Westinghouse Astronuclear Laboratory

NUCLEAR-POWERED ARTIFICIAL HEART PROTOTYPE SYSTEM DEVELOPMENT PROGRAM

QUARTERLY PROGRESS REPORT

April 1, 1974
Through
June 30, 1974

MASTER

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NUCLEAR-POWERED ARTIFICIAL HEART
PROTOTYPE SYSTEM DEVELOPMENT PROGRAM

PHASE III

QUARTERLY PROGRESS REPORT

April 1, 1974 through June 30, 1974

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Prepared for

UNITED STATES ATOMIC ENERGY COMMISSION

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INTRODUCTION AND SUMMARY

The Nuclear-Powered Artificial Heart Prototype System Development Program is being conducted by the Westinghouse Astronuclear Laboratory and its major subcontractor, the Philips Laboratories division of the North American Philips Corporation as Phase III of the USAEC's Artificial Heart Program under Contract No. AT(11-1)-3043. This report presents the technical progress and accomplishments on the active program tasks for the period from April 1, 1974 through June 30, 1974.

Thermal insulation component development under Task 1 continued during the reporting period. The 26 skirted cup test insulation package was assembled and tested. The guarded heater insulation test stands were evaluated using the 40 cup pack and the 5 cup ZrO_2 plasma-sprayed cup pack.

Thermal converter development was continued on five specific components; hot finger, control valve, oil pump, bellows seals, and shaft seals. The details of these development efforts and the present status are covered under Task 2.

Blood pump drive mechanism component development progress is discussed in Task 3. An investigation of the possible causes of failure of the flexible shaft in the February in-vivo implantation at the University of Utah was continued without isolating the failure mechanism. New, higher strength, flexible shafts were procured and tested and a test rig permitting pulsatile loading of shafts without use of a blood pump and circulation loop was assembled. Ball bearing and lubricant investigation was continued.

Under Task 4 work continued on the detail design of the test rig for the IVBM coolant loop. Preliminary testing of commercial heat pipes was completed and specifications were prepared for heat pipes satisfying the special requirements of the Intermediate System.

All design tasks for the electrical IVBM insulation package under Task 5 were completed.

The design of the IVBM thermal converter was completed and is described under Task 6. The weight exceeds the design goal by approximately 800 grams because the IVBM schedule did not permit time to evaluate and incorporate possible lighter weight material substitutions.

In Task 7 the blood pump drive mechanism design was completed and most of the components were released for manufacture or purchase.

Under Task 8 the previously developed two-stage implantation approach was subjected to a trial fit in a calf cadaver using wooden models. The configuration was determined to be unnecessarily complex and design iterations, described in this report, have resulted in simplification of both the components and the implantation procedures.

Progress in the fabrication of the insulation cups and fluff foil is reported under Task 10. The 60 cup electrical IVBM insulator package was manufactured, assembled, and placed on test.

The thermal converter fabrication carried out under Task 11 was significantly advanced. Detail parts and subassemblies for the fabrication of two engines are in process. Photographs of parts in process or completed as of mid-June are included in this report.

Procurement action was initiated for the blood pump drive mechanism fabrication effort under Task 12 and for the auxiliary components under Task 13.

TASK 1 - THERMAL INSULATION DEVELOPMENT

During this quarter, 1) the 26 skirted cup test insulation package was assembled and tested, and 2) the guarded heater insulation test stands were being evaluated using the 40 cup pack and the 5 cup ZrO_2 plasma-sprayed cup pack. Technical progress on each of these efforts is reported.

STATIC VACUUM TECHNOLOGY DEVELOPMENT

Outgas Identification

Outgassing work during this quarter was limited to evaluation of the test insulation package and the sixty-cup electrical IVBM. The calibrated leaks have been received and mass spectrometer calibration will be continued when the IVBM systems are completed. A description of the outgassing results on the test insulation package is discussed later.

SPACER AND CUP TECHNOLOGY DEVELOPMENT

A second set of 5 cups plasma-sprayed with the ZrO_2 spacer as described earlier* has been received. These cups are designed to fit over the 5 cups now on test to provide a 10 cup pack. An additional 10 cup pack set has been plated and will be coated with a spacer, the geometry and composition of which will be determined by the plasma-spray evaluation currently underway. No additional work has been done on the infrared scattering investigation during this quarter.

THERMAL EVALUATION TEST APPARATUS

A schematic of the thermal evaluation test apparatus is shown in Figure 1-1. A second test apparatus was made to permit attainment of schedular goals and to allow the evaluation of

*Nuclear Powered Artificial Heart Prototype System Development Program, Quarterly Progress Report, January-March, 1974, COO-3043-15.

THERMAL EVALUATION TEST APPARATUS

the 60 cup IVBM insulation systems without dismantling the 26 skirted cup test insulation package. Thermocouples were tack welded to the hot finger at the axial positions shown on Figure 1-1 and were distributed about the circumference at 90° intervals. A total of eight thermocouples were attached to the hot finger and 4 thermocouples were attached to the base of the hot finger. Thermocouples were also attached to the exterior of the outer container and in the flowing water stream at the inlet and outlet. A ball-in-tube-type flow meter is used to measure the water flow. Irregular water pressure made precise heat loss measurements at equilibrium conditions impossible and steps are being taken to provide a constant pressure head for the water flow metering system.

TEST INSULATION PACKAGE

The 26 skirted cup test insulation package was assembled on the Test Apparatus No. 1 after the test apparatus was instrumented, leak checked, and baked out.

CUP FABRICATION AND TEST PACKAGE ASSEMBLY

The skirted cups were produced by electroplating nominally 0.0005 inch thick nickel on to suitably prepared aluminum alloy mandrels. An as-electroformed skirted nickel cup is shown in Figure 1-2. After machining the cups to final configuration, the aluminum alloy mandrels were chemically removed. All but four cups were successfully removed from the mandrels and are shown in Figure 1-3. The problems associated with the unsuccessful etching of the four cups have been solved. The bottom skirt of each cup was slit to facilitate assembly and cut-outs were provided for instrumentation pass through. The bottom skirt detail is shown in Figure 1-4. The etching and cleaning procedure used for the skirted nickel foil cups is listed in Table 1-1. Table 1-2 is the procedure followed for applying the powdered ZrO_2 spacer material to the skirted nickel foil cups.

Figure 1-5 shows the test insulation package partially assembled onto the thermal insulation test apparatus hot finger. In order to assemble the skirted cups, it was necessary to slit the cups in two places about $1/2$ the distance up the outside wall, 180° apart. The slits were

Figure 1-2. Skirted Cup Configuration Al Mandrel
Electroplated with Ni Before Machining and Etching

Figure 1-3. Skirted Cups Used for the Test Insulation Package

Figure 1-4. Electroplated Ni Cup After Etching
Showing Bottom Skirt Detail

TABLE 1-1
PROCEDURE FOR ETCHING NICKEL FOIL CUPS
FROM ALUMINUM ALLOY MANDRELS

- 1) Immerse nickel plated aluminum alloy mandrel in NaOH solution for 4-8 hours. 250 g NaOH/1000 ml H_2O , temperature of solution $\geq 150^\circ F$.
(Caution: Do not allow solution to cool on partially etched cups)
- 2) Rinse immediately in flowing tap water.
- 3) Immerse in 20% HNO_3 solution for 1-3 minutes or until nickel is bright.
- 4) Rinse immediately in flowing tap water followed by rinsing with either distilled or demineralized water.
- 5) Rinse with grain ethyl alcohol.
- 6) Hot air dry and store.

