Dec. 5, 1967 J. K. LA FLEUR 3,355,903

SYSTEM OF POWER-REFRIGERATION

Filed Jan. 4, 1965 2 Sheets-Sheet 1

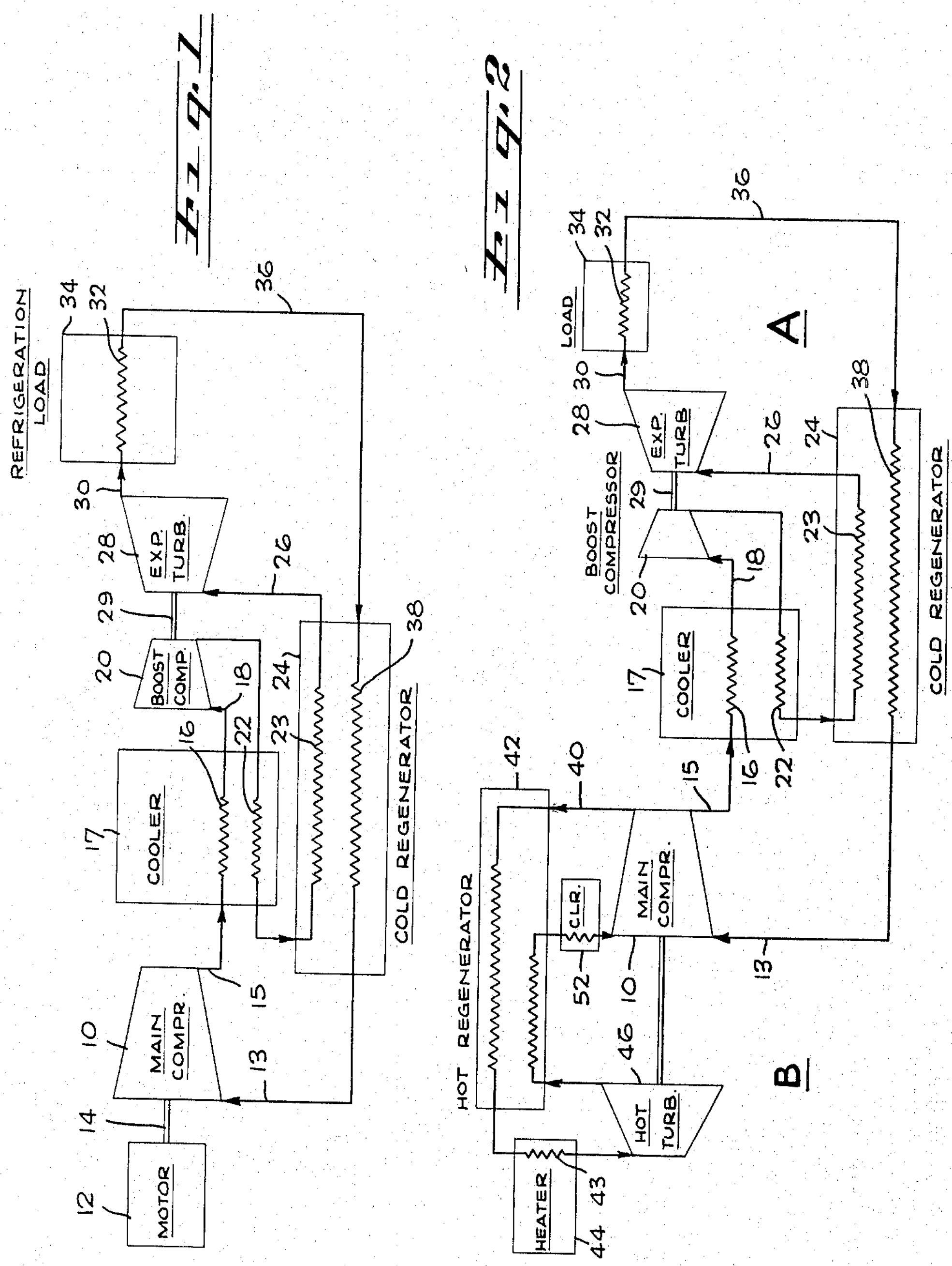


Fig. 1

Fig. 2

INVENTOR.
JAMES K. LA FLEUR
BY Max Geldin
ATTORNEY

Fig. 3

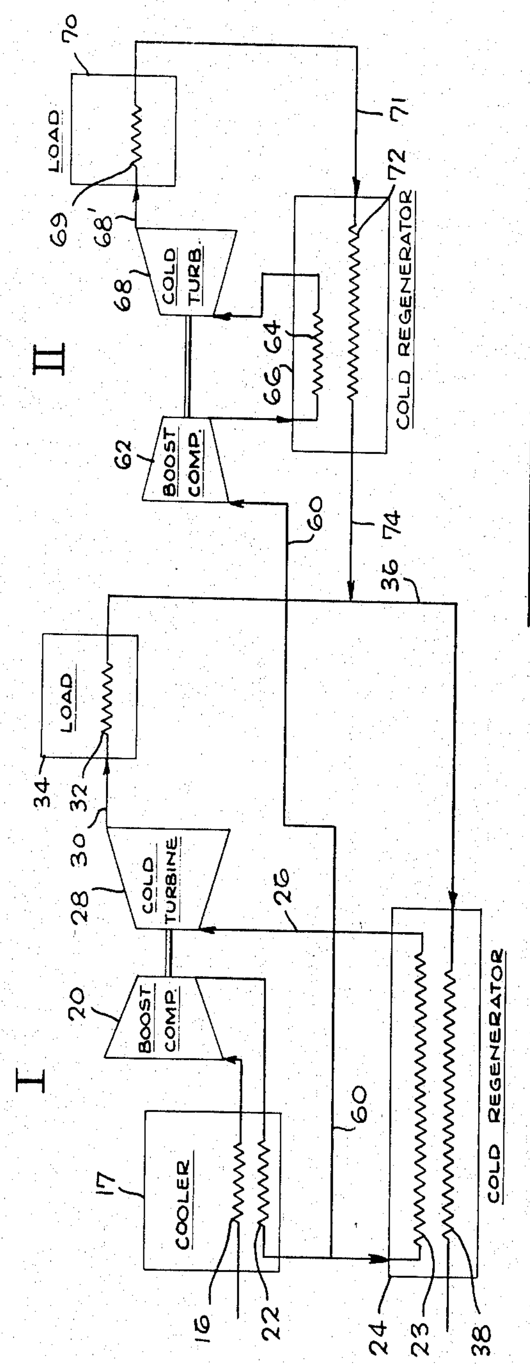
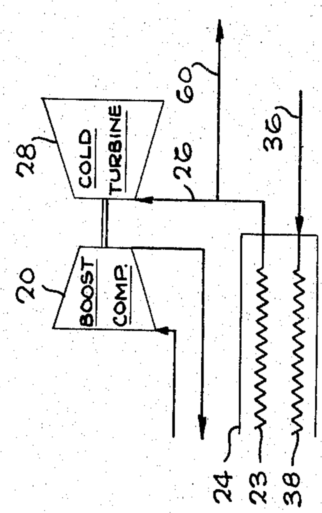


Fig. 4



JAMES K. LA FLEUR
INVENTOR.

BY Max Gilden

ATTORNEY

United States Patent Office

3,355,903

Patented Dec. 5, 1967

1

3,355,903

SYSTEM OF POWER-REFRIGERATION

James K. La Fleur, Hermosa Beach, Calif., assignor to The La Fleur Corporation, Los Angeles, Calif., a corporation of California

Filed Jan. 4, 1965, Ser. No. 422,955
9 Claims. (Cl. 62—88)

