Advanced Energy Systems Division

**ARTIFICIAL HEART
DEVELOPMENT
PROGRAM**

**QUARTERLY PROGRESS
REPORT**

January 1, 1977
Through
March 31, 1977

MASTER

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ARTIFICIAL HEART
DEVELOPMENT PROGRAM

PHASE III
QUARTERLY PROGRESS REPORT

JANUARY 1, 1977 THROUGH MARCH 31, 1977

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ADVANCED ENERGY SYSTEMS DIVISION
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INTRODUCTION AND SUMMARY

The Nuclear Powered Artificial Heart Prototype System Development Program is being conducted by the Westinghouse Advanced Energy Systems Division and its major subcontractor, the Philips Laboratories division of the North American Philips Corporation, as Phase III of the U. S. ERDA's Artificial Heart Program under Contract No. EY-76-C-02-3043. This report presents the technical progress and accomplishments on the active program tasks for the period from January 1, 1977 through March 31, 1977.

At the start of this reporting period the work program was directed to the completion of the IVBM system and the design of the Mark I Prototype System. As of February 1, 1977, however, the program was redirected, by ERDA decision, to provide an orderly phase out to be concluded by September 30, 1977. The aim of the present work plan is to provide as much useful information as possible.

New task numbers were assigned consistent with the various segments of the revised work plan and the general objectives of each new task are stated in this summary. Work performed in January under the prior direction is, with two exceptions, reported under the most closely related of the new tasks.

All Thermal Converter Research and Development effort under Task 50 was terminated as of January 31, 1977 and the work performed in January is reported under that task. The most significant accomplishment was the completion and successful testing of the prototype engine oil pump.

The Mark I Thermal Converter Design work under Task 62 was also terminated on January 31, 1977 and the January progress is reported under that task. Detail drawings were completed for the magnetic coupling and housing and for the cooler. Layouts were completed for the temperature compensated control valve and the oil pump.

New Task 65, Blood Pump Engineering Support, provides for the engineering efforts in support of maintaining, refurbishing, modifying, testing and implanting blood pumps, coupling mechanisms, cooling systems and electric drive motors. Included in the report under this task are the efforts under Task 51 - Blood Pump and Coupling Mechanism Research and Development and those portions relative to the blood pump under Task 54 - IVBM Modification Design and Task 58 - Field Support. Flexible shaft testing was continued and a new shaft with a heat treated Elgiloy wire core was placed on test. Bearing and lubricant testing continued without incident. Performance testing conducted on a blood pump with a compliance chamber resulted in good data reproducibility but a cardiac output lower than that obtained in similar tests without a compliance chamber. Thermal and power loss analyses of an IVBM blood pump with a directly attached electric motor were performed. Blood Pump Implant Experiment No. 41 was terminated 37 days after implantation.

The engineering effort in support of maintaining, refurbishing, modifying, testing and implanting of the electrically heated IVBM system and related equipment is provided under Task 66, IVBM System Engineering Support. Included in this report under Task 66 are the efforts under Task 49 - Thermal Insulation and Thermal Protection Research and Development, Task 52 - Waste Heat Rejection, Task 56 - IVBM System Performance Test and those portions of Task 54 - IVBM Modification Design and Task 58 - Field Support relative to the IVBM System or the thermal converter. Extensive testing of the electrically heated IVBM thermal converter was continued for both 1:1 and 1.1:1 gear ratios. Fabrication and outgassing of static vacuum multifoil insulation packages 5 and 6 was completed, pinchoff of packages 2, 3 and 4 was also completed. Detail drawings were completed for the thermal converter coolant line fittings and for the mold required to cast the thermal converter silastic covering. A successful sterilization test was performed in the thermal converter assembly and sterilization glove box.

New task 67 - Thermal Converter Support was not active in this period. This task provides the engineering effort to support implantations of the IVBM electrically heated thermal converter.

Task 68, Blood Pump Fabrication and Repair, provides for the maintenance, modification and

repair of blood pumps and related auxiliaries required to support implantations of blood pumps, both electrically driven and as part of complete IVBM systems. Incorporated in this report is the work under Task 55 - IVBM Fabrication relative to blood pumps. Blood pump No. 5 was assembled, tested and shipped to the University of Utah. Two compliance chambers were manufactured for pumps with a reduced right ventricle stroke volume.

New Task 69, IVBM System Preparation and Support, provides for the final fabrication and assembly, bench operational and performance testing and packaging and delivery of the electrically heated IVBM system and auxiliaries. It also provides for field assembly and check-out of these items, for assistance to animal experimenters, and for maintenance and repair services. Included in this report is the work performed under Task 55 - IVBM Fabrication as applicable to the thermal converter. In this period the electrically heated IVBM thermal converter assembly with coolant lines, thermal insulation and instrumentation leads was completed and the complete assembly was encapsulated in silastic.

Task 70, Life Testing, covers the life testing of the IVBM blood pump and of static vacuum multi-foil insulation packages. This report includes work done under Task 57 - IVBM System Life Testing. Life testing of blood pump No. 6 continued as did bakeout of static vacuum insulation packages without incident. A test of a backup duplicate of the IVBM electrical heater was terminated after 33 days due to a vacuum system leak.

Task 71, Quality Assurance, provides the quality control services required for the program, replacing Task 59 similarly titled. Activities continued under these tasks consistent with the program needs.

TASK 50 - THERMAL CONVERTER RESEARCH AND DEVELOPMENT

Preliminary layouts of the hot finger optical inspection fixture were prepared. The nature of the positioning mechanism was defined.

Results from the aluminum to titanium brazing investigations have been positive. The procedure which looks most promising is to first vacuum clad the titanium with a layer of aluminum, and then simply braze aluminum to aluminum. Samples of the first step were successful but the initial samples of the second step failed. However, the problem is not felt to be serious, and several procedural modifications to the aluminum-aluminum braze technique were being evaluated when work was suspended at the end of January.

