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PROGRESS REPORT

MASTER

TITLE: BIOMEDICAL ENGINEERING SUPPORT

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PROGRESS DURING PAST YEAR

Since the beginning of the contract in June, considerable knowledge has been gained concerning the power requirements of an artificial heart in the human, the efficiencies and losses of artificial hearts and the design restrictions of mating an artificial heart to a nuclear engine. A summary of the results of our study up to this time follows.

I. Projected Power Requirements of an Artificial Heart in the Human

Because of the scarcity of data relating cardiac output to various types of activity in humans, an indirect method of determining cardiac output was used. A linear relationship between cardiac output and oxygen consumption has been found by several investigators (1) (2) (3).

Equation 1 was derived from the data presented by Guyton (1):

$$Q = 6.9 V_{O_2} + 5.2 \quad (\text{Equation 1})$$

Q is cardiac output in l/min.

V_{O_2} is oxygen consumption in l/min (STPD)

Since the metabolic energy equivalent of oxygen is 4.825 Kcal/l, the rate of change of cardiac output with metabolic energy utilization is:

$$\frac{dQ}{d\dot{E}_m} = \frac{6.9}{4.825} = 1.43 \frac{\text{l/min}}{\text{Kcal/min}}$$

The average resting cardiac output for adult humans has been found to be approximately 6 l/min. The cardiac output may be calculated by adding the output required for activity to the resting value.

$$Q = 1.43 \dot{E}_m + 6 \text{ l/min} \quad (\text{Equation 2})$$

$\dot{E}_m$ is the metabolic energy utilization in excess of the basal metabolism (Kcal/min). Once an activity profile has been established and the energy requirements of each activity determined, the cardiac output profile can be calculated using Equation 2. The power required to drive an artificial left

ventricle is given by Equation 3:

$$\dot{E}_L = \frac{Q \text{ Pa}}{450 N_L} \text{ watt} \quad (\text{Equation 3})$$

Pa is the mean arterial pressure in mm Hg.

N_L is the efficiency of the ventricle.

The activity profiles used to calculate the daily power profile are based on the Reference Man and Woman described by the Food and Agriculture Organization of the United Nations (4). The following description of the Reference Man and Reference Woman is quoted from reference 5:

The Reference Man is 25 years of age. He is healthy, that is, free from disease and physically fit for active work. He weighs 65 kilograms. He lives in the temperate zone at a mean annual temperature of 10° C. He consumes an adequate well-balanced diet and neither gains nor loses weight. On each working day he is employed 8 hours in an occupation which is not sedentary, but does not involve more than occasional periods of hard physical labor. When not at work, he is sedentary for about 4 hours daily and may walk up to 1½ hours. He spends about 1½ hours on active recreation and household work. The Reference Man as defined above is assumed to require an average for the entire year, 3200 (kilo) calories daily.

The Reference Woman is a similarly healthy woman aged 25 years, and weighing 55 kilograms. She lives in the same environment as the Reference Man. She may be engaged either in general household duties or in light industry. Her daily activities include walking for about 1 hour and 1 hour of active recreation, such as gardening, playing with children, or nonstrenuous sport. The Reference Woman is assumed to require on an average for the entire year, 2300 (kilo) calories daily.

The actual weights of the man and woman used to obtain the power profiles are 68 kg and 60 kg, to match the energy tables of reference 6.

Table 1 shows the activity profile of the male along with the metabolic energy profile, cardiac output profile, right ventricular power profile, left ventricular profile and total heart power profile. Table 2 gives the same information for the female. The basal metabolic rates were determined from reference 5.