TABLE 1-2
PROCEDURE FOR APPLYING ZrO_2 SPACER MATERIAL
TO NICKEL FOIL CUPS

- 1) Weigh and record weight of cleaned nickel cup (see Table 1-1).
- 2) Dip each cup in ethyl alcohol- ZrO_2 slurry (0.48 g ZrO_2 (-325 mesh)/ 20 ml ethyl alcohol).
- 3) Prior to dipping each cup, stir the slurry solution to prevent settling of ZrO_2 particles.
- 4) Dry inside and outside surfaces of slurry coated cup using hot air gun.
- 5) Weigh and record weight of slurry coated cup.
- 6) Assemble cup onto appropriate hot finger. Where handling has removed ZrO_2 spacer material, use touch up brush and slurry solution to replace.

Figure 1-5. Test Insulation Package Partially Assembled

staggered during assembly so that no two slits would line up. Figure 1-6 shows a closeup of the bottom skirted assembly showing a typical slit and the notched bottom skirt to accommodate thermocouple instrumentation.

OUTGASSING EVALUATION (SKIRTED NICKEL FOIL CUPS)

The Thermal Evaluation Test Apparatus No. 1 without the nickel foil cups was first sealed and then outgassed while attached to the mass spectrometer system. The hot finger temperature was raised to 287°C . Higher temperatures were not attempted because of excessive power requirements for the uninsulated test apparatus.

Figures 1-7 and 1-8 show the mass spectra of the residual gases in the test apparatus at room temperature and at 287°C after outgassing at that temperature for 16 hours. These data show the relative intensity of each mass number normalized to that of the most abundant mass number. Figure 1-9 and Table 1-3 show the partial pressure of the 4 major species as calculated from the mass spectra data and measured total pressure using a proportionality approximation. A conductance for the tube joining the test package to the mass spectrometer system was calculated and ranged from 2.04 liter/sec for H_2 to 0.43 liter/sec for CO_2 . These conductances were then used to calculate the pressure drop through this tube. The pressure in the test apparatus was 11.8 times larger than the measured pressure in the mass spectrometer chamber.

Figures 1-10 through 1-15 show the normalized mass spectra for the offgassing obtained from the test insulation package after an overnight bake-out at the temperatures indicated on the figures. Gaseous species at mass 58 and 78 were observed early in the bake-out cycle. However, these species became less significant as bake-out continued. Initially water was the predominate gas in the empty system at room temperature (Figure 1-9 and Table 1-3). When the temperature was increased to 287°C , water vapor pressure decreased and hydrogen became the most predominate gas species. The hydrogen dissolved in the 304 stainless was being desorbed. The test apparatus was cooled and the 26 skirted nickel foil cups installed (see Figures 1-5 and 1-6). Outgassing of the test insulation package was then completed in two

Figure 1-6. Detail of Bottom Skirt
Showing the Slit Required for Assembly

Figure 1-7. Relative Intensities of Residual Gases in the Empty Thermal Evaluation Test Apparatus No. 1 at 25°C and 2.07×10^{-6} Torr Total Pressure

Figure 1-8. Relative Intensities of Residual Gases in the Empty Thermal Evaluation Test Apparatus No. 1 at 287°C and 3.77×10^{-5} Torr Total Pressure

Figure 1-9. Effect of Temperature and Pumping Time on the Partial Pressure of the 4 Major Gas Components (Test Apparatus No. 1 with 26 Skirted Nickel Foil Cups)

TABLE 1-3

PARTIAL PRESSURES OF THE FOUR MAJOR GASEOUS SPECIES
IN THE THERMAL EVALUATION TEST APPARATUS NO. 1

	$\underline{\text{H}_2^+}$	$\underline{\text{H}_2\text{O}^+}$	$\underline{\text{CO}^+ + \text{N}_2^+}$	$\underline{\text{CO}_2^+}$	$\underline{\text{Total Pressure}}$
Empty System, 25°C	9.63×10^{-8}	8.23×10^{-7}	1.51×10^{-7}	5.1×10^{-10}	2.07×10^{-5}
Empty System, 287°C	2.29×10^{-5}	2.64×10^{-7}	3.27×10^{-7}	1.85×10^{-8}	3.77×10^{-5}
26 Skirted Cups, 583°C	6.8×10^{-7}	8.34×10^{-9}	1.23×10^{-6}	4.67×10^{-7}	2.71×10^{-6}
26 Skirted Cups, 703°C	4.58×10^{-6}	6.79×10^{-7}	1.64×10^{-5}	5.38×10^{-6}	3.07×10^{-5}
26 Skirted Cups, 604°C (Reheat after removal of system)	2.67×10^{-6}	3.57×10^{-6}	1.33×10^{-5}	6.14×10^{-6}	3.18×10^{-5}
26 Skirted Cups, 778°C	4.15×10^{-6}	4.77×10^{-7}	2.11×10^{-5}	5.98×10^{-6}	3.54×10^{-5}
26 Skirted Cups, 859°C	9.82×10^{-7}	---	1.44×10^{-5}	3.62×10^{-7}	1.74×10^{-5}
26 Skirted Cups, 854°C	6.88×10^{-7}	---	9.0×10^{-6}	2.21×10^{-7}	1.1×10^{-5}

Figure 1-10. Relative Intensities of the Residual Gases in the 26-Cup Test Insulation Package at 583°C and 2.71×10^{-6} Torr Total Pressure (Thermal Evaluation Test Apparatus No. 1)

Figure 1-11. Relative Intensities of the Residual Gases in the 26-Cup Test Insulation Package at 703°C and 3.07×10^{-5} Torr Total Pressure (Thermal Evaluation Test Apparatus No. 1)

Figure 1-12. Relative Intensities of the Residual Gases in the 26-Cup Test Insulation Package at 604°C and 3.18×10^{-5} Torr Total Pressure After 2nd Heat-up (Thermal Evaluation Test Apparatus No. 1)

Figure 1-13. Relative Intensities of the Residual Gases in the 26-Cup Test Insulation Package at 778°C and 3.54×10^{-5} Torr Total Power After 2nd Heat-up (Thermal Evaluation Test Apparatus No. 1)

Figure 1-14. Relative Intensities of the Residual Gases in the 26-Cup Test Insulation Package at 859°C and 1.74×10^{-5} Torr Total Power After 2nd Heat-up (Thermal Evaluation Test Apparatus No. 1)

Figure 1-15. Relative Intensities of the Residual Gases in the 26 Cup Test Insulation Package at 859°C and 1.1×10^{-5} Torr Total Power After 2nd Heat-up (Thermal Evaluation Test Apparatus No. 1)

steps. After heating, the test insulation package was removed from the mass spectrometer system. A thermocouple feed through joint developed a leak and prevented any static vacuum time to be accumulated. The Thermal Evaluation Test Apparatus No. 2 was then outgassed on the mass spectrometer system prior to assembly of the electrical IVBM insulation system. After repairing the leak, Thermal Evaluation Test Apparatus No. 1 was reinstalled on the mass spectrometer for additional outgassing. During this time, temperatures up to 859°C were achieved. While at 859°C for 24 hours, the partial pressure of CO⁺, CO₂, and H₂ decreased with time (See Figure 1-9). The CO gas source has not been determined at this time. However, the 304 stainless steel hot finger is the most likely source since the electroplated nickel cups tested previously did not show excessive CO evolution on heating.

