United States Patent [19]

Purdy

[11] **3,828,371**

[45] **Aug. 13, 1974**

[54] **SELF-CONTAINED ARTIFICIAL HEART**

[75] Inventor: **David L. Purdy,** Indiana, Pa.

[73] Assignee: **ARCO Nuclear Company,** Philadelphia, Pa.

[22] Filed: **Dec. 18, 1970**

[21] Appl. No.: **99,635**

[52] **U.S. Cl.** ..... **3/1,** 3/DIG. 2, 128/1 D, 417/394, 417/468, 60/24, 60/25

[51] **Int. Cl.** **A61f 1/24**

[58] **Field of Search** ..... 3/1, DIG. 2; 417/394, 395, 417/321, 460, 468; 60/24, 25, 203; 92/117 R; 128/1 D, DIG. 3

[56] **References Cited**

UNITED STATES PATENTS

3,048,165	8/1962	Norton	3/DIG. 2
3,379,191	4/1968	Harvey	3/1 X

OTHER PUBLICATIONS

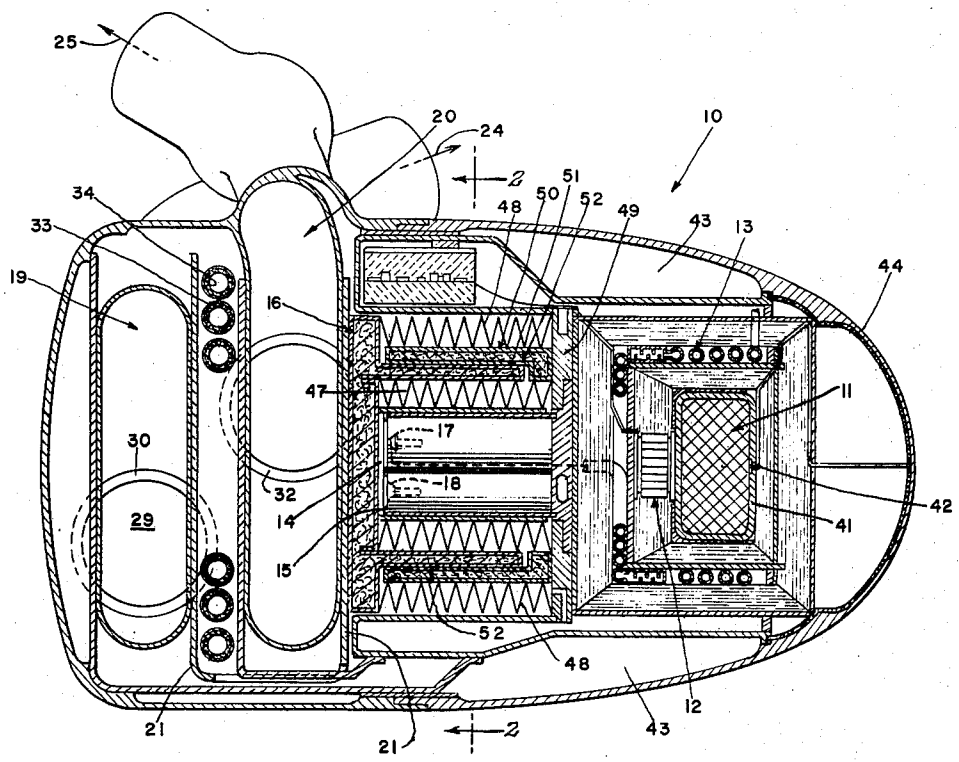
"The Development of An Inrapericardial Cardiac Replacement" by W. H. Burns et al., Transactions American Society for Artificial Internal Organs, Vol. XII, 1966, pages 272–274.

Primary Examiner—Richard A. Gaudet
Assistant Examiner—Ronald L. Frinks
Attorney, Agent, or Firm—John R. Ewbank

[57] **ABSTRACT**

A small, self-contained blood pump with integral power source comprising an isotopic thermal source which drives both a Rankine cycle steam engine and a thermoelectric converter which generates electricity to drive a physiologically-responsive beat rate control system, a solenoid-driven feed liquid pump, and a plumonary edema protection system.

18 Claims, 9 Drawing Figures



PATENTED AUG 1 3 1974

3,828,371

SHEET 1 OF 6

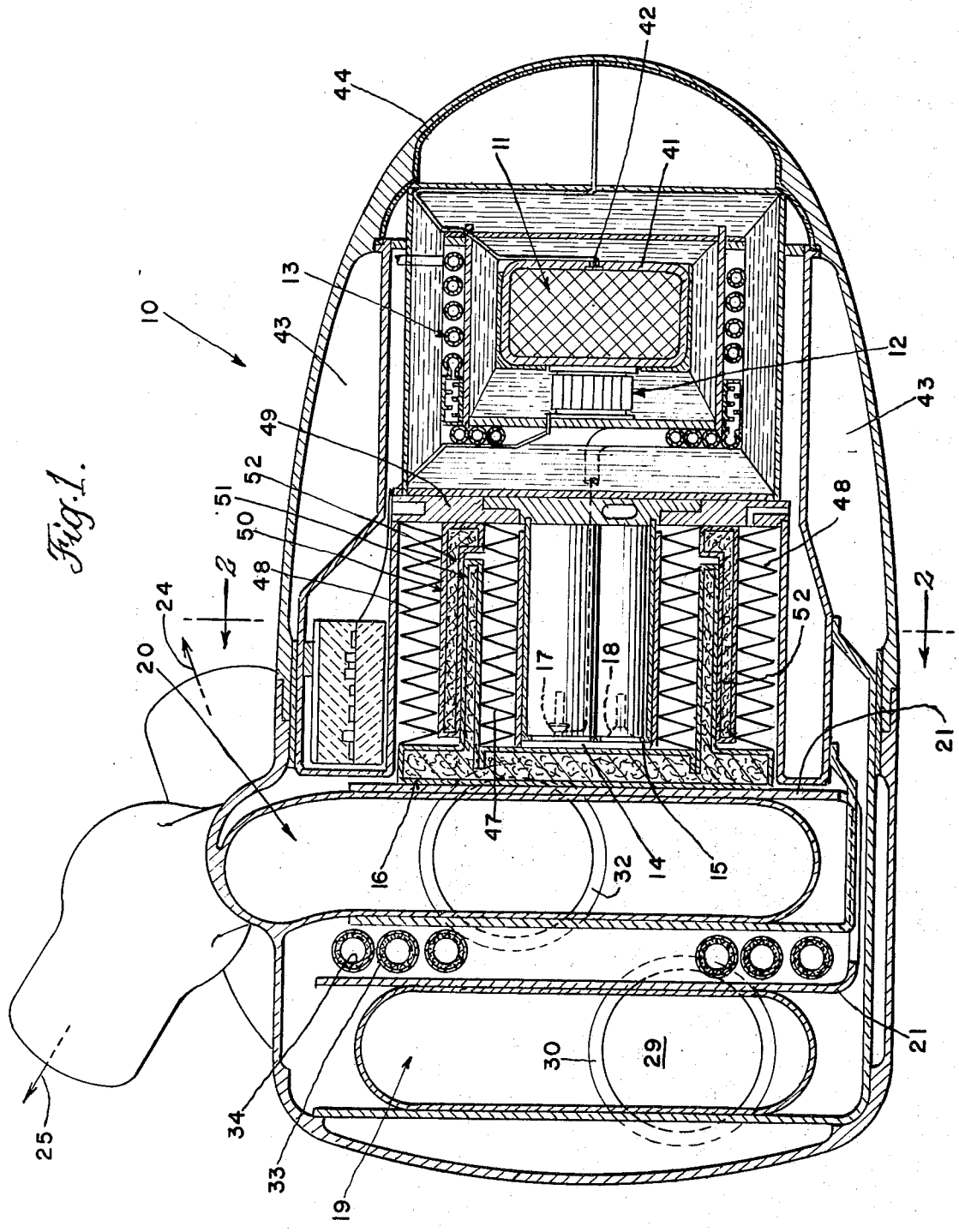


Fig. 1.