ACTIVITY, ENERGY, OUTPUT AND POWER PROFILES FOR MALE

(Age 25 years, Height 173 cm, Weight 68 kg)

ACTIVITY	DURATION Hours	RATE OF ENERGY UTILIZATION Kcal/min	CARDIAC OUTPUT L/min	POWER REQUIRED TO DRIVE ARTIFICIAL		
				RIGHT VENTRICLE Watt	LEFT VENTRICLE Watt	TOTAL HEART Watt
Sleep	8	0	6	0.33	2.22	2.55
Dressing, Etc.	1	2.12	9.03	0.50	3.35	3.85
Driving	½	1.62	8.32	0.47	3.08	3.55
Moderate Work	4	1.82	8.6	0.48	3.18	3.66
Walking	½	3.12	10.5	0.59	3.90	4.49
Lunch	½	0.26	6.37	0.36	2.36	2.72
Walking	½	3.12	10.5	0.59	3.90	4.49
Moderate Work	4	1.82	8.6	0.48	3.18	3.66
Driving	½	1.62	8.32	0.47	3.08	3.55
Moderate Exercise	1	3.82	11.5	0.65	4.25	4.90
Dinner	1	0.26	6.37	0.36	2.36	2.72
Relaxation	3	0.82	7.17	0.40	2.65	3.05

TABLE I

Aortic Pressure - 100 mmHg

Pulmonary art. pressure - 15 mmHg

Basal Metabolic Energy - 1700 Kcal/day

Artificial heart efficiency - 60%

Average power requirement - 3.23 watt

Total Metabolic Energy - 3294 Kcal/day

ACTIVITY, ENERGY, OUTPUT AND POWER PROFILES FOR FEMALE

(Age 25 years, Height 165 cm, Weight 60 Kg)

ACTIVITY	DURATION Hours	RATE OF ENERGY UTILIZATION Kcal/min	CARDIAC OUTPUT L/min	POWER REQUIRED TO DRIVE ARTIFICIAL		
				RIGHT VENTRICLE Watt	LEFT VENTRICLE Watt	TOTAL HEART Watt
Sleep	8	0	6	0.33	2.20	2.53
Dressing, Etc.	1	2.32	9.32	0.52	3.46	3.98
Domestic Work	5	0.5	6.72	0.37	2.47	2.84
Lunch	1	0.26	6.37	0.36	2.36	2.72
Driving	¼	1.62	8.32	0.46	3.08	3.54
Walking	1	1.86	8.66	0.48	3.22	3.70
Driving	¼	1.62	8.32	0.46	3.08	3.54
Domestic Work	2	0.5	6.72	0.37	2.47	2.84
Dinner	1	0.26	6.37	0.36	2.36	2.72
Domestic Work	½	0.5	6.72	0.37	2.47	2.84
Exercise	1	2.0	8.86	0.49	3.29	3.78
Relaxation	3	0.5	6.72	0.37	2.47	2.84

Aortic Pressure - 100 mmHg
Pulmonary Art. Pressure - 15 mmHg
Basal Metabolic Energy - 1480 Kcal/Day

Artificial Heart Efficiency - 60%
Average Power Requirement - 2.9 watt
Total Metabolic Energy 2304 Kcal/day

TOTAL HEART POWER PROFILE FOR MALE

AGE - 25 YEARS

HEIGHT - 173 CM

WEIGHT - 68 Kg

POWER REQUIRED TO
DRIVE HEART ~ WATTS

FIGURE 1

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TOTAL HEART POWER PROFILE FOR FEMALE

AGE - 25 YEARS

HEIGHT - 165 CM

WEIGHT - 60 Kg

POWER REQUIRED TO DRIVE
HEART - WATTS

AORTIC PRESSURE - 100 mmHg

PULMONARY ARTERY PRESSURE - 15 mmHg

HEART EFFICIENCY - 60 %

AVERAGE POWER - 2.9 WATT

DAILY ENERGY REQUIREMENT - 2304 KCAL

TIME - HOURS

F.M. DONOVAN 7/28/71

FIGURE 2

TOTAL HEART POWER VARIATION WITH BODY WEIGHT

AORTIC PRESSURE - 100 mmHg
 PULMONARY ART. PRESS - 15 mmHg
 HEART EFFICIENCY - 60%

POWER REQUIRED TO DRIVE HEART ~ WATT

TOTAL BODY WEIGHT ~ Kg

F.M. DONOVAN 3/29/71

FIGURE 3

TOTAL HEART POWER VARIATION WITH AGE

AORTIC PRESSURE - 100 mm Hg
PULMONARY ART. PRESS. - 15 mm Hg
HEART EFFICIENCY - 60 %

POWER REQUIRED TO DRIVE HEART ~ WATT

3.5

3.0

2.5

MALE, HEIGHT 173 CM, WEIGHT 68 KG

FEMALE, HEIGHT 165 CM, WEIGHT 60 KG

AGE ~ YEARS

F.M. DONOVAN 3/29/71

Figures 1 and 2 show the power profiles of the total heart for the male and female respectively. The variations in average power requirements of the artificial heart with weight for the 25-year-old man and woman are shown in Figure 3. The variations with age are shown in Figure 4. These variations were calculated from data given in reference 5.