Life testing of the rotary ferrofluid shaft seal continued. To the end of January, fixture No. 1 had accumulated 4382 hours of operation.

The ferrofluid filtering test continued through January. At that time, 3130 hours of operation had been accumulated with no change in pressure drop across the 2 micron filter.

The prototype engine oil pump was completed and tested. The pump is the most efficient of any yet constructed on this program. Typical performance characteristics with Tellus 25 oil at 600 rpm and 60 psig are:

Delivery:	0.0190 in ³ /sec
Input Power:	0.250 watt
Efficiency:	51%

Assembly of the rhombic drive for the lubrication system test fixture was initiated.

TASK 62 - MARK I THERMAL CONVERTER DESIGN

The following areas of Mark I design activity continued through January:

- The magnetic coupling and housing drawings (including the structural membrane) were completed.
- The cooler drawings were completed.
- A layout of the new temperature compensated control valve has been completed to aid in establishing a new mounting interface. The location of the control valve has not changed, but its manifold was modified to allow attachment of the valve to a horizontal shelf which extends above the flywheel housing.
- A roughing drawing for the crankcase was completed, and all machining procedures established. A braze drawing (for assembly of the buffer space) was finished, and the final machining drawing for the crankcase was started.
- A detailed layout of the oil pump was completed and an oil filter layout started. A smaller filter is required for the Mark I than had been constructed for the lubrication system test fixture.
- The Westinghouse interface drawing for the output of the magnetic coupling was studied and recommendations formulated. It was agreed that the right-angle gearbox O-ring would be incorporated into the gearbox flange rather than into the magnetic coupling membrane.
- The Westinghouse insulation package feedthrough interface drawing was also reviewed. The drawing of the hot finger feedthrough flange was updated to reflect the design shown in the interface drawing.

TASK 65 - BLOOD PUMP ENGINEERING SUPPORT

FLEXIBLE SHAFTS

The early failure of the first Elgiloy shaft, reported in the July - September 1976 Quarterly Progress Report*, was discussed with metallurgists at the Elgin Watch Company, the supplier of Elgiloy wire. It was learned that the fatigue strength of the Elgiloy shaft should be improved by heat treating the finished shaft cores at 980°F for 5 hours. An Elgiloy shaft with a heat treated core was then obtained from S.S. White and put on life test.

Other flexible shaft life tests in progress were continued. The test hours accumulated and shaft stiffness changes observed during this reporting period, as well as the total test hours to date, are shown in Table 65-1.

Testing of the IVBM type shaft with the Elgiloy wire core that had not been heat treated was terminated after 2531 hours of operation because broken core wires were observed when the shaft was relubricated. Although this shaft operated somewhat longer than the first Elgiloy shaft, which failed after 519 hours of operation, the performance of both shafts indicated that the core wire had a relatively low fatigue strength.

BLOOD PUMP BEARINGS AND LUBRICANTS

Life testing of standard and special blood pump bearings operating in jojoba and Vitrea 21 oils was continued. The bearing test hours accumulated during this reporting period and the total test hours to date are as follows:

Bearing MPB No.	Bearing Type	Oil	Test Hours Jan. thru March	Total Test Hours To Date
SR4	Ball - Single Row	Vitrea 21	2,160	17,880
F155	Ball - Double Row	Vitrea 21	2,160	5,664
F155	Ball - Double Row	Jojoba	2,160	12,528 ⁽¹⁾
F160	Ball - Double Row	Jojoba	2,160	11,496 ⁽²⁾
F338	Roller	Jojoba	2,160	7,248

(1) Oil changed from sperm to jojoba after 6,048 test hours.

(2) Oil changed from sperm to jojoba after 5,000 test hours.

*Westinghouse Advanced Energy Systems Division, "Nuclear Powered Artificial Heart Prototype System Development Program, Quarterly Progress Report COO-3043-26, July-September 1976", ERDA Contract EY-76-C-02-3043.

TABLE 65-1
 FLEXIBLE SHAFT LIFE TEST DATA

Type Shaft	Torque Loading	Test Hours Jan. thru Mar.	Total Test Hours To Date	Stiffness Change (in-oz/deg) Jan. thru Mar.
S.S. White - 3/16 Inch Dia. Core (Shaft No. 35)	Normal ⁽¹⁾ 2.75 x Normal	----- 1,577	2,088 13,842	----- None
S.S. White - 3/16 Inch Dia. Core (Shaft No. 156)	Normal 2.75 x Normal	----- 1,675	2,088 1,933	----- Decreased from 0.25 to 0.21
S.S. White - IVBM Config- uration (3/16 Inch Dia. Core), Grease Lubricated	Normal 2.75 x Normal	----- 1,572	964 8,639	----- None
S.S. White - IVBM Config- uration (3/16 Inch Dia. Core), Oil Lubricated	2.75 x Normal	1,577	9,207	None
S.S. White - IVBM Config- uration, Grease Lubricated, Teflon Lined Casing	2.75 x Normal	1,481	1,898	Decreased from 4.3 to 0.17.
S.S. White - IVBM Config- uration, Grease Lubricated, Elgiloy Wire Core (Not Heat Treated)	2.75 x Normal	165	2,531 ⁽²⁾	None
S.S. White - IVBM Config- uration, Grease Lubricated, Heat Treated Elgiloy Wire Core	2.75 x Normal	1,417	1,417	Decreased from 2.1 to 0.41.

(1) Pulsatile with amplitude of 0 to 24 to 0 in-oz and frequency of 4 pulses per second.

(2) Testing discontinued.

No change in frictional torque or evidence of significant wear of any of the bearings was observed during this testing.

Additional wear tests were performed with the four-ball tester to evaluate jojoba oil-additive combinations that could extend the operating life of the blood pump mechanism bearings and rollers. The most attractive additive tested is Argus Mark 260. The wear rate achieved by using one percent by weight of this additive in jojoba oil was 50 percent less than that obtained with pure jojoba oil. No significant swell or other physical change of silastic has been observed after 90 days of exposure to jojoba oil with Argus Mark 260 additive.

