

[54] **MODIFIED STIRLING CYCLE ENGINE-
COMPRESSOR HAVING A FREELY
RECIPROCABLE DISPLACER PISTON**

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[58] Field of Search.....92/85, 60, 134, 143; 60/24;
417/401, 402

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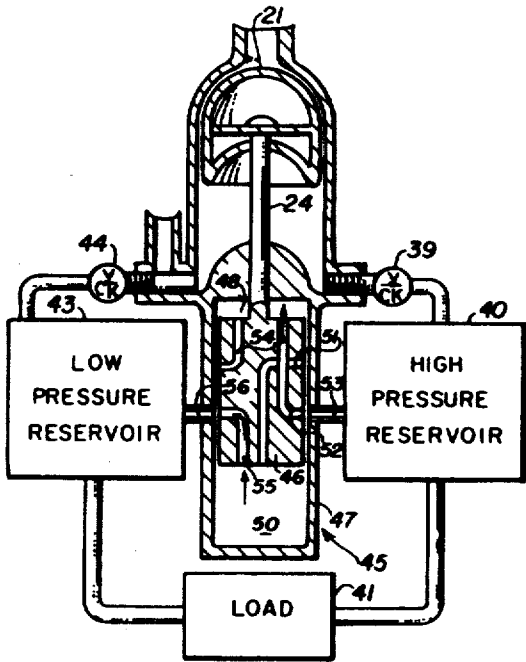
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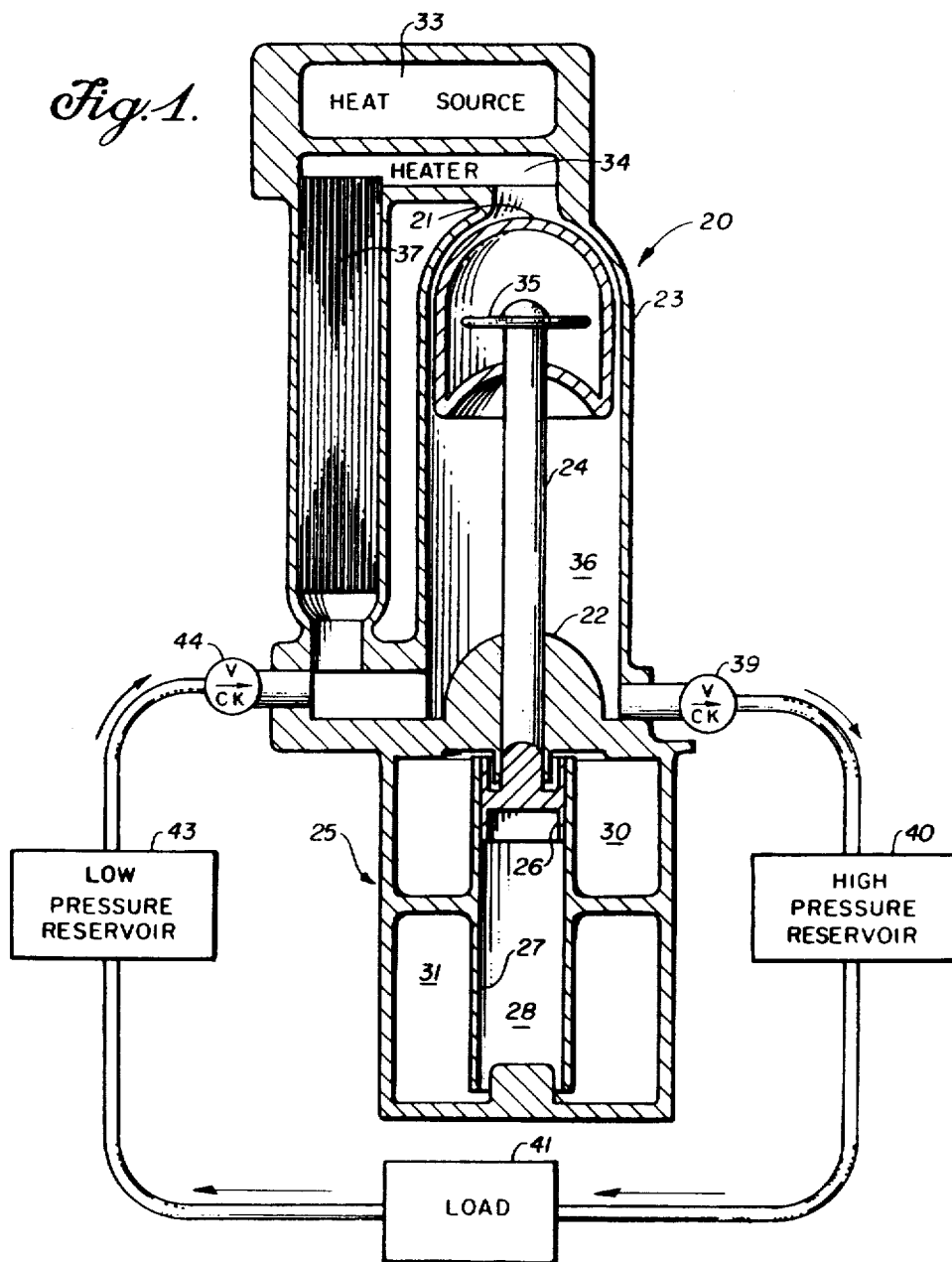
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[57] **ABSTRACT**

A modified Stirling cycle engine operable as a compressor and having its displacer piston directly connected to a reversing piston to which high and low pressures are alternately applied at opposite ends for reciprocally driving the pistons. In one embodiment, the reversing piston is mounted in a double acting compression cylinder which acts as an oscillating spring to drive the pistons whereby energy to sustain oscillation of the reversing piston within the compression cylinder is supplied directly from the displacer piston. In another embodiment, the pistons are driven by high and low pressure gases alternately applied from respective reservoirs to opposite sides of the reversing piston through valves operated by the reversing piston. The modified Stirling cycle engine is capable of unattended operation over a period of years in an inaccessible location and therefore, is especially well suited for supplying motive power for an artificial heart pumping system.