A paper based on this study, titled "Power Requirements of the Artificial Heart in Humans" by F.M. Donovan Jr. and W.J. Kolff will be presented at the Federation of American Societies for Experimental Biology meeting in Atlantic City, N.J. on April 12, 1972.

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II. Efficiencies and Losses in the Kwan-Gett Artificial Heart

The following powers were measured for the Kwan-Gett artificial left ventricle (Fig. 5):

1. Input power to the air drive line
2. Input power to the air chamber
3. Input power to the diaphragm
4. Output power from the diaphragm
5. Input power to the mock circulation

A venturi meter combined with an analog computer (Fig. 6) was used to determine the input power to the air drive line (location 1 of Fig. 5). A differential pressure transducer converts the pressure drop in the venturi meter to an electric potential which is in turn converted to a flow signal in a function generator. A multiplier converts the air flow signal and air pressure to power according to the equation:

$$\dot{E} = Q \times P \quad (\text{Equation 4})$$

Since only the input power is of interest, a switching circuit is used to set the air flow signal to zero during the time when air is flowing out of the system.

In order to measure the input power to the air chamber, the venturi meter is moved to the proximal end of the air drive line (location 2 of Fig. 5).

A volume sensing mock circulation was used in the determination of the power input to the diaphragm (location 3 of Fig. 5) and the power output from the diaphragm (location 4 of Fig. 5). The mechanical energy transfer at the moving boundary of a cyclic system is given by the equation:

$$E = \oint PdV \quad (\text{Equation 5})$$

FIGURE 5

AIR LINE POWER MEASUREMENT SYSTEM

FIGURE 6

E = energy transfer per cycle

V = Volume of the system

P = pressure of the system

$\oint$ refers to integration over one complete cycle. The rate of energy transfer across the diaphragm is given by:

$$\dot{E} = E \times \text{Heart Rate} \quad (\text{Equation 6})$$

The system used for these determinations is shown in Figure 7. Fluid is pumped into the arterial reservoir by the artificial heart. Fluid drains from the arterial reservoir through the resistance valve and flow meter into the venous reservoir and from the venous reservoir back into the artificial heart. The entire system is rigid except for the heart itself, so that the only way the volume of the system can change is by a change in the volume of fluid in the heart. A measure of the volume of fluid in the mock circulation is also a measure of the volume of the blood chamber of the heart. The proper arterial and venous compliances are provided by sealed air chambers in the mock circulation. The relationship between the volume of air and the pressure in these chambers is:

$$P = \left(\frac{C_1}{V} \right) r \quad (\text{Equation 7})$$

P = air pressure (absolute)

V = air volume

r = specific heat ratio for air

C_1 = constant

The process is essentially adiabatic because the heart rate is too rapid to allow time for thermal equilibrium between the air and walls of the system. For small changes in V, the fractional change of volume is small so that the pressure volume relationship can be approximated by:

$$\Delta P = C_2 \Delta V \quad (\text{Equation 8})$$

VOLUME MEASURING MOCK CIRCULATION

In the present system, an error of about 1% results from the approximation. The total volume change of the fluid in the mock circulation is obtained by adding the calibrated pressure signals from the two air chamber transducers to produce a volume signal. This signal now indicates the changes in volume of the heart blood chamber. The air chamber volume changes are equal in magnitude but opposite in sign to those in the blood chamber.

The volume signal is placed on the vertical axis of an oscilloscope and either the blood chamber or air chamber pressure signal is placed on the horizontal axis. The pressure volume diagrams are photographed and integrated manually with a planimeter.