A test rig was built for roller and track testing to evaluate the improvements in operating life that can be achieved with low wear surface treatments and coatings.

IVBM BLOOD PUMP PERFORMANCE EVALUATIONS

A compliance chamber assembly, described in the previous Quarterly Progress Report*, was assembled on Blood Pump No. 4, which will be used in the first IVBM system implantation experiment. A photograph of the pump with the compliance chamber is shown in Figure 65-1. Performance testing of the pump was then carried out using the mock circulation loop. A schematic diagram of the test setup is shown in Figure 65-2. The tests were performed with a constant arterial pressure of 100 mm Hg and a variable venous pressure ranging from approximately -5 to +20 mm Hg. The data collected showed good reproducibility. However, the maximum cardiac output measured was ~20% lower than that obtained in similar tests at the University of Utah without a compliance chamber. Further testing will be performed with another set of ventricles to determine whether variations between ventricles of the same type have an important influence on the performance of the pump.

IVBM BLOOD PUMP WITH ATTACHED MOTOR DRIVE

An IVBM blood pump with an attached electric motor drive will be evaluated in bench and in vivo testing. A drawing of this assembly is shown in Figure 65-3. The drive system

*Westinghouse Advanced Energy Systems Division, "Nuclear Powered Artificial Heart Prototype System Development Program, Quarterly Progress Report COO-3043-27, October-December 1976 ERDA Contract EY-76-C-02-3043.

Figure 65-1. IVBM Blood Pump with Compliance Chamber

Figure 65-2. Schematic Diagram of Blood Pump-Mock Loop Test Setup

Figure 65-3. IVBM Blood Pump with Attached Motor Drive

of the assembly is filled with oil, which lubricates the system and transports most of the heat generated by the motor and mechanism to the ventricle diaphragms, where it is rejected to the blood. A small portion of the heat generated is conducted through the pump and motor housings to adjacent tissue.

A thermal analysis of the assembly was performed to determine the maximum operating temperatures. The following results were obtained using thermal oscillating pump (TOP) experimental data and assuming that 12.2 watts of heat are generated.

- 1) The peak pump housing temperature is $\leq 105^{\circ}\text{F}$, and no thermal insulation is required around the housing.
- 2) The upper limit of the temperature of the oil in the motor housing is less than 119°F . With good mixing of the oil in the motor and pump housings, the maximum temperature of the motor housing oil should be about 105°F ; and no thermal insulation would be required around the motor housing.
- 3) If the upper limit motor housing oil temperature of 119°F is assumed, $3/16$ inch thick polyethylene insulation is required around the housing to limit the heat flux to adjacent tissue to 0.01 watt/cm^2 . However, if the most likely case is considered (105°F temperature), no insulation should be required.

A power loss analysis was performed to calculate the oil churning losses and the mechanical losses of the assembly.

Electric Motor Oil Churning Losses - For calculation purposes the rotor of the motor is taken to be a smooth sided disc with a close fitting radial housing. The justification for the assumption is that it has given reasonable estimates of such losses in the past.

There are two sources of loss. The first is the pumping loss of the sides of the disc. The second is the shear in the radial gap. The pumping loss of the sides is calculated after Stodola*. The power loss is given by:

$$P = -125 C_m \frac{\rho}{g} \left(\frac{\text{RPM}}{60} \right)^3 (r)^5 \quad \text{where:}$$

- ρ = surrounding oil density - lb_f/ft^3
- g = gravitational constant - 32.2 ft/sec^2
- RPM = disc revolving speed - rev./min.
- r = disc radius - ft
- P = power - $\text{ft-lb}_f/\text{sec}$
- C_m = coefficient of loss - dim.

C_m is a function of Reynold's No. defined as $\frac{\rho r^2 \omega}{g \mu}$ where

$$\omega = \text{disc revolving speed - radians/sec} = 2\pi \left(\frac{\text{RPM}}{60} \right)$$

$$\mu = \frac{\text{viscosity of oil - lb}_f \cdot \text{sec}}{\text{ft}^2}$$

At a blood pump beat rate of 120/minute, the motor revolving speed is approximately 2250 rpm. In vivo, at an anticipated temperature of 110°F , the properties of jojoba oil are:

$$\rho = 53 \text{ lb}_f/\text{ft}^3$$

$$\mu = 3.5 \times 10^{-4} \frac{\text{lb}_f \cdot \text{sec}}{\text{ft}^2}$$

The Reynold's No. is 2400. At this Reynold's No. according to the tests of Goldstein as reported in Stodola, the value of $C_m \sim 0.11$. Substituting these foregoing values for speed, density, C_m and disc radius in the power loss equation gives:

$$P = -0.27 \frac{\text{ft} \cdot \text{lb}_f}{\text{sec}} = 0.37 \text{ watt}$$

*Stodola and Lowenstein, "Steam and Gas Turbines" Vol 1, McGraw - Hill Book Co., Inc. 1947.

The power loss from shear, in steady laminar flow in the radial gap, is given by:

$$P = -\mu \frac{A}{\ell} V^2$$

where A = area of the disc rim - ft²

ℓ = radial gap width - ft

V = velocity of disc rim - ft/sec = $r\omega$

Substituting the appropriate values into the foregoing equation:

$$P = 0.127 \frac{\text{ft-lb}_f}{\text{sec}} = -0.17 \text{ watt}$$

or the sum of the two losses is 0.54 watts

Speed Reducer and Actuator Mechanism Oil Churning Losses - Tests have been run on a 7.5 to 1 planetary speed reducer connected to an existing blood pump actuator mechanism to determine the oil churning losses associated with these elements together. The results are shown in Figure 65-4a. This is a plot of input power versus speed. On this plot are two curves. The lower is the loss of the speed reducer actuator mechanism combination with greased parts and air in the chambers. The upper is the loss with oil completely filling the assembly. The difference is the loss from oil churning. The tests were run at no load to improve the accuracy in determining the difference or loss from oil churning. The load being carried by the parts will have little effect on the oil churning losses. As might be expected, the difference varies almost as the speed cubed. At a 120 beats/minute this loss is about 0.2 watt.