2 Claims, 8 Drawing Figures





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Fig. 2.

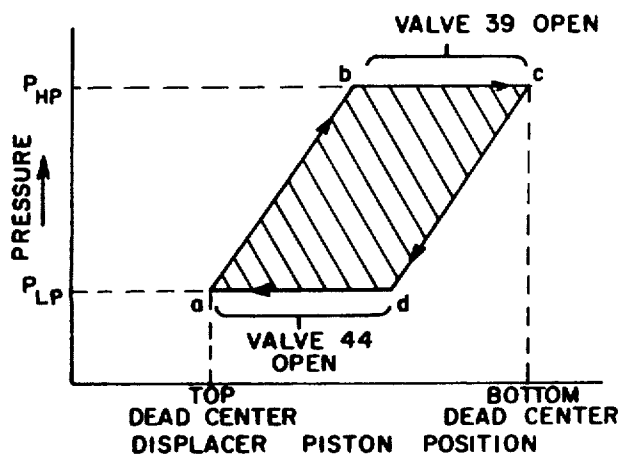


Fig. 3.

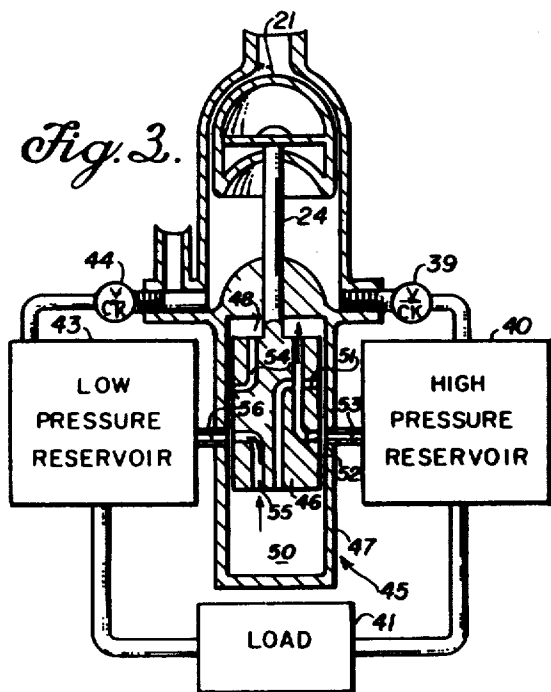
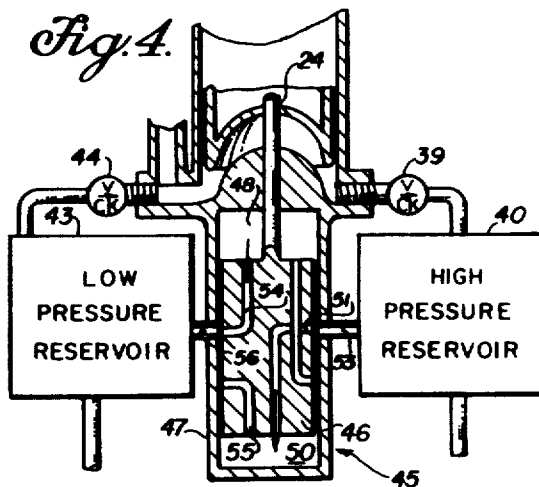
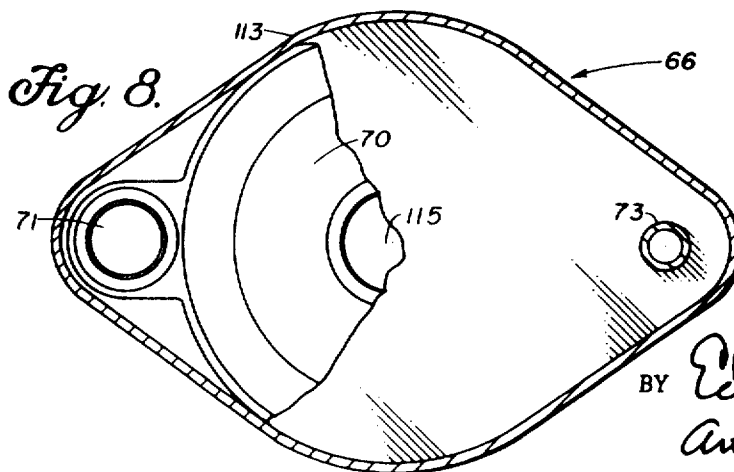
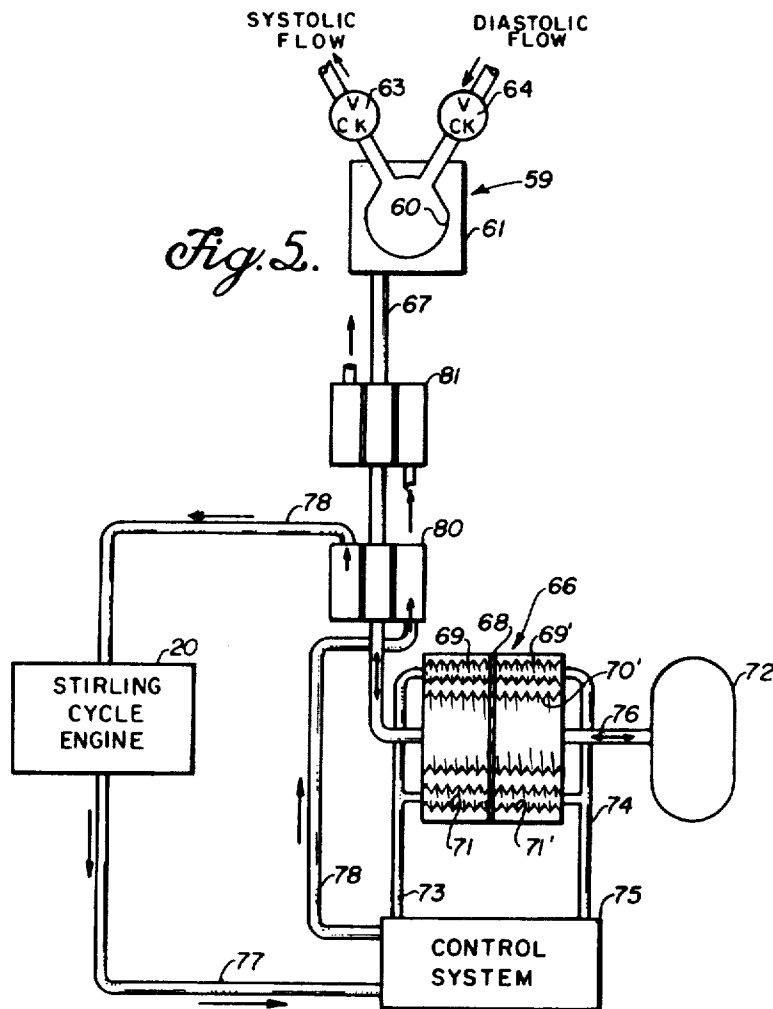


