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PROGRAM

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FOREWORD

This quarterly report was prepared by Sundstrand Aviation, a Division of Sundstrand Corporation, in accordance with the requirements of Contract AT (04-3)-651. Mr. Gerald S. Leighton, Division of Space Nuclear Systems, USAEC, Washington, D. C., administers the program, while Mr. A. Warren Adam serves as Project Engineer at Sundstrand. Mr. M. R. Schilling is the Contract Program Manager for Sundstrand.

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1.0 INTRODUCTION AND SUMMARY

The Organic Rankine Cycle Technology Program was initiated February 15, 1966, under United States Atomic Energy Commission, Contract No. AT(04-3)-651. The purpose of this program is to investigate the technology necessary to successfully develop an Organic Rankine Cycle power conversion system capable of long duration operation in a space environment. The specific working fluids to be evaluated are biphenyl and the eutectic mixture of biphenyl and biphenyl ether.

The program is divided into four principal tasks.

They are:

a. The Working Fluid Investigation

The purpose of this task is to investigate the pyrolytic degradation of biphenyl and the eutectic mixture of biphenyl and biphenyl ether.

b. The Bearing Investigation

The purpose of this task is to investigate performance and stability of non-rolling contact and rolling contact bearings operating in biphenyl.

c. The Condensate Pump Investigation

The purpose of this task is to evaluate small high speed pumps operating at high suction specific speeds with biphenyl.

d. The Boiler Investigation

The purpose of this task is to investigate heat transfer, stability and performance characteristics of organic working fluid boilers.

In addition, a detailed preliminary design of a complete power conversion system will be performed, as well as some miscellaneous analyses to be defined by the USAEC Project Manager.

Major activities and accomplishments during this reporting period were as follows:

a. Working Fluid Investigation

All four test loops were checked out and run during the previous quarter. Three of the four working fluid investigation loops have been operating almost continuously (less than 3 percent down time) since the last reporting period. These are loops 2, 3, and 4. Loop number 2 contains the eutectic and has 1642 hours endurance running as of October 1, 1967. Loop number 3 contains biphenyl and has a total accumulated time of 2536 hours as of October 1, 1967. However, at 1026 hours, a leak occurred in the loop and while repairing it, part of the inventory was lost. It was decided to replace the fluid

in this loop, establish a new baseline and restart the test. This was done. As a result, all information presented on this loop is based on running subsequent to the restart. Loop number 4 contains biphenyl and has 2200 hours endurance running.

During this reporting period, as a result of finding and repairing several very small leaks, the problem of buildup of condenser pressure has been dramatically reduced. None of the loops have had to be pulled down in approximately 1500 hours.

Both the biphenyl and the eutectic have shown excellent thermal stability to date. Both fluids are of very nearly the same quality as when they were put in the loops. As a result it was deemed useless to utilize loop number 1 to establish a correlation between detailed chemical analysis and an "in line" infrared spectrophotometer scan. During the time allotted for this test (1000 hours) no measurable degradation would have taken place. It was, therefore, decided to run this loop at 700°F turbine inlet temperature for at least 1000 hours. Startup of this loop is scheduled for the first part of October.

Because of the excellent stability being displayed by the eutectic, it was decided to use this in the bearing pump and boiler rigs in place of biphenyl, since it has the advantage of a lower freezing point.

b. Bearing Investigation

The bearing test rig and test loop have been designed and are now being fabricated. The bearings are presently being fabricated, with the exception of the hybrid, which is now in drafting. Delivery of the test rig is expected within the next few weeks and assembly of the system will start shortly.

c. Pump Investigation

All components of the pump test rig and test loop are on order or received. One of the three pumps to be tested has been received and the other two are being manufactured. Assembly of the test loop will start shortly.

d. Boiler Investigation

All major hardware for the boiler test loop has been received, and assembly of the loop is over 50 percent complete. Testing should start in four to six weeks.

The design study of a radioisotope heat source for an organic Rankine cycle space power system which was being conducted by Hittman Associates was completed. The study indicated the feasibility of a heat source design which could take advantage of the low temperature requirements of an organic system and use non refractory metals and still meet reentry and burial requirements.

2.0 TECHNICAL DISCUSSION

The following is a discussion of the work accomplished during this reporting period.

2.1 Working Fluid Investigation

The objective of this activity is to investigate the pyrolytic degradation of biphenyl and the eutectic mixture of biphenyl and biphenyl ether. To this end four hermetically sealed test loops, with sampling valves, have been fabricated, charged with either biphenyl or the eutectic mixture and operated for various lengths of time. To date both fluids have demonstrated excellent stability, probably indicating that the 650°F maximum bulk fluid temperature is below the point at which pyrolytic degradation becomes a measurable problem for these two fluids. For this reason the bearing, pump and boiler test loops will use the eutectic mixture of biphenyl and biphenyl ether, to take advantage of the operational simplicity

of having the fluid molten at room temperature.

