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OTHER REFERENCES

Final Report: Summary and Conclusions, Artificial Heart Program, The Children's Hospital Medical Center, Boston, Mass., Thermo Electron Engineering Corp., Waltham, Mass. Submitted to National Heart Institute, Bethesda, Md., March 1966, pp. 25-35 (Copy available in Group 335).

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[54] MULTIPLE FUNCTION BLOOD COUPLER

4 Claims, 5 Drawing Figs.

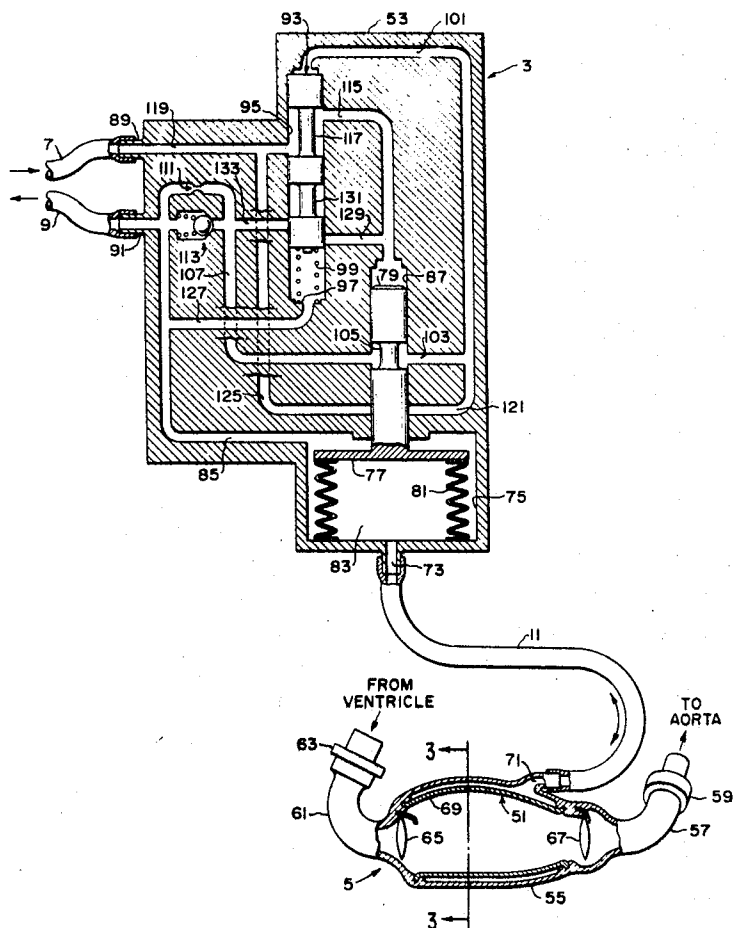
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 128/1, DIG. 3; 60/24, 25; 103/152, 44 D; 417/394

[56] References Cited

UNITED STATES PATENTS

3,379,191	4/1968	Harvey	3/1 X
3,434,162	3/1969	Wolfe	3/1

ABSTRACT: An integrated blood coupler for a totally implantable heart-assist circulatory support system incorporating a diaphragm-type blood pump adapted to be connected between the left ventricle and aorta of the host, in which the pumping energy for the assist pump is produced by an implantable power supply that inherently produces waste heat as a byproduct, wherein the waste heat is discharged to the blood stream through the diaphragm of the blood pump, and in which the diaphragm serves as the physiological sensor for producing pressure signals to synchronize the assist system with the circulatory system of the host.