The proposed speed reducer for this program will have an 18.9 reduction but will be attached to the same design actuator. The power out end is the same as the tested reducer. The power inlet end is different. It has a more rapidly revolving pinion of smaller diameter. Since oil churning loss varies as the revolving speed cubed and as the diameter to the fifth power, the oil losses may be slightly lower in the new design than in the tested assembly. In the tests performed, sperm whale oil was used instead of the presently proposed jojoba bean oil. These oils are very similar. The viscosity of the oils at a given temperature is about the same. The density of the jojoba oil is slightly less than that of sperm oil. Again, if anything, the churning losses should be slightly reduced.

Figure 65-4a Oil Loss-No Load

Figure 65-4b Speed Reducer Loss-Dry

Speed Reducer Power Loss - Total Mechanical Losses - The new 18.9 to 1 speed reducer has not been tested. Tests on the current 7.5 to 1 reducer are given in Figure 65-4b. These tests were run with greased parts and air filled chambers to allow the load losses to be separated from the oil churning losses. Because the speed reducer does have a friction loss at no load, the efficiency varies from 0 at no load to 87.5 percent at 1.75 watts input to 93 percent at 6 watts input. The efficiency is relatively flat from 30 percent to full load. It is estimated that the 2.52 increase in speed reduction from the current speed reducer to the new reducer will increase the losses from 7 to 10 percent at full load resulting in a full load efficiency of 90 percent for the 18.9 to 1 speed reducer.

The only additional mechanical loss besides the oil churning losses and the speed reducer losses is in the actuator mechanism. This loss is so small under load that we have not been able to measure it. The tare torque necessary to move any of the mechanisms must be by specifications less than 0.05 oz-in. Normal actual values are 0.01 oz-in.

The total mechanical losses at 6 watts output power from actuator mechanism to the blood pump at 120 beats/minute are then:

Speed Reducer Loss	0.62 watt
Speed Reducer & Actuator Mechanism Oil Loss	0.20 watt
Motor Oil Loss	0.54 watt
Total Mechanical Losses	<u>1.36 watt</u>

The overall mechanical efficiency of the electrical energy converter is therefore estimated to be 81.5 percent at full load at 120 beats/minute.

FIELD SUPPORT

Blood Pump Implant Experiment No. 41 was performed. The experiment was terminated 37 days after the blood pump was implanted because the condition of the test calf was deteriorating rapidly. When the animal was autopsied, a 1/4 inch long tear was observed in the left ventricle dome. It is believed that this tear was caused by the very high aortic pressures that

developed when the drive motor controller malfunctioned during the 18th day of the experiment and caused the motor to operate at a very high speed. Apparently, extensive bleeding occurred through the tear initially because anticoagulant drugs had been used to inhibit thrombus formation; but after the animal had received a large quantity of new blood, a clot formed at the tear and severely restricted the bleeding. The rapid deterioration of the animal's condition at the end of the experiment was attributed to severe sepsis around the motor and shaft and in the thorax.

After the drive motor controller that malfunctioned was examined, it was concluded that the malfunction was caused by overheating of a transistor module. The controller was then rebuilt with an improved circuit which should reduce heating and an external heat sink that will permit improved cooling.

TASK 66 - IVBM SYSTEM ENGINEERING SUPPORT

IVBM ELECTRICALLY HEATED THERMAL CONVERTER PERFORMANCE TESTING

Work continues on testing of the implantable electrically heated IVBM thermal converter. The test results to date are given in Table 66-1 for both 1:1 and 1.1:1 gear ratio cases. The converter was assembled according to the IVBM test plan operational procedures as revised for the electrically heated converter. Implantation weight oil was used in the crankcase and the speed control was initially locked in place. Heat was added to the crankcase using strip heaters and controlled to maintain $\sim 101^{\circ}\text{F}$. Cooling water to remove rejected waste heat was held constant at $\sim 120^{\circ}\text{F}$.

Runs 1, 2, 6, 7, 9 and 10 in Table 66-1 were made with the 1:1 gear box set-up and with the speed control locked in. Runs 3 and 5 are for the 1.1:1 gear box ratio case. Note, that only the initial data in Run 3 is for a locked-in speed control. The remaining data in Run 3 is for speed control conditions of 750 rpm and a torque of 4 in-oz. Run 8 should be disregarded altogether due to ineffective purging of the buffer gas and consequently possible contamination with either helium and/or air. The peak output power obtained in these tests is 4.8 watts. This compares to Philips maximum power output of 4.9 watts without a gear box attached. Scatter of the data in Table 66-1 can be attributed to difference in ambient room temperature, cooling water temperature and instrumentation accuracy and precision errors. After minimizing the effects of random errors, these data indicate ~ 0.5 watts higher power for the 1.1 gear ratio versus the 1.1:1 gear ratio case.

The data in Run 4 of Table 66-1 checks out the applicability of using the hysteresis brake in place of the dynamometer. Note that the recorded speeds are for the flywheel. These are 3:1 compared to the crankshaft. The hysteresis brake test gave comparable results to equivalent dynamometer type of load demands.