ABSTRACT OF THE DISCLOSURE

This invention is directed to a power-referigeration system, particularly design for the liquefaction of air, nitrogen and other gases of low boiling temperature, including a closed refrigeration cycle wherein a refrigerant gas such as helium is compressed, cooled, further compressed, regeneratively cooled, work expanded to low temperature, passed in heat exchange relation with a refrigeration load such as nitrogen for liquefying same, regeneratively heated and recompressed. In one embodiment, a portion of the further compressed refrigerant is additionally compressed, regeneratively cooled, work expanded for further reduction of temperature, passed in heat exchange relation with a second refrigeration load, regeneratively heated and recompressed. In another modification a hot power cycle is included, in which a portion of the compressed refrigerant, e.g., helium, is heated, expanded in a hot power turbine, cooled and recompressed, such power turbine providing the main source of power for compression of the refrigerant in both the power cycle and the refrigeration cycle.

This invention relates to a closed power-refrigeration system employing a gas as the refrigerant medium, and is particularly concerned with an improved versatile power-refrigeration system in which the expander for expansion and cooling of the refrigerant assists the main compressor, and employing means for this purpose which permits the expander to be located remote from the main compressor and in the immediate vicinity of the refrigeration load, thus increasing the efficiency of the system.

In my copending application Serial No. 318,564, now Patent Number 3,194,026, there is described and claimed a closed power-refrigeration system in which a gas is the common working medium in both a power cycle and a refrigeration cycle, that is, such cycles are interconnected so that the common working medium circulates between both cycles of the system. The system of said application comprises a closed gas turbine cycle having connected thereto a closed refrigeration cycle obtaining its motivation by diverting a portion of the common working medium from and returning such medium to the power cycle.

Thus, according to the process of said copending application, utilizing a very low boiling point gas such as helium as the common working medium, such medium is first compressed substantially and the compressed medium is then divided into a first stream and a second stream. The first stream circulating in the power cycle is heated to raise the temperature substantially, and the so-heated first stream drives a so-called hot turbine which comprises the main portion of the power for the compressor. The expanded first stream of gas exiting the hot gas turbine is then further cooled and returned to the compressor for recompression.

The above-noted second stream of compressed working medium, that is helium, circulating in the refrigeration cycle is cooled, and such cooled stream is used to drive a second or so-called cold turbine or expander. The expanded second stream of helium exiting the second turbine is now at a very low temperature, that is, a cryogenic temperature, and can function as a refrigerant by passing same in heat exchange relation with a medium to be

2

cooled, and the resulting or exiting second stream, after further heating thereof, is returned to said compressor for recompression.

According to the above application the power output of the cold turbine or expander, as in the case of the hot turbine, can be coupled directly to the shaft of the compressor to provide a portion of the power required for compressing the helium therein, or the cold turbine can be coupled to a generator to provide electrical power for any desired use.

However, although under certain circumstances it is desirable to have the power output of the cold turbine or expander in such system directly assisting the hot turbine in the task of driving the compressor, it may be neither feasible nor desirable to have the cold turbine coupled directly to the shaft of the compressor. Some of these conditions are as follows:

(1) The case where the refrigeration load is located a great distance from the turbo-compressor. Location of the cold turbine and its loading device at the place where the refrigeration is required would eliminate long fluid transfer lines operating at low temperatures, and would eliminate the attendant refrigerant losses to the atmosphere.

(2) The case where it is desirable to operate the cold turbine at a different rotational speed than the main compressor unit.

(3) The case where more than one compressor assembly is desirable.

(4) The case where more than one refrigeration expander or turbine is desirable, as for example, where refrigeration is required at two different temperature levels.

One object of the invention accordingly is the provision of an improved closed cycle power-refrigeration system, and including the stages of compression of a gas refrigerant and expansion thereof, particularly for production of a low temperature gaseous refrigerant medium, and wherein such expansion of the refrigerant gas furnishes power which is utilized in the power-refrigeration cycle.

Another object is the provision of a power-refrigeration system including compression and expansion stages for a refrigerant gas, wherein the power from expansion of the refrigerant is employed directly in the system to increase the efficiency of the compression stage.

