

June 15, 1965

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3,188,821

PNEUMATICALLY-OPERATED REFRIGERATOR WITH SELF-REGULATING VALVE

Filed April 13, 1964

9 Sheets-Sheet 1

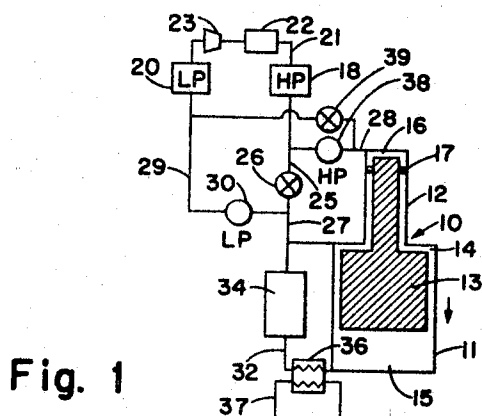


Fig. 1

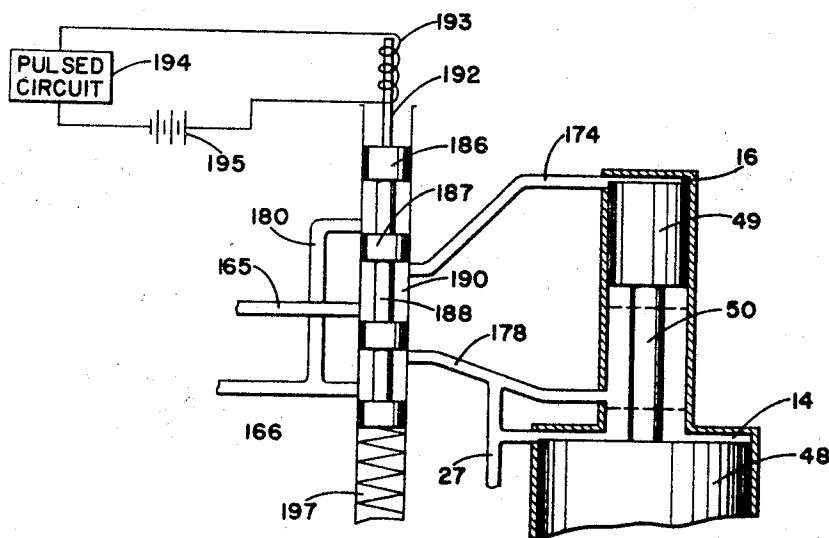


Fig. 10

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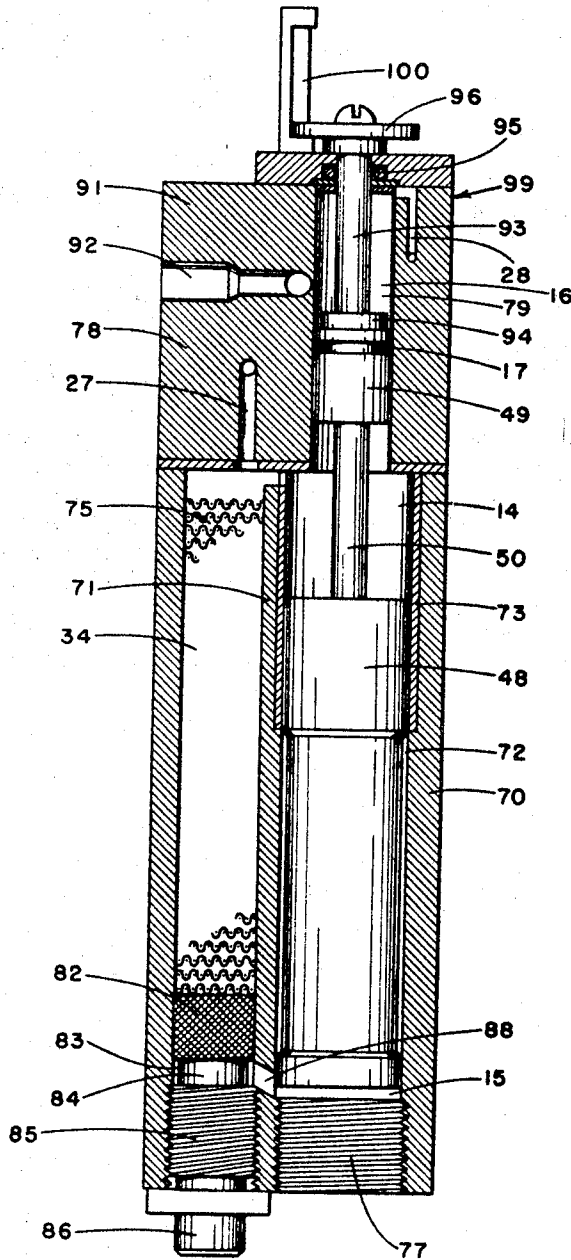


Fig. 2

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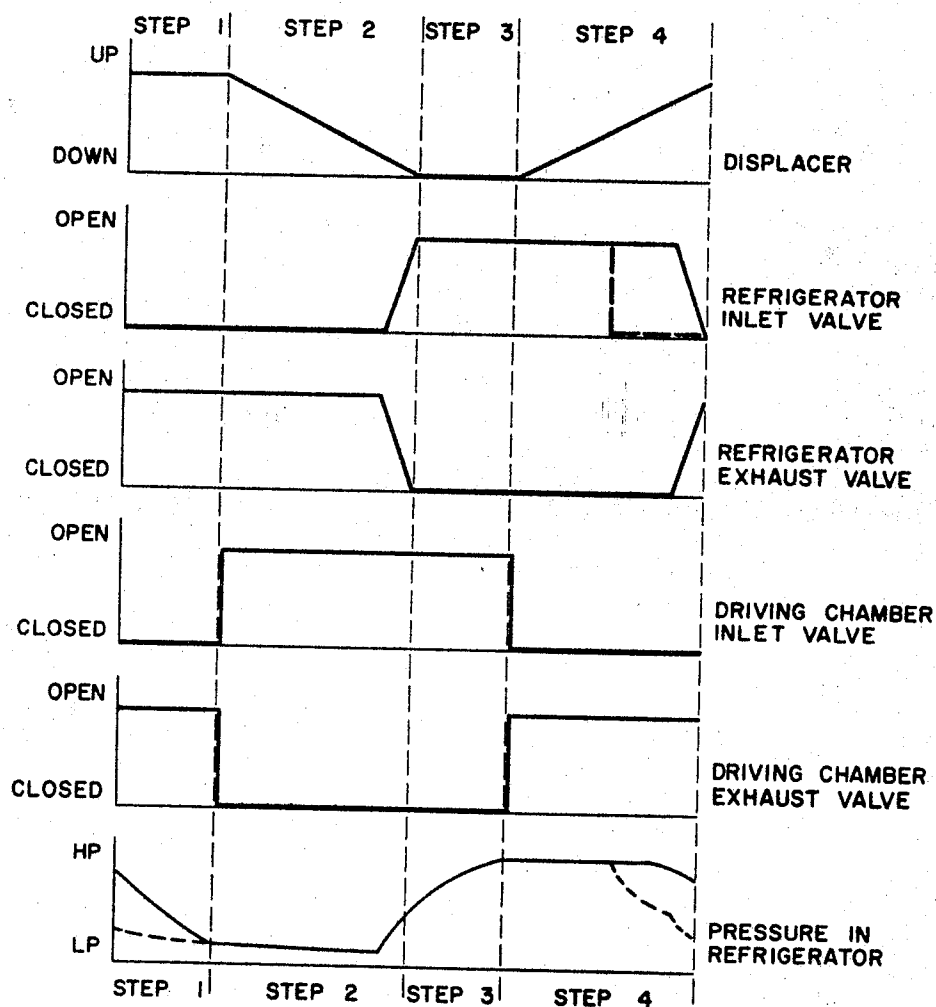