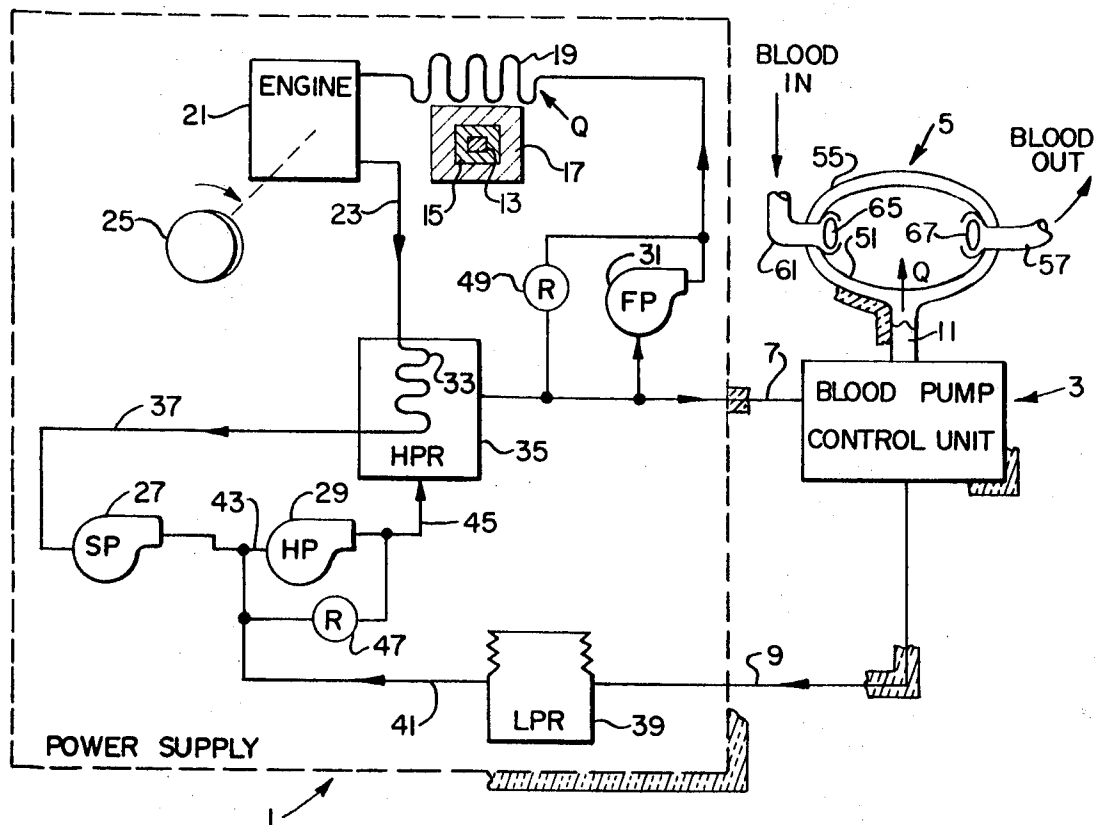
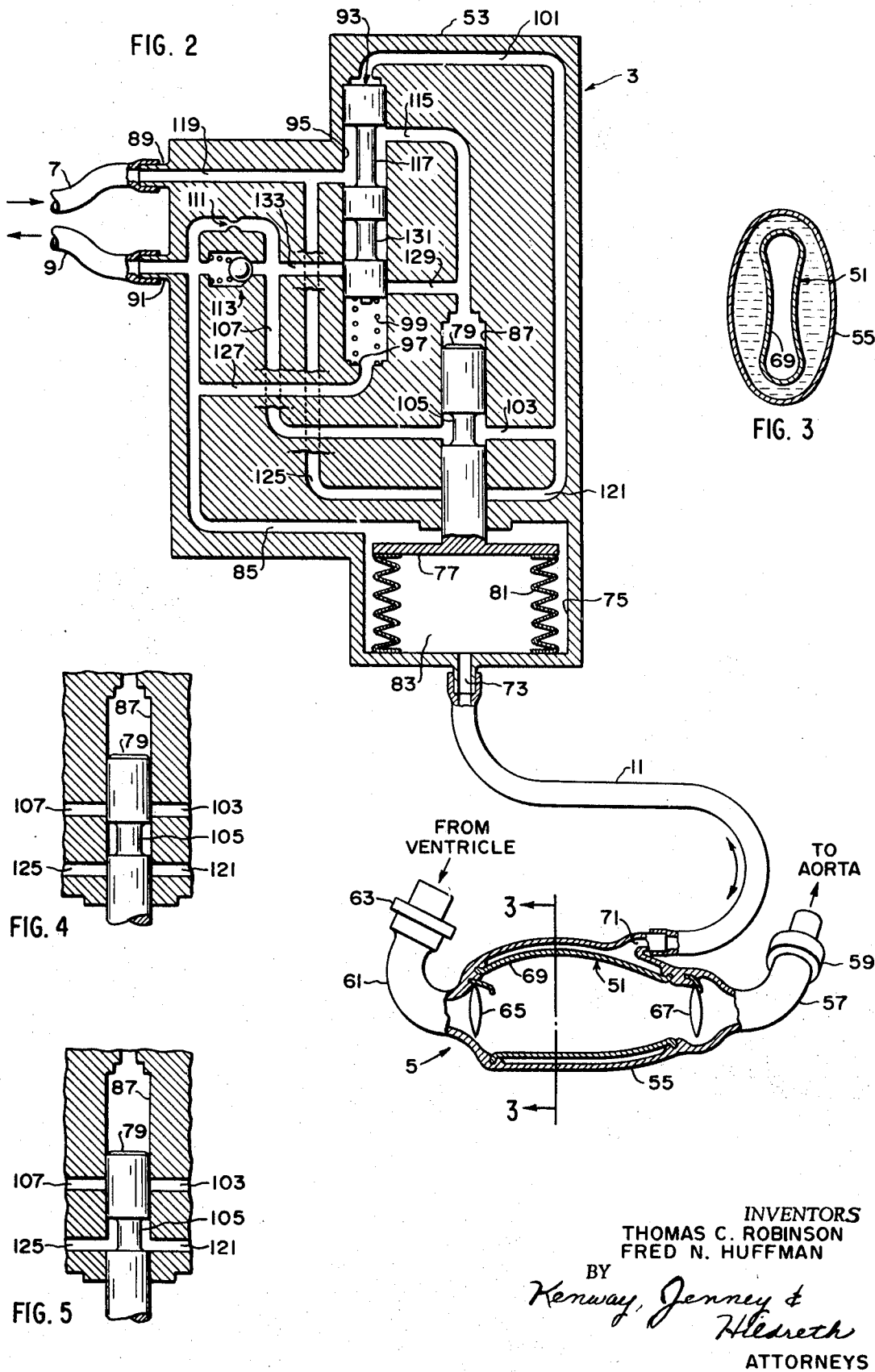