Figure 66-1 shows the effect of upper hot finger temperature on power output. In order to have power outputs greater than 4.0 watts to the pump, the hot finger temperature must be

TABLE 66-1

IMPLANTABLE ELECTRICALLY HEATED IVBM THERMAL CONVERTER PERFORMANCE TEST DATA

DATE (RUN NO.)	T/C 1	T/C 2	PROBE 1	PROBE 2	PROBE 3	SPEED	TORQUE	INPUT POWER	OUTPUT POWER	OIL PRESSURE	BUFFER ^(a) PRESSURE	WORKING PRESSURE	TIME	GEAR RATIO
	°F	°F	°F	°F	°F	rpm	in-oz	watts	watts	psig	psig	psig		
12/22/76 (1)	1439	1410	88.1	117.2	101.8	618	7.7	32.8	3.5	65	150	130/190	1121	1:1
12/22/76 (1)	1434	1415	90.2	119.6	102.2	614	7.9	32.8	3.6	65	150	130/190	1130	1:1
12/22/76 (1)	1463	1440	98.6	120.3	102.2	615	7.6	33.0	3.5	62	140	110/170	1215	1:1
12/22/76 (1)	1493	1460	99.8	120.5	101.7	615	8.6	33.0	3.9	63	150	125/185	1245	1:1
12/22/76 (1)	1500	1480	102.1	121.6	102.0	686	8.5	33.0	4.3	70	155	125/190	1307	1:1
12/22/76 (1)	1494	1475	101.9	121.5	102.4	620	9.1	33.0	4.2	62	160/170	125/190	1325	1:1
12/22/76 (1)	1500	1480	101.1	116.7	101.5	656	9.1	33.0	4.4	68	160/170	125/190	1408	1:1
12/22/76 (1)	1498	1475	103.5	118.7	101.6	658	9.5	33.0	4.6	66	165/175	150/195	1428	1:1
12/22/76 (1)	1491	1470	105.5	119.5	102.2	633	9.7	33.2	4.5	66	165/175	130/195	1524	1:1
12/29/76 (2)	1448	1410	90.3	119.2	103.8	627	7.7	32.6	3.6	65	165	125/180	1015	1:1
12/29/76 (2)	1438	1410	95.7	120.0	103.8	614	8.4	32.9	3.8	60	165	125/185	1030	1:1
12/29/76 (2)	1443	1412	99.7	119.3	103.7	614	8.8	32.9	4.0	60	160/170	120/185	1047	1:1
12/29/76 (2)	1451	1420	104.5	120.4	103.8	617	8.8	32.9	4.0	60	160/170	120/185	1100	1:1
12/29/76 (2)	1460	1430	107.2	120.8	103.6	632	8.8	32.9	4.1	62	160/168	120/185	1115	1:1
12/29/76 (2)	1464	1445	105.6	120.7	103.6	623	9.7	32.9	4.5	60	165/175	125/190	1125	1:1
12/29/76 (2)	1475	1450	107.4	122.0	103.7	631	9.8	32.9	4.6	60	165/175	125/190	1200	1:1
12/29/76 (2)	1484	1460	107.4	119.5	103.3	625	10.0	32.9	4.6	60	165/175	125/190	1250	1:1
12/29/76 (2)	1483	1455	107.9	119.3	103.3	620	10.0	32.4	4.6	60	165/175	125/190	1307	1:1
12/29/76 (2)	1482	1455	107.3	119.5	107.0	631	10.3	32.4	4.8	57	165/175	125/190	1323	1:1
12/29/76 (2)	1482	1455	107.6	119.4	104.4	618	10.2	32.4	4.7	60	165/175	125/190	1407	1:1
12/29/76 (2)	1482	1455	107.3	119.7	104.5	646	9.9	33.1	4.7	61	160/170	125/190	1430	1:1
12/29/76 (2)	1484	1460	106.1	119.0	101.5	645	9.6	33.1	4.6	65	160/170	125/190	1448	1:1
1/6/77 (3)	1439	1415	88.9	122.3	103.1	675	5.9	33.1	2.9	61	160/165	120/185	1018	1.1:1
1/6/77 (3)	1436	1410	89.3	122.8	103.4	688	7.2	33.1	3.7	61	165/175	125/190	1023	1.1:1
1/6/77 (3)	1436	1410	96.4	117.6	102.4	680	8.0	33.1	4.0	61	165/175	125/190	1045	1.1:1
1/6/77 (3)	1449	1420	102.2	119.5	102.4	690	8.2	33.1	4.2	62	165/175	125/190	1115	1.1:1
1/6/77 (3)	1456	1425	101.5	120.2	102.3	691	8.3	33.1	4.2	62	165/175	125/190	1135	1.1:1

T/C 1 - Hot Finger Temperature at Top
T/C 2 - Hot Finger Temperature at Bottom

Probe 1 - Outside Insulation Package Temperature
Probe 2 - Cooling Water Temperature
Probe 3 - Crankcase Oil Temperature

(a) 10 psig Should be Added to Buffer Gage Pressure for Correct Pressure.

TABLE 66-1 (Continued)