INVENTOR.
DAVID L. PURDY
BY Michael B. Fein
ATTORNEY

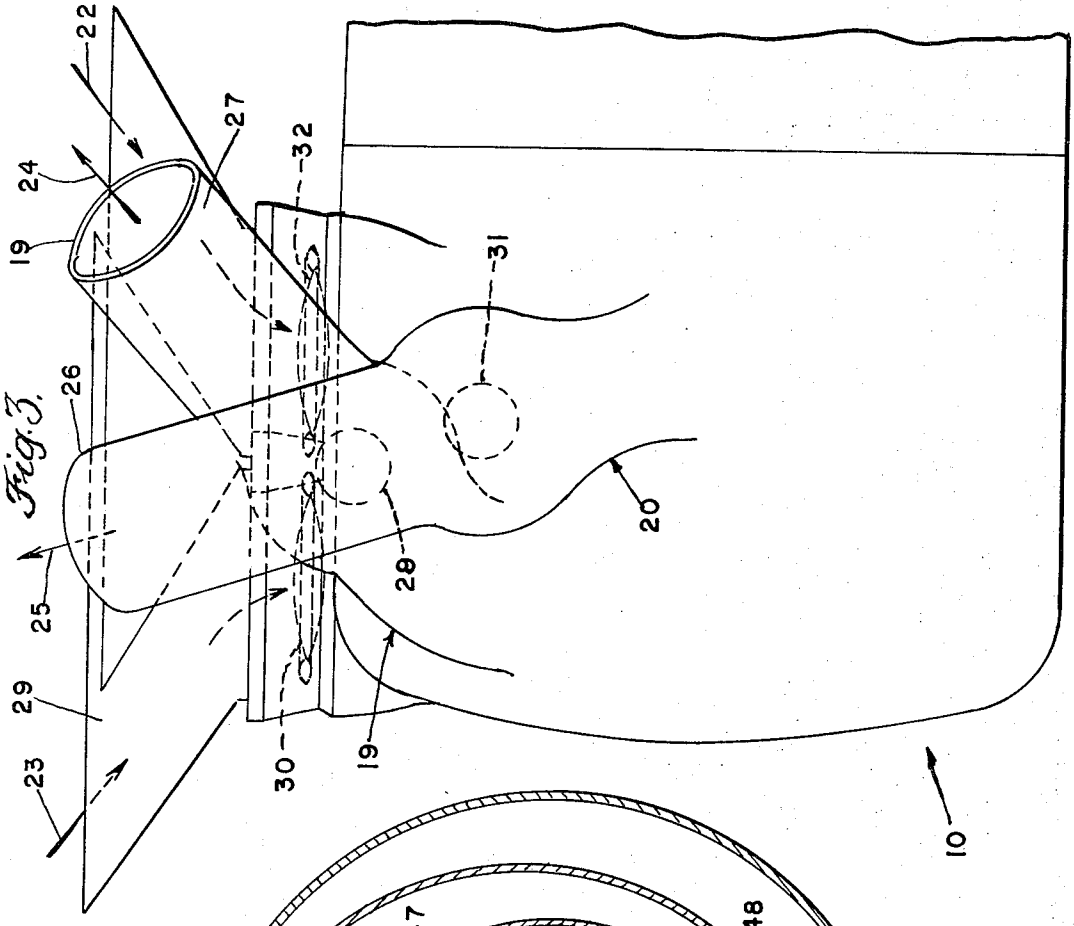


Fig. 3.