FIG. 1

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MULTIPLE FUNCTION BLOOD COUPLER

Our invention relates to prosthetic devices, and particularly to a novel integrated blood coupler for exchanging heat and mechanical energy with the blood in a heart-assist circulatory system that is totally implantable.

Many traumatic or pathological cardiac conditions can be corrected, or at least compensated for, by providing a pump to supplement the action of the natural heart and assist in maintaining normal blood circulation. One form of heart-assist system that has been proposed comprises a diaphragm-type pump adapted to be implanted in the thoracic cavity and connected between the left ventricle and the descending aorta. The left ventricle is chosen because it performs approximately 83 percent of the work done by the heart on the blood stream.

In order to operate the pump, it has been proposed to supply it with pneumatic or hydraulic energy through transcutaneous connections to an external fluid supply. To synchronize the supply of fluid under pressure to the pump with the natural circulatory system, it has been proposed to connect electrodes to the host to pick up the electrical signals produced by the physiological motor control system. Obviously, while quite useful in many respects, such a system greatly restricts the mobility of the host. And it is impractical to maintain transcutaneous connections to the implanted pump for long periods of time, because of the risk of infection. Accordingly, it would be highly desirable to have a circulatory support system that could be totally implanted in the body of the host and which could be left to function for relatively long periods of time without the need for continual surgical interference. The implantation of such an assist system does not present any insurmountable surgical or prosthetic difficulties in the present state of the medical arts, except that the size and weight of the apparatus is necessarily limited by the space available in the body for implantation without the excision of useful tissue. The apparatus necessarily requires a power supply capable of supplying pumping energy to the pump over a relatively long period of time, and preferably for several years, without regeneration. Control apparatus is required to synchronize the pump with the natural circulatory system. In the operation of the system, waste heat is inherently generated, and it is necessary to dissipate that heat without injury to the body of the host. It is the object of our invention to facilitate the exchange of heat and mechanical energy with an implanted blood pump without transcutaneous connections to external apparatus.

Briefly, the above and other objects of our invention are attained by a novel blood coupler comprising a modified left ventricular assist pump in which the diaphragm is made of thin flexible material with a relatively high heat transfer coefficient, and which is supplied with liquid hydraulic pumping fluid at a temperature somewhat above the temperature of the blood. The hydraulic fluid is cooled by heat exchange through a fixed volume of energy exchange fluid that is in contact with the diaphragm of the pump, and the cooled hydraulic fluid is returned to the power supply. The amount of heat removed in the blood pump is that required to maintain the system in equilibrium, and the amount of mechanical energy supplied to the pump is that sufficient to reduce the ventricular pressure of the host while maintaining a normal supply of blood in dependence on the demands of the host. A basic combination characteristic of our invention is an implantable power supply serving as a source of hydraulic fluid under pressure at elevated temperature, and as a sink of hydraulic fluid at lower pressure, and connected thermally and mechanically to the circulatory system by a blood coupler. The blood coupler comprises a control unit for synchronizing the transfer of mechanical energy to the blood from the power supply with the natural circulatory system, in the process removing both thermal and mechanical energy from the high-pressure fluid, to return low pressure, low temperature fluid to the power supply.