Still another object is the provision of a closed cycle power-refrigeration system of the type above-described in which the cold turbine or expander, and its loading device can be located adjacent the refrigeration load and at a distance from the compression stage.

Yet another object is the provision of a power-refrigeration system according to the above copending application, and including a closed hot power cycle and a closed refrigeration cycle interconnected with said power cycle, said cycles having a common compressor and employing a common working medium in both cycles, and incorporating means in the refrigeration cycle and driven by the power output of the cold turbine or expander in said cycle for assisting the hot turbine in the power cycle in the task of driving the common compressor.

Other objects and advantages of the invention will appear hereinafter.

The above objects are achieved according to the invention by incorporating an auxiliary or so-called "boost" compressor in the power-refrigeration cycle and using the cold turbine or expander in the refrigeration cycle to drive the boost compressor. Thus, the boost compressor is incorporated into the refrigeration cycle so as to accept the output of the main or primary compressor, and which in the system of my above copending application is driven by the hot turbine in the hot power cycle, and increases the pressure of the gas used as working fluid in the refrigeration cycle of the system. The increase in refrigerant gas pressure accomplished by the boost compressor can vary and is generally moderate, ranging, for example, from about 5% to about 25%, or higher, of the pressure of the gas from the main compressor exhaust. In this manner, although the power output from the cold turbine is used for such additional or incremental compression of the initially compressed working medium, and thus assists such main compressor, the cold turbine or expander is not directly connected or coupled to the main compressor for this purpose. Hence the cold turbine can be located at any desired distance from the main compressor and, for example, can be located closely adjacent the refrigeration load. This means that the piping between the cold turbine and the refrigeration load can be made relatively short so that essentially no loss of heat or refrigeration occurs even though the refrigeration load is located remotely from the compressor or hot power loop.

The system of the invention has further advantages. Thus, several cold loops or cycles may be operated in parallel as described in my copending application Serial No. 410,222, filed November 10, 1964, in an efficient manner from a single supply line, in order to operate several cold loops at different temperatures or to operate several cold loops at different locations. Further, although the auxiliary or boost compressor only adds a minor increment of pressure to the pressure of the refrigerant produced by the main compressor, the incorporation of such boost compressor in the refrigeration cycle as described above generally increases the efficiency of the system under the conditions of operation generally employed.

The principles of the invention can be applied basically to a system which contains but a single closed loop, that is, a closed refrigeration loop in which the main compressor is driven, for example, by an electric motor or a gas turbine. Further, the invention principles can be applied to advantage in the cold loop of the system of my above copending application Serial No. 318,564, and including a hot power loop in which the hot turbine drives the main compressor for furnishing the main source of power for the refrigeration cycle. An important feature of such a system is that the cold loop is a "mirror image" of the hot power loop. That is, the cold turbine with its attendant boost compressor in the refrigeration cycle, is constructed in the same manner as the hot turbine and the primary compressor in the hot power cycle. This facilitates manufacture and assembly of the turbocompressor and turbine units for both the hot power cycle and the cold refrigeration cycle, preferably employing units of the type described and claimed in my copending applications Serial Nos. 273,910, now Patent Number 3,201,941, and 274,045, now Patent Number 3,202,341, both filed April 18, 1963, for this purpose.

The power-refrigeration system of my above copending application Serial No. 318,564, and of the present invention have application for the liquefaction of air, nitrogen and other gases such as helium and hydrogen having very low boiling temperatures, and have particular application for producing refrigeration for economically liquefying air according to the system of my copending application Serial No. 273,883, now Patent Number 3,258,929, filed April 18, 1963. Thus, a particularly important application of the invention system is for the liquefaction of air and air components such as nitrogen, employing very low boiling gases, e.g. those having a boiling point lower than the boiling point of nitrogen, such as helium, hydrogen or neon, as the refrigerant working medium, and obtaining cryogenic refrigerant temperatures while maintaining the refrigerant in the gaseous state.