The input power to the mock circulation is calculated from the mean arterial pressure and mean flow rate by the equation:

$$\dot{E} = \bar{P} \times \bar{Q} \quad (\text{Equation 9})$$

$\bar{P}$ = Mean arterial pressure

$\bar{Q}$ = Mean flow rate

In fact, equation 9 is not correct even though it is commonly used to calculate cardiac output power. The equation is valid only for non-pulsatile flow. A calculation by the author using a mean pressure of 100 mm Hg and pulse width of 40 mm Hg with a sinusoidal arterial pulse wave and constant arterial resistnace indicates that the power calculated by equation 6 will be about 8% below the true value. Even though the error exists in equation 6, it was still used because power calculations in vivo are commonly done this way and power requirements of the artificial heart in humans were determined using this equation.

The results of one complete series of tests are presented for a constant heart rate of 120 beats per minute, mean arterial pressure of 100 mm Hg, systolic duration 42% of the cardiac cycle and a drive pressure of 6 psi. Venous pressure was varied from 0 to 20 mm Hg.

The effect of venous pressure on cardiac output is shown in Figure 8. Figure 9 shows the average powers at the five locations shown in Figure 5. Note that most of the power losses are associated with the air chambers because of the energy wasted in gas compression. The power losses in the diaphragm and valves are relatively small.

The efficiency was calculated for three locations by the equation:

$$N_i = \frac{\dot{E}_i}{\dot{E}_5} \times 100\% \quad (\text{Equation 10})$$

- N_i - efficiency for location i

$\dot{E}_i$ = power measured at location i

$\dot{E}_5$ = power input to mock circulation

Figure 10 shows the efficiencies calculated for the blood chamber, air chamber and distal air line. The blood chamber efficiency is an indication of the efficiency of the valves and fluid flow characteristics of the heart. The air chamber efficiency includes the efficiency of the diaphragm. The distal air line efficiency includes the effects of gas flow and compression.

The volumetric efficiency of the artificial heart was calculated from the equation:

$$\text{Volumetric Efficiency} = \frac{\text{Cardiac Output} \times 100}{\text{Stroke Volume} \times \text{Heart Rate}} \% \quad (\text{Equation 11})$$

A plot of volumetric efficiency against venous pressure is shown in Figure 11.

Figure 12 shows the maximum blood chamber pressures.

The artificial ventricle used to obtain the data in this section was a 7 cm Kwan-Gett hemispherical ventricle made of smooth Silastic flap inflow valve and a Silastic tricuspid outflow valve. The drive system used was a Kwan-Gett drive system. Some important points to note concerning power are:

CARDIAC OUTPUT

KWON-GETT LEFT VENTRICLE

No. KG T-14.2 LIFTV

ARTERIAL PRESS. - 100 mmHg

HEART RATE - 120 BEAT/min

SYSTOLIC DURATION - 42%

DRIVE PRESS. - 6 psi (320 mmHg)