The apparatus of our invention, and its mode of operation, will best be understood in the light of the following detailed description, together with the accompanying drawings, of a preferred embodiment thereof.

In The Drawings,

FIG. 1 is a schematic piping diagram of an implantable heart-assist system incorporating the multiple function blood coupler of our invention;

FIG. 2 is a schematic elevational view, with parts shown in cross section and parts broken away of a blood pump and blood pump control unit forming a part of the apparatus of FIG. 1;

FIG. 3 is a schematic cross sectional elevational view, taken substantially along the lines 3—3 in FIG. 2, showing a typical cross section through the blood pump of FIG. 2; and

FIGS. 4 and 5 are schematic diagrams of a piston and cylinder forming parts of the apparatus of FIG. 2, illustrating their relative position at different points in a cycle of operation.

Referring to FIG. 1, we have shown a heart assist system comprising generally a power supply designated 1, a blood pump control unit 3, and a blood pump 5. In general, the power supply 1 serves to supply hydraulic pumping fluid to the blood pump control unit 3 over a line 7 at high-pressure and elevated temperature, and received low-pressure fluid at a reduced temperature through a hydraulic connecting line 9. The blood pump control unit 3 acts in response to signals received from the blood pump 5, in a manner to appear, to supply hydraulic pumping fluid, under a pressure below that in the line 7, to the blood pump through a conduit 11, and to receive the hydraulic fluid from the blood pump under a somewhat lower pressure in response to the action of the natural ventricle.

The power supply 1 is described in more detail in U.S. Pat. No. 3,536,423, issued Oct. 27, 1970, on an application filed concurrently with the present application by Thomas C. Robinson for Dual Fluid Circulatory Support System and assigned to the assignee of our invention. For the purposes of our invention, it may comprise any suitable source of, and sink for, pumping fluid, in which the source fluid is under pressure, and has an elevated temperature by reason of carrying from the power supply the waste heat generated in the process of raising the pressure of the return fluid in the line 9 to the desired pressure for the line 7.

Since it is preferred to implant it in the body of the host, the power supply is necessarily required to be highly efficient and to be capable of producing the required hydraulic power output over a long period of time. Specifically, a hydraulic power output of between 5 and 20 watts for a period of at least a year, and preferably several years, is desired. The primary energy source for the power supply may be a rechargeable electrical device, but is preferably a radioactive isotope such as plutonium 238 nitride. Such a source is shown schematically at 13. Surrounding the radioactive isotope 13 is shielding material 15 that may be of 6-millimeter thick tantalum having an initial impurity of 1 part per million of plutonium 236. That amount of shielding is sufficient to keep the gamma dose rate equal to or less than the neutron dose rate for a period of 5 years.

Surrounding the shielded radioisotope 13 is a container of thermal energy storage material 17 that preferably comprises a two-phase constant temperature mixture of the eutectic composition of lithium chloride and lithium fluoride that melts at 930° F. In operation, that material adjusts its relative concentration of solid and liquid phases to maintain a constant temperature supply of heat to a boiler schematically indicated at 19. The boiler 19 serves to raise a thermodynamic working fluid, preferably the same fluid in the lines 7 and 9, and most preferably water, to a suitable temperature and pressure for operating a steam engine. For example, the temperature may be 900° F, and the pressure may be 800 p.s.i.a.

Working fluid under pressure from the boiler 19 is supplied to the intake manifold of a conventional steam engine 21. The

engine is preferably of the single cylinder type shown and described in the above copending application of Thomas C. Robinson in which a slug of fluid is admitted at the beginning of the power stroke, and is exhausted to a line 23 at the end of each power stroke. The engine preferably drives a fly wheel 25, a sump pump 27, a hydraulic pump 29, and a feedwater pump 31, for purposes to be described.

Exhaust working fluid from the engine 21 is transmitted over a line 23 to a condenser 33 located in a high-pressure reservoir 35 to be cooled and condensed by the liquid in the high-pressure reservoir. Condensate at a low pressure of, for example, 2.9 p.s.i.a. is transmitted from the condenser over a line 37 to the inlet of the sump pump 27.

The outlet of the sump pump 27 is connected to a low-pressure reservoir 39 over a line 41. The sump pump 27 is also connected over a line 43 to the inlet of the hydraulic pump 29. The pressure at the outlet of the sump pump 27 may be, for example, 15 p.s.i.a. Since the pressure at the inlet of the sump pump 27 is the lowest in the closed fluid cycle, net flow of leakage water, that accomplishes the function of lubricating the moving parts in the system, is to the inlet side of the sump pump.