Figure 1-16 shows the rate of temperature increase and total pressure change as a function of time when 6.26 watts of electrical power was applied to the heater. Most of the outgassing occurred during the first 200 minutes.

THERMAL PERFORMANCE

The heat loss through the insulation (Q_I) was calculated from the conduction (Q_C) losses and total power input (P) by

$$Q_I = P - Q_C \text{ (watts)} \quad (1)$$

where

$$Q_C = Q_{TW} + Q_{TC} + Q_{MIN-K} + Q_{HL} \quad (2)$$

and where

$$Q_{TW} = \text{heat loss down cylinder wall}$$

$$Q_{TC} = \text{heat loss down thermocouple instrumentation}$$

$$Q_{MIN-K} = \text{heat loss down MIN-K 2002}$$

$$Q_{HL} = \text{heat loss down nickel heater leads}$$

Figure 1-16. Rate of Temperature Increase for 26 Skirted Foil Cup Test Insulation System
6.26 Watts Applied to the Heater

Figure 1-17 shows the net heat loss through the insulation (Q_i) and the total conduction heat losses as a function of temperature. Table 1-4 is a tabulation of the individual contributions to the heat losses for each temperature. The heat loss as a function of temperature through the insulation increased rapidly with temperature, indicating that a large portion of the heat loss is due to radiation.

CUP PACK INVESTIGATION

The 40 cup pack and 5 cup pack were exchanged between the two guarded heater test stands in order to more accurately evaluate the performance of the guarded heater apparatus. A complete set of data is being gathered and will be reported at a later date when completely analyzed.

Figure 1-17. Heat Loss as a Function of Temperature for the 26 Cup Test Insulation Package

TABLE 1-4
HEAT LOSSES FOR 26 CUP TEST INSULATION PACKAGE
WITH SKIRTED BOTTOM CUPS (THERMAL EVALUATION TEST APPARATUS NO. 1)

* Mean Temp. (°C)	Max. Temp. (°C)	Conduction Heat Losses (watts)			Power Input Watts	Heat Loss Insulation
		Thin Wall	Min-K 2002	Heater Leads & T. C.		
573	582.2	3.91	0.28	0.67	6.62	1.76
596	603.9	4.13	0.29	0.69	7.35	2.24
691	700.9	5.01	0.34	0.84	10.00	3.81
770	779.0	5.82	0.38	0.98	12.49	5.31
843.8	858.0	6.56	0.42	1.03	15.58	7.58
845.6	859.7	6.57	0.42	1.03	15.58	7.56

* Hot Area = 81.5 cm^2 (Does not include thin wall)

TASK 2 - THERMAL CONVERTER DEVELOPMENT

Component development efforts proceeded in five areas during this quarter: hot finger materials, control system, oil pump, bellows seals, and shaft sealing.

HOT FINGER MATERIALS INVESTIGATIONS

The thrust on this subtask during the past quarter has been to initiate a series of tests aimed at determining stress-rupture data for thin-walled Udimet 700 cylinders. The data are needed for comparison with the published data currently used for design. Thin-walled cylinders machined from both wrought bar stock and from powder metallurgically prepared Udimet 700 are to be evaluated.

The test results will be correlated using the Larson-Miller parameter (a standard method for predicting the stress rupture behavior of materials at high temperature). The parameter, as derived from the Arrhenius equation, combines temperature and time-under stress as follows:

$$P = T (20 + \log t)$$

where

P = parameter

T = temperature, °R

t = time, hours

A relationship between the value of the parameter P and the stress level required for rupture can be established experimentally. Special Metals Corporation has done this for Udimet 700 bar stock; Figure 2-1 is a plot of their data, which was used to establish the design of the IVBM hot fingers. The new data will be used to design the Intermediate System thermal converter.

Figure 2-2 is a schematic of the high temperature stress-rupture test setup. The apparatus includes an electric furnace with automatic temperature regulation supplied by a feedback

Figure 2-1. Rupture Stress versus Larson-Miller Parameter for Udimet 700

Figure 2-2. Schematic of High Temperature Stress Rupture Apparatus

control system. Temperature fluctuations can be limited to $\pm 2.5^{\circ}\text{C}$. The stress-rupture specimen is introduced from the right end in Figure 2-2. A constant flow of argon gas is introduced at the left end to prevent corrosion on the exterior of the hot sample. For this purpose, welding grade argon is first fed through a copper catalyst to remove residual oxygen and then through a molecular sieve to reduce the dew point of the gas to below -40°C . The sample is first heated to temperature, then charged to a predetermined pressure with ultra high purity argon to prevent internal corrosion. The gas charge is sealed in the sample for the duration of the test. Pressure fluctuations of $\pm 1\%$ due to room temperature fluctuations have been observed. Pressure and temperature are recorded simultaneously on a multi-channel recorder. A loss in sample pressure is indicative of the rupture of the specimen. The time of the failure is obtainable from the recorder's data trace.

A test specimen is shown in Figure 2-3. The thin wall section is approximately 1 inch in diameter and 1.5 inches long.

Presently, the first of three thin-walled cylinders fabricated from conventional bar stock is under test. It is anticipated that testing of the powder metallurgically prepared specimens will begin late in the next quarter.

CONTROL VALVE

Fabrication of the parts for the control valve (see Quarterly Report January-March 1974*) is complete. The valve is actuated by changes in gear pump oil pressure caused by engine speed increments or decrements due to system load changes. Increasing oil pressure causes a "short-circuit" path to open between the engine's compression and buffer spaces thus spoiling the compression ratio. This reduces the engine overall efficiency, and hence the power output. The first assembled valve is shown in Figure 2-4.

*Nuclear Powered Artificial Heart Prototype System Development Program, Quarterly Progress Report, January-March, 1974, COO-3043-15.

Figure 2-3. Thin-Walled Udimet 700 Stress-Rupture Specimen

Figure 2-4. IVBM Control Valve

Initial tests of the valve have begun. They include proof pressurization and measurements of its effective spring rate and internal leakage. Next, argon flow rate versus changes in oil pressure will be measured and evidence of internal hysteresis sought. Upon successful completion of these preliminary characterization tests, the valve will be mated with a bench model engine. Its oil pressure input will be varied externally and measurements will be taken of engine output versus oil pressure. Finally, the valve will be mated with the IVBM converter to test the stability of its operation while externally varying the shaft load.