FLUID - 33% GLYCERIN IN H₂O

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AVERAGE POWER

KWAN-GETT LEFT VENTRICLE

No. KG T-14.2 LIFTV

ARTERIAL PRESS. - 100 mmHg

HEART RATE - 120 BEAT/min

SYSTOLIC DURATION - 42%

DRIVE PRESS. 6 psi

FLUID - 33% GLYCERIN IN H_2O

DONOVAN 12/26/71

FIGURE 10

EFFICIENCIES

KWAN-GETT LEFT VENTRICLE

No. K-G T-14.2 LIFTV

ARTERIAL PRESS. - 100 mmHg

HEART RATE - 120 BEAT/min

SYSTOLIC DURATION - 42%

DRIVE PRESS - 6 psi

FLUID - 33% GLYCERIN IN H_2O

DONOVAN 12/26/71

FIGURE 11

VOLUMETRIC EFFICIENCY

KWAN-GETT LEFT VENTRICLE

No. KG T-14.2 LIFTV

ARTERIAL PRESS. 100 mmHg

HEART RATE - 120 BEAT/min

SYSTOLIC DURATION - 42%

DRIVE PRESS - 6 PSI

FLUID - 33% GLYCERIN IN H_2O

MAXIMUM BLOOD CHAMBER PRESSURE

KHAN - GETT LEFT VENTRICLE

NO. K-G T 14.2 LIT TV

ARTERIAL PRESSURE - 100 mmHg

HEART RATE - 120 BEAT/min

SYSTOLIC DURATION - 42%

DRIVE PRESSURE - 6 PSI

FLUID - 33% GLYCERIN IN H₂O

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1. The power loss in the air drive line and in the air chamber is due mainly to compression of the gas and is relatively constant regardless of cardiac output. This power loss is approximately 2 watts.
2. The power loss in the diaphragm itself is also relatively constant and is approximately 0.3 watts.
3. The remaining power loss is due to the regurgitation and frictional pressure drop across the valves and the viscous effects in the heart itself. This loss varies with cardiac output, varying from 0 at 0 cardiac output to approximately 0.4 watts at 10.4 liters per minute cardiac output.
4. The efficiency of greatest importance in the design of a power supply for a diaphragm type artificial heart is the efficiency measured at the input to the diaphragm. In this heart the efficiency for energy input to the diaphragm is approximately 70 to 75% in the normal range of cardiac outputs from 6 to 10.4 liters per minute.
5. A final item which is of importance in the design of any pump is the volumetric efficiency. In the range of normal cardiac outputs from 6 to 10.4 liters per minute, the volumetric efficiency of this particular heart is approximately 90%.

The effects of heart rate and arterial pressure on the efficiency and power measurements are summarized in the following paragraph.

Arterial pressure has little effect except at high venous pressures where increased arterial pressure reduces the output. At low venous pressures, the heart rate has little effect on cardiac output. At high venous pressures, the cardiac output is reduced by a reduction in heart rate.

The average input power to the heart diaphragm is increased by increasing

the arterial pressure. The effect of heart rate on input power to the heart diaphragm is practically the same as the effect of rate on cardiac output. The efficiency of the artificial heart measured at the input to the diaphragm is increased by an increase in arterial pressure and practically unaffected by changes in rate except at low venous pressures where increasing the rate tends to reduce the efficiency. The volumetric efficiency decreases with increasing arterial pressure because of increased valve leakage. Increasing the heart rate tends to increase the volumetric efficiency. The maximum air chamber pressure increases with decreasing arterial pressure and increases with decreasing rate. It should be kept in mind that the maximum air chamber pressure is a function, not only of the force required to move the diaphragm, but also a function of the air supply. The maximum blood chamber pressure is a good indication of the maximum force required to move the diaphragm. Increasing the arterial pressure increases the maximum blood chamber pressure. The heart rate had little effect on maximum blood chamber pressure.

A paper titled "Thermodynamic Study of the Artificial Heart Using a Volume Sensing Mock Circulation" by F.M. Donovan Jr. will be presented at the Biomedical Engineering Society meeting in Baltimore, Md. on April 8, 1972.

III. In Vivo Verification of In Vitro Tests

One animal experiment has been completed in which the mock circulation measurements on the artificial heart were verified. The following is a clinical summary of that experiment.

A. Clinical Summary of Experiment TH 72 C7 H1 AEC 1

On February 4, 1972, a 7 cm K-G heart made of Silastic, coated with dispersion using Silastic flap inflow and Silastic tricuspid outflow valves, was implanted using deep hypothermia with circulatory arrest in an 84 kg female calf. This heart was capable of pumping a maximum of 11 L/min. No problems were encountered during the surgical procedure itself. During the first 24 hours after surgery the animal showed some signs of brain damage. The symptoms were what appeared to be uncontrolled muscular contractions which increased to convulsions from time to time. The animal was treated with anti-convulsants, sedatives and steroids for a period of 24 hours. At the end of this time, the symptoms of brain damage had disappeared and the animal appeared to be quite content. However, after the first day the animal made only feeble attempts to stand up. The animal was extubated at 10 hours and received no respiratory support from that point on. The pH remained relatively constant throughout the experiment, between 7:45 and 7:55. After the first five hours of pumping, no sodium bicarbonate was required to maintain the pH. Except for some variations during the first 10 hours of pumping, the pCO_2 remained normal between 35 and 45 mg Hg. The arterial oxygen saturation remained above 89% after the first 10 hours without any respiratory support. The hematocrit remained relatively constant throughout the experiment. No blood was given after the first 24 hours of pumping, and the hematocrit remained above 25% until termination at 117 hours. The