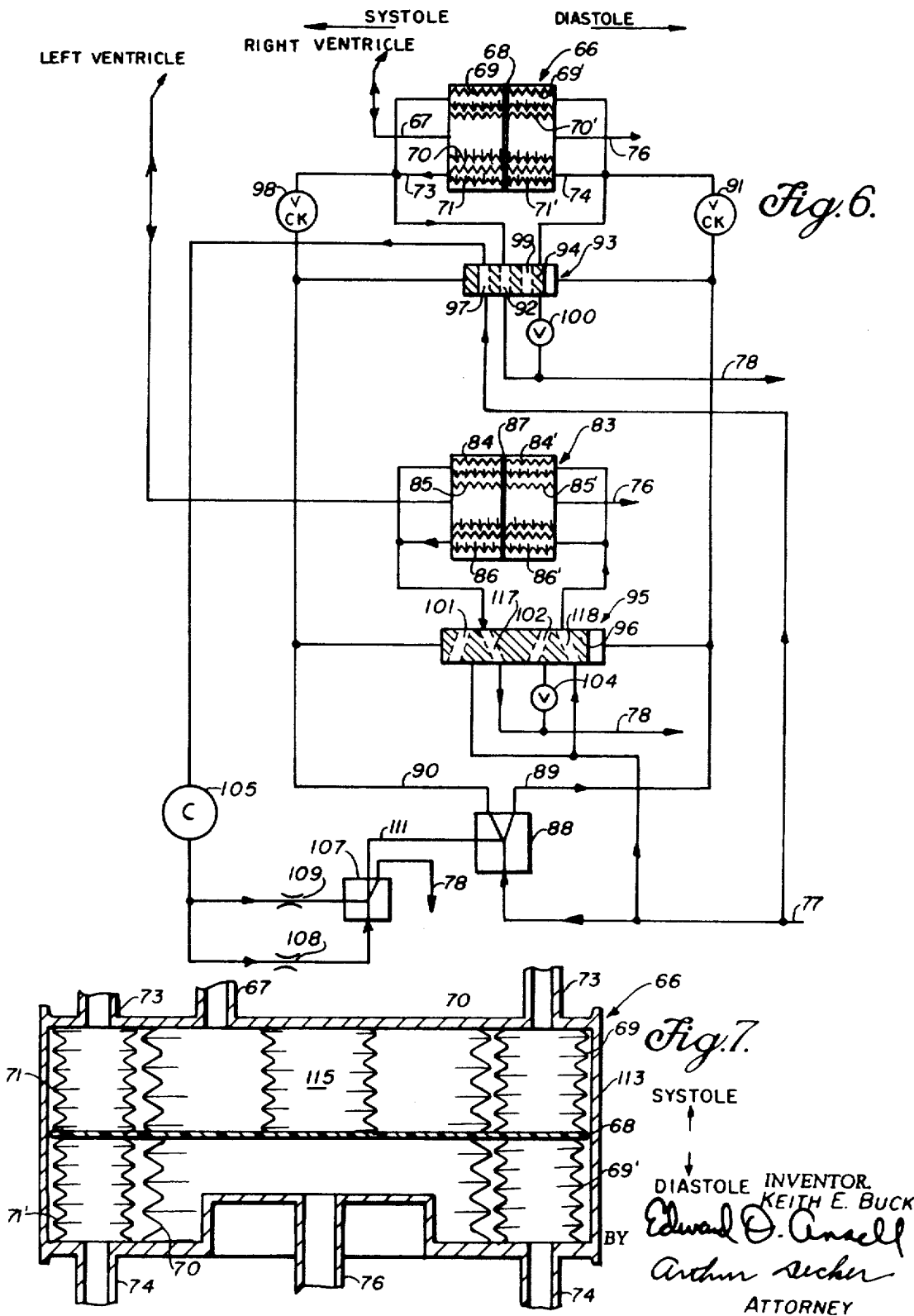
Fig. 4.



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MODIFIED STIRLING CYCLE ENGINE-COMPRESSOR HAVING A FREELY RECIPROCABLE DISPLACER PISTON

This is a division of application Ser. No. 744,204, filed July 11, 1968, now U.S. Pat. No. 3,597,766.

BACKGROUND OF THE INVENTION

The present invention relates to Stirling cycle engines, and more particularly, the invention pertains to a modified Stirling cycle engine having a freely reciprocable displacer piston.

Characteristic of conventional engines and compressors is the requirement that there be a number of rotating, load-bearing, lubricated parts. Commonly, such machines are accessible for lubrication, repair and servicing, and it is not required that they be operated unattended over a period of years. However, it is required in some systems, for example, in an implantable heart system or in an outer space life support system, that a device for supplying motive power be operated continuously over a period of years in an inaccessible location without benefit of servicing or repair. Conventional engines and compressors are found to be unsatisfactory for use in these systems; the relatively large number of parts of conventional engines and compressors increases the possibility of a malfunction, while their seals and bearings bear relatively high loads, are subject to wear and require lubrication.