The invention will be more readily understood from the description below of certain embodiments of the invention taken in connection with the accompanying drawing wherein:

FIG. 1 is a schematic drawing or flow sheet of one embodiment of the invention;

FIG. 2 is a schematic representation of a preferred embodiment of the invention;

FIG. 3 is a schematic illustration of another modification of the invention; and

FIG. 4 illustrates a modified form of the system shown in FIG. 3.

Referring to FIG. 1 of the drawing, in this embodiment the main compressor **10** is coupled at **14** to an electric drive motor **12**. A gaseous refrigerant medium, e.g., helium, is fed at approximately ambient temperature to the inlet **13** of the main compressor **10**, and the compressed helium exhausted from the compressor at **15** is passed through a coil **16** of an atmospheric cooler **17** to the inlet **18** of the boost compressor **20**.

The pressure of the helium gas is increased in the boost compressor **20** and is exhausted therefrom and is passed through a coil **22** of the atmospheric cooler **17** to a cold regenerator **24**. The compressed helium gas is passed through coil **23** of cold regenerator **24** in heat exchange relation with helium gas returning from the refrigeration load, as hereinafter described, and then is introduced into the inlet side **26** of the expander or cold turbine **28**. The cold turbine **28** is interconnected by a common shaft **29** with the boost compressor **20** for driving said compressor. The expanded and further cooled helium gas exiting the cold turbine at **30** is then passed through a coil **32** of the refrigeration load **34**. Said coil **32** can be a coil in a condenser for liquefying therein a gas such as nitrogen, or a coil in the top of an air separation or rectification column as described in my above copending application Serial No. 273,883. The helium which is heated by passage through the refrigeration load is conducted by a conduit **36** to the cold regenerator **24** and passed therein through a coil **38** in heat exchange relation with the compressed helium gas in coil **23**, for cooling same, and following passage of the heated helium through the cold regenerator **24** it is recirculated to the inlet **13** of the main compressor as noted above.

It is accordingly seen that the power derived from the cold turbine **28** is employed by boost compressor **20** for further compressing the initially compressed helium in the main compressor **10**, and hence cold turbine **28** assists the main compressor **10** in its task of building the pressure of the helium up to a greater pressure at the intake of the expansion turbine **28**. Hence, by means of the boost compressor **20**, the power output of the cold turbine **28** is employed directly in the power refrigeration loop without being coupled directly to the main compressor **10**. This permits the cold turbine **28** and its loading boost compressor **20** to be located closely adjacent the refrigeration load **34** so that the conduit **30** connecting the cold turbine outlet with the refrigeration load is relatively short, with substantially no heat or refrigeration losses resulting from passage of the cold expanded refrigerant from the exhaust of cold turbine **28** to the refrigeration load.

FIG. 2 shows the application of the invention principles in the preferred system of my above copending application Serial No. 318,564. As will be seen the cold or refrigeration cycle, designated A in FIG. 2, is the same as that shown in FIG. 1 and the same part numbers are employed in FIG. 2 for corresponding parts in FIG. 1. The letter B in FIG. 2 represents the hot power cycle of the system for supplying the power to the main compressor **10**, in place of the electric motor **12** employed in FIG. 1.

Again, for purposes of illustration and by way of example, the system of FIG. 2 will be described below as employing helium as the working gas medium for both the power and refrigeration cycles. The temperatures and pressures hereinafter are only by way of example, and all pressures are expressed in pounds per square inch absolute and temperatures are in degrees Rankine (° R.). Assuming the whole system of power and refrigeration has been in operation for a sufficient time to reach the intended operating conditions of temperature and pressure, helium enters the compressor **10** at a pressure of 181 p.s.i. and at ambient temperatures of 530°, and the helium is discharged from the high pressure side of the compressor at 268 p.s.i. and 618°. The flow from the compressor outlet is divided into two high pressure streams, namely a power stream which flows through branch **40** or the power loop, and the refrigeration stream which flows through branch **15** or the refrigeration loop. The high side of the power stream, or the hot stream, first passes through one side of a regenerator **42** called the hot regenerator where the gas is heated to 1,493° at the outlet. From the regenerator **42** the power stream passes through the heat exchange coil **43** of a heater **44** which can be a combustion chamber and which serves to heat the helium to 1,660°. Any suitable source of heat can be employed in the heater **44**. The exiting power stream is then led to and used to drive a hot turbine **46** which provides the power for driving the compressor **10**. The gas expands and cools in turbine **46**, the pressure dropping to 190 p.s.i. and the temperature dropping to 1,498° and then passes through the other side, that is the low pressure side of the hot regenerator **42** wherein the gas is cooled while heating the high side power stream in countercurrent flow thereto to approximately the compressor discharge temperature. Finally, the gas passes through a precooler or sump **52** from which the gas is returned to the compressor **10**. The precooler, either water or air cooled, serves to bring the medium down to ambient temperature.