The detailed status and operational history of each of the working fluid investigation loops is given in Section 2.1.1. The results of the physical and chemical analyses of the samples processed to date are given in Section 2.1.2.

2.1.1 Test Loop Status

Three of the four working fluid investigation loops (loops #2, 3, and 4) have been operating virtually continuously since the last reporting period. The condenser non-condensable gas pressure build up problem mentioned in the last report has been dramatically reduced in these loops by locating and repairing several small air leaks in the sub-atmospheric portion of the loop. Since these repairs, the condenser hot wells have not been vented to a vacuum at all, the only gas removal being via the scheduled 250 ml. gas samples.

The objectives of loops #3 and 4 have been interchanged due to an operational problem being experienced with loop #4. For some as yet unexplainable reason the pump in loop #4 suddenly became incapable of supplying the boiler with more than approximately 60 PSIA pressure. Thus, the flow rate in this loop is slightly less than the design flow of 170 lb/hr. Since loop #4 is nearing the 2500 hour mark it has been decided to terminate its operation at that point and

consider loop #4 the 2500 hour biphenyl loop. Loop #3 will be run for 5000 hours.

The sampling schedule for these two loops has been revised and is presented along with the schedules for loops #1, and 2, in Table 2.1.1. The schedule for loop #3 shows it operating for 6000 hours; however, as will be described in Section 2.1.1.3 the present charge of biphenyl in loop #3 was injected into the loop at approximately 1000 hours elapsed time on loop #3's clock.

2.1.1.1 Loop #1

Loop #1 was intended to be a 1000 hour loop to establish a correlation between IR traces taken by a Beckman IR5 spectrophotometer through the liquid and vapor IR cells with the corresponding liquid and gas samples taken at the time of the IR traces. This loop was started just one day before the heat rejection system failure shutdown all the loops. At approximately the same time, it was discovered that the spectrophotometer was inoperable and in need of repair or replacement. Since that time the loop has not been restarted, as a replacement for the IR5 was not available on a suitable basis.

Because of the excellent thermal stability being demonstrated by the working fluids in the other working fluid investigation loops, it is deemed highly unlikely that any degradation could be detected in 1000 hours by an IR spectrophotometer. For this reason the objective of

TABLE 2.1-1 SAMPLING SCHEDULE
FOR THE WORKING FLUID INVESTIGATION LOOPS

[illegible]

establishing an IR degradation correlation has been dropped. Loop #1 will be used to investigate the pyrolytic degradation of biphenyl at a fluid outlet temperature of 700°F for a minimum of 1000 hours. The sampling schedule for this loop is shown in Table 2.1.1. The new thermodynamic cycle points for loop #1 are shown in Figure 2.1.1.

2.1.1.2 Loop #2

Loop #2 is the Control Loop. Its purpose is to expose the biphenyl-biphenyl ether eutectic to cycle conditions typical of a Rankine cycle power system for 5000 hours. It also provides a basis for comparison of the thermal stability between biphenyl and the eutectic mixture.

This loop was run for 136.5 hours in a checkout configuration to debug the system components and to establish the capability of unattended operation. At this point the loop inventory was drained, the boiler tube was replaced, the components were inspected and cleaned as well as possible and the loop was reassembled for long endurance operation.

The present charge (22 lbs.) of the eutectic mixture was injected into the loop on 7-19-67. From 7-19-67 to 10-1-67 a total of 1692 operating hours have been accumulated, which indicates that this loop had less than 3% downtime during this period.

The operating history of several important parameters for loop #2 are shown in Figure 2.1.2. The flow rate is not shown on this plot but it is directly proportional to the

Point	Temperature °F	Pressure PSIA	Enthalpy* BTU/LB
1	295.2 (EST)	.90 (EST)	58
2	300 (Arbitrary)	114.5	60
3	593	114	211
4	700	108.5	274
5	694	103.5	377.5
6	700	103.5	380
7	679	1.0	380
8	338	.98	229
9	316	.98	221
10	310 (EST)	.90 (EST)	65

*Data Per Monsanto Research Corporation July, 1963

FIGURE 2.1-1 Thermodynamic Cycle Points For 700°F
Biphenyl Loop

FIGURE 2. 1-2 OPERATING HISTORY OF LOOP #2

boiler outlet pressure, its design value being 170 lb/hr. at 68 PSIA boiler outlet pressure.

As is apparent from this plot the control system for maintaining nozzle inlet temperature, (which is a few degrees cooler than the boiler outlet temperature due to heat losses between the boiler and nozzle) is capable of very close control. It is also apparent that the control system for maintaining condenser temperature does reasonably well, considering the changing amount of non-condensables in the condenser and their deleterious effect on condensing coefficients along with the changing ambient temperature for the heat rejection system. The boiler pressure control system has shown a tendency to drift slightly on the other loops but did a very good job on this loop. The main perturbation of boiler pressure occurred after the long shutdown on 9-13. It was determined that this was due to the fact that the boiler power modulator degraded to the point where the flow rate (i.e. outlet pressure) had to be reduced to maintain boiler outlet at saturated or slightly superheated conditions. This situation was rectified when the degraded power modulator components were replaced.