The hydraulic pump 29 raises the pressure of the fluid in the low-pressure reservoir to approximately 80 p.s.i.a. and supplies it to the high-pressure reservoir 35 at that pressure over a line 45. A relief valve 47 is connected across the hydraulic pump 29 to ensure that the pressure in the high-pressure reservoir does not exceed the desired value.

The feedwater pump 31 raises the pressure of the fluid in the high-pressure reservoir from 80 p.s.i.a. to approximately 400 p.s.i.a. for admission to the boiler 19. Stalling of the engine 21 is prevented by a relief valve 49 connected across the feedwater pump 31.

The low-pressure reservoir 39 is expansible, as schematically indicated, to fluctuate in volume with the variations in demand for pumping fluid as dictated by the demands upon the assist system by the host. It will also be regulated in accordance with the demand on the engine to maintain system stability, in a manner that will next be described.

As will appear, the blood pump control unit 3 will demand more or less high-pressure fluid through the line 7, in dependence on the demands of the host for a larger blood supply, as when exercising, or for a smaller blood supply, as when at rest. That variation in demand will cause changes in the pressure in the high-pressure reservoir 35.

The pressure in the reservoir 35 will determine the work done by the hydraulic pump 29. Since the boiler temperature and pressure are constant, because of the constant temperature of the thermal energy storage material 17, the engine 21 will do a constant amount of work per stroke. Thus, the engine will adjust its speed to the demand by varying the speed of the flywheel 25, dividing the energy produced per stroke between the flywheel and the hydraulic pump 29.

When the host demands more pumping fluid, and therefore reduces the pressure in the high-pressure reservoir 35, the engine will speed up to increase the speed of the pump 29, causing the pressure in the reservoir 35 to be increased. When the pressure in the reservoir 35 rises, the larger amount of energy demanded by the pump 29 will cause the flywheel to slow down, thus lowering the pressure in the reservoir 35. The engine 21 thus acts as a load responsive coupling between the heat supply to the boiler 19 and the mechanical energy supplied to the blood pump control unit 3 over the line 7.

As noted above, the engine 21 also drives the sump pump 27 and the feedwater pump 31. However, because the flow through those pumps is only that needed to maintain the necessary rate of flow of working fluid to the engine 21, it is considerably smaller than the flow through the hydraulic pump 29. For example, in practice, the flow through the hydraulic pump 29 may be approximately 5,000 times the flow through the pumps 27 and 31. Thus, the work required of the hydraulic pump 29 is the primary factor governing the speed of the engine 21.

In its relation to the blood pump control unit 3, the power supply 1 simply comprises a source of fluid under pressure in the line 7 at an elevated temperature, and a sink of fluid at a lower pressure, with reduced temperature, in the line 9. As indicated in FIG. 1, all of the parts of the power supply just described form a sealed system located within a sealed, evacuated, insulated housing and connected to the blood pump control unit over insulating hydraulic lines so that no excessive heat transfer takes place between those components and the body of the host.

As will be described, the blood pump control unit 3 transfers heat and mechanical energy from the power supply to the blood pump 5. The amount of heat transferred is that sufficient to maintain the system in equilibrium, and the amount of mechanical energy is that determined by the demands of the host as communicated to the physiological control system. As will appear, both heat and mechanical energy are exchanged through an intermediate fixed volume of energy exchange fluid and thence across the fluid boundary established by a thin flexible bladder 51 between the blood and the pumping fluid in the blood pump 5.

Referring now to FIGS. 2 and 3, the blood pump control unit 3 and the blood pump 5 will next be described.

The control unit 3 comprises a housing generally designated 53, of metal such as stainless steel or the like, divided and connected together in any convenient way, not shown, to facilitate assembly, and including the moving parts and passages which together function to control the supply of pumping energy to the blood pump. As shown, the blood pump 5 is interconnected with the blood pump control unit by a flexible tube 11 of any suitable conventional synthetic resin or the like. The exterior surfaces of all parts, including the power supply 1, the lines 7 and 9, the blood pump control unit 3, the hydraulic line 11, and the blood pump 5, are preferably coated with a surface which encourages tissue ingrowth, as by flocking with a relatively matted coat of Dacron fibers or the like in a manner known in the art per se. In addition to this outer coating, an intermediate layer of thermal insulation, such as a layer of silicone rubber, not shown, is preferably provided to prevent heat transfer to the host except through the blood pump in the manner to be described.