OIL PUMP

Figure 2-5 shows the component parts of the IVBM oil system gear pump. The pump gears were received from Moore Special Tool Company in mid-May and upon inspection proved to be of excellent quality. The first pump assembly is being completed in June. Design verification and life testing will begin early in the next quarter.

Material selection and proof-of-principle tests of the capillary wicking system have been carried out. An analysis of candidate wire gauge mesh sizes (see Table 2-1) led to the selection of 325 x 325, 0.0011 inch wire diameter stainless steel mesh for further study.

TABLE 2-1

<u>Mesh</u>	<u>Wire Diameter Inches</u>	<u>Theoretical Wicking Height - Inches</u>	<u>Max. Flow Rate Attainable in³/sec (3 layer mesh)</u>
270 x 270	0.0011	5.0	0.053
270 x 270	0.0016	6.3	0.045
325 x 325	0.0011	6.6	0.066
325 x 325	0.0014	8.2	0.047
400 x 400	0.0011	9.4	0.061

The wicking height of Vitrea 21 oil in a three-layer sample of the candidate mesh measured 5.75 inches compared with the theoretically predicted value of 6.6 inches. This height

Figure 2-5. IVBM Gear Pump

would still permit a flow rate of $0.053 \text{ in}^3/\text{sec}$ through the IVBM intake system, more than six times the anticipated flow rate.

The test setup in Figure 2-6 simulates the IVBM oil intake system and was used to measure the flow rate at which surface tension breakdown occurs. The intake wicks are immersed in oil, while the wicks exposed to air are housed in lucite at a height of 2.5 inches above the oil's free surface (simulating the maximum wick spacing in the IVBM system). The system was primed with oil and a Phase II oil pump used to circulate the oil. The flow rate which caused air ingestion into the exposed wick was measured. The candidate wick described above maintained an oil flow of $0.051 \text{ in}^3/\text{sec}$ without breakdown, confirming the design selection.

The Phase III oil pump tests to be performed in the next quarter will combine pump design verification with further demonstration of the capillary wick intake system.

BELLOWS SEAL

Testing of electrodeposited nickel bellows from Servometer Corporation was resumed in mid-May following delivery of three new bellows assemblies and rework of the bellows test fixture. Figure 2-7 is a photograph of the reworked fixture. The oil pump has been internalized and the flywheel (not visible) has been enlarged.

The first bellows placed on test was one which had been fabricated to the same specification as the two earlier bellows (previously reported*), but which had a slightly lower spring rate. The bellows was installed to reciprocate with 85% of its stroke in compression and 15% in extension per the manufacturer's recommendation. These bellows failed after approximately 2×10^5 cycles. The failure point was a circumferential crack on a central convolution, identical to that on the earlier bellows.

*Nuclear Powered Artificial Heart Prototype System Development Program, Quarterly Progress Report, January-March, 1974, COO-3043-15.

Figure 2-6. Capillary Wick Test Setup

Figure 2-7. Bellows Seal Test Fixture

A second bellows was then placed on test. This bellows had been designed to a revised specification in which the wall thickness and spring rate had been markedly reduced. The bellows was installed to reciprocate with the same percentage of stroke in compression and extension as the previous unit. A failure was detected within 4×10^5 cycles. The manufacturer could find no reason for this failure.

The third bellows available for test was intended to be identical to the second, but its pressure rating was found to be below specification due to an insufficient wall thickness (i.e. it was a reject). However, it was leak tight, and a decision was made to use it. This time, prior to testing, the bellows' force versus compression/extension characteristics were mapped and the data used by Philips to establish a new cycling regime. Based on the data, a decision was made to cycle the bellows 55% in compression and 45% in extension. This time, an attempt has been made to separate the possible effects of quality, deflection stress, and pressure stress on the bellows. This bellows is still under test; as of mid-June, approximately 7×10^6 cycles have been accumulated with no pressure across the bellows. The performance to date has indicated that the bellows is of good quality and can survive the deflection stresses. If failure occurs rapidly after application of a derated pressure based on actual wall thickness, this will be a clue that the bellows pressure ratings have been overstated by the manufacturer.

Due in part to the performance of Servometer's electrodeposited bellows to date, preliminary contacts have been made with two manufacturers of welded bellows. During the coming quarter, samples of "final configuration" welded and electrodeposited bellows will be procured for evaluation.

SHAFT SEALS

The flywheel shaft seal is a combination of screw thread viscosity pumping groove and cylindrical clearance seal (see previous quarter report*). Testing of a prototype shaft seal was

*Nuclear Powered Artificial Heart Prototype System Development Program, Quarterly Progress Report, January - March 1974, COO-3043-15.

successfully completed in April following 650 hours of continuous operation against one atmosphere pressure gradient. Prior to this test, the same seal had been tested for over 700 hours against a pressure head of twelve inches of oil with no evidence of leakage. These tests have demonstrated the feasibility of the seal concept. Further verification will await actual bench testing of the IVBM converter.

The thermal converter/blood pump shaft seal was described in the last quarterly report*. It consists of a left- and a right-hand screw thread viscosity pumping groove. The oils on either side of the seal are pumped inwards toward an interface across which no mixing or mass transfer should occur; the difference in viscosity of the two oils is accommodated by the number of threads cut into each half of the seal.

Testing of this seal is continuing. Over 1000 hours of testing were accumulated with Vitrea 21 oil on the engine side and sperm oil on the blood pump side. The tests were performed at room temperature with the two oil reservoirs at atmospheric pressure. In early June, a new test was configured with a positive oil pressure on the sperm oil reservoir equal to a ten inch column of sperm oil. The apparatus is shown in Figure 2-8. Over 300 hours of continuous operation have accumulated with no net transfer of oil from one side to the other.

The tests on the thermal converter/blood pump seal have demonstrated that the screw thread viscosity seal can be used to separate two oils of known viscosity for moderate lengths of time.

*Nuclear Powered Artificial Heart Prototype System Development Program, Quarterly Progress Report, January-March, 1974, COO-3043-15.

Figure 2-8. Thermal Converter/Blood Pump Seal Test Apparatus

TASK 3 - BLOOD PUMP DRIVE DEVELOPMENT

FLEXIBLE SHAFT DEVELOPMENT

The investigation of possible causes of failure of the flexible shaft used in the February in-vivo implantation experiment at the University of Utah was continued. No conclusive identification of the failure mechanism was made. The broken shaft was returned to the manufacturer for failure analysis, and the vendor reported that the failure was overload induced and not due to faulty manufacture. The blood pump used during the experiment was returned from Utah, disassembled and examined for residual evidence of overload; no such evidence was apparent.