Fig. 3

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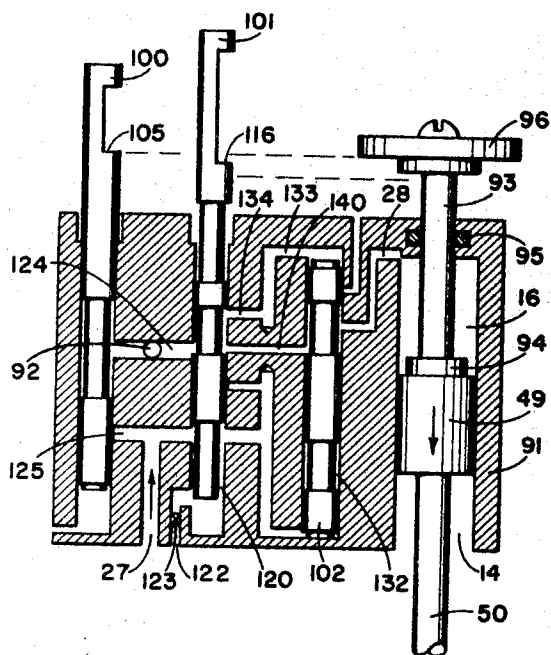
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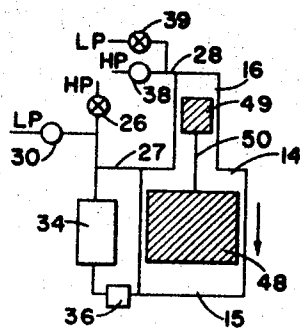
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(A)



(B)

(STEP 2)

Fig. 5

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PNEUMATICALLY-OPERATED REFRIGERATOR WITH SELF-REGULATING VALVE

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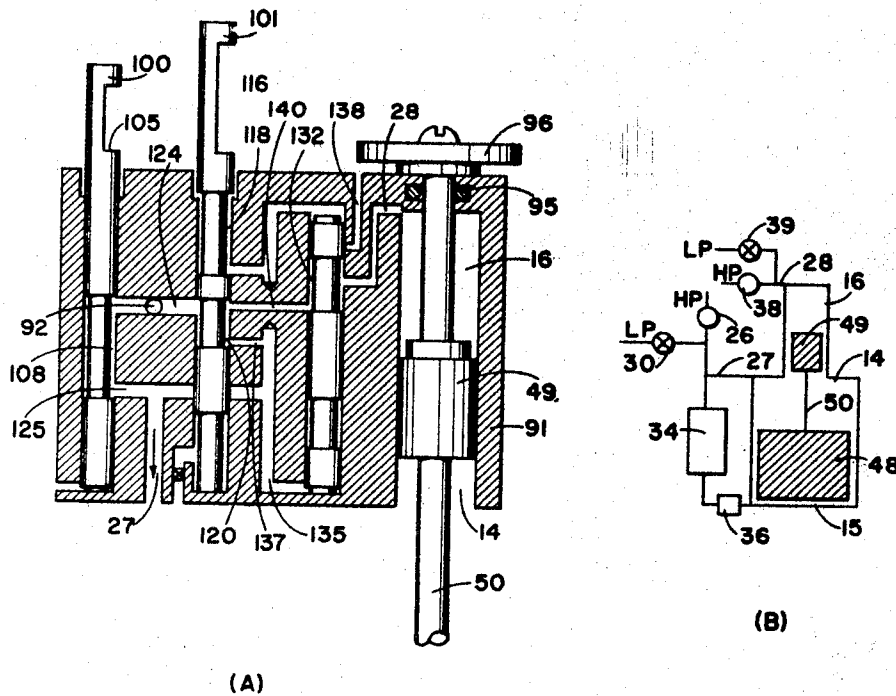


Fig. 6

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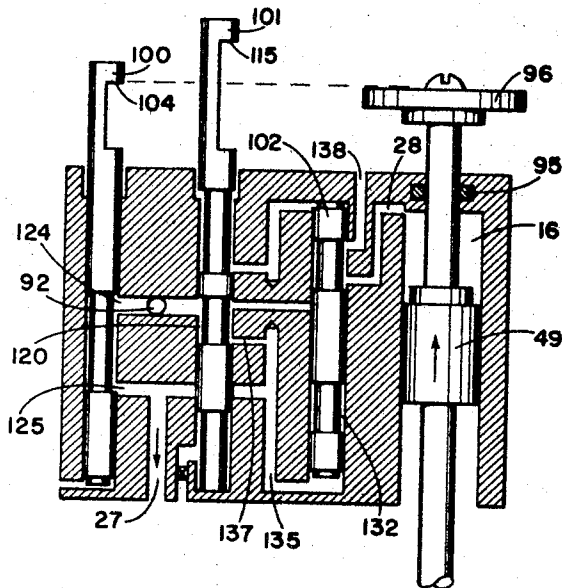
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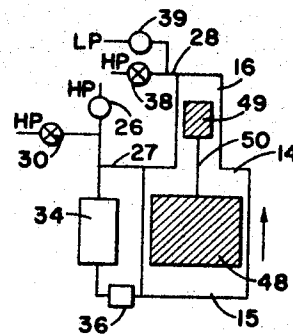
PNEUMATICALLY-OPERATED REFRIGERATOR WITH SELF-REGULATING VALVE

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(A)



(B)

(STEP 4)

Fig. 7

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PNEUMATICALLY-OPERATED REFRIGERATOR WITH SELF-REGULATING VALVE

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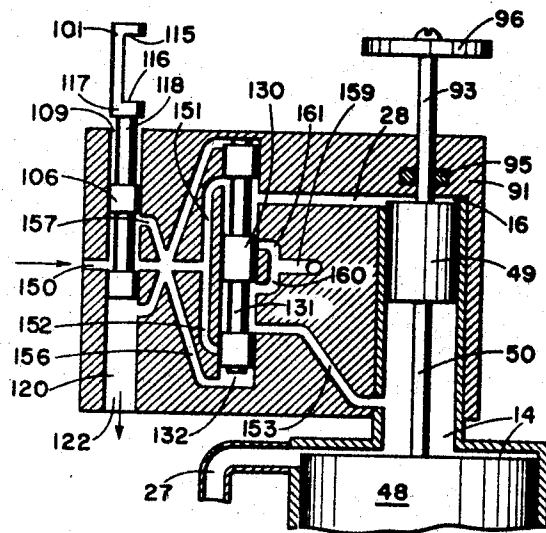