SUMMARY OF THE INVENTION

In brief, the present invention pertains to a Stirling cycle engine operable as a compressor. The engine is provided with a single main moving part that is guided in dry running bearings which are loaded only by the weight of the moving part. More particularly, the invention is a modification of a type of Stirling engine which utilizes a displacer piston for reciprocating a working gas between a hot zone and a cold zone. The hot and cold zones are separated by a regenerator through which the working gas is moved with the displacer piston. When the gas is in the hot zone it is heated and expanded, thereby raising the pressure in both zones to the point that high pressure gas may be extracted from the engine through a valve. During transfer of the gas from the hot zone to the cold zone, heat is transferred to the regenerator to thereby cool and contract the gas and lower the pressure in both hot and cold zones to the point that low pressure gas may be introduced into the system through another valve. When the engine is used in a closed system, the working gas may be recirculated, whereby the high pressure gas is extracted from the engine, applied to a load where it is expanded for operation of the load, and then exhausted from the load at a low pressure suitable for reintroduction into the engine.

The main feature of the invention is the provision of a reversing piston that is integrally connected to the displacer piston with a connecting rod. Kinetic energy is extracted from the engine and differentially and alternately applied to opposite ends of the reversing piston for reciprocating the reversing piston and displacer piston without resort to rotating mechanism or high load seals and bearings. In one embodiment, the energy may be differentially applied to the reversing piston with opposing oscillative springs, such as coil springs, magnetic springs or compressible gas mass springs, acting on opposite ends of the reversing piston. Energy to sustain spring oscillations is supplied to the springs through the connecting rod and the reversing piston by the expanding engine working gas acting on an area of the displacer piston equal to the cross-sectional area of the connecting rod where it passes through the engine wall. Alternatively, the pistons may be driven with successive masses of compressed gas whereby high and low pressure working gas is alternately supplied through valves to opposite ends of the reversing piston.

An object of the invention is to provide a Stirling cycle engine in which the number of parts, the wear, and the need for lubrication are minimized.

Another object is to directly drive the displacer piston of a Stirling cycle engine with energy derived from the engine.

Another object is to drive the displacer piston of a Stirling cycle engine with a differentially operated reversing piston that is integral with the displacer piston.

Other objects and advantageous features of the invention will be apparent in a description of a specific embodiment thereof, given by way of example only, to enable one skilled in the art to readily practice the invention, and described hereinafter with reference to the accompanying drawing.

BRIEF DESCRIPTION OF THE DRAWING

FIG. 1 is a diagram partially in cross section of a modified Stirling cycle engine according to the invention.

FIG. 2 is a graph showing cylinder pressure as a function of position of the displacer piston of the Stirling cycle engine shown in FIG. 1.

FIG. 3 is a diagram partially in cross section of a second embodiment of the invention showing a reversing piston in a first position.

FIG. 4 is a diagram partially in cross section of the embodiment of FIG. 3 showing the reversing piston in a second position.

FIG. 5 is a schematic diagram of a portion of an artificial heart pumping system that is driven with a modified Stirling cycle engine such as shown in FIGS. 1 or 3.

FIG. 6 is a schematic diagram of a control system for the artificial heart pumping system of FIG. 5.

FIG. 7 is a cross-sectional diagram of a bellows used in the artificial heart pumping system shown in FIGS. 5 and 6.

FIG. 8 is a top view of the bellows of FIG. 7 with portions broken away.

DESCRIPTION OF AN EMBODIMENT

Referring to the drawing, there is shown in FIG. 1 a modified Stirling cycle engine 20 having a displacer piston 21 mounted for reciprocation within a displacer cylinder 23. A connecting rod 24 has one end integrally connected to the piston 21, while the other end extends through a bearing 22 for cooperation with a spring system 25 which is used to oscillate the piston 21 within the cylinder 23. Interaction between the spring system 25 and the piston 21 is by means of a reversing piston 26 mounted on the lower end of the connecting rod 24. The spring system 25 is comprised of a reversing cylinder 27 within which the reversing piston 26 is reciprocated. The cylinder 27 defines a reversing chamber 28, the upper portion of which connects with an upper compression chamber 30, while the lower portion connects with a lower compression chamber 31. Heat is continuously supplied to the engine 20 by means of a heat source 33 which may conveniently be a radioisotope such as plutonium-238. The entire engine 20 including the heat source 33 may be encapsulated in a tungsten alloy radioactivity shield which is provided with an outer polyethylene shield to reduce the surface neutron dose. Heat is transferred from the source 33 to a heating chamber 34 for heating a working gas that fills the chamber 34 and the entire interior space of the engine 20. Helium has been found to be a suitable working gas.

For purposes of explanation, the interior of the engine 20 may be referred to as being divided into a hot zone and a cold zone. The hot zone includes the heating chamber 34 and the space and walls adjacent thereto, in particular the upper portion of the cylinder 23. The cold zone includes a space 36 in the lower part of the cylinder 23, all connecting passages thereto and adjacent engine walls. The hot and cold zones are separated with a regenerator 37 which acts as a heat sink and permits free flow of the working gas between the hot and cold zones. It should present a large surface area to the gas for efficient transfer of heat between the regenerator and the gas. The regenerator could be comprised of a stack of steel wool, or alternatively, it could be comprised of a bundle of thin metal straws that provide many small vertical gas passages. The displacer piston 21 also separates the hot and cold zones and should be fabricated of light gauge material having a low

thermal conductivity to provide a small mass and to limit heat transfer between the two zones. Thermal radiation from one end of the piston to the other may be limited by means of a radiation baffle such as 35. The walls of the displacer cylinder 23, as well as other portions of the engine, should also be made of material having a low thermal conductivity to limit heat loss by conduction from the engine.

The engine 20 is suitable for supplying a load 41 with successive compressed masses of the working gas. High pressure working gas may be extracted from the engine 20 through a check valve 39 and then accumulated in a high pressure reservoir 40 from which a continuous supply of high pressure working gas may be applied to the load. Energy transfer from the gas to the load causes a reduction in gas pressure. The gas is then exhausted to a low pressure reservoir 43 from which a continuous supply of low pressure gas is available for reintroduction into the engine 20 through a check valve 44.