DATE (RUN NO.)	T/C 1	T/C 2	PROBE 1	PROBE 2	PROBE 3	SPEED	TORQUE	INPUT POWER	OUTPUT POWER	OIL PRESSURE	BUFFER PRESSURE ^(a)	WORKING PRESSURE	TIME	GEAR RATIO
	°F	°F	°F	°F	°F	rpm	in-oz	watts	watts	psig	psig	psig		
1/6/77 (3)	1466	1440	104.6	120.9	102.5	692	8.4	33.1	4.3	64	165/125	125/192	1215	1.1:1
1/6/77 (3)	1477	1450	103.3	120.8	102.6	684	8.5	33.1	4.3	61	165/175	125/190	1256	1.1:1
1/6/77 (3)	1489	1460	106.7	120.6	103.5	750	4.0	33.1	2.3	65	165/175	125/182	1350	1.1:1
1/6/77 (3) ^(b)	1489	1460	106.7	120.6	103.5	763	4.0	33.1	2.3	65	165/175	125/182	----	1.1:1
1/6/77 (3)	1489	1460	106.7	120.6	103.5	755	4.5	33.1	2.5	65	165/175	125/182	----	1.1:1
1/6/77 (3)	1489	1460	106.7	120.6	103.5	761	5.0	33.1	2.8	65	165/175	125/182	----	1.1:1
1/6/77 (3)	1489	1460	106.7	120.6	103.5	751	5.5	33.1	3.0	65	165/175	125/182	----	1.1:1
1/6/77 (3)	1489	1460	106.7	120.6	103.5	753	6.0	33.1	3.3	65	165/175	125/182	----	1.1:1
1/6/77 (3)	1489	1460	106.7	120.6	103.5	750	6.5	33.1	3.6	65	165/175	125/182	----	1.1:1
1/6/77 (3)	1489	1460	106.7	120.6	103.5	746	7.0	33.1	3.9	65	165/175	125/182	----	1.1:1
1/6/77 (3)	1489	1460	106.7	120.6	103.5	746	7.5	33.1	4.1	65	165/175	125/182	----	1.1:1
1/6/77 (3)	1489	1460	106.7	120.6	103.5	734	8.0	33.1	4.3	65	165/175	125/182	----	1.1:1
1/6/77 (3)	1489	1460	106.7	120.6	103.5	713	8.5	33.1	4.5	65	165/175	125/182	----	1.1:1
1/6/77 (3)	1489	1460	106.7	120.6	103.5	662	8.8	33.1	4.3	65	165/175	125/182	----	1.1:1
1/6/77 (3)	1489	1460	106.7	120.6	103.5	712	8.0	33.1	4.2	65	165/175	125/182	----	1.1:1
1/6/77 (3)	1489	1460	106.7	120.6	103.5	740	7.0	33.1	3.8	65	165/175	125/182	----	1.1:1
1/6/77 (3)	1489	1460	106.7	120.6	103.5	749	6.0	33.1	3.3	65	165/175	125/182	----	1.1:1
1/6/77 (3)	1489	1460	106.7	120.6	103.5	754	5.0	33.1	2.8	65	165/175	125/182	----	1.1:1
1/6/77 (3)	1489	1460	106.7	120.6	103.5	755	4.0	33.1	2.2	65	165/175	125/182	----	1.1:1
1/6/77 (3)	1489	1460	106.7	120.6	103.5	763	3.0	33.1	1.7	65	165/175	125/182	----	1.1:1
1/7/77 (4) ^(c)	1425	1380	86	115	102	1915	---	33.0	---	63	155/165	120/180	1013	1.1:1
1/7/77 (4)	1453	1420	95	119	102	1847	---	33.1	---	63	155/165	120/180	1053	1.1:1
1/7/77 (4)	1469	1440	102	121	102	1852	---	33.1	---	63	165/175	125/190	1147	1.1:1
1/7/77 (4)	1478	1450	106	121	102	1896	---	33.1	---	63	165/175	125/190	1230	1.1:1
1/7/77 (4)	1487	1460	105	119	101	1887	---	33.1	---	63	165/175	125/190	1325	1.1:1
1/7/77 (4)	1492	1470	104	119	102	1822	---	33.0	---	62	165/175	125/190	1407	1.1:1
1/11/77 (5) ^(d)	1444	1410	91	117	102	682	6.8	33.1	3.4	62	160/165	120/185	1015	1.1:1
1/11/77 (5)	1454	1400	99	121	102	684	7.4	33.1	3.7	63	160/168	120/183	1049	1.1:1
1/11/77 (5)	1457	1435	102	122	103	678	8.2	33.1	4.1	58	163/173	125/190	1100	1.1:1
1/11/77 (5)	1468	1440	106	123	104	717	8.2	35.1	4.3	59	165/172	125/190	1147	1.1:1
1/11/77 (5)	1470	1440	107	121	103	721	8.2	33.1	4.4	62	167/173	125/190	1215	1.1:1

(b) Speed Control Set. Torque Increased in ~0.5-in-oz Steps.

(c) Hysteresis Brake Used. Note Flywheel is 3:1 to Crankshaft.

(d) Note: Speed Control Valved Locked In.

TABLE 66-1 (Continued)

DATE (RUN NO.)	T/C 1	T/C 2	PROBE 1	PROBE 2	PROBE 3	SPEED	TORQUE	INPUT POWER	OUTPUT POWER	OIL PRESSURE	BUFFER ^(a) PRESSURE	WORKING PRESSURE	TIME	GEAR RATIO
	°F	°F	°F	°F	°F	rpm	in-oz	watts	watts	psig	psig	psig		
1/11/77 (5)	1472	1440	107	122	103	720	8.2	33.1	4.4	63	163/173	125/190	1306	1.1:1
1/11/77 (5)	1477	1445	105	121	103	687	8.3	33.1	4.2	58	160/170	123/188	1340	1.1:1
1/11/77 (5)	1492	1465	107	118	102	691	8.1	33.1	4.1	58	167/175	128/195	1457	1.1:1
1/12/77 (6)	1457	1418	88	112	102	674	6.8	33.1	3.4	65	155/165	125/185	1024	1:1
1/12/77 (6)	1435	1395	97	116	102	691	6.8	33.1	3.5	65	155/165	125/185	1050	1:1
1/12/77 (6)	1470	1440	108	117	102	616	8.1	33.1	3.7	60	155/165	125/185	1145	1:1
1/12/77 (6)	1492	1455	107	119	102	631	8.1	33.1	3.8	60	155/165	120/185	1235	1:1
Note: Run No. 6 Never Came Up to Full Power. Shut Down and Restart Next Day (Run No. 7.)														
1/13/77 (7)	1434	1395	89	112	100	619	7.9	33.1	3.6	61	160/165	125/185	1010	1:1
1/13/77 (7)	1449	1405	102	116	100	607	8.7	33.1	4.0	59	155/165	120/185	1058	1:1
1/13/77 (7)	1491	1450	108	118	100	628	9.0	33.1	4.2	60	155/165	120/185	1215	1:1
1/13/77 (7)	1500	1470	109	119	100	631	9.0	33.1	4.2	60	155/165	120/185	1245	1:1
1/13/77 (7)	1503	1470	108	119	100	628	9.3	33.1	4.3	61	160/170	125/190	1302	1:1
1/13/77 (7)	1504	1470	108	118	100	625	10.0	33.1	4.6	59	165/175	125/195	1313	1:1
1/13/77 (7)	1503	1470	110	120	100	621	10.0	33.1	4.6	59	165/175	125/195	1403	1:1
1/13/77 (7)	1504	1475	110	119	100	618	10.0	33.1	4.6	59	165/175	125/195	1429	1:1
1/13/77 (7)	1505	1475	109	120	100	631	9.9	33.1	4.6	60	165/175	125/195	1502	1:1
1/20/77 (8)	1433	1400	93	113	103	621	3.5	33.2	1.6	58	155/165	120/182	1048	1:1
1/20/77 (8)	1460	1435	103	116	104	633	4.0	33.2	1.9	58	155/165	120/182	1129	1:1
1/20/77 (8)	1500	1475	103	117	104	625	4.5	33.2	2.1	57	155/165	115/180	1234	1:1
1/20/77 (8)	1510	1480	105	118	104	649	5.0	33.2	2.4	59	160/170	112/186	1353	1:1
Note: Run No. 8 Never Came Up to Power. Shut Down and Check Converter (Run No. 9).														
1/25/77 (9) ^(e)	1476	1435	85	109	102	704	6.6	33.2	3.4	70	155/165	120/185	1020	1:1
1/25/77 (9)	1451	1410	93	113	102	703	7.0	33.2	3.6	70	155/165	125/180	1050	1:1
1/25/77 (9)	1459	1420	99	113	101	703	7.2	33.2	3.7	69	155/165	125/180	1138	1:1
1/25/77 (9)	1482	1440	101	116	102	680	7.3	33.8	3.7	67	150/160	125/175	1230	1:1
1/25/77 (9)	1488	1455	100	115	102	704	8.8	33.2	4.6	67	165/175	125/185	1303	1:1
1/25/77 (9)	1473	1440	102	113	102	620	8.9	33.8	4.1	62	165/172	125/190	1411	1:1
1/25/77 (9)	1497	1465	102	115	102	621	9.4	33.2	4.3	61	165/175	125/195	1502	1:1