The blood pump 5 comprises an outer housing 55 of stainless steel or the like, covered as just described and provided with an outlet passage 57 adapted to be grafted to the aorta of the host by a suitable conventional graft connection 59. An inlet passage 61 is adapted to be secured to the left ventricle by means of a conventional suture ring 63. The pump is provided with an inlet check valve 65 and an outlet check valve 67 adapted to control the flow of blood to and from the pump in a conventional manner known in the art.

Within the housing 55 is the thin, flexible bladder 51, preferably of polyurethane having a wall thickness on the order of magnitude of 0.03 inch. That material is desirable because it is highly durable, flexible, and chemically inert in the environment in which it will be used, and it can be made relatively thin while retaining a safe margin of strength. It is desirably thin, because, as noted above, it is preferably used as a heat exchange surface to exchange heat between the hydraulic fluid from the control unit 3 and the blood stream. Preferably, the interior surface 69 of the bladder 51 is flocked with Dacron fibers and after implantation becomes coated with an autologous pseudoendothelium surface of the type described above. It has been found that the total heat transfer surface available is adequate if the bladder is of appropriate size for the volume of blood to be supplied at each stroke. Specifically, a total bladder area of approximately 19.7 square inches is satisfactory.

The flexible hydraulic connecting tube 11 is connected between a suitable outlet fitting 71 formed in the housing 55 and a corresponding fitting 73 on the blood pump control unit 3.

The fitting 73 is formed at the outlet of a cylinder 75 in which there is an expansible chamber formed by a piston 77

sealed to the end of the cylinder 75 by means of an expansible metal bellows 81. In the space 83 inside of the bellows 81 and piston 77 is a fixed trapped volume of fluid communicating through the tube 11 with the chamber around the diaphragm 51 in the blood pump 5. The fluid in the space 83 and in the outer portion of the blood pump 5 is preferably an isotonic aqueous saline solution, to minimize the consequence of any leakage that might occur into the blood. The space around the bellows 81 and piston 77 is in communication with the exhaust fluid line 9, by way of a passage 85 formed in the housing 53 of the blood pump control unit. That arrangement permits expansion and compression of the expansible chamber formed by the bellows and piston, and facilitates heat transfer between the isotonic pumping fluid and the fluid from the power supply.

Formed integral with the piston 77 is a smaller piston 79 slideable in a cylinder 87 formed in the housing 53. The ratio of the areas of the pistons 79 and 77 is such that high-pressure fluid, at approximately 80 p.s.i.a. supplied to the pump control unit in a manner described above, will be converted to approximately 15 p.s.i.a. in the space 83 to simulate the systolic pressure that would be produced in the natural circulatory system by a normally functioning heart.

High-pressure hydraulic fluid is supplied to the blood pump control unit 3 through the flexible line 7, and low-pressure exhaust fluid at approximately 15 p.s.i.a. is returned to the fluid pressure source through the flexible line 9. The high-pressure line 7 is connected to the unit 3 by means of a suitable fitting shown at 89, and the low-pressure line is connected to a suitable fitting 91 formed in the housing 53. The valve 93 is urged to the position shown by a spring 99, and is at times switched down to the lower position described above by hydraulic means to be described.

In the position of the parts shown, the upper end of the spool valve 93 is in communication with the low-pressure return line 9 over a passage 101, a passage 103, a reduced portion 105 formed on the piston 79, a passage 107, and a restricted orifice 111 in parallel with a spring-biased check valve 113. At the same time, the upper part of the piston 79 is connected to the high-pressure inlet passage 7 over a conduit 115, a reduced portion 117 formed on the spool valve 93, and a passage 119.

In a second position of the piston 79, lower than in FIG. 3 and illustrated schematically in FIG. 4, ports 103 and 107 are closed by the piston 79, and the fluid above the spool valve 93 is trapped so that the spool valve cannot move. In a third position of the spool valve 79, still lower than in FIG. 4 and illustrated schematically in FIG. 5, the upper portion of the spool valve 93 communicates with the high-pressure line 7 through the passage 101, a passage 121, the reduced portion 105 formed on the piston 79, a passage 125, and the passage 119. In that position, the conduits 103 and 107 remain closed by the upper portion of the piston 79.

The lower portion of the spool valve 93 communicates directly with the return line 9 through a passage 127. In the second position of the spool valve 93, in which it is at the bottom of the cylinder 95 and engaging the ledge 97, the passage 115 is closed by the top portion of the spool valve 93 and the top of the cylinder 79 is in communication with the return line 9 over a passage 129, a second reduced portion 131 formed on the spool 93, a passage 133, and the reduced orifice 111 in parallel with the check valve 113.