arterial blood pressure was maintained quite well throughout the experiment. Mean arterial pressure after the first ten hours did not drop below 100 mm Hg. The central venous pressure measured in the femoral vein tended to increase during the experiment from a value of about 15 mm Hg at 10 hours to a value of 20 mm Hg near termination. The cause of this increasing femoral venous pressure is not known. However, the cardiac output as determined from a mock circulation comparison after the experiment, indicated that the cardiac output increased from approximately 6 L/min at 10 hours to approximately $8\frac{1}{2}$ L/min at 117 hours. This would correspond to a right atrial pressure of -1 mm Hg and a left atrial pressure of 1 mm Hg at 19 hours and at 117 hours, a right atrial pressure of 3 mm Hg and left atrial pressure of 6 mm Hg. The free plasma hemoglobin remained low throughout the experiment, never increasing above a value of $8\frac{1}{2}$ mg%. This is to be expected since this was a smooth heart. The functional residual capacity of the lungs tended to decrease with some variation throughout the experiment. A control value was $3\frac{1}{2}$ liters; this decreased at 100 hours to about 2.9 liters. The lung function toward termination, however, was actually improving. This corresponds to an increase in the functional residual capacity toward termination. The oxygen consumption remained relatively constant throughout the experiment at a value of about 400 ml/min. The tidal volume of the lungs remained relatively constant at about 600 ml. This corresponds to a control tidal volume of the same value. The power input to the distal end of the air drive line decreased from a value of about $7\frac{1}{2}$ watts at 10 hours to a value of about $6\frac{1}{2}$ watts at 117 hours. These values are slightly higher than the values measured during mock circulation tests. However, the drive system used in the mock circulation test could not be used in

the animal experiment because of mechanical difficulties and the drive system used in the animal experiment produced higher air flows, thus producing the higher distal air line input powers. The mock circulation results were verified after the experiment by using the same drive system on a mock circulation. The results produced on the mock circulation were then very close to the results measured in the animal. At termination, the animal was doing quite well, having good kidney function and good lung function. However, there was an infection inside the chest which probably originated from the chest incision. It is suspected that this infection took place while the animal was in the tub of warm water being rewarmed to a normal body temperature after the hypothermia. At autopsy, multiple large emboli were found in the arteries of both lungs. A total of 11 small old infarcts were found in the kidneys. This discrepancy in the number of clots found in the lungs and the kidneys seems to indicate that there was a great deal more clot formation in the venous system than in the arterial system. I do not know the reason for this. It may be that the hypothermia procedure itself, which uses one hour of circulatory arrest, produced clots in the venous system which were flushed through the right ventricle into the pulmonary system. I do not know this for a fact. There were virtually no clots in the artificial heart itself. As a result of this experiment, it was concluded that the power and efficiency measurements made on the small K-G ventricle are valid when compared to similar conditions in the animal.

B. Discussion of the Experiment

The power input to the distal end of the air drive line during the experiment is shown in Figure 13. An indirect determination of cardiac output was made by comparison with mock circulation results using the same heart and drive system. Figure 14 shows the results of this determination. These values of cardiac output are in the same range as

AVERAGE POWER INPUT TO DISTAL AIR LINE
TH 72 CTH1 AEC1

POWER ~ WATT

TIME ~ hrs

2/4/72 DOKOVAN

FIGURE 13

CARDIAC OUTPUT DETERMINED FROM
MOCK CIRCULATION TESTS
TH72 CTH1AEC1

CARDIAC OUTPUT ~ L/min

TIME ~ hr

3/4/72 DONOVAN

FIGURE 14

values now being determined directly from an animal with a total heart replacement. Femoral artery pressure is shown in Figure 15. Note that the mean arterial pressure remained relatively constant at about 100 mm Hg even though the systolic pressures were greater than 150 mm Hg. Figure 16 shows a record taken 82 hours after the artificial heart had been implanted in the calf. There appears to be some degree of damping in the femoral artery pressure line. For comparison, a mock circulation record is shown in Figure 17. The arterial pressure wave actually looks more like what we normally see in the calves. Note the similarities in average input power to the left air drive line and left air drive line pressure. In Figures 18 and 19, the instantaneous power input to the left air drive line is shown for comparison of animal results to mock circulation results.

