one of said pressures, and cooling the other of said portions of said one heat exchange zone with expanded fluid at the other of said pressures.

16. Refrigeration method as claimed in claim 8, in which said one heat exchange zone is comprised of two portions in parallel, recovering refrigeration from at least a portion of the work-expanded fluid in one of said portions, adiabatically expanding fluid emerging from said one heat exchange zone, and using adiabatically expanded fluid to cool the other said portion of said one heat exchange zone.

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ROBERT A. O'LEARY, *Primary Examiner*.

MEYER PERLIN, *Examiner*.

W. E. WAYNER, *Assistant Examiner*.

UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,285,028

November 15, 1966

Charles L. Newton

It is hereby certified that error appears in the above numbered patent requiring correction and that the said Letters Patent should read as corrected below.

Column 1, line 18, after "will" insert -- not --; line 55, for "zone," read -- zone --; line 60, for "rectilineearly" read -- rectilinearly --; column 2, lines 45 and 46, after "possible" insert a comma; column 4, line 40, for "or" read -- of --; column 7, line 11, for "realatively" read -- relatively --; line 40, for "is" read -- it --; column 8, line 9, for "157" read -- 147 --; line 36, for "pulse" read -- phase --; column 10, line 15, after "material" insert -- in --; column 11, line 65, after "said" strike out "other".

Signed and sealed this 12th day of September 1967.

(SEAL)
Attest:

ERNEST W. SWIDER
Attesting Officer

EDWARD J. BRENNER
Commissioner of Patents