The cold or refrigeration stream of helium flowing from the exhaust of the compressor **10** at **15** then passes through the refrigeration cycle A in the manner described above with respect to FIG. 1. Again, for purposes of illustration the helium which is cooled in the air chamber **17** or aftercooler, is cooled to 530°, approximately ambient temperature, the pressure drop being slight, e.g., about 5 p.s.i. In the boost compressor **20**, the pressure of the helium gas is increased to about 300 p.s.i. and following passage of the further compressed helium through the cold regenerator **24**, the helium is reduced to a temperature of about 141°. The helium gas emerging from the regenerator **24** then expands in the cold turbine **28**, the temperature of the helium dropping to 128°. This is approximately the tempertaure of the helium refrigerant at the inlet to coil **32** of the refrigeration load **34**. The medium to be cooled in the refrigeration load **34** may be a gas such as air to be liquefied, as previously noted, and its components separated as by rectification. Such refrigerate gas is passed countercurrent to the flow of the helium refrigerant. The low pressure helium exiting the refrigeration load returns to the cold regenerator **24** where it serves to cool the compressed helium, and the helium then completes its refrigeration loop by returning to the compressor **10** at ambient temperature and compressor inlet pressure of 181 p.s.i.

In the embodiment of FIG. 3 is shown a modification of the systems of FIGS. 1 and 2, employing a refrigeration cycle according to the invention, consisting of two separate cold loops. These separate cold loops are designated I and II in FIG. 3, of the drawing.

The cold loop I is the same as described above with respect to the embodiments of FIGS. 1 and 2. The second cold loop II is provided by diverting a portion of the compressed refrigerant, e.g., helium, following compression thereof in the first boost compressor **20** and cooling in cooler **17**, through line **60** to a second "boost" compressor **62**, thus further increasing the pressure of the helium gas so diverted. This further compresesd refrigerant gas is then passed through a coil **64** of a second cold regenerator **66** to further reduce the temperature of said compressed helium gas by passage thereof in countercurrent heat exchange relation with cold helium returning from the second refrigeration load **70**, as described below. The further cooled and compressed helium exiting the cold regenerator **66** is passed to the intake of a second cold turbine **68**, causing expansion and a further lowering of temperature of the helium from the exhaust of such turbine. The cold turbine **68** is coupled to the second boost compressor **62** for driving same.

The cooled expanded helium or refrigerant exiting the cold turbine **68** is passed via line **68'** through a heat exchange coil **69** of a second refrigeration load **70** for cooling the refrigerate medium. After giving up heat to the refrigeration load **70** the refrigerant gas now at a higher temperature is passed via line **71** through coil **72** of the cold regenerator **66** in countercurrent heat exchange relation with the compressed helium passing through coil **64** for cooling same as above noted. The further heated helium exiting the cold regenerator **66** is then conducted via line **74** into the line **36** which carries the refrigerant gas from the first refrigeration load **32** to the first cold regenerator **24**, for further heating of the returning helium therein prior to return of all of the refrigerant to the intake of the main compressor **10**. Both of the boost compressors **20** and **62** in the system of FIG. 3 operate at approximately the same temperature, e.g., near ambient temperature. Thus, in accordance with the modification of FIG. 3, two cold loops I and II are provided which can be operated at different locations.