(e) Disassembled T/CNV, Checked and Reassembled in Glove Box. No Noticeable Problem. Refilled Oil in Crankcase and Added Buffer Purge Line.

TABLE 66-1 (Continued)

DATE (RUN NO.)	T/C 1	T/C 2	PROBE 1	PROBE 2	PROBE 3	SPEED	TORQUE	INPUT POWER	OUTPUT POWER	OIL PRESSURE	BUFFER PRESSURE ^(g)	WORKING PRESSURE	TIME	GEAR RATIO
	°F	°F	°F	°F	°F	rpm	in-oz	watts	watts	psig	psig	psig		
1/31/77 (10) ^(f)	1477	1445	80	107	102	619	3.9	33.2	1.8	60	155/165	120/185	1047	1:1
1/31/77 (10)	Power-off												1127	1:1
1/31/77 (10)	Stalled Converter and Re-Started (Power On)												1142	1:1
1/31/77 (10)	1425	1395	92	116	103	631	7.6	33.2	3.5	60	155/165	120/182	1156	1:1
1/31/77 (10)	1469	1430	95	118	102	627	8.5	33.2	3.9	60	155/165	120/182	1252	1:1
1/31/77 (10)	1480	1440	95	118	103	622	9.4	33.2	4.3	60	165/175	125/190	1311	1:1
1/31/77 (10)	1488	1450	95	115	102	624	9.6	33.2	4.4	59	165/175	125/190	1408	1:1
1/31/77 (10)	1495	1460	96	116	102	621	9.7	33.2	4.5	59	165/175	125/195	1515	1:1
2/10/77 (11) ^(g)	1082	1000	80	102	83	0	0	33.2	0	0	0	0	0940	---
2/10/77 (11)	1115	1070	81	87	80	0	0	10.0	0	0	0	0	1047	---
2/10/77 (11)	1207	1190	85	80	74	0	0	10.0	0	0	0	0	1307	---
2/10/77 (11)	1252	1225	88	83	76	0	0	10.0	0	0	0	0	1440	---
Note: T/C 2 Increasing Over 1200°F. Limit Lower Input Power.														
2/10/77 (11)	1241	1225	89	84	76	0	0	7.9	0	0	0	0	1455	---
Note: T/C 2 Decreasing Rapidly Increase Input Power.														
2/10/77 (11)	----	1200	---	---	---	0	0	8.6	0	0	0	0	----	---
Note: T/C 2 is Holding at 1200°F at 8.6 watts Power Input.														

(f) New Hot Finger O-Rings Added. Slight Buffer Pressure Leak Corrected.

(g) Conduction Test to Maintain Lower Hot Finger Temperature at 1200°F for Overnight Heat-up. Note Converter Off/No Cooling Water.

Figure 66-1. Upper Hot Finger Temperature versus Thermal Converter Power Output

greater than 1450°F . The change in power with temperature in Figure 66-1 is $0.01 \text{ watt}/^{\circ}\text{F}$. Also, note that the scatter in the data seems to diminish at high upper hot finger temperatures of $\sim 1500^{\circ}\text{F}$.

The effect of the speed control on the thermal converter performance is shown in Figure 66-2. For a minimum speed of $\sim 750 \text{ rpm}$, the speed control valve was set at $\sim 4 \text{ in-oz}$ torque, see Run 3 in Table 66-1. The torque was increased in $\sim 0.5 \text{ in-oz}$ intervals until the converter showed signs of stalling. This occurs at $\sim 661 \text{ rpm}$ in Figure 66-2. The torque was then backed off at $\sim 1.0 \text{ in-oz}$ intervals. Speed then increased rapidly and returned to the $\sim 750 \pm 10 \text{ rpm}$ setting.

In Table 66-1 there is a small difference in output power for buffer pressure cases of 180 psig versus 170 psig. Pressures in excess of 180 psig would be too large and could possibly damage the diaphragms. The 180 psig charge pressure would be the most efficient and maximum allowable operating pressure and is recommended for future testing and implantation.

The $\sim 33 \text{ watts}$ power input is adequate to reach and maintain steady state power outputs of 4.2 to 4.8 watts with the gear box attached. Input powers in excess of this could result in hot finger temperatures $> 1500^{\circ}\text{F}$. The 1500°F is a maximum upper thermal limit to ensure hot finger structural integrity.