Fig. 8

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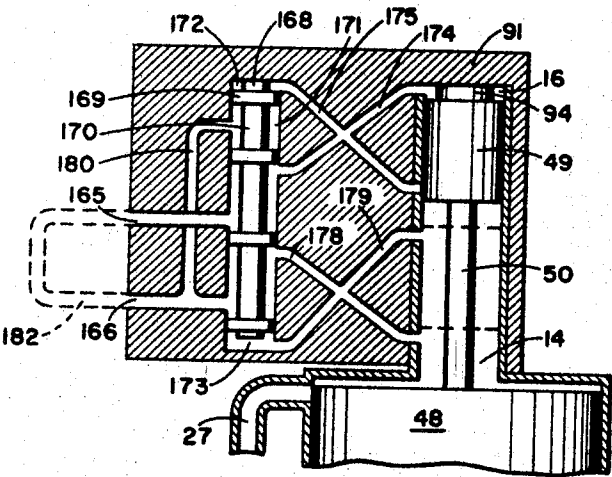
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Fig. 9



STEP	VALVE CHAMBERS		DRIVING CHAMBER 16	REFRIGERATOR CHAMBER 14
	172	173		
1	L +	L	H	L
↓ 2	H ↓	L	H	L ↑
3	H ↓	L +	H ↓	L ↑
4	L	L +	L	H
↑ 4	L	H	L ↑	H ↓
	L +	H ↓	L ↑	H ↓

Fig. 9a

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PNEUMATICALLY-OPERATED REFRIGERATOR WITH SELF-REGULATING VALVE

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8 Claims. (Cl. 62-6)

This invention relates to apparatus for developing low temperature refrigeration, and more particularly to refrigeration apparatus which includes a novel valve system which makes the apparatus self regulating, and in a preferable form requires no external driving means other than a source of the high-pressure expensible fluid used in the refrigerator. It further relates to the refrigeration apparatus for producing net refrigeration in a system in which some of the work extracted from the compressing, cooling, and expanding of a fluid is in the form of thermal energy, wherein the fluid leaving the system is at a temperature higher than that at which it entered the system.

In United States Patent No. 2,966,035, issued to Gifford, there is described a refrigeration method and apparatus which is directed to a so-called "no-work" cycle in which refrigeration is obtained by removing more sensible heat from a system than is taken into the system by the refrigerating fluid used. Although the cycle described in U.S.P. 2,966,035 has been found to be very successful in producing refrigeration, even as low as 10° K., the method and apparatus of that cycle possess an inherent disadvantage in that the equipment required to control the flow of fluid and thus to achieve refrigeration by the method and cycle described is expensive and difficult to assemble.

In a copending application of Walter H. Hogan, Serial No. 322,782, filed November 12, 1963, and assigned to the same assignee as this application, there are described method and apparatus for developing low temperature refrigeration in which the apparatus includes a third driving chamber of variable volume. The purpose of this third chamber in the overall refrigeration cycle is to control and drive a displacer in the refrigerator, the displacer in turn being responsible for the required volume variations of two enclosed chambers and the ultimate delivery of refrigeration to an external load. The self-regulating valve of this invention is particularly well suited to the control of this third driving chamber, and the use of the self-regulating valve makes it possible to construct an inexpensive, extremely reliable small refrigerator which may be operated on shop air in an open cycle or on a source of compressed fluid in a closed cycle.

Several examples of the use and value of a small, inexpensive refrigerator which may, if desired, be operated on shop compressed air may be cited. Most medical and biology laboratories require small amounts of low-temperature refrigeration for such work as the preparation of tissues for microscopic examination and the freezing of solutions. Usually, refrigeration needs are met by liquid nitrogen or solid CO₂. For those requiring large quantities of continuous refrigeration, this is not too difficult. But, it is not easy to obtain just one liter of liquid nitrogen or one pound of solid CO₂; and, if a small amount of cooling is desired continuously for weeks around the clock, it is difficult to arrange for this using cryogenic fluid or solids. Many experiments that require temperatures below 233° K. (-40° C.)—the nominal lower limit of Freon refrigeration—must be performed at temperatures fixed by the refrigerant used, e.g., liquid nitrogen (about 77° K.) and solid CO₂ (about 195° K.). Temperatures between 100° K. and 230° K. have been difficult to realize experimentally.

It would therefore be very desirable to have available a small self-contained unit which could be plugged into

the compressed-air line in the laboratory or shop and which would deliver the small amount of refrigeration needed at any temperature down to 100° K. at a moment's notice, and if necessary hold it for weeks at a time. The refrigerator described herein can meet such a need; for through the use of the valve means disclosed it may employ compressed air both for motive power and for the refrigeration thus eliminating all need for valve motive means. It is portable, can be connected to a compressed-air line, and is ready to use within a few minutes. This refrigerator may also be operated on cryogenic fluids (e.g. nitrogen and helium), it may use external means for operating the valve system and it may be used in a closed system to develop cryogenic temperatures.

It is therefore a primary object of this invention to provide a refrigeration apparatus which can be operated on a compressed fluid, which is inexpensive to construct and operate, and which at the same time achieves the advantages associated with the no-work cycle. It is another object of this invention to provide an apparatus of the character described which makes possible a small, inexpensive, efficient refrigeration apparatus which has many and varied uses, including incorporation in a cold trap, the cooling of detection devices, and the use as a laboratory tool. It is yet another object of this invention to provide a refrigeration apparatus of the character described which incorporates a valve system that is self-regulating, preferably requires no external power, is completely integrated into the refrigeration apparatus, and is reliable over an extended period of time. 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 relation of one or more of such steps with respect to each of the others and the apparatus embodying features of construction, combinations of elements, and arrangement of parts which are adapted to effect such steps, all as exemplified in the following detailed disclosure, and the scope of the invention will be indicated in the claims.

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

FIG. 1 is a simplified diagrammatic view of the pneumatically driven no-work refrigeration apparatus in which valving means are generally indicated;

FIG. 2 shows a typical embodiment of a refrigerator, partially in cross-section, constructed in accordance with this invention and incorporating one embodiment of the valve means;

FIG. 3 illustrates a typical operational sequence for the cycle of this invention showing the operation of the displacer and the valves, as well as the pressure variations in the refrigerator;

FIGS. 4-7 show one embodiment of the valve means in diagrammatically extended views along with simple sketches of the refrigerator, the figures corresponding to steps 1-4 of the cycle, respectively, as sequentially diagrammed in FIG. 3 and described in the text;

FIG. 8 is a modification of the valve system of FIGS. 4-7 in which early cut-off of high-pressure fluid into the refrigerator is not provided;

FIG. 9 is another modification of the valve system in which the expensible fluid is used as the sole force for operating the valve;

FIG. 9a is a table summarizing the pressure changes in the chambers of the apparatus of FIG. 9; and

FIG. 10 is yet another modification of the valve system in which an external force is used to actuate the valve system.

In FIG. 1 the apparatus is shown in simplified form for convenience in describing the cycle of this invention.