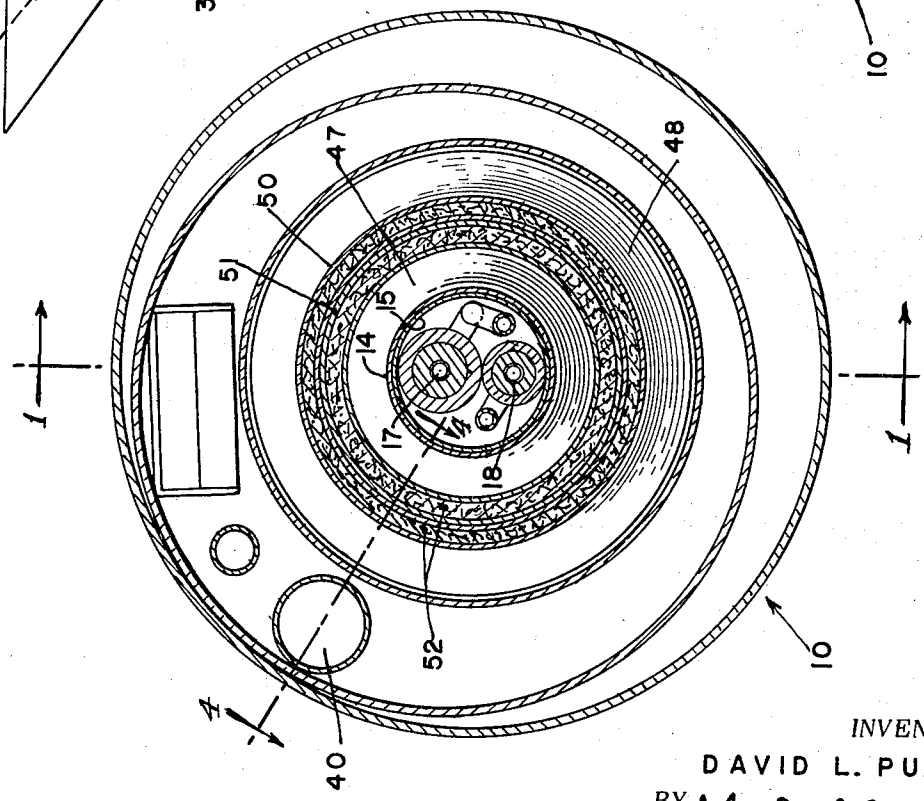


Fig. 2

INVENTOR.
DAVID L. PURDY
BY Michael B. Fein
ATTORNEY

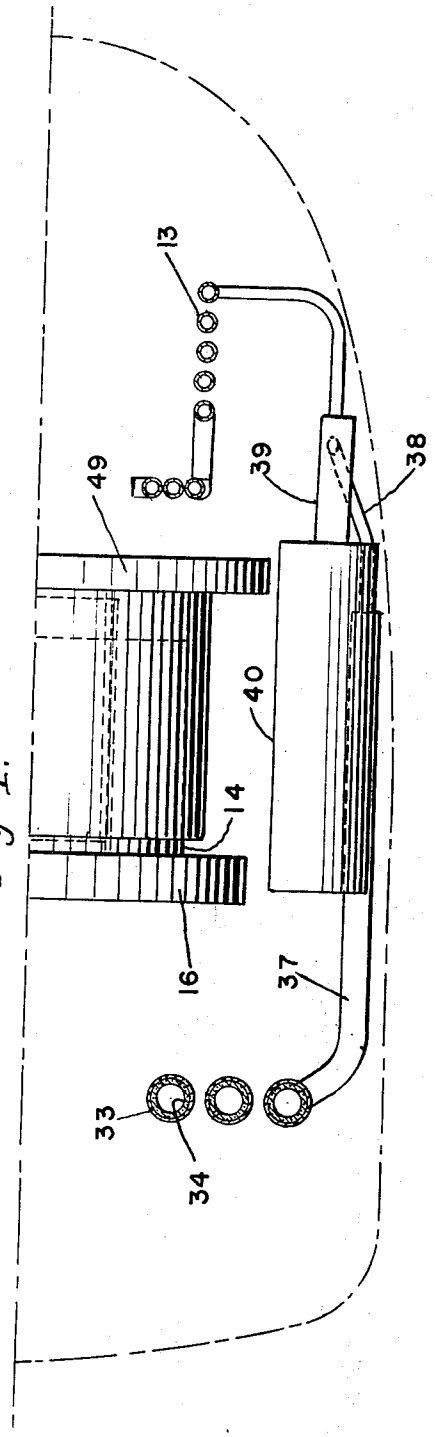


Fig. 4.

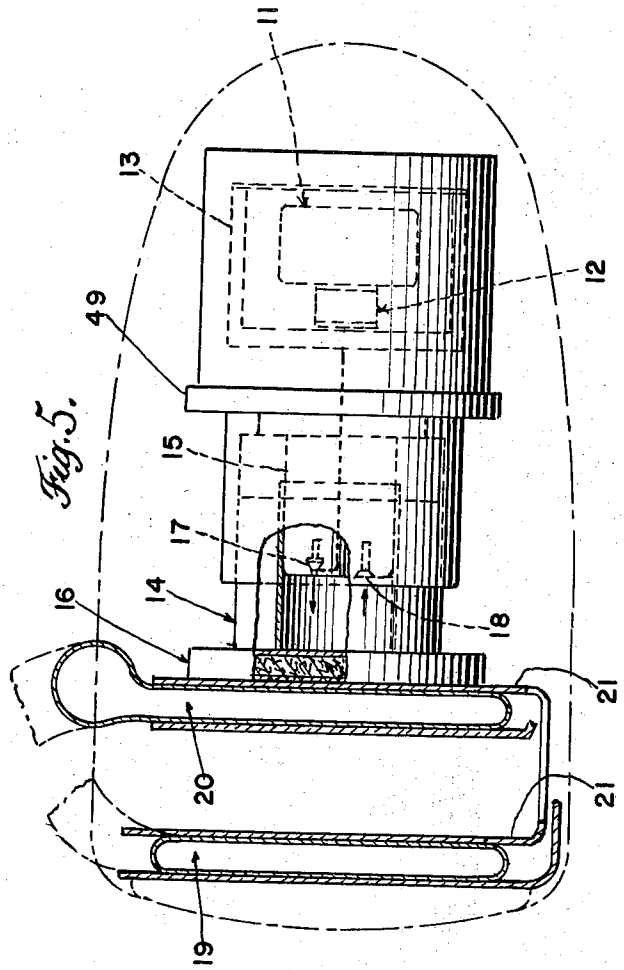


Fig. 5.

INVENTOR.
DAVID L. PURDY
BY Michael B. Fein
ATTORNEY

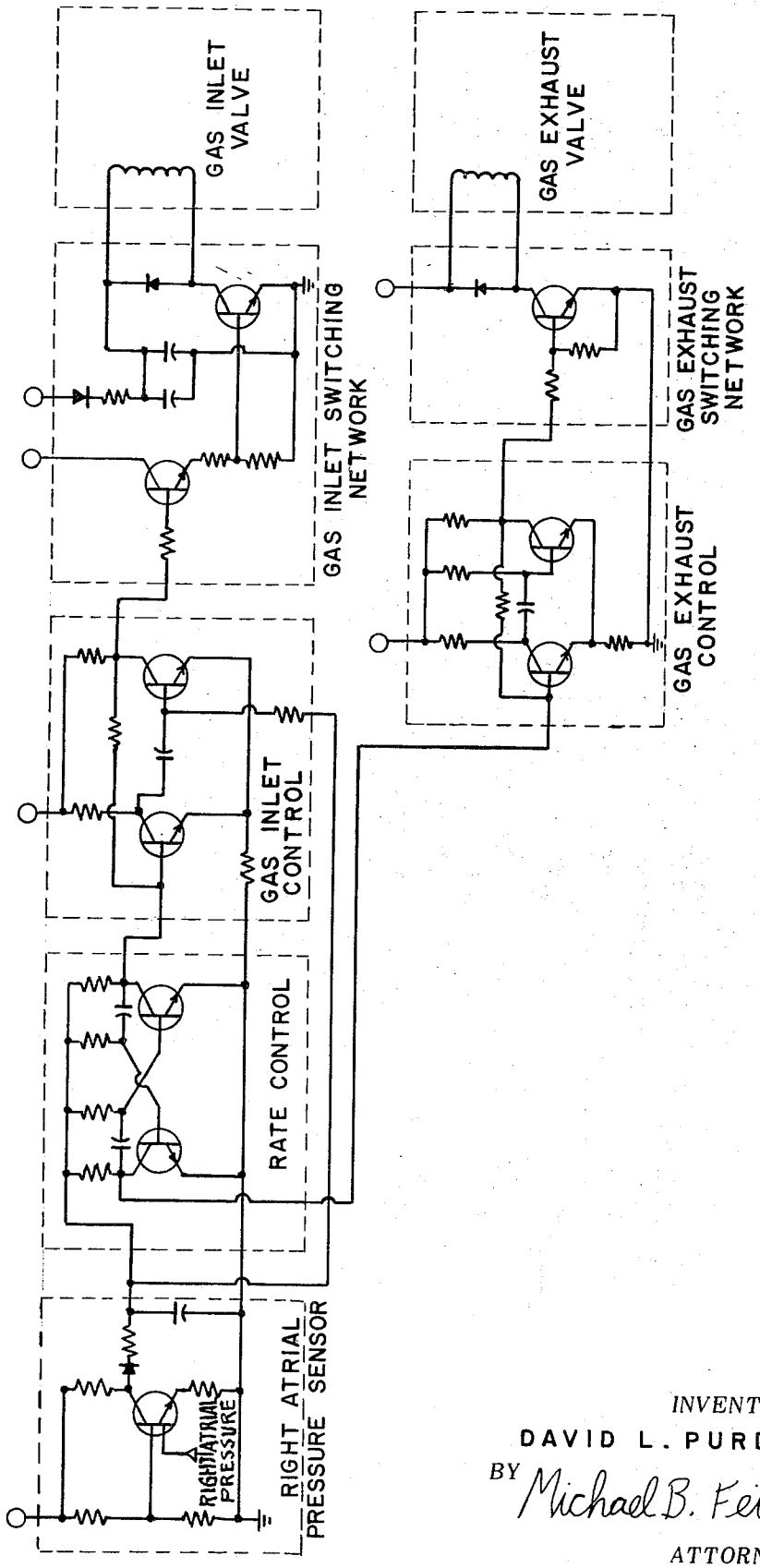


Fig. 6.