To determine whether an excessively high vacuum in the mechanism chamber could have been responsible for the shaft failure, a test was performed in which a blood pump was operated at normal pressure and flow conditions and the shaft input torque was measured as the vacuum was increased above the normal 4 to 5 inch Hg. Although the pump began to squeak at about 8 inch Hg, the maximum value of the basic torque-time curve did not change significantly from the normal 24 in-oz when the vacuum was increased to the maximum possible value (reported by the University of Utah for the implant experiment to be 16 inch Hg). However, spikes in the torque-time curve that increased the maximum torque value began to appear at about 12 inch Hg and gradually increased in number and magnitude to a value of about 44 in-oz at 16 inch Hg. A second vacuum test was performed, and the vacuum was increased to 19 inch Hg, where a maximum spike torque of about 84 in-oz was reached. The results of the second test indicated that very high spike torques and possibly a shaft failure could be caused by a very high vacuum, but vacuum levels attained during the Utah experiment were not judged high enough to have been responsible for the shaft failure.

After the vacuum test, the pump was disassembled and the yoke and crankshaft assembly were photographed. These photographs (see Figures 3-1 and 3-2) show that the roller and yoke bearing surfaces were severely scored at the high vacuum conditions when the yoke was not able to resist the atmospheric pressure forces that tend to collapse the yoke around the roller.

Figure 3-1. Yoke after High Vacuum Test

Figure 3-2. Crankshaft Assembly after High Vacuum Test

Photographs of the yoke and crankshaft assembly removed from the pump used in the February Utah experiment are shown in Figures 3-3 and 3-4 and the lack of scoring confirms the conclusion that vacuum levels as high as 19 inch Hg were not attained at Utah.

A test in which a shaft was kinked so that the casing retained a permanent bend similar to the one observed in the Utah shaft after testing did not reproduce the Utah failure.

Another test in which the blood pump ventricles were confined to narrow restrictions, simulating speculated constraints applied by adjacent organs and the rib cage, produced no effect detrimental to the flexible shaft. Compliance and break strength testing of several shafts showed good correlation with the vendor predictions.

The endurance test reported in the previous quarterly report* was continued for another 54 hours, but was discontinued after a total of 250 hours of operation because the rate of change of the no-load windup began to level off and the no-load windup observed did not appear to be responsible for the early failure of the Utah shaft.

Five P-1190 type flexible shafts with improved strength cores in which the outer wire layer was wrapped in the windup direction, but with casings similar to those used in the previous shaft design were procured from S. S. White. Two of the shafts were sent to Utah for in-vivo implant experiments, and the remainder were retained at WANL for laboratory testing. One of the shafts sent to Utah was used in an implant experiment started on May 29. This experiment was terminated about 14 hours after the blood pump was turned on for reasons not associated with the shaft. The second shaft was used in an Utah implant experiment started on June 10. This experiment was terminated about 44 hours after the blood pump was turned on for reasons not associated with the shaft. Utah reports no change in the appearance of either of the flexible shafts used in these experiments was observed in the postmortem examinations. A more detailed examination will be conducted at WANL when the shafts are returned.

*Nuclear Powered Artificial Heart Prototype System Development Program, Quarterly Progress Report, January-March 1974, COO-3043-15.

Figure 3-3. Yoke after February Utah Implant Experiment

Figure 3-4. Crankshaft Assembly after February Utah Implant Experiment

Torsional stiffness and ultimate strength measurements of one of the shafts retained by WANL were made. The results obtained, compared below with those obtained with a shaft similar to the one used in the February Utah experiment, indicate that the new shaft is more than twice as stiff and 25 percent stronger than the previous shaft in the winding direction. The failure in the ultimate strength test (see Figure 3-5) occurred in the core transition section where the core changed from a round to a square cross-section.

	<u>New Shaft</u>	<u>February Shaft</u>
Spring Rate		
Clockwise	0.5 in oz/deg	0.94 in oz/deg
Counter Clockwise (Operating Direction)	1.1 in oz/deg	0.48 in oz/deg
Ultimate Strength - Counter Clockwise	292 in oz/deg	233 in oz/deg

A test rig was assembled for life testing flexible shafts under pulsatile torque loading without using a blood pump and a mock circulation loop. The pulsatile loading is provided by a hysteresis brake excited with 120 cycles/min sinusoidal current and a dc bias adjusted to obtain maximum torque pulse values with the blood pump operating at any given output condition.

BALL BEARING AND LUBRICANT INVESTIGATIONS

Another ball bearing friction test similar to the ones reported in the previous quarterly report was performed using an SR-4 ball bearing and Mobil +K lubricating oil. The test was performed with the bearing rotating at design speed, 120 rpm, and with a radial load twice as high as the maximum design load, 50.8 lbs. The torque required to rotate the bearing, tabulated below, did not change significantly throughout the test, and an examination of the bearing after the test did not reveal any signs of wear or damage.

<u>Time, Hr.</u>	<u>Torque, mg-mm</u>
96	21,500
432	22,500
1032	22,800
1536	23,800

Figure 3-5. P-1190 Type S.S. White Flexible Shaft after Ultimate Strength Test

Immersion testing was continued to evaluate the compatibility of elastomer compounds, silastic MDX 4-4515 and fluorosilicone MDX 4-4026, with candidate oils for the drive mechanism cavity. The results after 90 days of testing, tabulated below, are not significantly different from those obtained after 38 days of testing and reported previously.

<u>Elastomer</u>	<u>Oil</u>	<u>Percent Swell</u>	
		<u>38 Days</u>	<u>90 Days</u>
MDX 4-4515	Sperm	3.3	3.0
MDX 4-4515	Vitrea 21	14.5	12.8
MDX 4-4515	Santotrac 30	45.0	41.2
MDX 4-4515	Transformer 55 plus Additive	34.4	31.4
MDX 4-4026	Sperm	0.5	0.7
MDX 4-4026	Vitrea 21	1.0	1.1
MDX 4-4026	Santotrac 30	5.8	5.5
MDX 4-4026	Transformer 55 plus Additive	2.9	3.0
MDX 4-4026	Mobil +K	0.1	0.2

TASK 4 - AUXILIARY COMPONENTS DEVELOPMENT

IVBM COOLANT LOOP

Detailing of the test rig for the IVBM coolant loop and pump is nearly complete. The test rig is designed to accept the entire coolant pump, including the coolant tubes inside the blood pump, the check valves, and the bellows assemblies, and to simulate the action of the blood pump mechanism. An electrically heated mockup of the thermal converter cold side heat exchanger will allow hydraulic and thermal simulation of the entire coolant loop.

The test rig is designed to measure the force required to drive the coolant pump directly. This, combined with the displacement of the driving member, will allow direct calculation of the power input to the pump. The motion of one of the bellows pumping chambers will also be measured. As the system will be filled with water, which is incompressible, the compression of one pumping chamber will provide an accurate measure of the instantaneous flow rate at the bellows. Provisions have been made for measuring the pressure inside each pumping chamber, and the integral of pressure difference times the flow rate will enable the gross hydraulic power produced by the pump to be computed. Measurements of the net flow through the system can be compared with flow at bellows to evaluate the performance of the check valves.