Preferably, the pumping fluid in the cylinder 75 surrounding the piston 77 and the bellows 81, the high-pressure fluid in the line 7, and the low pressure fluid in the line 9, are all a part of the same closed system of hydraulic fluid that is preferably water. Moving parts such as the spool valve 93 and the piston 79 are preferably provided with graphite bearings, not shown, and some leakage is permitted so that the water serves as the lubricant for the moving parts.

The operation of the apparatus of our invention will next be described on the assumption that the power source of FIG. 1 is in operation to provide high-pressure working fluid at 80

p.s.i.a. and an elevated temperature of, for example, 140° F., to the line 7, and to receive low-pressure fluid at approximately 15 p.s.i.a. and a reduced temperature of approximately 115° F. and selected to produce a net average temperature rise in the blood stream of approximately one-quarter to one-half of a degree. Upon those assumptions, and on the further assumption that the parts have just reached the position shown in FIG. 2, operation of the apparatus of FIGS. 2 and 3 will be described, with reference to FIGS. 2 and 3 and to the schematic diagrams of FIGS. 4 and 5.

In the position shown in FIG. 2, the bladder 51 will have been filled with blood in an amount equal to that supplied by the last systolic contraction of the ventricle plus a residual amount allowed to prevent contact of the opposite walls of the bladder 51, as seen in FIG. 3. The reason for preventing the walls of the bladder from coming into contact is to prevent damage to blood cells that may be occasioned thereby.

With the parts in the position shown in FIG. 2, the piston 79 will be in communication with the high-pressure fluid in the line 7 as described above, and the piston 77 will be driven down to express fluid in the expansible chamber 83 into the outer chamber of the blood pump 5. That will cause contraction of the bladder 51 as shown in FIG. 3, the closing of the inlet valve 65, and the opening of the outlet valve 67 to express blood to the aorta. The spool valve 93 will be initially held in the position shown in FIG. 2 by the spring 99. The top of the spool valve 93 is exposed to return pressure in the line 9 over the conduits 101, 103, 107 and the reduced orifice 111. The bottom of the spool valve is also at exhaust pressure, to which it is exposed over the line 127.

As the piston 79 descends to the position illustrated in FIG. 4, the passage 103 will be cut off, and the fluid above the spool valve 93 will be trapped, locking the spool valve in the position shown for the time being. As the piston 79 nears the bottom of its stroke, the reduced portion 105 will expose the passage 121 to the passage 125, admitting high-pressure fluid from the line 9 to drive the spool valve 93 down into its bottom position. That position is illustrated in FIG. 5. In that position, the passage 115 will be closed by the top part of the spool valve 93, and the passage 129 will be connected to the passage 133 over the reduced portion 131 of the spool valve 93. Nothing further will occur until the next systolic contraction of the natural ventricle.

When the spool valve 93 is against the ledge 97 in FIG. 2, the apparatus will await the next systolic contraction of the natural heart. When that occurs, blood under pressure will be supplied from the ventricle to the inlet conduit 61, opening the check valve 65 and closing the check valve 67 in the blood pump. The bladder 51 will expand as it fills with blood, expressing fluid between the housing 55 and the bladder 51 upward through the conduit 11 to the expansible chamber 83. That will cause the piston 77 to be raised.

As the piston 77 is raised, carrying with it the piston 79, the first significant event will be the closing of the passage 121 to trap high-pressure fluid over the spool valve 93 and hold it down against the ledge 97. The next significant event will be the opening of the conduit 103 to the conduit 107 by the reduced portion 105 on the piston 79 as it continues to travel upward under natural ventricular pressure, transmitted from the blood pump 5 and multiplied by the ratio of the areas of the pistons 77 and 79. When that occurs, the top of the spool valve 93 and the top of the piston 79 will both be in communication with the restricted orifice 111, whereas the bottom of the spool valve 93 is directly in connection with the return line 9.

There will be a pressure drop across the orifice 111 that depends upon the flow of fluid through the orifice occasioned by the upward movement of the piston 79. That pressure drop will remain until, towards the end of the natural systole, the ventricular blood pressure drops and movement of the piston 79 ceases. Until that time, the back pressure exerted by the piston 77 and the blood pump 5 will be limited by the check valve 113, which is set to unload at a predetermined pressure that will not overtax the natural ventricle.

When the end of the natural systole occurs, with the corresponding pressure drop described above, the spring 99 will snap the valve 93 back to the position shown in FIG. 2 and a new pumping cycle will begin. Since that can occur at any time after the ports 103 and 107 are opened by the reduced portion 105 of the piston 79, the volume of fluid taken into the expansible chamber 83 will be determined by the amount of the volume of blood expelled during the natural systole, and may vary from stroke to stroke in dependence on the demands of the host. This same volume is always expelled at the next stroke, because the volume discharged from the chamber 83 is limited by the opening of the ports 121 and 125 as the piston 77 approaches the bottom of its stroke.