Thermal conduction tests were also made with the converter shutdown. These are given in Run 11 of Table 66-1. The purpose of these tests was to establish an upper limit electrical heater power input that could be naturally conducted and convected to the surroundings (no cooling water) and yet not exceed a 1200°F hot finger temperature limit. This would then permit safe over-night preheat-up of the converter prior to testing. The 8.6 watts input power case reached a steady state hot finger temperature of $\sim 1200^{\circ}\text{F}$.

The electrically heated thermal converter has been potted with a protective covering of silastic. Preparations are currently underway to do additional performance evaluation of the potted converter. Performance data collected will be compared with that given in Table 66-1. If results are comparable, system testing of the converter will begin.

Figure 66-2. Crankshaft Speed versus Thermal Converter Power Output

IVBM SYSTEM TESTING

Preparations are underway to mate the electrically heated thermal converter with the oil filled blood pump No. 4. Performance evaluation of the system will be made using the mock circulation loop. Blood pump No. 4 (differential pump with compliance chamber) individual performance testing has already been conducted on the mock loop.

THERMAL INSULATION RESEARCH AND DEVELOPMENT

Outgassing and pinchoff of static vacuum packages 2, 3 and 4 was completed and packages 3 and 4 were placed on life test. Fabrication and outgassing of packages 5 and 6 was completed. After pinchoff these packages will be placed on life test. Emittance evaluation of two cups was conducted on the modified test apparatus.

THERMAL CONVERTER ASSEMBLY

An assembly drawing required for assembling the coolant lines, instrumentation and insulation on the thermal converter was completed. A detail drawing for manufacturing the coolant line fittings was also completed.

A plastic mold was designed for encapsulating the thermal converter in Silastic, and the detail drawing required to manufacture the mold was completed.

IVBM STERILIZATION

An inflatable seal was designed for the door of the thermal converter assembly and sterilization glove box because the "O" ring seal originally specified could not seal the large gaps between the door and the box. Also, drawings were prepared for making the glove box modifications required to accommodate the inflatable seal.

Although no leakage was detected around the glove box door after the inflatable seal was installed, leaks were found around the window seals and the piping penetrations. An attempt

was made to seal the areas that leaked with Silastic, but a subsequent leak test indicated that the leakage rate out of the box was still excessive. An exhaust hood was then installed over the box to draw off any gas that may leak from the box.

A sterilization test was performed according to the updated IVBM final assembly and sterilization procedure reflecting the use of the electrically heated thermal converter. Positive results were obtained with the Steritest specimens. All specimens in the glove box showed complete sterilization of the bacterial spores culture medium.

TASK 68 - BLOOD PUMP FABRICATION AND REPAIR

Two compliance chambers were manufactured for oil filled IVBM blood pumps with a reduced right ventricle stroke volume. Photographs of the chamber housing and cover are shown in Figure 68-1.

Blood Pump No. 5 was assembled with grease lubricated bearings and gears so that it could be operated with a dry mechanism chamber in animal experiments. After the pump performed satisfactorily in a 5 hour checkout test, it was shipped to the University of Utah.

Figure 68-1. IVBM Blood Pump Compliance Chamber Housing and Cover

TASK 69 - IVBM SYSTEM REPAIR AND SUPPORT

The coolant lines, thermal insulation and instrumentation leads were assembled on the thermal converter and secured in position. The assembly was then installed in a mold made from the drawing described under Task 66 and encapsulated in Silastic. A photograph of the converter after encapsulation is shown in Figure 69-1.

A spare displacer rod/yoke assembly for the IVBM thermal converter was completed.

Figure 69-1. IVBM Thermal Converter Encapsulated in Silastic

TASK 70 - LIFE TESTING

BLOOD PUMP

Life testing of Blood Pump No. 6 was interrupted after 3,000 hours of operation so that the mechanism and the jojoba oil in the mechanism cavity could be examined. No evidence of significant wear of the mechanism was observed, but the color of the oil was darker than it was when it was put into the pump. A sample of the oil removed from the pump was sent to the Westinghouse Research Laboratory for analysis, and the remainder was poured back into the pump. The oil analysis indicated that the change in oil color was caused by a very small amount of wear debris. After new jojoba oil was added to fill the pump, life testing was resumed. At the end of this reporting period, a total of 4,149 operating hours had been accumulated.

STATIC VACUUM INSULATION TEST PACKAGES

The status of the static vacuum test packages at the end of this reporting period is summarized in Table 70-1. A complete time-temperature history of the bakeout cycles for the static vacuum packages is presented in Figure 70-1. This completes the bakeout of the static vacuum packages.

IVBM ELECTRICAL HEATER

A coiled heater on a custom ceramic form was tested for 33 days at 850°C at a power level of 28 watts with no observable degradation of the heating element. Testing was suspended because of a leak in the vacuum system.

TABLE 70-1
STATIC VACUUM PACKAGE PROCESSING HISTORIES (TO 3/31/77)

Insulation Package	Bakeout Time (days)	Static Vacuum Time Prior to Pinchoff (days)	Pinchoff Date
No. 1 - 60 Cups No Getter	53	36	10/6/76 176 days
No. 2 - 60 Cups Al-Zr Getter	20	43	12/22/76 99 days
No. 3 - 60 Cups No Getter	24	23	2/2/77 57 days
No. 4 - 30 Cups No Getter	29	37	3/4/77 27 days
No. 5 - 45 Cups Al-Zr Getter	20	31	-
No. 6 - 60 Cups 27 cups with plasma sprayed ZrO ₂ spacers Al-Zr Getter	20	31	-

Figure 70-1. Bakeout History for Static Vacuum Packages (to 3/31/77)

TASK 71 - QUALITY ASSURANCE

Quality Engineering and Quality Control activities continued at a level consistent with the program procurement and fabrication activities. Routine receiving and in-house fabrication inspections were conducted as required.