The complete test rig will permit evaluation of the overall hydraulic performance of the coolant loop, along with the various components of the loop. The test rig is designed so that the pump components can be submerged in oil while operating. This will permit the rig to be used to measure the thermal performance of the coolant loop, and to estimate the frictional losses due to the presence of the oil.

HEAT PIPE HEAT REJECTION SYSTEM

Preliminary testing in a horizontal orientation of two commercial flexible heat pipes has been completed. One of the pipes was found to be faulty and the other was minimally satisfactory in the horizontal position.

A set of specifications has been prepared in preparation for developing heat pipes that can meet the requirements for the Intermediate System. These specifications require a 20 watt capability with the pipe oriented in any direction. Various design alternatives will be examined to determine the best compromise between size, temperature drop and cost, as well as ease of implantation.

TASK 5 - INSULATION DESIGN

All design tasks required for completion of the electrical IVBM insulation package have been completed. Work on the nuclear IVBM will begin on July 1, 1974.

A template used to control the fluff foil contour was designed and fabricated.

TASK 6 - THERMAL CONVERTER DESIGN

The design of the IVBM thermal converter was completed in mid-May and all parts of the engine have been released for fabrication. While the present engineering drawings are sufficient for the fabrication effort at Philips Laboratories, a decision was made to expand and formalize the IVBM drawing package in preparation for transmittal to WANL. The drafting effort from mid-May through June has thus included the construction of an indented parts list, a "top" assembly drawing of the converter, and several major subassembly drawings. Additionally, drafting support for incorporation of engineering change orders will continue through the fabrication and assembly phases of the IVBM program.

The IVBM engine design draws heavily upon the engine technology proven in Phase II. The most significant performance improvements are in the hot finger design and the engine's improved mechanical efficiency. The mechanical drive, bearings, and gas seals, however, are direct descendants of their bench model predecessors. The other changes evident in the design are those aimed at meeting size and weight goals, and implantation protocol requirements, of the first fully implantable system.

The IVBM thermal converter is shown in Figure 6-1. The IVBM hot finger contains two Udimet 700 alloy, thin-walled, cylinders. The annular space between them is filled with a stainless steel wire-mesh regenerator. The outer Udimet wall is a pressure vessel, forming a boundary between the engine working gas (argon at an average pressure of 13 atmospheres) and the vacuum insulation package which surrounds it. The inner Udimet wall is under virtually no pressure differential; it provides containment for the regenerator mesh package. Both walls are nominally 0.004 inches in thickness and 1.670 inches long to minimize thermal conduction losses from the heat source.

The Pu-238 heat source, as shown in Figure 6-1, is housed at the extreme tip of the hot finger. The heat source is inside the working space of the engine, bounded with very little

Figure 6-1. IVBM Thermal Converter

clearance by a nickel 200 cylinder, the top of the outer Udimet wall, and the top of the inner Udimet wall. The nickel cylinder provides a good thermal path between the heat source and the slotted heater ring which, in turn, heats the working gas. The heater ring has replaced the troublesome gap type heat exchanger used in Phase II. Although not shown in Figure 6-1, a Udimet 700 Belleville washer between the top of the inner wall and the base of the Pu-238 heat source is used to prevent motion of the heat source in its housing.

An alternate hot finger, designed for use during development testing, is being constructed. It is designed to house an electric cartridge heat source while simulating the nuclear finger in all other respects.

The displacer is a thin-walled Udimet 700 cylinder filled with "Min-K" insulation. The sole function of the displacer is to shuttle gas between the cold space at the base of the regenerator and the hot space at the top of the regenerator. The displacer is pressurized with argon and sealed so that its internal pressure is always above that in the working space, thus obviating the possibility of buckling due to external pressure and ensuring no contamination of the working space by the Min-K. A rider ring at the base of the regenerator insures that all the working gas shuttles through the regenerator mesh and not through the annulus between the displacer and the inner liner. The rider ring is a spring loaded, "Bal-Seal" made of glass and molybdenum-disulfide loaded Teflon.

The power piston partially compresses the working gas on its upstroke (the remainder of the compression is accomplished by the displacer's downstroke) and transmits the thermodynamic cycle power output to the drive mechanism on its downstroke. A piston ring, identical in construction to the displacer rider ring, minimizes potential diminution of the compression wave due to "blow by" leakage.

The gas space below the piston ring, called the buffer space, contains a large charge of argon at the mean cycle pressure. The gas charge is large enough so that no work output is

lost in compressing the gas below the piston on its downstroke. As can be seen in Figure 6-1, this gas is housed in an enclosed toroidal cavity in the aluminum crankcase structure. A fill valve (not shown) is built into the wall of this cavity and serves as a charging port for the engine.

The ambient cooler makes possible the rejection of the Stirling cycle thermodynamic waste heat from the working gas to a coolant stream circulated by the blood pump. The cooler consists of a copper core, stainless steel housing and nitrided steel liner. The copper core contains longitudinal slits for the gas stream and circumferential grooves for the coolant stream. These two fluids are, of course, separated by solid metal. The steel enclosure contains the flanges by which the cooler assembly is mated to the hot finger and crankcase, as well as connection ports for coolant lines. The nitrided steel liner functions as a wear resistant running surface for the displacer and piston rings.

The reciprocating motion of piston and displacer are transmitted to the rhombic drive rotating crankshafts by the piston rod/yoke and displacer rod/yoke assemblies, respectively. The piston rod is a hollow steel cylinder guided by an oil fed bushing in the crankcase wall. The rod is integral with the piston yoke; four connecting links join the yoke pins to the crankthrows on the crankshafts. The displacer rod reciprocates within the piston rod, guided by two oil fed bushings. It, too, is integral with its yoke, and two connecting links connect it to the crankshafts. Two oil supported polyurethane rolling diaphragm seals, or "roll socks", seal the gas charged spaces of the engine from the crankcase. The outer roll sock seals the potential leakage path from the buffer space below the piston down the exterior of the piston rod. The inner roll sock seals the path from the working space below the displacer down the annulus between the displacer and piston rods.

The drive's two crankshafts are supported at each end by pillow blocks mounted to the interior crankcase structure. Timing gears (on the left in Figure 6-1) synchronize the motion of the two crankshafts. One of these gears drives a 3:1 stepup gear which increases the speed of the

flywheel from the nominal rhombic drive speed of 600 rpm to 1800 rpm. Four counterweights on the crankshaft's cheeks are used to perfectly balance the mechanical drive. The right end of one of the crankshafts directly drives the oil lubrication system gear pump (not shown) while the right end of the other shaft transmits the engine's output power to the blood pump gear box through an intermediary output shaft. This shaft contains a viscosity seal to prevent loss of oil from the blood pump to the engine.

The flywheel is mounted on a common shaft with the pinion gear. Two oil fed journal bearings support its weight. The flywheel must run in air so as to minimize its viscous drag. To accomplish this, it is housed in an aluminum enclosure, isolated from the crankcase by a viscosity seal on the flywheel shaft. A connection for an external drive system (for start-up) has been provided on the flywheel housing.