Turning now to FIG. 1, it is possible to identify the component parts of a typical refrigeration apparatus constructed in accordance with this invention. A fluid-tight enclosed space generally designated as 10 is made up of a lower or refrigeration section 11, and an upper or driving section 12. It will be appreciated that the terms "upper" and "lower" are used in a relative sense, and that the refrigeration apparatus may be oriented in any manner, these terms being employed only to correspond to the orientation illustrated in the figures. Within the fluid-tight enclosed space 10 is a displacer 13 conforming essentially to the configuration of the enclosed space and movable therein in a manner to define first, second and third chambers of variable volume, designated as 14, 15 and 16 respectively. Chambers 14 and 15 may be considered as part of the refrigeration system while chamber 16 forms a driving chamber. Inasmuch as a pressure differential must exist between volumes 14 and 16, it is necessary to employ a fluid-tight seal 17 as indicated.

In the literal sense, displacer 13 is actually a combination of a displacer and a piston; however, for convenience of description it is referred in this general description as a "displacer." It will also be noted that although the apparatus of FIG. 1 incorporates the no-work principle (rejection of thermal energy equivalent to refrigeration produced), it also provides for the delivery of some deliberate nonthermal work external of the system, and is directed to apparatus providing pneumatic driving means for this system.

Associated with the refrigerator is a high-pressure fluid source 18 (e.g. a compressed gas such as air or helium) and a low-pressure fluid reservoir 20 which may be a fluid reservoir to form a closed cycle or which may vent to the atmosphere in an open cycle. In FIG. 1 a closed cycle is illustrated, and in order to complete it there is provided a fluid conduit 21 between high-pressure source 18 and low-pressure reservoir 20, and as a part of this fluid conduit a cooler 22 (and clean-up system if required) and a compressor 23 are furnished. From high-pressure fluid source 18 there is a high-pressure line 25, controlled by valve 26, which leads into a fluid conduit 27 communicating with the refrigerator position including the first chamber 14 and second chamber 15, and also controlled by valve 38 which leads into fluid conduit 28 communicating with the third chamber 16. Likewise, the low-pressure reservoir has a fluid conduit 29, controlled by valve 30, communicating with the fluid conduit 27, and also controlled by valve 39 which also leads into conduit 28 and chamber 16. Fluid conduits 27 and 32 make up a fluid path between the first chamber 14 and the second chamber 15. Incorporated as a portion of this fluid path is a heat storage means 34 which is typically a regenerator. Located in fluid conduit 32 is a refrigeration load 36 which may be a heat station or a heat exchanger capable of circulating a heat transfer fluid through a conduit 37 in out-of-contact heat exchange with cooled fluid flowing from the second chamber 15 out through the system into the low-pressure reservoir.

FIG. 2 illustrates one embodiment of the apparatus of this invention as constructed into a practical working laboratory refrigerator using a single source of compressed fluid for the refrigeration and driving chambers and venting to the atmosphere. Thus the refrigerator of FIG. 2 is of the open cycle type.

In the apparatus of FIG. 2 the refrigeration portion is enclosed in a cylinder block 70 which contains within it a separating wall 71, thus defining a refrigeration cylinder 72, which has a cylinder lining 73, and a volume suitable for the regenerator 34 which in this case is shown to consist of stacked copper screening 75. A block 77 encloses the bottom of the refrigeration section, while the top portion 78 contains within it a cylinder 79 forming that portion in which the piston 49 operates to define the driving chamber 16. The regenerator 34 terminates in a knurled heat station 82. An annular header 83, a shaft

84, a threaded portion 85, and a shaft 86 make up the means for delivering refrigeration to an external load. A channel 88 (corresponding in this case to fluid path 32 of FIG. 1) communicates between the cold second chamber 15 and the header 83, thus the coldest fluid in the system is brought into contact with the shaft 84 and delivers refrigeration through thermal conductivity to the external shaft 86.

The self-regulating valve is indicated generally by numeral 99. Fluid is introduced into the apparatus both for use in the refrigeration section and in the driving chamber through a conduit 92, and this in turn communicates by channels (not shown) in the valve block 91 with the fluid conduit 27 designed to communicate with the first chamber 14, and through fluid conduit 28 which communicates with the third chamber or driving chamber 16. A shaft 93 is provided to extend upwardly from the piston 49 and to actuate the valve system described below. This shaft is attached to piston 49 through a bumper 94 and passes through fluid-tight sealing means 95. It terminates in a valve-actuating disc 96.

FIGS. 4-7 are diagrammatically extended drawings of one embodiment of a self-regulating valve system constructed in accordance with this invention. The method of illustration in FIGS. 4-10 makes it possible clearly to show the channels and spools in the valve system. In each of FIGS. 4-7 there is also included a simplified sketch of the pneumatically operated refrigerator shown in FIGS. 1 and 2. In the refrigerator sketches those valves which are closed are represented by an "x" in a circle, and those which are open are represented by an open circle. The valves are also labelled HP and LP to indicate whether they are designed to introduce high pressure fluid or exhaust low pressure fluid. It will be appreciated that in presenting such an extended view such as that used in FIGS. 4-7 the valve actuating disc 96 is not shown in actual contact with the valves, but contact is illustrated through the use of dotted lines. The manner in which contact is made is shown for example in FIG. 2.

In the embodiment of FIGS. 4-7 three slide or spool valves are provided and these are valve 100 which controls the flow of fluid into chamber 14 and 15 of the refrigerator; valve 101 which controls the exhausting of fluid from chambers 14 and 15 of the refrigerator; and valve 102 which is a pilot valve controlling the flow of fluid to the driving volume 16 and hence controlling the motion of the piston 49 and displacer 13. The pilot valve 102 is a snap action device which is gas operated to control the movement of piston 49 which in turn will be seen to mechanically control valves 100 and 101.

Valve 100 as it is illustrated in FIGS. 4-7 is designed to achieve early cut-off of the high-pressure fluid entering the refrigeration portion of the apparatus. The purpose of this early cut-off will be described in the detailed presentation of the cycle and the operation of the self-regulating valve system. It will be seen that valve 100 has an upper cam face 104 and a lower cam face 105. The spool portion is comprised of large diameter sections 106 and small diameter sections 107. In all of the spools, the large diameter sections are of a dimension to form fluid-tight contact with the internal walls of the channels in which they move; and the small diameter sections are of a dimension to form an annular passage with the internal walls of the channels. If the refrigerator is to operate in the orientation shown in FIG. 2, then there will be built into the design of valves 100 and 101 sufficient friction to prevent them from dropping or sliding down in their respective channels before actuation downward by disc 96. Spool valve 100 moves within channel 108 which, as will be seen in FIG. 4, has an exhaust port 109 (formed by a larger diameter channel section) and a venting port 110. Neither of these ports 109 or 110 control the introduction or discharge of fluid into the system, but serve as fluid balancing means.

In a similar manner valve 101 has an upper cam face 115

and a lower cam face 116 and is formed of large diameter sections 117 and small diameter sections 118. This valve moves within channel 120 which is vented to the atmosphere through an enlarged section 121 and provides the exhaust 122 to the atmosphere from the refrigerator portion of the apparatus. Within exhaust channel 122 is a choke valve 123, the purpose of which is to control the rate at which the fluid is exhausted from the refrigerator portion of the apparatus. Within exhaust channel 122 is a choke valve 123, the purpose of which is to control the rate at which the fluid is exhausted from the refrigerator portion. Channels 124 and 125 communicate between channels 108 and 120. The high-pressure fluid inlet 92 communicates with channel 124 and brings fluid into the valve system.