The gas within the chamber 28 and the connecting chambers 30 and 31 is made to be equal to the mean pressure of the working gas in the interior space of the engine 20 when the piston 26 is centralized in the chamber 28. Upon application of heat to the chamber 34 by means of the source 33, the mass of working gas in the hot zone is raised in temperature, causing a corresponding rise in pressure. Since the hot and cold zones are separated through open passages in the regenerator 37, the pressures in both hot and cold zones are always virtually equal. Consequently, as the pressure is raised in the hot zone, the pressure of all of the working gas within the engine 20 is raised. Continued heating of the working gas will cause the pressure to rise above the mean pressure maintained within the chamber 31 and the lower part of the chamber 28. The rise in pressure of the working gas acts on an area of the displacer piston 21 that is equal to the small cross-sectional area of the connecting rod 24 where it extends through the bearing 22. As the pressure of the working gas rises above the mean pressure, a downward force is exerted on the displacer piston 21, driving it and the reversing piston 26 downward, compressing the gas within the chamber 31. The pressure of the working gas continues to rise until it is equal to the pressure within the high pressure reservoir 40, at which point the check valve 39 opens for transfer of working gas to the high pressure reservoir 40. There will, therefore, be no further rise in engine pressure. The compressed gas in the chambers 28 and 31 results in a force acting upward on the reversing piston 26 that becomes greater than the force acting downward. The displacer piston 21 is driven upward thereby, causing the large mass of working gas in the hot zone to be transferred through the regenerator 37 to the cold zone. As the hot gas is moved through the regenerator, heat is transferred from the gas to the regenerator. Thus, the gas moved into the space 36 has been cooled by its passage through the regenerator. Since the greatest mass of working gas is now in the cold zone and is at a reduced temperature, the pressure of all of the working gas is correspondingly reduced according to the ratio $P_2/P_1 = T_2/T_1$, typical of a constant volume process. A reduction in the pressure of the working gas to a point slightly below that in the low pressure reservoir 43 causes the check valve 44 to open for reintroduction of working gas from the reservoir 43 to the cold zone of the engine 20. Movement of the displacer piston 21 to top dead center is aided by the kinetic energy imparted to the pistons 21 and 26 by the previously compressed gas in the chambers 31 and 28. The upward movement of the reversing piston 26 causes the gas in the chamber 30 to compress so that upon the displacer piston reaching top dead center a force is applied to the reversing piston 26 from the compressed gas in the chamber 30, driving the reversing piston, and therefore the displacer piston, downward. This downward movement again transfers working gas from the cold zone through the regenerator 37 to the hot zone. As the gas moves into the hot zone it picks up heat from the regenerator and is further heated by the radioisotope source. A large mass of gas is heated thereby, causing a corresponding rise in pressure of all the working gas. The rise in pressure of the

working gas acts on the small area of the displacer piston 21 equal to the cross-sectional area of the portion of the connecting rod that passes through the bearing 22. The force acting through the displacer piston plus the force due to the compressed gas in the chamber 30 drives the reversing piston 26 and displacer piston 21 downward. The forces acting downward, including the kinetic energy imparted to the displacer piston 21, the connecting rod 24 and the reversing piston 26, carry the piston 26 to bottom dead center, compressing the gas in the chamber 31. Upon a rise in pressure of the working gas to that in the high pressure reservoir, the working gas is extracted through the check valve 39 and the cycle is continued in the manner described hereinbefore.

It will be observed that the alternate compression and expansion of gas in the chambers 30 and 31 constitutes an oscillating spring for reciprocating the displacer piston 21. These oscillations are sustained with energy supplied by the displacer piston on its downward stroke to make up for frictional fluid and mechanical losses. The energy for driving the displacer piston downward is derived from the expansion of engine working gas into the increased engine space resulting from movement of the connecting rod from the interior of the engine. During this period the working gas has a high average pressure. During the upward stroke of the displacer piston, the working gas has a low average pressure. Thus, the driving energy during the downward stroke is greater than the energy returned to the displacer piston during the upward stroke, the difference being available to drive the piston.

A more precise description of the operation of the engine 20 may be had by reference to FIG. 2 which is a graph of pressure as a function of displacer piston position. The displacer piston 21 is shown in FIG. 1 in its top dead center position which corresponds to point a in FIG. 2. At this point, the valves 39 and 44 are closed. From point a the displacer piston is driven toward bottom dead center by the force of the compressed gas in the chamber 30 and by the increasing pressure in the interior of the engine resulting from increased gas temperature. Upon the displacer piston 21 reaching its centralized position corresponding to point b in FIG. 2, a sufficient mass of gas will have been transferred to the hot zone to cause a rise in pressure that opens the valve 39. From point b to the end of the downward stroke, gas is transferred from the engine to the high pressure reservoir 40. The velocity of the piston is reduced by the increasing pressure in chamber 31 until the piston is stopped at bottom dead center, point c. From this point, the piston is moved upward, initially by the force of the compressed gas in the chamber 31 and also by the decreasing pressure in the interior of the engine resulting from decreased gas temperature. Upon the displacer piston 21 reaching its centralized position corresponding to point d in FIG. 2, a sufficient mass of gas will have been transferred to the cold zone to cause a pressure decrease that opens valve 44. For the remainder of the upward stroke gas is transferred from the low pressure reservoir to the engine.

It will be appreciated from the description of the engine 20 that the displacer piston 21, the connecting rod 24, and the reversing piston 26 constitute a single integral part, and that this part is guided by bearing surfaces which can experience a load no greater than the weight of the part. The bearings, therefore, may be dry running and they will experience little or no wear over extended periods. High performance seals are not required since the chambers 30 and 31 are operated around the mean engine pressure and any leakage will be balanced. It will be further appreciated that the single moving part is self-reversing without the aid of other moving mechanism such as cranks or wheels which would require lubrication and are subject to higher loads and a higher degree of wear.