As noted above, the fluid in the line 79 carries excess heat extracted from the working fluid in the condenser 33 in FIG. 1. That heat is discharged to the blood stream in a manner next to be described.

The pumping fluid in the blood pump 5, the line 11 and the expansible chamber 83 exchanges heat with the fluid in the hydraulic lines 7 and 9 through the conductive metal walls of the piston 77 and the bellows 81. The fluid in the expansible chamber 83 is transferred back and forth between the blood pump control unit 3 and the blood pump, and exchanges heat with the blood through the diaphragm 51. The excess heat in the power supply system is thereby discharged without causing any physiologically significant increase in blood temperature. The heat that is added to the blood is dissipated by the normal physiological processes of perspiration, conduction, convection and respiration.

It will be apparent that in the apparatus just described, the bladder 51 in the blood pump serves both to exchange heat between the power supply and the blood stream and to sense the natural ventricular rhythm and transmit a pressure control signal to the blood control unit 3 toward the end of the natural systole. The volume of fluid taken into the chamber 83 at each stroke is determined by the volume of blood delivered to the pump by the left ventricle during its last systolic contraction. That volume is determined in dependence on the current needs of the host as communicated to the natural heart by the physiological motor control system of the host. Thus, the circulatory support system is fully synchronized with the natural circulatory system both in timing and in flow rate.

While we have described our invention with respect to the details of a preferred embodiment thereof, many changes and variations will become apparent to those skilled in the art upon reading our description, and such can obviously be made without departing from the scope of our invention.

Having thus described our invention, what we claim is:

1. A blood coupler for a heart-assist circulatory support system comprising power supply means for producing from a supply of hydraulic pumping fluid at a first temperature and a first pressure a supply of hydraulic fluid at a second higher temperature and a second higher pressure, a blood pump comprising a thin resilient expansible bladder sealed in a housing between openings adapted to be connected in a blood circula-

tion system, said openings being provided with check valves to produce a pulsing unidirectional flow of blood through said bladder when hydraulic fluid is forced in and out of said housing outside of said bladder, and fluid exchange means connected between said housing and said power supply by a supply line containing pumping fluid at said first temperature and pressure and a return line containing pumping fluid at said second temperature and pressure, said fluid exchange means comprising an inlet chamber, an outlet chamber, a communicating passage between said inlet chamber and said outlet chamber, and thermally conductive piston means movable in said communicating passage to vary the volume of said inlet chamber with respect to the volume of said outlet chamber, means connecting said outlet chamber to said housing to exchange hydraulic fluid with said pump, means responsive to a drop in pressure in said bladder for connecting said supply line to said inlet chamber to admit a slug of fluid to said inlet chamber, thereby moving said piston means to drive fluid into said pump to compress said bladder while cooling the fluid in the inlet chamber and heating the fluid in the outlet chamber, while cooling the fluid in the housing and heating blood in the bladder, and means responsive to the volume of said outlet chamber for connecting said inlet chamber to said return line and disconnecting said supply line when said outlet chamber reaches a predetermined minimum volume.

2. The apparatus of claim 1, in which said means connecting said outlet chamber to said housing comprises an expansible chamber forming a closed and sealed container of constant volume with the space in said housing and outside of said bladder, said constant volume container being filled with hydraulic fluid.

3. A blood coupler for a heart-assist circulatory support system, comprising an implantable blood pump comprising a housing, a thin resilient bladder mounted in said housing and having a pair of openings adapted to be connected for unidirectional blood flow in a mammalian circulatory system, power supply means for producing from a supply of fluid at a predetermined low temperature and pressure a supply of fluid at high temperature and pressure, and fluid motor means connected to said housing by a fluid exchange passage and connected to said power supply by a supply line of fluid at said high temperature and pressure and a return line of fluid at said low temperature and pressure, said fluid motor means comprising means energized by the difference in pressure between said supply and return lines to supply pumping fluid at one temperature and pressure to said housing to compress said bladder and transfer heat through said bladder to blood in said bladder and to return cooled fluid at said low temperature and pressure to said return line.

4. The blood coupler of claim 3, in which said fluid exchange passage comprises an expansible chamber connected to and forming with the space in said housing outside of said bladder a sealed container of constant volume, and a fixed charge of hydraulic fluid filling said sealed container.