INVENTOR.
DAVID L. PURDY
BY Michael B. Fein
ATTORNEY

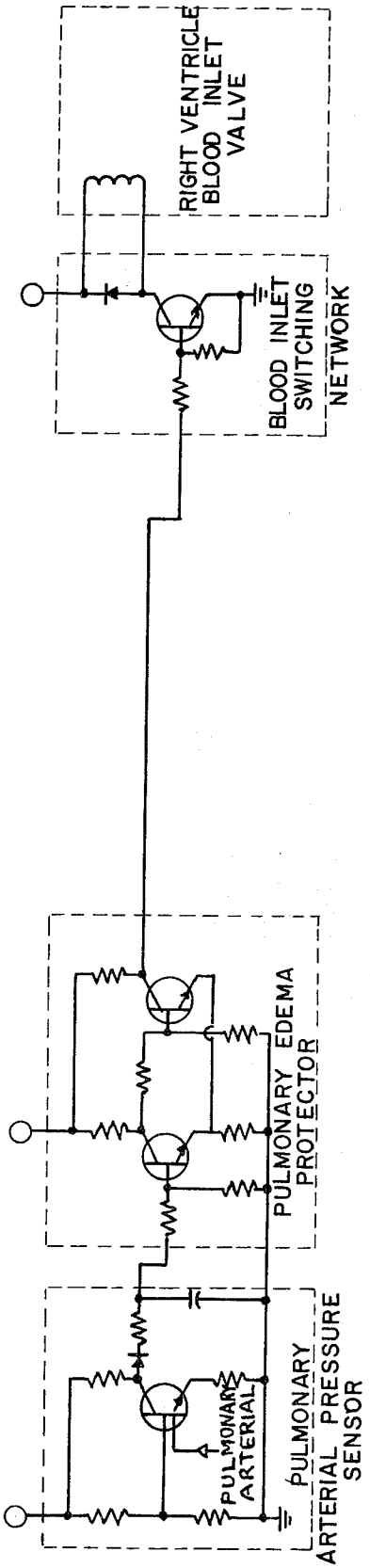


Fig. 7.

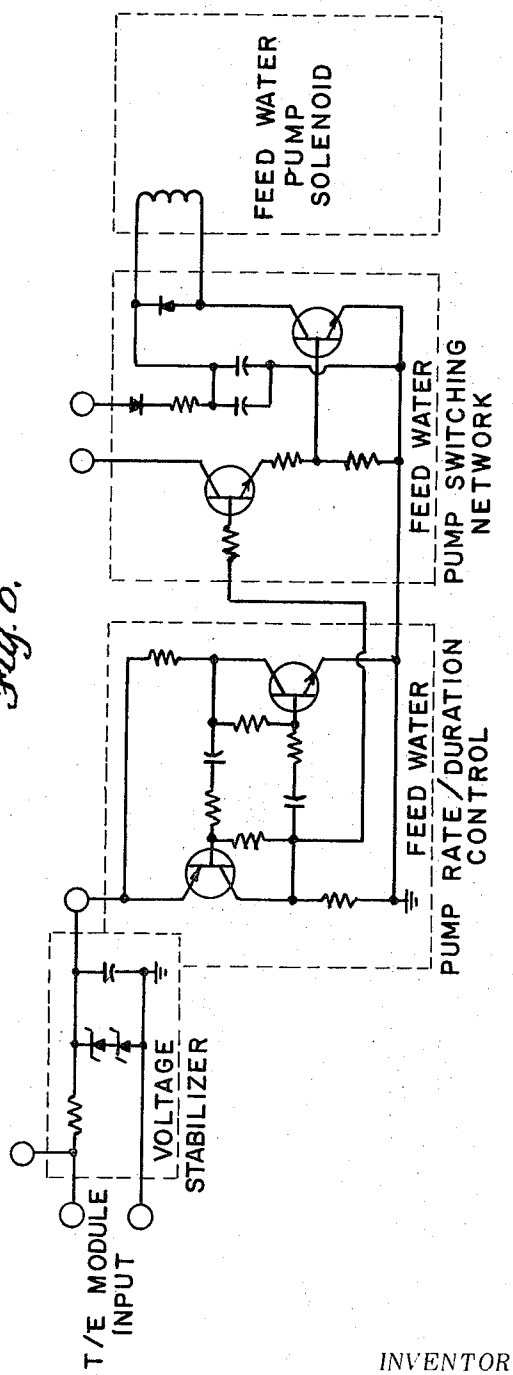
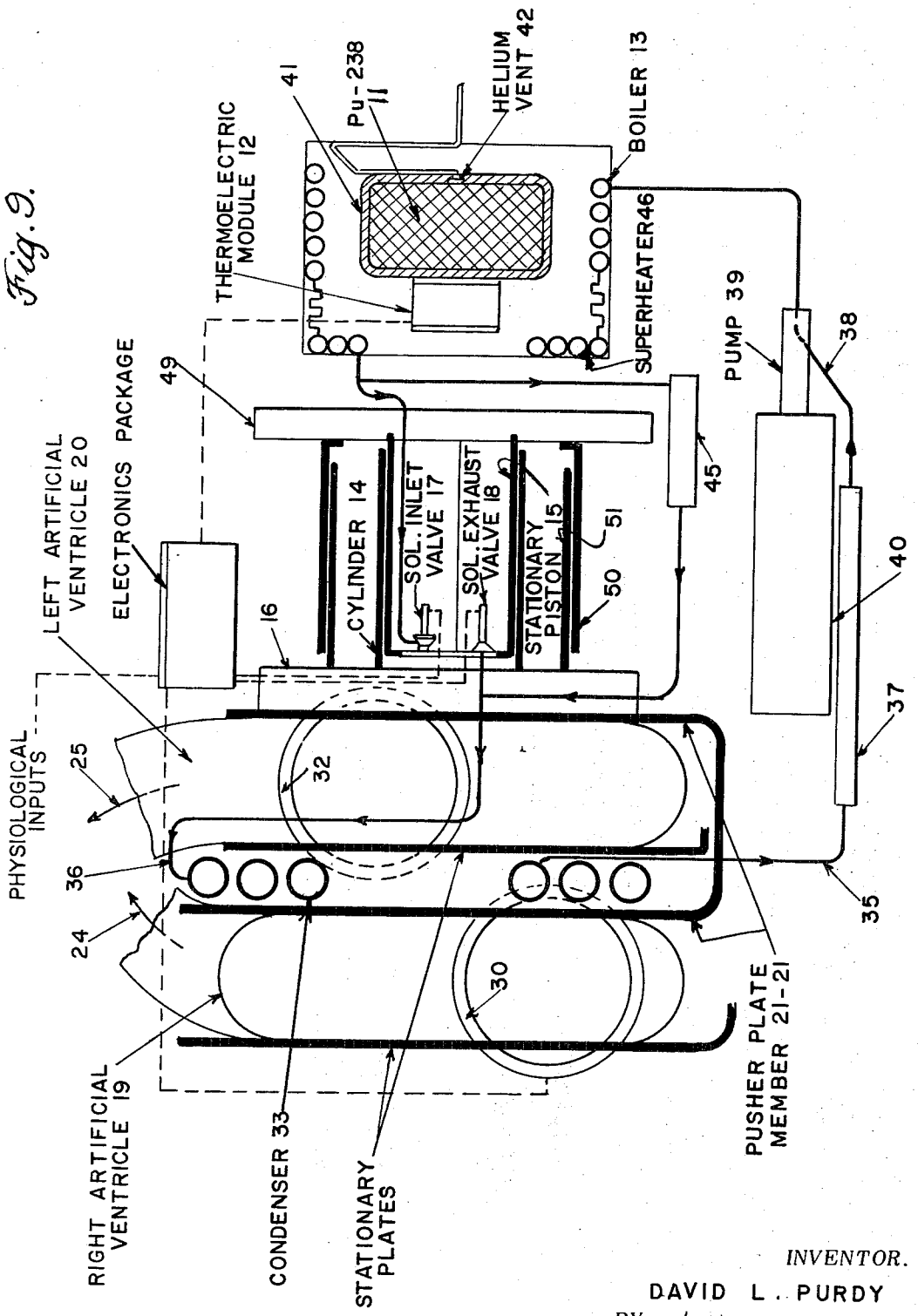


Fig. 8.