A control valve mounted to the flywheel housing (not shown in Figure 6-1) maintains the speed of the engine nearly constant over the engine's load range. The valve senses oil pump output pressure and crankcase pressure; changes in the difference between these two values adjust the magnitude of a leakage (or "short-circuit") between the working space and buffer space. The details of operation of the valve are given in the subsection covering Task 2.

Figure 6-2 is a schematic of the engine oil lubrication system. Four capillary intake wicks (see the subsection covering Task 2) are located on the pillow blocks in the crankcase. The crankcase will be filled with sufficient oil so that one wick will always be wetted regardless of engine orientation. These wicks are plumbed to the intake of the miniature gear pump which is mounted on one of the pillow blocks. The full discharge of the oil pump passes through a cylindrical filter element within the crankcase. The filtered output is routed in two parallel paths to the outer roll sock oil cavity and the rhombic drive flywheel shaft bearings. Static pressure taps connect the filter output to the control valve and pressure transducer fitting. Additionally, auxiliary oil system connections (severed and sealed prior to implantation) are provided to enable support of the rolling diaphragm seals in an intentionally stalled, gas charged, engine.

Figure 6-2. IVBM Oil Circuit

The oil pump has been designed to deliver a flow rate of $0.008 \text{ in}^3/\text{sec}$ at 110 psig and 600 rpm. The oil system has been conservatively designed to require slightly less than this flow rate under worst case conditions at rated pressure. Therefore, provision for a bypass capillary tube between the pressurized oil space and the crankcase is included to permit final trimming of the oil system's pressure after assembly and run-in.

The unit contains a total of twenty-one oil fed bearings; six hydrodynamic journal bearings, six hydrodynamic crank pin bearings, six combination hydrodynamic/squeeze-film yoke pin bearings, and three hydrostatic guide bushings. The loads carried by the IVBM engine drive mechanism are identical to those in the bench model engine. However, a size reduction in the IVBM drive was made possible by reducing the bearing diameters and lengths while simultaneously decreasing their diametral clearances from 0.0005 inches to 0.0003 inches.

Table 6-1 presents an estimated weight breakdown for the IVBM thermal converter. The weight is projected to exceed the goal by roughly 800 grams. The overage is primarily due to the inability to incorporate desirable weight reducing materials in a timely fashion into the current system. Present plans call for the evaluation of materials such as aluminum and beryllium for the ambient cooler, titanium and beryllium for the rhombic drive, and titanium and beryllium for the crankcase to be delayed until the Intermediate System is designed.

TABLE 6-1
IVBM WEIGHT ESTIMATE

<u>Item</u>	<u>Weight, Grams</u>
Hot Finger	350
Ambient Cooler	320
Rhombic Drive	415
Crankcase	580
Flywheel	295
Control Valve	80
Miscellaneous (oil, fittings, etc.)	280
Pu-238 Heat Source and Insulation	400
Total	<u>2,720</u>
Goal	1,900

The IVBM thermal converter will be equipped with several types of instrumentation to permit full evaluation of its performance during both laboratory bench tests and in-vivo experiments at the University of Utah. The hot finger has provisions for four thermocouples (to be installed by WANL), while the electric hot fingers will have five (to be installed by Philips). Three miniature pressure transducers will be installed to monitor working space, buffer space, and oil system, pressures. Additionally, a magnetic pickup will be mounted in the flywheel housing to sense engine speed and crank position.

TASK 7 - BLOOD PUMP DRIVE MECHANISM DESIGN

The design work on the blood pump drive mechanism was completed, and most of the component detail drawings were released for manufacturing or procurement. Detail change recommendations received from Sealol, the vendor selected for the bellows coolant pump, have been incorporated in the coolant pump drawings. A detailed calculation of the blood pump drive mechanism weight will be carried out.

TASK 8 - SYSTEM DESIGN AND INTEGRATION

IMPLANTATION STUDIES

For a two-stage implantation, an implantable electric motor will be required to operate the blood pump during the period between the first and second implantation operations. In addition, the thermal converter must be coupled to the flexible shaft and coolant lines and the electric motor removed as part of the second and final operation of the implantation sequence. The configuration reported on in the previous Quarterly Progress Report* was found to be unnecessarily complicated following a trial fit using wooden models in a calf cadaver. As a result of this observation, the configuration of the implantation hardware was simplified by elimination of the gooseneck fitting to the implantable electric motor. The resulting configuration is shown schematically in Figure 8-1.

Using this scheme, the coupler always remains attached to the blood pump mechanism. There is no period of time during the second operation when at least one power source is not connected to the blood pump. As a result, in case of difficulties in joining the thermal converter to the coupling mechanism, the blood pump can be restarted quickly. In addition, no auxiliary electric motor connection is required to start the thermal converter, as the implanted electric motor is available to start the thermal converter. This somewhat simplifies the thermal converter design.

This scheme, however, has several disadvantages. Although the blood pump always has power available, thus protecting the calf in case of difficulties in connecting the thermal converter, there is no power source connected to the thermal converter during this period. Therefore, if difficulties are encountered, there may be a delay in restarting the converter, which could lead to over-heating the converter. Secondly, the location of the implantable motor relative to the thermal converter is such that it would tend to interfere with the transition between the auxiliary and permanent coolant lines and the removal of the auxiliary oil lines.

*Nuclear Powered Artificial Heart Prototype System Development Program, Quarterly Progress Report, January-March 1974, COO-3043-15.

Figure 8-1. Coupling Mechanism - Scheme A

As a result of these drawbacks, the recommended configuration shown in Figure 8-2 has been developed. With this scheme, the coupler (right angle gear box) is no longer permanently connected to the shaft, but is provided as part of the thermal converter and part of the implantable motor. The starting motor, which also serves as a dummy load when operating the converter on the bench, is coupled to the flywheel end of the converter. The starting motor is not removed until after the converter is implanted and started. This eliminates the period of time when no power is available to restart the converter in case of difficulties. In addition, the area where the coolant and auxiliary oil lines are connected to the converter is unobstructed.

The configuration shown in Figure 8-2 offers several advantages over that shown in Figure 8-1. The coupler requires only one input shaft, simplifying the design of the coupler. In addition, the removable connection is in a more accessible location, which should reduce the probability of encountering difficulties during implantation. The elimination of one input shaft to the coupler eliminates the requirement for a seal at that location, as well as allowing better location for the bearings inside the coupler. Both of these changes will contribute toward reducing the frictional losses in the coupler and reducing the size of the coupler.

If the motor housing is designed to conform to the thermal converter envelope as shown in Figure 8-2, site preparation required during the second implantation operation will be minimized. With the previous configuration, the site would have to be prepared for the motor in the first operation, and reshaped to fit the converter during the second operation. In addition, an electric heater can be incorporated in the motor housing. This would allow controlled amounts of heat to be supplied during the recovery period between operations, promote vascularization of the tissue bed surrounding the thermal converter and possibly enhance the ability of the tissue to accept heat from the converter without damage.