A second embodiment of the invention is shown in FIG. 3 in which the spring system 25 of FIG. 1 is replaced with a displacer piston reversing arrangement 45 that is directly actuated with high pressure working gas alternately applied to opposite sides of a reversing piston 46. The reversing piston 46 is

integrally connected to the connecting rod 24 and is mounted for reciprocation within a reversing cylinder 47. The interior of the cylinder 47 is separated by the piston 46 into an upper chamber 48 and a lower chamber 50. The piston 46 is provided with valve passages 51 and 52 for alternate connection with a passage 53 from the high pressure reservoir 40. Thus, during reciprocation of the piston 46, the passages 51 and 52 are alternately and briefly connected to the chambers 50 and 48 respectively to thereby force the reversing piston first in one direction and then the other. To relieve the pressure in the chamber opposite the one to which the high pressure working gas is applied, a pair of valve passages 54 and 55 are provided in the piston 46 for alternate and brief connection through a valve passage 56 to the low pressure reservoir 43.

In operation, with the reversing piston 46 in the position shown in FIG. 3, high pressure working gas is briefly applied through the valve passage 52 to the chamber 48, while the gas within the chamber 50 is exhausted through the passage 55 to the low pressure reservoir. The differential pressures applied to opposite ends of the reversing piston 46 cause the piston 46 and the piston 21 to be driven downward. Upon movement of the piston 46 to the position shown in FIG. 4, the gas in the chamber 48 has been expanded to a pressure slightly above that in the low pressure reservoir 43, and the gas in the chamber 50 has been compressed to a pressure slightly below that in the high pressure reservoir 40. The pressure difference between the two chambers is further increased by brief gas flow from high pressure reservoir 40 to chamber 50 and from chamber 48 to low pressure reservoir 43. Differential pressures are thereby applied to opposite ends of the piston 46 in a direction opposite to those previously applied, thereby exerting a net upward force on the piston 46.

Thus, as with the first embodiment, the displacer piston 21 may be reciprocated by means of the reversing arrangement 45 using a single moving part that may be guided with dry running bearings that are not subject to a load greater than the weight of the part. Similarly, there will be little wear, no high performance seals or bearings are required, and no additional moving mechanism is required.

For the reasons discussed, the engines shown in FIG. 1 and FIG. 3 are susceptible of unattended operation over extended periods. A particular application of this type of engine is to transduce heat energy to a compressed working gas for operation of a heart pumping system. A heart pumping system for one artificial ventricle 59 is shown in FIG. 5. The ventricle 59 is comprised of a flexible sac 60 mounted within a semi-rigid case 61. The space between the sac 60 and case 61 and the connecting passage thereto is filled with a pumping fluid, preferably a liquid having the heat transfer characteristics and viscosity of water but which is a nonpolar fluid in order to minimize any reaction between the components of the blood and the pumping fluid which may result from permeation of the blood components through the thin flexible sac 60. Liquid fluorocarbons or silicones have the characteristics desired for the pumping fluid. The pumping fluid between the sac and the case is alternately pumped into the space and removed therefrom to cause rhythmic contraction and expansion of the sac 60. During expansion of the sac 60 there is a diastolic blood flow through a check valve 64 into the sac, while during contraction of the sac, blood is forced through the check valve 63 for systolic blood flow.

Reciprocation of the pumping fluid to cause rhythmic contraction and expansion of the sac 60 is by means of a pumping chamber 66 that is connected to the case 61 through a line 67. The chamber 66 is comprised of a movable plate 68 to which three sets of bellows 69 and 69', 70 and 70', and 70 and 71' are attached. The bellows 70 receives the pumping fluid through line 67, while the bellows 70' is directly opposite the bellows 70 and is filled with a fluid which is maintained at ambient atmospheric pressure at all times. This pressure is maintained in the bellows 70' by means of a flexible sac 72 which may be surgically located in the pleural cavity so as to be exposed to ambient atmospheric pressure at all times. The at-

mospheric pressure in the bellows 70' is used in a manner more fully described hereinafter, as a reference for the pumping fluid in the bellows 70 so that diastolic blood flow is at a pressure substantially equal to atmospheric pressure. Since the veins are easily collapsed, any venous pressure less than atmospheric could cause collapse of the veins with consequent blocking of diastolic blood flow.

The pumping chamber 66 is actuated with high pressure working gas from the engine 20 under control of a control system 75. The bellows 69 and 71 are commonly connected over a line 73 to the control system, while the bellows 69' and 71' are commonly connected over the line 74 to the system 75. High pressure working gas from the engine 20 is applied to the system 75 over a high pressure line 77, which line also constitutes a high pressure reservoir, while working gas is returned to the engine 20 from the system 75 over a low pressure line 78, which constitutes a low pressure reservoir. The control system 75 is operable for alternately connecting the lines 73 and 74 to the high and low pressure lines 77 and 78 at a rate equal to the natural pulse rate. Differential pressures are thereby applied to the plate 68 through the bellows 69 and 69', and the bellows 71 and 71' to cause the plate to reciprocate leftwards and rightwards. This causes the pumping fluid in the bellows 70 to be reciprocated through the line 67 to actuate the artificial ventricle 59.

Excessive heat may be removed from the working gas by transferring it to the blood stream. However, care must be taken not to overheat the blood and thereby raise the temperature of the recipient body above normal levels. This may be avoided by first transferring heat from the working gas to the pumping fluid in the line 67 by means of a heat exchanger 80 serially connected in the low pressure line 78. The pumping fluid preferably is a liquid having a heat capacity and mass flow rate that is much higher than that of the working gas. Thus, the temperature rise of the pumping fluid due to the excessive heat in the working gas is only a fraction of a degree as opposed to the relatively high temperature in the line 78. The heat added to the pumping fluid is distributed to the blood circulating system in two ways. One is by means of the heat exchanger 81 serially connected with the line 67 with its input connected to the line 67 and its output serially connected with the circulatory system, for example, with an aortic bypass. The heat in the pumping fluid is also transferred to the blood directly through the walls of the sac 60.