INVENTOR.
DAVID L. PURDY
BY Michael B. Fein
ATTORNEY

Fig. 9.



INVENTOR.
DAVID L. PURDY
BY Michael B. Fein
ATTORNEY

SELF-CONTAINED ARTIFICIAL HEART

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates generally to a single unit mechanical device capable of circulating blood in the human body in place of a human heart and capable of surgical implantation in the thoracic cavity in a single operation.

2. Description of the Prior Art

Previous nuclear powered mechanical heart devices such as the one shown in U.S. Pat. No. 3,379,191 of Apr. 23, 1968, were comprised of two separate units, one to be implanted in the thoracic cavity and separate power source unit to be implanted in the abdominal cavity with a connecting line to pass the steam generated at the boiler unit of the power source and return the used steam to a condenser and then back to the power source. Another disadvantage of the prior art devices was that the artificial ventricles were mechanically coupled to the recipricating piston and when the piston drew blood into the ventricles, the atrial system tended to collapse under the negative pressure induced therein. Adequate precautions were not taken against pulmonary edema which resulted from continuous pumping of blood to the lungs beyond capacity of the blood vessels therein. Although prior art devices could be set at a selected beat rate, no one has previously conceived of means for varying the beat rate or blood pump output of an implantable artificial heart according to the body's need for blood as a natural human heart does.

SUMMARY OF THE INVENTION

It is therefore an object of this invention to provide a single unit artificial heart device having an integral energy source and controls adapted to be implanted in the pericardial sac in place of a human heart.

It is a further object of this invention to provide a radioisotope powered artificial heart having a Rankine cycle steam engine and a thermoelectric module allowing close simulation of the functions of a human heart by electrical control of pumping rate and pulmonary to systemic pumping ratio in response to physiological need.

Another object is to provide an artificial heart which is more efficient and longer lasting than previous devices.

Another object is to provide an artificial heart which is lighter than previous devices.

Antoher object is to efficiently and effectively vent isotopic decay by-product helium to the bloodstream surrounding a radioisotope-powered artificial heart.

A further object is to provide an improved means for passing excess heat from thermal energy driven artificial heart devices directly to the bloodstream.

Another object is to provide an implantable artificial heart which operates effectively without regard to position or attitude of the wearer. Other objects of this invention will become apparent from the description of the invention which follows.

Broadly, the invention is a self-contained artificial heart including a radioisotope source of thermal energy, a thermoelectric module adapted to convert a first portion of said thermal energy into electric power which is used to drive a feedliquid pump and an electronic control circuit adapted to simulate a natural heart's action by varying the pulse and flow rate in response to a physiological variable, and a boiler of a Rankine cycle steam engine adapted to convert a second portion of the thermal energy into mechanical pumping power.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a longitudinal section taken approximately on the line **1—1** of FIG. **2** of a self-contained artificial heart constructed in accordance with one embodiment of the invention;

FIG. **2** is a cross-section taken on the line **2—2** of FIG. **1**;

FIG. **3** is a fragmentary plan view of the left hand end portion of FIG. **1**;

FIG. **4** is a diagramatic one half plan view taken on the line **4—4** of FIG. **2**;

FIG. **5** is a part sectional and part elevational view illustrating the piston and cylinder and associated right and left artificial ventricles in compressed position;

FIG. **6** is a circuit diagram of the beat rate and stroke length control system;

FIG. **7** is a circuit diagram of the right ventricle blood inlet valve control system;

FIG. **8** is a circuit diagram of the feedliquid pump control system; and

FIG. **9** is a schematic of the electrical and working fluid flow system.

DETAILED DESCRIPTION OF THE INVENTION AND THE PREFERRED EMBODIMENTS

Referring to the drawings which show an illustrative embodiment of the blood pump device of the invention, the device **10** contains a source of thermal energy **11** preferrably a radioisotope and most preferably a compound of plutonium ^{238}. A thermoelectric converter **12** is in proximity to the thermal energy source **11** and functions to convert a first portion of the thermal energy from Pu compound **11** to electrical energy. Also in close proximity, preferably surrounding the source of thermal energy, and most preferably surrounding the converter **12**, is a monotube boiler **13** which functions to vaporize and superheat the working fluid. The working fluid maybe any one suitable for use in a Rankine cycle engine such as hydrocarbon, halogenated hydrocarbons such as that family of compounds known as the "Freons," or water. The working fluid is changed from its liquid to its gaseous state in the boiler **13** by a second portion of the thermal energy and is passed to an expansion zone **14** established by stationary piston **15** and reciprocally movable cylinder head assembly **16** through a solenoid controlled inlet valve **17** in said stationary piston **15.** The stationary piston **15** also contains a solenoid-operated exhaust valve **18.** The cylinder head assembly **16** moves first away from the piston **15** when the inlet valve **17** is opened and the exhaust valve **18** is closed, and second toward the piston **15** when the exhaust valve **18** is opened and the inlet valve **17** is closed. When the cylinder head assembly **16** is moving away from the stationary piston **15,** it compresses an artificial right ventricle **19** and an artificial left ventricle **20** simultaneously to expel blood therefrom by means of a pusher plate member **21—21** which is attached to the cylinder head **16** but is preferably not physically attached to the ventricles **19** and **20.** When the cylinder head **16** is moving back toward the

piston **15**, it causes the pusher plate **21—21** to move away from the ventricles **19** and **20**, allowing them to expand and allow blood to enter naturally as indicated by arrows **23** and **22** (respectively for ventricles **19** and **20**) in FIG. **3**; that is, as a result of the pressure in the atrial system and not as a result of the negative pressure which would be cause if the pusher plate **21** were attached directly to the ventricles **19** and **20** and forced them open. When the ventricles **19** and **20** are compressed as shown in FIG. **5** as a result of the force of cylinder head assembly **16**, blood is caused to be expelled as indicated by arrows **24** and **25** (respectively for ventricles **19** and **20**) in FIG. **3** into both the systemic and the pulmonary systems of the mammal in which the blood pump **10** is implanted.