Pilot valve 102 is likewise formed of large diameter sections 130 and small diameter sections 131. This valve operates in channel 132 which at its upper end communicates with channel 120 through branch channels 133 and 134 and its lower through branch channels 135, 136, and 137. Channel 132 exhausts to the atmosphere through exhaust channel 138, and communicated with the driving chamber 16 through channel 28. Channel 132 also communicates with the main fluid inlet channel 124 by way of channel 140.

An examination of the entire valve system shown in FIG. 4 will show that by the proper movement of pilot valve 102 high-pressure fluid is either introduced or exhausted from driving chamber 16 and hence motion is imparted to piston 49 and to valves 100 and 101 which control the operation of the refrigerator. Pilot valve 102 is in turn controlled by the pressure conditions existing in the apparatus as will be explained in detail. As will become apparent it is only necessary to attach the fluid inlet line 92 to the source of high-pressure fluid to operate the apparatus as an open cycle refrigerator. If on the other hand it is desired to operate it as a closed cycle, then it is necessary to provide a common conduit means (e.g. conduit 29 of FIG. 1) communicating with exhausts 121, 122, and 138. Such conduit means can then be used to introduce the low pressure exhaust fluid into a compressor (23 of FIG. 1) which in turn then supplies the high pressure fluid to a suitable reservoir 18 for furnishing high-pressure fluid into inlet 92 (comparable to conduit 25 of FIG. 1). Thus there is formed a closed cycle as illustrated in FIG. 1.

It will now be possible to describe a refrigeration cycle both in terms of the operation of the valve system and the piston-displacer of the refrigerator to illustrate how the apparatus operates as a pneumatically driven, self-actuating refrigerator. In this description reference should be had to FIG. 3, which is an operational sequence of the apparatus as well as to FIGS. 4-7. In FIG. 3 the width between the vertical lines which define the steps are not meant to be interpreted as an indication of the relative lengths of time required to perform each step. It will also be appreciated that a diagrammatic representation such as this is in fact a somewhat simplified presentation of the actual cycle. The temperature history diagram of the no-work portion of the cycle which is performed in this apparatus and is responsible for the delivery of refrigeration to an external load is essentially that which is illustrated in FIG. 5 of U.S.P. 2,966,035.

In FIGS. 4-7, the displacer and piston are drawn as a separate displacer 48 and a separate piston 49 to correspond to the embodiment of FIG. 2 which incorporates the valve system of this invention. Valves 26, 30, 38, and 39 in FIGS. 4B, 5B, 6B and 7B are used merely to represent the actions of the valves 100, 101, and 102, and the control which these spool valves have over the flow of fluid within the system.

To begin the cycle description, it will be assumed that the conditions shown in FIG. 4 obtain, and the displacer 48 and driving piston 49 are in their uppermost position, having reached that condition at the end of

the preceding cycle. This is in fact a situation which obtains only momentarily. The first step comprises the opening of the low-pressure valve 30 (FIG. 4B) associated with the refrigerator section to a low-pressure region and the consequent expansion and further cooling of the fluid within chamber 15 and within the regenerator 34. In reaching its uppermost position the actuating disk 96 has contacted upper cam faces 104 and 105 of valves 100 and 101, respectively, and mechanically forced these spools into the position shown in FIG. 4A. An examination of FIG. 4A will show that fluid from the refrigerator is discharged through conduit 27 into channel 120 through channel 125 and to the atmosphere by way of exhaust channel 122, the fluid flow being controlled by choke valve 123. At the same time the position of pilot valve 102 (FIG. 4A) closes off any high pressure fluid to drive volume 16 and opens up this volume to the atmosphere through channels 28, 132, and exhaust channel 138.

The exhausting of the high-pressure fluid from the refrigerator during this first step decreases the gas pressure within the system including that on the bottom of pilot valve 102 by virtue of the fluid path existing through channels 27, 125, 120, 136 and 135. There comes then a point where the pressure of the exhaust fluid acting upon the bottom end of the pilot valve 102 is less than the pressure of the fluid reaching the upper portion of pilot valve 102 by way of channels 124, 120, 134, and 133. This differential in gas pressure snaps pilot valve 102 to its bottommost position as shown in FIG. 5. This in turn initiates step 2 which comprises the movement of the piston and displacer downwardly as shown in FIG. 5B. This downward movement of displacer 48 serves to sweep the cold expanded fluid from chamber 15 back through heat exchanger 36 to deliver refrigeration and through regenerator 34 into the low-pressure region (in this case the atmosphere) and into chamber 14. During its discharge, the refrigeration fluid exchanges heat in the regenerator and in doing so is warmed to a temperature above that at which the high-pressure fluid was originally supplied as will be explained subsequently. This difference in temperature is a measure of the amount of refrigeration extracted from the fluid.

FIG. 5B illustrates that during this second step the low-pressure valve 30 remains open and the high-pressure valve 38 which permits the delivery of high pressure fluid to driving chamber 16 is opened. Turning now to FIG. 5A it will be seen how the spool valve of this invention controls and achieves this desired fluid flow. With the pilot valve 102 in its bottommost position, high-pressure fluid from inlet 92 flows by way of channels 124, 120, 140, 132, and 28 into driving chamber 16 thus providing the necessary pneumatic actuation of piston 49 in a downwardly direction. This is possible inasmuch as the pressure acting upon the bottom of displacer 48 is decreasing due to the fact that cold low-pressure fluid is exhausting from the refrigerator and the high-pressure fluid is entering chamber 16 thus increasing the pressure within it and setting up a pressure differential. As piston 49 moves downwardly actuating disc 96 mechanically engages cam face 105 of valve 100 and in doing so sets this valve in motion in a downwardly direction. Subsequent to the engagement with valve 100, actuating disc 96 engages lower cam face 116 of valve 101 and likewise mechanically moves this spool downwardly. During this downward movement it will be seen that conduit 27 from the refrigerator is still open to the exhaust by way of channels 125, 120, and 122. Thus the cold fluid of chamber 15 continues to be swept from the refrigerator portion of the system as required in this step.

With the arrival of displacer 48 at its lowermost position (FIG. 5B), step 3 begins. This step is illustrated in FIG. 6. In this third step the high-pressure valve 26 (FIG. 6B) into the refrigeration system is opened permitting high-pressure fluid to flow into chambers 14 and

15. The high-pressure fluid entering chamber 14 compresses residual fluid left there during step 2. This compression heats fluid and this heated fluid is then mixed with the remaining high-pressure incoming fluid. The mixed temperature of the high-pressure fluid in chamber 14 is therefore higher than the temperature of the incoming fluid, and provides an intermediate temperature fluid for passage through regenerator 34. In this third step the displacer 48 and piston 49 dwell temporarily in their lowermost position by virtue of the fact that high-pressure fluid is being delivered to driving chamber 16 as well as to the refrigerator portion of the apparatus. The conduits to the exhaust side are both closed off (FIG. 6B).