In FIG. 4 there is shown a modification of the system of FIG. 3. In the modification of FIG. 4, the refrigerant for the second cold loop II is provided by diverting a portion of the compressed refrigerant, e.g., helium, following cooling thereof in the cold regenerator **24**. Hence the refrigerant temperature at the inlet to the second boost compressor **62** in this modification is at a substantially lower temperature than that of the refrigerant at the inlet to the first boost compressor **20**, and hence in this case the boost compressors **20** and **62** operate at substantially different temperatures.

Thus, in the modification of FIG. 4, it will be noted that as a result of the further compression of the helium in the second boost compressor **62** followed by passage thereof through the second cold regenerator **66** and the further expansion of the thus further compressed and cooled helium in the second cold turbine **68**, the resulting refrigerant gas delivered to the second refrigeration load **70** is at a lower temperature than the refrigerant gas delivered from the exhaust of the first expander **28** to the first refrigeration load **34**. Thus, in accordance with the modification of FIG. 4 there is provided two cold loops I and II supplying refrigerant gas at different temperatures for loads requiring different degrees of refrigeration, and further such two cold loops can be operated at different locations.

The principles of the invention in accordance with the modifications of FIGS. 3 and 4 can be applied particularly to the system described and claimed in my copending application Serial No. 410,222, noted above.

It will be understood that although the modifications of FIGS. 3 and 4 show the principles of the invention as applied to the operation of two cold loops, the invention can be applied for provision of a system employing more than two cold loops in a closed refrigeration cycle, e.g., 3 or more such cold loops.

From the foregoing, it is seen that the invention provides a novel and improved power-refrigeration system comprising a closed cycle and including a main compressor, cooling means and an expander, and preferably employed in conjunction with an interconnected hot power cycle for actuation of the main compressor by means of a hot gas turbine, employing means in the form of a boost or auxiliary compressor in the refrigeration cycle and driven by the mechanical energy derived from the expander, which increases the versatility of the system and improves its efficiency and which assist the driving means, e.g., the motor or gas turbine, in driving the main compressor.

While I have described particular embodiments of my invention for the purpose of illustration it should be understood that various modifications and adaptations thereof may be made within the spirit of the invention, as set forth in the appended claims.

I claim:

1. A power-refrigeration process which comprises compressing a gaseous refrigerant, cooling said compressed refrigerant, further compressing said refrigerant, subjecting said so compressed refrigerant to regenerative cooling, expanding said further cooled refrigerant to accomplish work and further reducing the temperature of said refrigerant, said work being employed for said further compression of said refrigerant, passing said expanded and cooled refrigerant to a refrigeration load to cool same, employing the exciting refrigerant for said regenerating cooling of said compressed refrigerant, subjecting a portion of said further compressed refrigerant to additional compression, subjecting said additionally compressed refrigerant portion to regenerating cooling, expanding said cooled refrigerant portion to accomplish work and further reducing the temperature of said refrigerant portion, said work being employed for said additional compression of said refrigerant portion, passing said expanded and cooled refrigerant portion to a second refrigeration load to cool same, employing the exiting refrigerant portion for said regenerative cooling of said compressed refrigerant portion, and returning refrigerant heated in the above regenerative cooling stages for said first mentioned compression of said refrigerant.

2. A power-refrigeration process as defined in claim 1, wherein said refrigerant portion is diverted from the main refrigerant stream prior to said first mentioned regenerative cooling.

3. A power-refrigeration process as defined in claim 1, wherein said refrigerant portion is diverted from the main refrigerant stream subsequent to said first mentioned regenerative cooling.

4. A power-refrigeration process as defined in claim 1, wherein said refrigerant is helium.

5. A power-refrigeration process as defined in claim 1, wherein said refrigerant is helium and wherein said refrigeration load in each case is nitrogen to be cooled and liquefied.