By transmitting the engine cylinder force directly to the blood, a pulse shape very similar to that of the human heart can be obtained, resulting from the high initial force as gas initially enters the cylinder and rapidly decreasing as the engine cylinder moves. Blood indicated by the arrow **25** from the left artificial ventricle **20** is passed to a connection **26** to the patient's aorta while blood **24** from the right artificial ventricle **19** is passed to a specially designed pulmonary artery connection **27** containing an outlet valve **28.** The inlet **29** to this right artificial ventricle **19** preferably contains an electromagnetically controlled valve **30** to be described in more detail later in the specification. The aorta connection **26** also contains a valve **31** to prevent backflow of blood **25** in the opposite direction. The left ventricle **20** also contains a blood inlet valve **32** which allows blood **22** only to enter the left ventricle **20.**

The aorta connection **26** pulmonary, artery connection **27**, left and right artificial ventricles **20** and **19** are constructed of any suitable medical grade material which is compatable with blood and body tissues. Natural and synthetic polymer materials such as polyurethane, dacron, hepranized silastic, and silicon polymers are merely exemplary; the particular material selected does not form a part of the present invention.

A capillary condenser tube **33** is connected to the piston exhaust valve **18** and preferably has an inner surface lined with a fibrous metal wick **34.** For example, such a wick-type of capillary lining may be formed from sintered titanium-aluminum-vanadium alloy. Exhaust vapor entering the condenser tube **33** at **36** (FIG. **9**) condenses on the porous wick **34** and fills the wick pores. The condensate flows through the wick **34** to the exit **35** (FIG. **9**) of the condenser and then through a subcooler **37** (FIG. **4**) to the inlet **38** of the feedliquid pump **39.** The condensate is retained in the wick by capillarity regardless of the position or attitude of the heart device. The capillary condenser **33** has a large surface area and rejects heat to an interstitial fluid **43** which in turn rejects its heat to the blood in the ventricles **19** and **20** and maximizes the distribution of heat while minimizing the blood temperature rise. The feedliquid pump **39** is preferably driven by an electrically operated solenoid **40** driven by an electronic control system shown in FIG. **8** at a constant rate. From the feedliquid pump **39** the working fluid is passed back to the boiler **13** where it is vaporized again.

The availability of the electric power from the thermoelectric module or converter provides for electronic control of various functions of this artificial heart which make it superior to any prior art artificial heart. The thermo electric module **12** is preferably a series of silicon-germanium semi-conductor thermocouples. The thermoelectric converter **12** provides electricity to electrical control circuits (shown in FIG. **6**) which control the electromagnetic gas inlet valve **17** and the electromagnetic exhaust valve **18** in the piston **15**, which function to control precisely either or both the stroke length and the cycle rate of the movable cylinder head assembly **16.** In the preferred embodiment, the electrical control circuit (FIG. **6**) is adapted to vary the pulse rate and the stroke length in response to a physiological variable such as blood pressure, variations in which are detected by means of a sensor such as a pressure sensitive transistor thereby varying the rate of pumping of blood in response to the physiological variable, closely simulating the behavior of a natural human heart.

The converter **12** also provides electricity for another electrical control circuit (shown in FIG. **7**) which is preferably provided to control an electromagnetic valve **30** at the blood indicated by arrow inlet **29** to the right artificial ventricle **19** and is adapted to control the amount of blood **23** entering the right ventricle **19.** A sensor (not shown) of pulmonary blood pressure is provided which signals the control circuit (FIG. **7**) when the pulmonary blood pressure rises above a predetermined level and causes the electromagnetic valve **30** to be closed until the pulmonary blood pressure drops to an acceptable level. Pulmonary edema is thereby effectively prevented because of the artificial heart's adaptability to change the systemic system to pulmonary system pumping rate ratio.

Since the rate of blood pumping and hence flow of working fluid through the cylinder may be varied, and the feedliquid pump **40** preferably operates at a constant rate, there will be excess vapor during the major portion of normal activity and during periods of low blood flow power demands. A relief valve **45** (FIG. **9**) is provided to release excess vapor from the boiler superheater **46** into the condenser **33** at **36** at a predetermined pressure.

The source of thermal energy **11** previously mentioned is preferably compound of a Pu_{238} isotope and is shielded preferably by a platinum capsule **41** having an absolute filtered vent **42** (FIG. **1**) to duct helium generated by said isotope **11** during the course of this decay directly into the interstitial fluid **43.** The helium permeates the silastic covering **44** into the bloodstream. A microsphere fuel form is coated first with thoria and then with platinum-rhodium to form a ductile mass which withstands any credible impact as well as fire or any credible accident.

An internal cylindrical bellows **47** and an external cylindrical bellows **48** (FIGS. **1** and **2**) are provided, one end of each being welded to the movable cylinder head **16** and the other end of each being welded to a stationary member **49** which is affixedly attached to the piston **15.** The internal bellows **47** forms a hermetic seal to prevent any possible working fluid escape and to vent any vapor leakage past the cylinder **14** directly to the condenser **33.** In the preferred embodiment, there is provided a xenon-filled annular chamber defined by bellows **47** and **48.** Much of such annular chamber is oocupied by thermally insulating, slidably interfitting Min-K cylindrical cans **50** and **51** which act as thermal insulators. Surrounding this annulus is the external bellows **48** which provides a hermetic seal for xenon **52** containment. Xenon **52** provides the dual function of lowering the thermal conduction of the annulus and

generating a null force on the piston **15** when the cylinder **14** at its smallest volume. With the movement of the cylinder head assembly **16** away from the piston **15,** the two bellows **47** and **48** expand are lengthened and the xenon pressure reduces, thereby increasing the propensity of the gas pressure forces other than the working fluid pressure to urge the cylinder head assembly **16** toward the position providing the smallest volume for expansion zone **14.** As the cylinder head assembly **16** advances, it asserts a direct force onto the two artificial ventricles **19** and **20,** thereby expelling the blood. At the completion of the pump stroke the pressure in the cylinder will have dropped and the exhaust valve **18** will open for at least a portion of the return stroke.

DESCRIPTION OF CIRCUITRY

The artificial heart is controlled by circuitry responsive to some physiological function such as the average blood pressure, filtered to eliminate the variations from beat to beat. In FIG. **6,** dotted lines enclose certain electronic functions, which have inter-relationships shown by the schematic diagram. A variable voltage signal indicative of the variations in blood pressure is regulated by the "Right Atrial Pressure Sensor" unit, there being a suitable transducer in the right atrium. The human body is thus a significant participant of the feedback loop.

Particular attention is directed to the feature whereby this average blood pressure signal varies both the stroke and the rate of the artificial heart, thus simulating the normal heart's capacity for increasing both the volume per beat and the rate of the pumping action. That portion of FIG. **6** within the dotted lines identified as "Rate Control" is a multivibrator, the rate of which is controlled by the average blood pressure. The "Gas Inlet Control" is an emitter coupled monostable vibrator, the pulse width of which is varied by the average blood pressure. The train of thus regulated pulses actuates a driven circuit identified as a "Gas Inlet Switching Network" whereby the gas inlet valve **17** solenoid is energized to control both the stroke and the rate of the reciprocating cylinder head assembly **16.** The exhaust valve **18** is regulated by a solenoid energized through a "Gas Exhaust Switching Network" driven by the signal from the "Gas Exhaust Control," the frequency of the pulses being the complimentary output of the "Rate Control" regulated by the feedback signal from the human body through the " Right Atrial Pressure Sensor."

The current from the thermoelectric converter **12** energizes the circuits of FIGS. **6, 7,** and **8.** Within each set of dotted lines, any transistor described as a second transistor is the one on the right, the leftward transistor being called the first transistor.

The reciprocation rate of the cylinder head assembly **16** is controlled by the rate at which the inlet valve **17** is opened. A less than maximum stroke length is achieved by shortening the duration of the opening of the inlet valve **17.** The exhaust valve **18** is electrically actuated toward the open position during at least some portion of the cycle when the intake valve is not so actuated.