During this third step the spools of the valve occupy their lowermost position as shown in FIG. 6. This means that high-pressure fluid entering by way of inlet 92 can flow through channels 124, 108, and 125 into conduit 27 and thence into the refrigerator (chambers 14 and 15) as required. This position of the spools also permits high-pressure fluid to flow by way of channels 124, 120, 140, 132, and 28 into driving chamber 16. An examination of FIG. 6 will show that all exhaust paths from the refrigerator and driving chamber are cut off.

With the buildup of high-pressure fluid in the system a point is reached in which the high-pressure fluid acting upon the bottom end of pilot valve 102 and reaching it by way of channels 124, 120, 137, and 135 is sufficient to snap the pilot valve 102 back into its upper position. As will be seen in FIG. 7A this position of pilot valve 102 opens driving chamber 16 to the atmosphere to exhaust its high-pressure fluid by way of channels 28, 132, and 138. This in effect means that step 4 begins with the closing of the high-pressure valve 38 and the opening of low-pressure valve 39 (FIG. 7B) associated with the driving chamber 16 and that the step consists of the upward movement of the displacer and piston by virtue of the pressure differential which exists between chambers 15 at high-pressure and 16 at low pressure.

During step 4 the high-pressure valve 26 associated with the refrigerator portion of the apparatus remains open, thus permitting additional high-pressure fluid to mix with the heated high-pressure fluid being transferred from chamber 14 to chamber 15. This in effect provides a high-pressure fluid of temperature intermediate between the incoming fluid and fluid from chamber 14 which passes into the regenerator 34 and passes through it giving up heat to the cooler regenerator matrix, and enters the cold chamber 15 as high-pressure, initially cooled fluid.

As shown in FIG. 3 in the dotted line in the refrigerator inlet valve sequence diagram, it is possible to close this high-pressure valve 26 (FIG. 7B) in step 4 somewhat before the end of the step, i.e. some time after chamber 15 has reached at least one-half of its maximum volume. The valve system of FIGS. 4-7 is designed to achieve this early cut-off while that in FIG. 8 is designed to follow the solid line refrigerator inlet valve sequence diagram in FIG. 3. Although leaving the high-pressure valve 26 open for the full stroke provides the greatest gross refrigeration, the regenerator losses are greatest. Closing the high-pressure valve 26 before the end of step 4 provides less refrigeration, but also less regenerator loss, which frequently results in more net refrigeration available for less fluid circulation. Therefore, there is offered an alternative in the operation of this high-pressure valve in step 4. The effect which this early cut-off of the high-pressure valve 26 controlling the refrigeration fluid has upon the pressure within the refrigerator is illustrated also in FIG. 3 by the dotted line. It should be noted that after early cut-off the fluid in cold chamber 15 is expanded and further cooled during completion of step 4.

The manner in which this fluid flow is achieved by the self-regulating valve of this invention is illustrated in FIG. 7A. The difference in pressure acting upon the bottom

of the displacer 48 and the top of piston 49 is responsible for driving actuating disc 96 upwardly to contact first upper cam face 104 of valve 100 and then upper cam face 115 of valve 101. Valve 100 is designed in FIG. 7A to attain the early cut-off previously described. This means that as it moves upwardly, valve 100 isolates channel 108 from channel 125 thereby cutting off the supply of high-pressure fluid entering through inlet 92. In the condition illustrated in FIG. 7A the cut-off has not been completely accomplished but it will be appreciated that with continued upwardly movement this will be done. Thus although FIG. 7B illustrates high-pressure valve 26 open, it will not remain open in this embodiment throughout the entire step. By virtue of the position of pilot valve 102 fluid from driving chamber 16 continues to discharge by way of channels 28, 132, and 138. Valve 101 remains in the position indicated until the end of the step at which point it is raised to the position it occupies in FIG. 4A to commence the cycle again.

At the end of step 4 the displacer 48 and piston 49 are in their uppermost positions, the driving chamber 16 and volume of chamber 14 are at a minimum, while the cold chamber 15 has reached a maximum volume and contains initially cooled, (and perhaps further cooled) high-pressure fluid, the pressure and the temperature depending upon the time at which the high-pressure valve 26 in step 4 was closed.

It is now possible to look more closely at the thermodynamics of the cycle and the role of the driving chamber. At the end of step 4 chamber 15 has attained maximum volume and is filled with fluid which has been initially cooled by virtue of its passage through regenerator 34 (FIG. 7B). Then the cycle begins again with the exhausting of the initially cooled fluid from the refrigerator and there occurs a further cooling of the fluid due to its adiabatic expansion. At the beginning of step 2 the low-pressure fluid in chamber 15 is at a lower temperature than that of the high-pressure fluid that filled chamber 15 by virtue of the adiabatic expansion of the residual gas during step 1 in chamber 15 from high pressure to low pressure. The high pressure in chamber 16, being in excess of the low pressure in chamber 15, forces the displacer 13 downwardly expelling the fluid in chamber 15 initially through heat exchanger 36. In this heat exchanger the temperature of the fluid can be raised to substantially the temperature of the fluid in chamber 15 before its expansion, thereby providing refrigeration to fluid in conduit 37 (FIG. 1) or to any other suitable heat source. The low-pressure fluid then enters the cold end of the regenerator 34 at substantially the same temperature as that of the high-pressure fluid leaving regenerator 34 during the pressurizing of chamber 15 in step 4. During passage of this fluid through the regenerator 34 heat is extracted from the regenerator matrix to increase the temperature of the fluid so that on leaving the regenerator 34 at the warm end the fluid temperature is substantially the same as that temperature of the entering high-pressure fluid during step 4 which, it will be remembered, was higher than the temperature of the high-pressure fluid being supplied through inlet 92 from the high-pressure fluid source. The fluid leaving regenerator 34 fills expanding chamber 14 with low pressure fluid and the excess is exhausted. Since this fluid leaves the refrigeration system at a higher temperature than the fluid supplied to the system, thermal energy is extracted from the system.

It has been pointed out that chamber 16 is a driving chamber and further explanation of its operation will be helpful. A portion of the cross-sectional area of displacer 48 can be considered equivalent and opposite to the cross-sectional area of the piston 49 to which it is mechanically connected. Because these two chambers 14 and 15 are connected through the fluid path comprised of conduits 27 and 32 (FIG. 1) it is obvious that there will always be substantially fluid pressure equality within these two cham-

bers; and therefore there exists no net force between these two chambers by virtue of these equivalent displacer cross-sectional areas. There is also in chamber 15 a cross-sectional area of displacer 48 which may be considered to be equivalent and opposite to the cross-sectional area of the piston 49 in chamber 16. Whenever there is a fluid pressure unbalance, brought about by the control of the valves, between the fluid in chamber 16 and in chamber 15 there is a net force operating on the displacer 48 which is equivalent to the difference in pressure between these two chambers multiplied by the cross-sectional areas of the piston 49 in chamber 16. Therefore by suitable control of the pressurization and depressurization of the fluids in these chambers as described in the cycle steps, the displacer 13 can be made to move upwardly or downwardly or to dwell. Since chamber 16 is not part of the refrigeration system as are chambers 14 and 15, this chamber has been called the driving chamber.