It is believed to be highly desirable that an artificial heart pump should have a stroke profile and pulse rate similar to those of the natural heart in order to accommodate the dynamic changes in vascular impedance. This requires that an artificial heart be capable of pulsatile flow and be operable for varying the duration of systole and diastole, as well as heart rate and stroke volume, as required by the changing needs of the vascular system. A control system to accomplish these objectives is shown in FIG. 6 which is a diagram of portions of FIG. 5 and further including detailed controls and pumping means for actuating both left and right ventricles of an artificial heart.

The pumping chamber 66, described with reference to FIG. 5 previously, is shown in FIG. 6 for supplying the pumping fluid to an artificial right ventricle, while a second pumping chamber 83 is shown for supplying the pumping fluid to an artificial left ventricle. The pumping chamber 83 is comprised of three sets of bellows 84 and 84', 85 and 85', and 86 and 86' with the bellows of each set symmetrically arranged on opposite sides of a movable plate 87. The chamber 83 operates in the same manner as the pumping chamber 66 described hereinbefore. A prime objective of the control system is to simultaneously actuate the pumping chambers 66 and 83 to effect synchronous systolic and diastolic cycles simultaneously in the artificial right and left ventricles. This is accomplished by means of a conventional bistable fluidic amplifier used as a fluid switch and indicated in FIG. 6 as switch 88 with its input connected to the high pressure working gas line 77. The high pressure working gas is transferred through the switch to one

or the other of a pair of output lines 89 and 90. Flow through either one of the outputs is stable until output flow is blocked at which time output flow from the switch is transferred to the opposite output line.

During a systolic cycle, output of the switch 88 will be into the line 89 which is directly connected through a check valve 91 to the bellows 69' and 71' of the pumping chamber 66. The line 89 is also connected to an input of a spool valve 93 so as to drive a movable valve element 94 leftward to the position shown in FIG. 6. With the element 94 in the position shown, a valve passage 92 in the element connects the bellows 69 and 71 through the line 73 to the low pressure working gas line 78. Thus, high pressure working gas is applied to the bellows 69' and 71', while the bellows 69 and 71 are connected to the low pressure line 78. The differential pressure forces thereby applied to the plate 68 cause it to be moved leftward to carry out a systolic cycle. Similar but larger, differential pressure forces are applied to the plate 87 to effect systolic actuation of the artificial left ventricle simultaneous with actuation of the right ventricle by means of a spool valve 95 having a movable valve element 96. The output line 89 is connected to an input of the valve 95 such that upon application of the output of the switch 88 to the line 89, the movable element 96 is driven leftward to the position shown in the FIG. 6. With the element 96 in this position, the low pressure line 78 is connected through a valve passage 117 directly to the bellows 84 and 86, while the high pressure line 77 is connected directly to the bellows 84' and 86' through a valve passage 118. The differential pressure forces thereby applied to the movable plate 87 drive it leftward to carry out a systolic cycle simultaneous with actuation of the plate 68. Upon movement leftward of the plate 68 to the limit of its travel, the gas in the line 89 can no longer expand in the bellows 69' and 71', thereby causing a high pressure to be built up in the line 89. This causes the output of the switch 88 to become unstable and to switch to the line 90. The line 90 is connected to an input of each of the valves 93 and 95 such as to drive the movable elements 94 and 96 fully rightward. The high pressure in the line 90 is also connected through a check valve 98 to the bellows 69 and 71, while the bellows 69' and 71' are connected through a valve passage 99 and a throttle valve 100 to the low pressure line 78. The differential pressure forces thereby applied to the plate 68 drive it rightward to actuate the artificial right ventricle to carry out a diastolic cycle. A diastolic cycle is simultaneously carried out with respect to the artificial left ventricle by means of the pumping chamber 83 whereby the movable plate 87 is driven rightward by differential pressure forces applied thereto. The high pressure line 77 is connected directly to the bellows 84 and 86 through a valve passage 101 in the element 96, while the bellows 84' and 86' are connected to the low pressure line 78 through a valve passage 102 and a throttle valve 104. The diastolic cycle is continued until the movable plate 68 reaches its end-of-travel at which time a higher pressure is built up in the line 90 causing the output of the switch 88 to switch to the line 89 to initiate a systolic cycle. Systole and diastole are thereby rhythmically and synchronously accomplished with the described system.

In order to increase or decrease blood pumping rates in response to physiological needs, the pumping chambers 66 and 83 are made responsive during diastole to respective atrial pressures. This is accomplished with the throttle valves 100 and 104 being placed respectively under control of right and left atrial pressures by means of pressure sensors (not shown) surgically attached to the right and left atriums. The rate of diastolic exhaust from the pumping chambers may thereby be made to conform to the current physiological need as exhibited by atrial pressures.

Because of the relaxed condition of the pumping chambers 66 and 83 during diastole, especially during very relaxed bodily activities, it is desirable to ensure initiation of systole after a predetermined period even though the pumping chamber 66 has not completed its diastolic movement. This may be accomplished by applying high pressure working gas from the

line 77, through the spool valve passage 97, to a fluidic capacitor 105 during systole. The capacitor 105 is thereby normally maintained at a high pressure; its output is applied to the main input of a monostable fluidic switch 107 through a restrictor 108; and the output is also applied through a second restrictor 109 to a switching input of the switch. The switch 107 has an unstable output connected to the low pressure line 78 and a stable output connected over a line 111 to a switching input of the switch 88. Under normal conditions, the high pressure gas applied through restrictor 109 to the control input of the switch 107 causes the main input to the switch through the restrictor 108 to be directed to the low pressure line 78. Normally the capacitor 105 has a sufficient capacity to maintain the output of the switch 107 directed to the line 78 throughout each diastolic cycle. However, should the diastolic cycle not be terminated by the end of a predetermined period, the pressure in the capacitor 105 becomes insufficient to maintain the output of the switch 107 directed to the line 78. This causes the output of the switch 107 to be directed over the line 111 to the switching input of the switch 88 to ensure that its output is into the line 89 to initiate systole and thereby maintain the minimum desired pulse rate.