6. A power-refrigeration process which comprises heating a compressed gas, said compressed gas flowing in a closed power loop, introducing said hot compressed gas into a prime mover and expanding said gas, cooling said gas and compressing said gas, the work from said prime mover being employed for said last mentioned compression, circulating a portion of said compressed gas in said closed power loop and circulating the remainder of said compressed gas as refrgierant in a closed refrigeration loop which comprises cooling said compressed refrigerant, further compressing said refrigerant, subjecting said so-compressed refrigerant to regenerative cooling, expanding said further cooled refrigerant to accomplish work and further reducing the temperature of said refrigerant, said work being employed for said further compression of said refrigerant, passing said expanded and cooled refrigerant to a refrigeration load to cool same, employing the exiting refrigerant for said regenerative cooling of said compressed refrigerant, and returning the refrigerant heated in said regenerative cooling for said first mentioned compression of said refrigerant.

7. A power-refrigeration process which comprises heating helium gas, said compressed gas flowing in a closed power loop, introducing said hot compressed helium gas into a prime mover and expanding said gas, cooling said helium and compressing said helium, the work from said prime mover being employed for said last mentioned compression, circulating a portion of said compressed helium gas in said closed power loop and circulating the remainder of said compressed helium gas as refrigerant in a closed refrigeration loop which comprises cooling said compressed helium, further incrementally compressing said cooled helium, subjecting said so-compressed helium to regenerative cooling, expanding said further cooled helium to accomplish work and further reducing the temperature of said helium gas to cryogenic temperatures, said work being employed for said further compression of said helium, passing said expanded and cooled helium to a refrigeration load to cool same, employing the exiting helium for said regenerative cooling of said compressed refrigerant, and returning the helium heated in said regenerative cooling for said first mentioned compression of said helium.

8. A power-refrigeration system which comprises a refrigeration cycle including, in combination, the components consisting of a first compressor, a first cooler, a second boost compressor, a cold regenerator, an expander, said expander being connected in driving relation with said boost compressor, a refrigeration load, first conduit means connecting the exhaust side of said first compressor in seriatim with each of said components, and second conduits means communicating with said first conduit means and connecting said refrigeration load with the intake side of said first compressor and passing through said cold regenerator in heat exchange relation therein with said first conduit means; a heater, a power turbine, third conduit means connecting the exhaust side of said first compressor and the intake side of said hot turbine and passing through said heater, a second cooler, and fourth conduit means connecting the exhaust side of said power turbine and the intake side of said first compressor and passing through said second cooler.

9. A power-refrigeration system which includes, in combination, the components consisting of a first compressor, means for driving said first compressor, a cooler, a second boost compressor, a first cold regenerator, a first expander, said expander being connected in driving relation with said second boost compressor, a first refrigeration load, first conduit means connecting the exhaust side of said first compressor in seriatim with each of said components, and second conduit means communicating with said first conduit means and connecting said refrigeration load with the intake side of said first compressor and passing through said cold regenerator in heat exchange relation therein with said first conduit means, a third boost compressor, a second cold regenerator, a second expander, said second expander being connected in driving relation with said third boost compressor, a second refrigeration load, third conduit means connecting said first conduit means between said second boost compressor and said first expander in seriatim with said third boost compressor, said second cold regenerator, said second expander and said second refrigeration load, and fourth conduits means communicating with said third conduit means and connecting said second refrigeration load with said second conduit means between said first refrigeration load and said first cold regenerator, and passing through said second cold regenerator in heat exchange therein with said third conduit means.

References Cited

UNITED STATES PATENTS

244,236	7/1881	Hill	62—403 X
2,409,159	10/1946	Singleton	62—402 X
2,458,894	1/1949	Collins	62—40 X
2,909,903	10/1959	Zimmermann	62—40 X
3,144,316	8/1964	Koehn et al.	62—40 X
3,213,631	10/1965	Kniel	62—40 X

NORMAN YUDKOFF, *Primary Examiner.*

V. W. PRETKA, *Assistant Examiner.*