It is evident from these records that the mock circulation results agree with the in vivo results.

FIGURE 16

TH72C7H7AEC1

82 hr

32

82 hr ↑

FIGURE 17

MOCK CIRCULATION RECORD

TH 72 C 7 H 1 A E C 1 M

82 hr

82 hr AFTER IMPLANTATION

FIGURE 18

INSTANTANEOUS INPUT POWER TO
LEFT AIR DRIVE LINE

7H72 CH1 AEC1

82%

100%

100%

100%

100%

FIGURE 19

MOCK CIRCULATION RECORD

40 WATT INSTANTANEOUS INPUT POWER TO
30 LEFT AIR DRIVE LINE
20
10
0

TH 72 C741 REC 1 M 82 h1

IV. In Vitro Test of Nuclear Powered Heart

Some consideration has been given to the establishment of an in vitro procedure for testing the nuclear powered artificial heart. The system must be tested on a mock circulation system which closely simulates, as far as the heart is concerned, the circulatory system of a 70 Kg human. A schematic of such a system is shown in Figure 20. The volumes shown are normal for a human, but need not be the same in a mock circulation. The compliances and resistances must be accurately matched, however.

The pulmonary resistance is a passive quantity and changes very rapidly with changes in pulmonary artery pressure. The systemic resistance is an active quantity and changes with a time constant of about 10 seconds with changes in systemic artery pressure. The baroreceptors are responsible for this response. The cardiac output in this system will be varied by changing the systemic venous pressure. The artificial heart itself will either be surrounded by a vacuum of about 5 mm Hg to simulate the vacuum in the chest cavity, or all of the pressures in the system will be referenced to a value 5 mm Hg greater than atmospheric pressure. The effect on the system will be the same in either case.

The transient response of the system will be determined with particular attention given to determining if there is a transient condition which may produce damaging effects in the patient, such as high pulmonary or aortic pressures or exceedingly low or high atrial pressures.

FIGURE 20

SCHEMATIC OF MOCK CIRCULATION FOR TOTAL HEART

C = COMPLIANCE $\left(\frac{\Delta V}{\Delta P}\right) \sim \frac{\text{ml}}{\text{mmHg}}$

R = RESISTANCE $\sim \frac{\text{mmHg}}{\text{ml/min}}$

V = VOLUME $\sim \text{ml}$

V. Preliminary Pump Design

A sketch of a preliminary artificial heart design suitable for mechanical drive is shown in Figure 20. The heart consists of a metal ring through which any necessary driving mechanisms can pass and to which flexible ventricles are attached. Each ventricle consists of a sac attached at one side to the mechanical actuator and attached at the other side to a flexible housing. The actuator itself will move along the axis of the heart. The diagram shows the actuator at one end of its travel so that the left ventricle is at the end of systole and the right ventricle is at the end of diastole. The actuator then moves to the other end, producing systole in the right ventricle and diastole in the left ventricle. This produces an alternating pulse in the left and right ventricle.

Response to Starling's Law is accomplished by allowing the housing to partially collapse at reduced stroke volumes. This also provides the reference pressure to the chest cavity so that no other compliance bag is necessary. The heart is designed so that with a volumetric efficiency of 90% based on measurements with the current Kwan-Gett heart, the cardiac output will be 12 liters per minute with a rate of 120 beats per minute.

There will be some bearing problems in maintaining a linear motion in the actuator, but they should not be unsurmountable. This design may lend itself to a variety of conversions from rotary shaft motion to the reciprocating motion necessary for the heart. The overall length of the device of 10.1 cms could be increased if absolutely necessary, to 14 cms. The outside dimensions of the device as shown in the schematic are the same as the outside dimensions of two 7 cm Kwan-Gett ventricles placed back to back.