FIG. 8 is a modification of the valve system of FIG. 7. In the valve means of FIG. 8 the early cut-off portion of the valve has been omitted. This means then that the refrigerator operates on the cycle indicated in FIG. 3 by the solid lines rather than by the dotted lines which pertain to the use of the early cut-off valve such as is used in FIGS. 4-7. In the valve modification of FIG. 8 the spool valve corresponding to 100 is eliminated and only slide valve 101 is actuated by the disc 96. In this figure the same numerals refer to the same elements in the valve systems illustrated.

In the valve block 91 of FIG. 8 high-pressure expansible fluid is introduced into the refrigerator system and the driving chamber through conduit 150, which in turn is in communication with branch conduits 151 and 152. An examination of FIG. 8 will show that the high-pressure fluid is introduced into the driving chamber 16 by way of channels 150, 151, 132 and 28. This, it will be appreciated, is equivalent to the combination of channels 92, 124, 120, 140, 132 and 28 of FIGS. 5 and 6. In a like manner high-pressure fluid is introduced into the refrigeration portion of the apparatus of FIG. 8 through channels 150, branch channel 152, and channels 132 and 153. This in turn is equivalent to the combination of channels 92, 124, 108, 125 and 27 of FIGS. 6 and 7. Connections into the refrigeration system are provided through channel 153 which in FIG. 8 is equivalent to channel 27 in FIGS. 4-7.

As in the case of the valving system of FIGS. 4-7 the flow of the fluid into the various chambers is controlled by the snap action of pilot valve 102 operating in channel 132. This in turn requires a control of fluid into the top or bottom portion of channel 132 in order to force the valve 102 up or down as is required. High-pressure expansible fluid is introduced into the bottom portion of channel 132 by means of channel 156 and this is equivalent to a combination of channels 137 and 135 in FIG. 7. High-pressure fluid is introduced into the top of channel 132 by means of channel 157 and this in turn is equivalent to channels 133 and 134 of FIG. 5. Low-pressure fluid is exhausted from channel 132, in which pilot valve 102 travels, through line 159. More specifically, low-pressure fluid is exhausted from driving chamber 16 by way of channels 28, 132, 161 and 159, which is equivalent to channels 28 and 138 of FIGS. 4 and 7. In a like manner low-pressure fluid is exhausted from the refrigeration portion of the apparatus by way of chamber 14 through channels 153, 132, 160 and 159. This is in turn equivalent to using channels 27, 123 and 120 in the apparatus of FIGS. 4 and 5.

From an examination of the apparatus of FIG. 8 it will be seen that it operates in precisely the same manner as the valve system of FIGS. 4-7. It travels through the same identical cycle and the only difference which is obtained is that the high-pressure fluid entering the refrigeration portion of the apparatus continues to flow into

the apparatus until the displacer has reached its uppermost position.

FIG. 9 illustrates a valve system which is controlled entirely by expansible fluid and therefore does not require any mechanical actuation of auxiliary spools such as valves 100 and 101 in FIGS. 4-8. This in turn requires a balancing of the pressures in the various volumes as will be apparent from the following description of the operation of this valve means. The entire valving is achieved through the use of the pilot valve 168. High-pressure fluid enters through line 165 and low-pressure fluid is exhausted through line 166. Pilot valve 168 is in turn formed of large diameter sections 168 which make a fluid tight seal with the inner walls of the channel 171 in which it operates, and small diameter sections 170 which form annular channels with the inner walls of channel 171. The pilot valve channel may also be considered to have an upper chamber 172 and a lower chamber 173 into which high-pressure fluid may be introduced and low-pressure fluid withdrawn in order to control the up and down movement of the pilot valve 168.

High-pressure fluid is delivered into the driving chamber 16 by way of channel 174 and high-pressure fluid is introduced into the upper chamber 172 of channel 171 by way of driving chamber 16 by means of channel 175. Channel 178 serves as the communication between the valving system and the refrigeration portion of the apparatus, and it will be seen to be in fluid communication with chamber 14 which is of course in turn in fluid communication with chamber 15 (not shown) through the fluid path 27 and the regenerator (not shown). This channel 178 serves both to introduce high-pressure fluid into the refrigeration system and to exhaust low-pressure fluid therefrom. There is also provided a channel 179 which, as will be seen, serves to exhaust fluid from the lower chamber 173 of the channel 171. Finally, branch channel 180 serves as a connection between the main part of channel 171 and the main exhaust line 161 of the refrigerator.

As pointed out previously, it is possible to make any one of these refrigerator systems incorporating the valve of this invention into a closed cycle system. This is schematically illustrated in FIG. 9 by the dotted lines which provide a connection 182 between the low-pressure exhaust 166 and the high-pressure inlet 165. It will, of course, be appreciated that between these two channels 166 and 165 auxiliary equipment such as a compressor and a cleanup system must be supplied as is illustrated in FIG. 1.

The operation of the valve system of FIG. 9 may be explained more readily with reference to the small table of FIG. 9a. Assume, as in the cases previously described, that the apparatus begins and has as its first step the temporary remaining of the piston 49 and the displacer 48 at their top dead center position. This then represents the moment just prior to the time at which the pilot valve 168 will be driven downward. Under these circumstances there is low-pressure fluid in chamber 172, the plus sign after the L in the table indicating that a small amount of residual fluid has remained therein and has been slightly compressed. There is also at this time low-pressure fluid in chamber 172 and high-pressure fluid is beginning to enter driving chamber 16. The refrigerator, as represented by chamber 14, is at low pressure. Tracing through the channels of FIG. 9 it will be seen that all of these conditions obtain at this point. The second step then, as before, is the movement of the piston 49 and the displacer 48 toward their bottom-most position as indicated by the left-hand arrows. Under these circumstances, high-pressure fluid will flow into chamber 172 as soon as the piston 49 has been driven sufficiently downwardly to open up the entrance of channel 175 from the high-pressure driving chamber 16. This will in effect cause the pilot valve 168 to be driven to its lower-most

position and to leave residual low-pressure fluid in chamber 173. At the same time, high-pressure fluid will be building up in the driving chamber 16 while the low-pressure fluid which remains in the refrigerating system will begin to increase in pressure.

The third step in the cycle is the point at which the piston and displacer occupy bottom dead center momentarily. As indicated in the chart in FIG. 9a, this means that there will be, at this particular moment, low-pressure fluid in both chambers 172 and 173 which sets up the conditions making it possible to snap the pilot valve 168 back into its uppermost position. At the same time the driving chamber 16 will have exhausted through channels 174, 173, 180, 166 and high-pressure fluid will be entering and continue to enter through channel 178 into the refrigeration portion of the system.

Finally, the fourth step in keeping with the cycles described herein constitutes the moving upwardly of the piston 49 and the displacer 48. Under these circumstances there will be a small amount of residual fluid in chamber 172 which will be compressed and the introduction of high-pressure fluid into chamber 173 will force the pilot valve 168 to snap into its uppermost position. It will also be appreciated that during this upward movement of the piston and displacer the driving chamber is increasing in pressure while the refrigerator is exhausting cold fluid and the pressure within the refrigerator section is decreasing.