The gas inlet valve solenoid is controlled by a "Gas Inlet Switching Network." A "Gas Inlet Control" is an emitter-coupled monostable vibrator whose pulse is triggered by the train of pulses from the "Rate Control," the pulse width being varied by the signal from the "Right Atrial Pressure Sensor." Thus, when the body sends back more blood toward the heart, the pumping capacity is increased in part as a result of increasing the stroke by increasing the pulse width.

The "Gas Inlet Switching Network" is a driver circuit comprising a first and second transistor. A positive current is directed through a diode, a resistor, the solenoid coil for the inlet valve **17** and the collector and emitter of the second transistor. The base of the second transistor is controlled by the emitter signal from the first transistor developed across a resistor voltage divider. The emitter of the second transistor is also connected by two parallel capacitors to the collector through the solenoid winding in the valve **17** for the gas inlet. A diode in parallel with the solenoid winding for the valve **17** of the gas inlet serves to prevent any adverse effects from the intermittent potential in the solenoid. In the operation of the "Gas Inlet Switching Network," the low power signal from the "Gas Inlet Control" regulates both the frequency and duration of valve opening, and the switching network unit controls the flow of the higher power current to the solenoid of the valve **17.**

The "Gas Inlet Control" is an emitter-coupled monostable vibrator and includes two common emitter connected transistors, the emitters being maintained above ground by a resistor to ground. The base of a first transistor of the "Gas Inlet Control" is connected through a resistor to the collector of the second transistor, which provides an output signal from the "Gas Inlet Control." The collectors of the first and second transistors of the gas inlet control are connected through their respective resistors to a positive potential. The signal on the collector of the first transistor is coupled to the base of the second transistor through a capacitor. The pulse width is increased when the heart rate is increased because the "Gas Inlet Control" is modulated by the output signal of the right atrial pressure sensor. For example, such atrial signal can be connected through a resistor to the base of the second transistor.

The "Rate Control" unit is an R-C coupled common emitter multivibrator. The base of each transistor is connected by a capacitor to the collector of the other transistor and by a resistor to the positive signal from the "Right Atrial Pressure Sensor." Similarly, the collector of each transistor is connected through a resistor to such positive signal from the "Right Atrial Pressure Sensor."

The operation of the "Rate Control" unit can be clarified by noting that a positive signal from the "Right Atrial Pressure Sensor" is converted by the multivibrator to two trains of pulses at a right of the general magnitude of a natural heart beat, the pulses from one side of the multivibrator being directed to the "Gas Exhaust Control" and the other train of pulses from the other side of the multivibrator being directed to the "Gas Inlet Control." The frequency of the multivibrator increases when the body needs more blood circulation as communicated by the positive signal from the "Right Atrial Pressure Sensor."

The "Right Atrial Pressure Sensor" includes a transducer responsive to the pressure in the right atrium, such transducer being associated with the base of the transistor in such unit. A voltage divider between the positive terminal of the source of electrical potential and ground provides a controlled voltage to the base. The emitter of the transistor is connected by a resistor

to ground. The collector is connected by a resistor to the positive terminal of the source of electrical potential. The output signal at the collector is coupled to supply the positive potential for the multivibrator by an isolating diode in series with a resistor. A capacitor is connected between such resistor and ground. Such association of the electronic components in the unit designated as the "Right Atrial Pressure Sensor" provides a filtered signal (the beat to beat variations being rejected) which is a smoothly varying positive signal indicative of average atrial pressure, and this signal regulates the variations of both the "Rate Control" unit and the "Gas Inlet Control" for controlling both the rate and stroke of the reciprocations of the cylinder head assembly **16.** In this manner, the entire system closely simulates the response of a natural heart to right atrial pressure.

The "Gas Exhaust Control" is similar in configuration and operation to the "Gas Inlet Control." A signal consisting of a train of pulses from the multivibrator is applied to the base of the first transistor. The bias, however, is derived directly from the positive potential source, rather than from the positive output of the "Right Atrial Pressure Sensor" because the working fluid can flow through an open exhaust valve during the same fraction of a cycle without regard to whether the inlet valve was long open for a full stroke or a shorter time for a partial stroke.

The "Gas Exhaust Switching Network" includes a transistor, the base of which is connected through a resistor to ground. The solenoid coil operating the gas exhaust valve is connected in series with the collector to the positive potential source. A diode bypasses the solenoid coil of the gas exhaust valve **18** to protect the transistor from a voltage spike when the solenoid current is interrupted.

In the operation of the circuitry of FIG. **6,** the pressure sensor at the right atrium provides a positive signal upon which is impressed the collector voltage developed by the base current generated by the right atrial pressure. The pulse rate of the "Rate Control" is controlled by the voltage of the "Right Atrial Pressure Sensor" to provide a train of pulses to the "Gas Inlet Control" and the "Gas Exhaust Control." The respective gas inlet and exhaust switching networks are operated by their controls so that the valves are actuated at rates determined by the pressure in the right atrium, and the inlet switching network is additionally controlled to narrow the proportion of maximum pulse width sent to the gas inlet valve solenoid coil except when a predetermined high pressure of the right atrium is exceeded. Thus, as the body sends back blood to the heart at a greater rate, the heart's pumping capacity is increased by increasing both the stroke of the cylinder head assembly **16** and the frequency or number of strokes per minute.

FIG. **7** depicts a "Pulmonary Edema Protector" and is effectively a blood switching system which prevents the flow of blood to the lungs during those periods when the average pulmonary blood pressure is excessive. When the pulmonary, arterial, average pressure rises above a predetermined value, the Schmidt trigger changes state and closes blood inlet valve **30** by which the blood would flow to the lungs through the right ventricle. The "Pulmonary Edema Protector" includes two transistors, the emitters of which are connected together and maintained above ground potential by a resistor. Each collector is connected through a resistor to the positive terminal, and the bases are each biased by a resistor to ground. The input signal is coupled through a resistor from the "Pulmonary Arterial Pressure Sensor" to the base of the first transistor, and the output signal from the collector of the first transistor is coupled by a resistor to the base of the second transistor.

The signal at the collector of the second transistor of the "Pulmonary Edema Protector" is coupled through a resistor to the base of the single transistor in the "Blood Inlet Switching Network," a circuit similar to the "Gas Exhaust Switching Network" described above with respect to FIG. **6.**

In operation, the opening or closing of the right ventricle blood inlet valve **30** is controlled by the "Blood Inlet Switching Network." Such valve is closed in response to any signal from the Pulmonary Edema Protector," which signal is sent only during the brief moments when the pulmonary arterial pressure exceeds the predetermined limit. The "Pulmonary Edema Protector" protects the system so that the lungs are protected from blood circulation rates greater than the lungs can at that moment satisfactorily process, even when the flow of blood back to the heart might suggest a greater circulation rate. Thus, the inlet valve **30** for the blood for the right ventricle is closed during those moments appropriate for responding to the ability of the lungs to process such rate of blood circulation, but is open much of the time.