FIGURE 21

MECHANICALLY DRIVEN ARTIFICIAL HEART

ALL DIMENSIONS ARE IN CENTIMETERS

STROKE VOLUME = 111 ml

DRAWN TO DOUBLE SCALE

STROKE LENGTH = 3.88 cm

VI. Compliance with Contract Requirements

All contract requirements have and are being met. The co-investigator, Francis M. Donovan Jr., has devoted approximately 75% of his time to this contract and will continue to devote 75% of his time during the remainder of the current contract term.

VII. Technical Reports

Two abstracts concerning this work have been published and papers presented at the Biomedical Engineering Society meeting and the Federation of American Societies for Experimental Biology meeting. These abstracts are shown below:

1. Donovan, F.M. Jr. and Kolff, W.J.: "Power requirements of the artificial heart." Federation of American Societies of Experimental Biology. Atlantic City, N.J. April, 1972.

Knowledge of the power requirements of the artificial heart is necessary for the proper design of a long-term implantable heart drive system. The artificial heart power requirements were determined for a hypothetical 25-year-old, 68 kg male, 173 cm tall requiring 3294 Kcal/day of metabolic energy and 25-year-old 60 kg female, 165 cm tall, requiring 2304 Kcal/day. These figures are based on the reference man and woman described by the Food and Agricultural Organization of the United Nations. Profiles of daily activity were established and the cardiac output for each activity determined by oxygen consumption obtained from metabolic data. The artificial heart power requirement for each activity was calculated from the cardiac output using aortic and pulmonary artery pressures of 100 and 15 mm Hg and an artificial heart efficiency of 60%. For the

male, the average power is 3.23 watt (cardiac output of 7.6 L/min) with a maximum of 4.9 watt (11.5 L/min) and minimum of 2.55 watt (6 L/min). Average power for the female is 2.9 watt (6.9 L/min) with a maximum of 3.98 watt (9.3 L/min) and minimum of 2.53 watt (6 L/min). For constant age and height, the average power increases as body weight increases (3.28 watt for 80 kg male, 3.05 watt for 70 kg female). With increasing age at constant body weight and height, the average power decreases (2.95 watt for 70-year-old male, 2.62 for 70-year-old female). Supported by U.S. Atomic Energy Commission Contract No. AT(11-1)-2155.

2. Donovan, F.M. Jr.: "Thermodynamic Study of the Artificial Heart Using A Volume Sensing Mock Circulation." Biomedical Engineering Society, April, 1972.

The purpose of this study was to determine the energy requirements and to study the causes of energy losses in the Kwan-Gett artificial heart (hemispherical diaphragm type of heart made of silicon rubber). The study was conducted in vitro. A venturi air flow meter coupled to an analog computer was used to determine energy input to the air drive lines. A mock circulation with built-in volume transduction was used to produce pressure volume diagrams which were used to calculate the energy transfers across the diaphragm. Thirty-three % Glycerin in water was pumped through the system by the heart. The proper arterial and venous compliances were provided by air chambers in the mock circulation. The pressure in these chambers was used to indicate the volume of fluid in the heart at any instant. The cardiac output and arterial pressure in the mock

circulation were used to calculate the power output of the heart.

At an output of 10.4 L/sec the input air power to the heart was 5.2 watt. The energy lost in compressing and moving the air was 2.0 watt.

Movement of the diaphragm required 0.3 watt while fluid flow and

valve leakage losses were 0.6 watt. The overall efficiency of the

heart under these conditions was 45%. Excluding the air flow and

compression losses increased the efficiency to 72%. The main energy

losses were caused by the compressibility of the driving air. Energy

dissipation by the diaphragm was minor. The fluid flow and valve

leakage losses amounted to about 26% of the total energy transferred to

the fluid by the diaphragm.

VIII. Remainder of Contract Term

During the remainder of the contract term approximately four animal experiments will be conducted to determine more accurately the in vivo power requirements of the Kwan-Gett artificial heart. By the end of the contract term all contract requirements will have been met.