A. Blood Pump Driven by Electric Motor

B. Converter Started with Electric Motor

C. Blood Pump Driven by Converter

Figure 8-2. Coupling Mechanism - Scheme B

TASK 10 - INSULATION FABRICATION

Mandrels for electroforming both the electrical and nuclear IVBM insulation system cups have been machined. The insulation cup set for the electrical IVBM has been manufactured, assembled and placed on test. The same procedures used for the test insulation package and reported in Task 1 were employed during the fabrication of the electrical IVBM insulation system on the Thermal Evaluation Test Apparatus No. 2. These procedures are somewhat simplified from those reported previously*. The experience derived from the test insulation package has demonstrated that these techniques are adequate. Because the mandrels have been etched in-house, close control of the handling after etching can be maintained. The fluff foil insulation was fabricated from Ni-200, 0.00075" sheet stock and 0.002" Ni expanded mesh foil. Figure 10-1 shows two rings and two expanded mesh spacers. About 65 sets of expanded mesh-foil layers were utilized. The annular rings were slit and assembled on the hot finger after dipping in the alcohol-ZrO₂ slurry. Figure 10-2 shows a partial installation of the fluff foil on the hot finger of the Thermal Evaluation Test Apparatus. The cups were added one at a time after the fluff foil assembly was completed. After each cup was added, the fluff foil layers were examined closely to insure that each cup fit properly. Figure 10-3 shows the assembly after installation of cup number 40. When completed, cups number 59 and 60 completely enclosed the fluff foil.

*Nuclear Powered Artificial Heart Prototype System Development Program, Quarterly Progress Report, October-December 1973, COO-3043-13.

Figure 10-1. Nickel Foil and Expanded Nickel Mesh Annular Rings for "Fluff" Foil Assembly

Figure 10-2. Fluff Foil Partially Assembled on
Thermal Evaluation Test Apparatus No. 2

Figure 10-3. Electrical IVBM Insulation Partially Assembled on Thermal Evaluation Test Apparatus No. 2

TASK 11 - THERMAL CONVERTER FABRICATION

Fabrication of the two IVBM thermal converters is well underway. Parts and subassemblies for all areas of the engine are presently in work. Assembly of the first converter is underway. Photographs of parts in progress or completed as of mid-June have been included in this report to illustrate the status of this task.

Figure 11-1 is a photograph of the "electric" hot finger following brazing of the nickel 200 electric heater housing and gas side heat exchanger ring to the Udimet 700 finger. Following final machining and instrumentation, the outer hot finger will be delivered to WANL for assembly to the vacuum insulation package. The Udimet inner liner and regenerator mesh (not shown) will undergo final machining concurrently with WANL's insulation efforts.

Figure 11-2 is an exploded view of the parts of the "nuclear" hot finger. The inner Udimet 700 liner is at the extreme left, shown prior to final machining. The nickel 200 gas side heater and Pu-238 heat source housings are shown prior to brazing (Figure 11-3 shows the heater/housing assembly after brazing). To the right of the heat source housing are the monel 400 hot finger flange and Udimet 700 outer finger in the rough machined state. Completion of the finger necessitates brazing of the heater/housing assembly into the finger, brazing the monel 400 flange to the finger, and final machining of the assembly. At that stage, the finger will be delivered to WANL for instrumentation and addition of the insulation assembly. Concurrently, the inner liner will be completed and mated to the regenerator mesh.

Figure 11-4 is a photograph of the ambient temperature heat exchanger assembly. The exploded view shows the copper heat exchanger core, stainless steel housing, and coolant fittings, prior to brazing. The assembly photo depicts the configuration after brazing. Following brazing, only a length adjustment (face-cut) is required to complete the assembly.

Figure 11-1. Electric Hot Finger Brazement

Figure 11-2. Nuclear Hot Finger Element

Figure 11-3. Heater Ring/Heat Source Housing

Figure 11-4. Ambient Cooler Assembly

Figure 11-5 depicts the power piston showing the piston face, piston ring (Bal-seal), and piston ring retainer plate. The parts are complete with the exception of a final face-cut on the piston to be accomplished after assembly of the entire rhombic drive mechanism.

Figure 11-6 illustrates the displacer, showing the Udimet 700 outer wall, "Min-K" insulation, the base plate (showing the 10μ filter plate on one side and the pinch-off closure ring on the other), the rider ring (Bal-seal), and rider ring retaining nut. The assembly photograph shows a displacer following insertion of the insulation, welding of the outer wall to the base plate, pressurization with argon, pinch-off, and welding of the closure ring. Final machining of the displacer base and retaining nut are all that remain.

Figure 11-7 shows a Nitralloy 135 (modified) steel displacer rod and 304L stainless steel displacer yoke prior to brazing. After brazing, quenching, and tempering, the assembly will be machined to final dimensions.

Figures 11-8 and 11-9 illustrate the displacer yoke pins and piston yoke pins, respectively. Both pins (as well as all oil lubricated journal surfaces in the drive mechanism) are made of Nitralloy 135 (modified) steel. The pins, as shown, still have their machining "ends" attached. Following nitriding and final grinding, these ends will be removed.

Figure 11-10 shows a typical connecting link (the piston connecting links possess right and left hand symmetry and are slightly wider than the displacer connecting links). The yoke pin bushings have been soldered in place. Only final machining of the bores remains to be done.

Rhombic drive parts not depicted include the piston rod/yoke, counterweights, flywheel shaft, output shaft, crankshafts, and timing gears. Fabrication of the counterweights and piston rod/yoke assemblies were initiated in early June. The timing gears are purchased parts, and have been received.

Figure 11-5. Piston Assembly

Figure 11-6. Displacer Assembly

Figure 11-7. Displacer Rod and Yoke

Figure 11-8. Displacer Yoke Pin

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Figure 11-9. Piston Yoke Pin

Figure 11-10. Connecting Link

Photographs of the control valve and oil pump have been included in the subsection covering Task 2. Figure 11-11 is a photograph of the completed oil filter assembly.

Figure 11-12 shows the 6061 aluminum buffer volume housing after preliminary machining; the internal gussets on the side-walls can be seen in the photo. After the upper crankcase (not shown) is brought to a similar state, the two will be brazed together and re-heat treated to the T6 condition. Final machining is scheduled to begin in mid-July with completion of the first crankcase scheduled for early August. The lower crankcase (or "oil pan") will be initiated in early July and completed in time to mate with the upper crankcase. Among the major parts not shown but which are presently under work are the flywheel and hub, flywheel housing, and flywheel cover.

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Figure 11-11. Oil Filter

Figure 11-12. Buffer Space Housing

TASK 12 - BLOOD PUMP DRIVE MECHANISM FABRICATION

Most of the raw materials that will be required to manufacture the blood pump drive mechanism components have been procured. Purchase requisitions have been issued for all the components that will be purchased. Orders have been placed for the ball bearings and linear ball bushings.

TASK 13 - AUXILIARY COMPONENTS FABRICATION

A purchase requisition was issued for procuring the coolant bellows pumps for three blood pumps and the coolant pump experiment in Task 4, and responses to requests for quotation were received from Sealol and Metal Bellows. Sealol was selected because they are well qualified and their price including tooling was substantially less than that of Metal Bellows.