In FIG. **8,** the voltage source is conducted through a zener diode voltage stabilizer to a feed liquid "Pump Rate/Duration Control," a multivibrator comprising two transistors of opposite conductivity type. The emitter of the first transistor is connected directly to the positive potential. The collector of the second transistor is connected by a resistor to such positive potential. The collector of the first transistor is connected through a resistor, and the emitter of the second transistor is connected directly to ground. The bases of the two transistors are interconnected by a symmetrical network, each including a base-to-collector resistor and a capacitor and resistor in series between the base of one transistor and the collector of the other. The feed liquid "Pump Switching Network" is essentially of the same configuration and operation as the "Gas Inlet Switching Network" of FIG. **6.**

In the operation of the circuitry of FIG. **8,** the oscillator of the rate control unit provides a train of pulses of controlled duration which actuate the heavy duty switching of the switching network unit to energize the solenoid **40** to operate the pump **39** at a predetermined constant rate. By appropriate choice of the resistors in the symmetrical base-collector network of the feed liquid pump rate/duration control, the relative time between adjacent pulses as well as the pulse duration can be readily controlled.

The embodiments of ny invention described in great detail are merely illustrative of the invention. Certain obvious modifications might eventually be apparent to those skilled in this art without departing from the spirit and scope of my invention as set forth in the claims.

What is claimed is:

1. An implantable artificial heart having a housing of a size to fit within the chest cavity after removal of a major portion of the natural heart, said housing enclosing:

a radioisotope thermal energy source;

a thermoelectric converter positioned to convert a first portion of the thermal energy of the radioisotope to electrical energy;

a Rankine cycle engine, said engine having a working fluid boiler tube positioned to absorb a second portion of thermal energy of the radioisotope, said engine having a stationary piston and a reciprocally movable cylinder head assembly;

artificial left and right ventricles arranged so that when said cylinder head assembly moves in one direction, said ventricles are compressed to expel blood therefrom; and

electrical control means energized by said thermoelectric converter, said electrical control means regulating at least one of the rate and stroke of reciprocation of said cylinder head assembly.

2. The device of claim **1** wherein said engine contains:

a condenser tube extending from a piston exhaust valve to a feedliquid pump, said condenser tube comprising capillary internal surfaces.

a feedliquid pump driven by a solenoid adapted to pump working liquid to said boiler tube, and

said boiler tube at least partially surrounding said thermal energy source said boiler tube being adapted to convert a working fluid from liquid to gas.

3. The device of claim **1** further including a pusher plate assembly reciprocatingly actuated by said cylinder head assembly adapted to simultaneously compress both said left ventricle and said right ventricle.

4. The device of claim **1** wherein said thermoelectric converter is comprised of a series of silicongermanium semiconductor thermocouples and is disposed adjacent to said source of thermal energy.

5. The device of claim **1** wherein said isotope is a Pu_{238} compound and is shielded by a platnium capsule.

6. The device of claim **5** wherein said capsule contains an absolute filtered vent to conduct helium generated by said isotope directly into an interstitial fluid and thereafter into the bloodstream.

7. The device of claim **1** further including sensing means for sensing a physiological variable, electrical control circuits powered by electricity from said thermoelectric converter and adapted to electronically regulate at least one of the cycle rate and cylinder stroke length of the reciprocally moving cylinder head assembly in response to said physiological variable to actuate a signal feed back means to the control circuits, there being an electromagnetic working fluid inlet valve and an electromagnetic working fluid exhaust valve regulated by said control circuits.

8. The device of claim **7** wherein said electrical control circuits have means adapted to vary both pulse rate and cylinder stroke length.

9. The device of claim **8** wherein said sensing means senses blood pressure, and wherein there are electronic means converting the signal to a filtered smoothly varying potential indicative of average blood pressure, said potential being applied to a multivibrator to regulate the oscillation frequency, and to a control for the working fluid inlet valve to regulate the width of pulse and duration of inlet valve opening.

10. The device of claim **1** in which the electrical control means powered by electricity from said thermoelectric converter includes sensing means to determine average pulmonary blood pressure, an electromagnetic valve at the blood inlet to the right artificial ventricle adapted to control the time when blood may enter said right ventricle, said control means being adapted to hold said valve closed when said average pulmonary blood pressure is sensed to be above a predetermined level.

11. The device of claim **2** wherein said condenser tube is a tube having an inner surface lined with metal wick which is adapted to condense working fluid gas to liquid and conduct capillary flow of condensate regardless of attitude of device.

12. The device of claim **11** wherein said metal wick has a composition of sintered titanium-aluminum-vanadium alloy.

13. The device of claim **2** wherein said feedliquid pump solenoid is controlled by an electrical circuit which is adapted to reciprocate a piston in said pump at a controlled rate so as to supply working liquid to said boiler tube at a controlled rate.

14. The device of claim **2** further including a flexible cylindrical bellows exterior to said piston adapted to prevent working fluid from leaking from said cylinder and to direct any leakage of working fluid to said condenser.

15. The device of claim **14** further including a second flexible bellows exterior to and concentric with the first bellows, the annular inter-bellows zone containing xenon providing a relative gas pressure adapted to compensate against adverse effects from varying pressures affecting said cylinder head assembly.

16. The device of claim **2** further including a condenser and a relief valve direction excess gaseous working fluid from said boiler tube to said condenser, said valve being adapted to release excess gas from said boiler at times when the pressure in said boiler exceeds predetermined limits.

17. A self-contained implantable artificial heart comprising:

a compound of Pu_{238} isotope source of thermal energy;

a thermoelectric converter positioned adjacent said isotope and adapted to convert a first portion of said thermal energy into electric power;

an electric solenoid driven feed pump adapted to force liquid working fluid into a boiler tube;

a boiler tube surrounding the combination of said isotope source and said thermoelectric converter adapted to boil said liquid working fluid received from said feed pump by converting a second portion of said thermal energy, said boiler tube directing resultant vapor of said working fluid toward a vapor inlet valve;

a Rankine cycle working fluid engine driven by the hot working fluid vapor, said engine having a reciprocally movable cylinder head assembly;

an electromagnetically operated inlet valve for vapor of the working fluid adapted to allow vapor to pass from said boiler into an expansion zone;

an electromagnetically operated vapor exhaust valve adapted to allow vapor to pass out of said expansion zone;

a low pressure capillary condenser adapted to condense vapor to liquid working fluid and to reject condensate heat into an interstitial fluid, said liquid

working fluid being directed from said condenser to said feed pump;

left and right artificial ventricles adapted to be simultaneously compressed by said reciprocating cylinder head assembly and to expel blood when compressed, said interstitial fluid having heat transfer relationship with said artificial ventricles; and

a housing enclosing said source, converter, pump, boiler tube, engine, inlet valve, exhaust valve, condenser, and ventricles, said housing being of a size to fit within the chest cavity after removal of a major portion of the natural heart.

18. The device of claim **17** wherein means adapted to sense a physiological variable actuate electrical control means adapted to vary the opening and closing of said inlet and exhaust valves, thereby modifying the blood circulation rate in response to changes in said physiological variable.

* * * * *

UNITED STATES PATENT OFFICE

CERTIFICATE OF CORRECTION

Patent No. 3,828,371 Dated August 13, 1974

Inventor(s) David L. Purdy

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Claim 16, line 2, "direction" should read -- directing --.

Signed and sealed this 26th day of November 1974.

(SEAL)
Attest:

McCOY M. GIBSON JR.
Attesting Officer

C. MARSHALL DANN
Commissioner of Patents

FORM PO-1050 (10-69)

USCOMM-DC 60376-P69
★ U.S. GOVERNMENT PRINTING OFFICE : 1969 O—366-334