The provision of right and left pumping chambers 66 and 83, in the system described with reference to FIG. 6, is particularly advantageous since such an arrangement permits synchronous pumping of respective right and left artificial ventricles and yet it still permits independent control of the ventricles with respect to blood flow rates. The bellows of the chambers also provide a convenient interface between the gaseous portion of the system and the liquid portion, wherein the gaseous system is preferable for energy transfer from the heat source and for operation of the control portion of the system, while the pumping liquid is preferable for its optimum heat transfer characteristics and as a means for positively actuating the artificial ventricles. The particular bellows arrangement further provides convenient means for maintaining venous pressures substantially at ambient atmospheric pressure during diastole to prevent collapse of the veins as mentioned hereinbefore. The chambers 66 and 83 may be made substantially identical. The chamber 66 is shown in greater detail in cross section in FIG. 7. The chamber 66 includes a housing 113 in which the bellows 69, 70 and 71 are mounted on one side of the plate 68 while the bellows 69', 70' and 71' are mounted on the opposite side. A top view of the pumping chamber 66 is shown in FIG. 8 to better illustrate the relative sizes and positions of the bellows. The housing 113 is filled with a gas having a pressure that is always higher than the internal pressure of any of the bellows in order to prevent bellows squirm. A chamber 115 is centrally located within the bellows 70 and a vacuum atmosphere is provided within the chamber during its manufacture. The chamber 115 is required to provide a reduced area on the plate 68 on which the pressure within the bellows 70 acts as compared with the area on the side of the plate 68 on which the atmospheric reference pressure acts. This arrangement provides a compensating force that counteracts the mean arterial hydrostatic pressure which is transmitted through the pumping fluid to bellows 70. The compensating force causes centering of the plate 68 when the bellows 70 is subjected to mean arterial pressure. This permits the application of equal gas pressure differentials on each side of the plate during systole and diastole. The throttle valve control system 100 ensures that no significant vacuum (suction) is transmitted by the bellows 70 to the corresponding atrium during diastole, and further ensures that the rate of movement of plate 68 is determined by venous pressure. Thus, during diastole, the rate of movement of plate 68 is determined by venous pressure with respect to atmospheric. This corresponds to the natural heart function whereby the ventricles relax during diastole to be filled under venous pressure.

While an embodiment of the invention has been shown and described, further embodiments or combinations of those described herein will be apparent to those skilled in the art without departing from the spirit of the invention or from the scope of the appended claims.

I claim:

1. A Stirling cycle engine for compressing a working gas from a low pressure to a high pressure, and having a hot zone and a cold zone, said Stirling cycle engine comprising:

- a displacer cylinder having opposite end portions respectively disposed in the hot and cold zones,
- a source of thermal energy operably associated with the end portion of said displacer cylinder disposed in the hot zone for heating the working gas in the hot zone,
- a regenerator having opposite ends respectively extending into the opposite end portions of said displacer cylinder within the hot and cold zones,
- a displacer piston mounted for reciprocation in said displacer cylinder to transfer the working gas between said zones through said regenerator,
- a reversing piston,
- a connecting rod extending between said displacer piston and said reversing piston and having its opposite ends respectively secured thereto,

means for alternately applying forces at the opposite ends of said reversing piston to effect reciprocation of said reversing piston and said displacer piston,

respective high and low pressure reservoirs of working gas maintained at said high and low pressures,

means separately connecting each of said high and low pressure reservoirs to said displacer cylinder at the end portion thereof disposed in the cold zone,

a first valve means in said means connecting said high pressure reservoir to said displacer cylinder,

a second valve means in said means connecting said low pressure reservoir to said displacer cylinder,

said displacer piston being positioned in the end portion of said displacer cylinder disposed in the hot zone at the beginning of its stroke and said first and second valve means being closed to prevent communication between the end portion of said displacer cylinder disposed in the cold zone and said high and low pressure reservoirs respectively,

said first valve means opening in response to the movement of said displacer piston toward the end portion of said displacer cylinder disposed in the cold zone increasing the pressure of the working gas in said displacer cylinder to a magnitude at least equal to the pressure of the working gas in the high pressure reservoir for admitting working gas into the high pressure reservoir from said displacer cylinder until the end of the displacer piston stroke,

said displacer piston in its return stroke moving toward the

end portion of said displacer cylinder disposed in the hot zone so as to decrease the pressure of the working gas in said displacer cylinder closing said first valve means, and said second valve means opening in response to the continued movement of said displacer piston in its return stroke decreasing the pressure of the working gas in said displacer cylinder to a magnitude no greater than the pressure of the working gas in the low pressure reservoir for drawing working gas from said low pressure reservoir into said displacer cylinder,

whereby the working gas is pumped from said low pressure reservoir to said high pressure reservoir which serves as a source of high pressure gas for doing work.

2. In a Stirling cycle engine, for compressing a working gas from a low pressure to a high pressure, and having a hot zone and a cold zone, the combination of:

- a regenerator having ends that extend into said hot and cold zones;
- a displacer cylinder having first and second ends extending respectively into said hot and said cold zones;
- a displacer piston mounted for reciprocation in said cylinder to transfer said working gas between said zones through said regenerator;
- energy transfer means including a reversing piston, a connecting rod having first and second ends, said first end being integral with said displacer piston and said second end being integral with said reversing piston;
- reversing means including means for applying high and low pressure gas masses alternately at opposite ends of said reversing piston, for reciprocation of said reversing piston and said displacer piston,
- high and low pressure reservoirs of said working gas maintained respectively at said high and low pressures,
- and wherein said reversing means includes a reversing cylinder in which said reversing piston is mounted for reciprocation, said cylinder having first and second closed ends, said reversing piston having first and second inlet passage means for alternately connecting said high pressure reservoir to said first and second closed ends of said cylinder, said reversing piston having first and second outlet passage means for alternately connecting said first and second closed ends of said cylinder to said low pressure reservoir, the connections of said high pressure reservoir to said closed ends being opposite to the connections of said low pressure reservoir to said closed ends.

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