FIG. 10 is a valve system which operates, as far as the control of the piston and displacer is concerned, in a manner identical to that by which FIG. 9 operates. However, in the valve system of FIG. 10 there is provided external means for operating the spool valve 186 in place of the channels which introduce high-pressure fluid into chambers 172 and 173 and exhaust low-pressure fluid therefrom. Thus, channels 179 and 175 are eliminated in the valve system of FIG. 10.

In the valve system of FIG. 10, the pilot valve 186 is, as is customary, formed of larger diameter sections 187 which are in fluid tight sealing relationship with the internal walls of channel 190 and of small diameter sections 188 which forms the necessary annular channels with the internal walls of channel 190. In this FIG. 10 like numerals refer to like elements of FIG. 9. Lacking the fluid pressure control of FIG. 10 it is, of course, necessary to provide some external force for controlling the upward and downward movement of the spool 186. In FIG. 10 this is illustrated to be an electrical control. The spool 186 has a mechanical extension 192 which in turn is in actuating relationship with a solenoid drive 193. This in turn is driven by a pulse circuit 194 from a suitable power source 195. Inasmuch as the solenoid drive is designed to give the necessary downward thrust to the spool 186, provision must be made to furnish an upward thrust and this is done in the embodiment in FIG. 10 by means of the coil spring return 197. It is of course within the scope of this invention to provide other mechanical means for actuating the spool 186 in the necessary direction at the required time intervals. For example this external force may take the form of a mechanical drive connected to a flywheel or any other suitable driving device. Thus, the valve in FIG. 10 is not self-actuated but is a spool-type valve which is capable of controlling the flow of fluids at various pressures into and out of the driving chamber 16 and the refrigerator section as is represented by chamber 14.

The self-actuation of the valve system used in conjunction with the pneumatically driven refrigerator is obvious from the description of the cycle in terms of the steps set forth in FIGS. 4-9. It is apparent that by connecting high-pressure fluid inlet 92 of FIG. 4 or high pressure channels 150 and 165 of FIGS. 8 and 9, respectively, with a source of high-pressure fluid, e.g. shop air, the refrigerator of this invention starts operating and after

cool-down to a steady stable operation is capable of delivering refrigeration to an external load for an extended period of time without being attended. It is only necessary to supply high-pressure fluid to it. This in turn means that it is free from the requirement of external motive power such as might be required for example to continuously actuate a rotary valve. The result is a unique, self-actuating, self-regulating refrigerator which is flexible in performance, the degree of refrigeration depending upon the quantity, quality and pressure of the fluid supplied. It is also within the scope to provide a pneumatically driven "no-work" refrigeration apparatus which has a spool valve operated by an externally supplied driving means as illustrated in FIG. 10.

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 the above constructions without departing from the scope of the invention, it is intended that all matter contained in the above description or shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

I claim:

1. Refrigeration apparatus operating on a compressed expansible fluid comprising in combination

(a) cylinder means;

(b) chamber-volume defining means movable within said cylinder means and comprising a displacer mechanically joined to a piston;

(c) first and second refrigerating chambers and a third driving chamber, the volumes of which are defined by the movement of said chamber-volume defining means such that when the volumes of said first and third chambers increase the volume of said second chamber decreases and when the volumes of said first and third chambers decrease the volume of said second chamber increases;

(d) a fluid path connecting said first and second chambers;

(e) thermal storage means associated with said fluid path; and

(f) valve means, comprising in combination

(1) high-pressure fluid conduit means communicating with said first and second refrigerating chambers and with said third driving chamber,

(2) low-pressure fluid exhaust means communicating with said third driving chamber,

(3) a pilot spool valve channel in fluid communication with said high-pressure fluid conduit means and with said low-pressure fluid exhaust means,

(4) a pilot spool valve translationally movable within said channel;

(5) actuating means adapted to move said pilot spool valve in a manner to control the flow of fluid into and out of said chambers through said high-pressure fluid conduit means and said low-pressure fluid conduit means thereby to impart to said chamber-volume defining means a predetermined motion, said motion being defined in four steps and consisting of said chamber-volume defining means dwelling in an uppermost position moving downwardly, dwelling in a lowermost position, and moving upwardly, respectively.

2. Refrigeration apparatus in accordance with claim 1 wherein said actuating means is said compressed expansible fluid on which said refrigeration apparatus operates whereby said refrigeration apparatus is self-actuating and self-regulating.

3. Refrigeration apparatus in accordance with claim 1 wherein said actuating means is an externally applied force.

4. Refrigeration apparatus in accordance with claim 3

wherein said actuating means includes electrical pulsing means adapted to move said pilot spool valve in one direction and mechanical means adapted to move it in the opposite direction.

5. Refrigeration apparatus operating on a compressed 5
expansible fluid, comprising in combination

- (a) cylinder means;
- (b) chamber-volume defining means movable within said cylinder means and comprising a displacer mechanically joined to a piston; 10
- (c) first and second refrigerating chambers and a third driving chamber, the volumes of which are defined by the movement of said chamber-volume defining means such that when the volumes of said first and third chambers increases the volume of said second chamber decreases and when the volumes of said first and third chambers decrease the volume of said second chamber increases; 15
- (d) a fluid path connecting said first and second chambers;
- (e) thermal storage means associated with said fluid path; and 20
- (f) valve means, comprising in combination
 - (1) high-pressure fluid conduit means communicating with said first and second refrigerating chambers and with said third driving chamber, 25
 - (2) low-pressure fluid exhaust means communicating with said third driving chamber,
 - (3) a pilot spool valve channel in fluid communication with said high-pressure fluid conduit means and with said low-pressure fluid exhaust means, 30
 - (4) a pilot spool valve movable within said channel;
 - (5) a slide valve channel in fluid communication 35 with said pilot valve channel and with said high-pressure fluid conduit means and said low-pressure fluid exhaust means,
 - (6) a slide valve movable within said slide valve channel and adapted to control the flow of fluid 40

to said pilot spool valve channel and to said chambers,

(7) actuating means adapted to move said slide valve in a manner to control the flow of fluid into and out of said chambers through said high-pressure fluid conduit means and said low-pressure fluid exhaust means thereby to impart to said chamber-volume defining means a predetermined motion, said motion being defined in four steps and consisting of said chamber-volume defining means dwelling in an uppermost position, moving downwardly, dwelling in a lowermost position, and moving upwardly, respectively.

6. Refrigeration apparatus in accordance with claim 5 wherein said piston terminates externally of said cylinder means in a disc which is in mechanical engagement relationship with said slide valve and serves as said actuating means.

7. Refrigeration apparatus in accordance with claim 5 further characterized by having a second slide channel and attendant slide valve adapted to cut off the flow of high-pressure fluid into said first and second refrigerating chambers after said chamber-volume defining means has completed at least one-half of its downward movement in the second step of its said motion.

8. Refrigeration apparatus in accordance with claim 5 wherein said low-pressure fluid exhaust means is in fluid communication within said high-pressure fluid conduit means through fluid compressor means whereby said refrigeration apparatus is a closed system.

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