The shutdowns listed on Figure 2.1.2 are:

- 7-24 - loss of 28 volt DC power supply for instruments and control console.
- 8-27 - power outage at test site.
- 9-13 - power outage at test site.

In addition to these there were several other very short shutdowns due to scheduled power outages, loss of N_2 pressure at the test site, and other momentary power interruptions.

A set of measured cycle conditions for loop #2 along with the predicted or design cycle conditions are given in Table 2.1.2.

2.1.1.3 Loop #3

Loop #3 is now the 5000 hour biphenyl loop. It formerly was a 2500 hour loop but, due to operational problems encountered with loop #4, loop #3 has been redesignated the 5000 hour loop.

Loop #3 was charged with biphenyl on 5-15-67 and run for 1025 hours. At that time a weld on the liquid sample line broke and air leaked into the condenser. The loop was shutdown for repairs.

While repairs were underway a freeze plug in the hotwell outlet line that was being worked on unfroze and a significant amount of biphenyl (about 20-25% of the loop inventory) was spilled.

It was decided to drain the rest of biphenyl as well as reasonably possible without dismantling the loop. Approximately 80% of the initial inventory was removed,

TABLE 2.1-2 LOOP #2 CYCLE
POINT COMPARISON

POINT	P (PSIA)		T (° F.)	
	PROPOSED	ACTUAL	PROPOSED	ACTUAL
1	.98	1.4	296.7	228
2	79		300	228
3	78.5		565	535
4	73		650	650
5	68	69.5	642	650
6	68	69.5	650	647
7	1.0		636.5	635
8	.98		340	335
9	.98	1.4	322	316
10	.90	1.4	317	316

including the spill. On 7-28-67 22 lbs. of new bipheny was injected into the loop and the loop was operated for approximately 100 hours after which samples were taken for analysis and the excess inventory was drained.

The time of injection of the new fluid constituted a new start for this loop, and it will be run for 5000 hours from time of restart.

From 7-28 to 10-1 loop #3 has been in operation for a total of 1510 hours, which indicates less than 3% down time during this period.

The operating history of the several important parameters for loop #3 are shown in Figure 2.1.3. It can be seen from this plot that the boiler outlet pressure tended to drift a bit more than loop #2. The condenser pressure is seen to be very low for the entire 1510 hours, probably indicating that this loop is slightly more hermetic than the others.

The shut downs are the same as listed for loop #2. A set of measured cycle conditions along with the design value of these cycle conditions for loop #3 are given in Table 2.1.3.

2.1.1.4 Loop #4

Due to operational problems encountered with loop #4 it has been decided to run this loop for only 2500 hours. As of 10-1-67 this loop has operated a total of 2200 hours.

FIGURE 2. 1-3 OPERATING HISTORY OF LOOP #3

TABLE 2. 1-3 LOOP #3 CYCLE POINT COMPARISON

POINT	P (PSIA)		T (° F.)	
	PROPOSED	ACTUAL	PROPOSED	ACTUAL
1	.90	.8	296.7	272
2	79		300	272
3	78.5		556	526
4	73		650	650
5	68	73	642	650
6	68	73	650	647
7	1.0		636.5	635 (EST.)
8	.98		334	321
9	.98	.8	316	288
10	.90	.8	310	288

After the loop shut down caused by the heat rejection system failure, the pumping system of loop #4 has been unable to provide the boiler with more than approximately 60 psia inlet pressure and this inlet pressure capability seems to be degrading with time. This can be seen in Figure 2.1.4 which is a plot of the operating history of loop #4.

As is apparent from this plot, the loop was plagued by shut downs early in its life. The shut downs listed are:

- 6-7 - total power failure at test site.
- 6-10 - electrical outage due to storm.
- 6-12 - electrical outage due to storm.
- 6-16 - unexplained shutdown.
- 6-22 - heat rejection system failure.
- 7-24 - 28 volt DC failure at test site.
- 7-30 - unexplained shutdown.
- 8-27 - power outage at test site.
- 9-11 - unexplained shutdown.
- 9-13 - total power failure at test site.

The numerous early shut downs made it difficult to get the loop operating at design point conditions, while the unexplained difficulty of supplying the boiler inlet with more than approximately 60 psia after the 6-22 shut down prevented design point operation during the subsequent time period.

FIGURE 2.1-4

OPERATING HISTORY OF LOOP #4

A comparison of measured cycle conditions to predicted or design conditions for loop #4 is shown in Table 2.1.4. for a point in time before the 6-22 shut down.

2.1.2 Sample Analysis

The general procedures used for obtaining samples from the loops has been described in an earlier report and will not be covered here. The analytical procedures are basically the same as described earlier with one significant change which has vastly improved the detection of low boiling materials, notably benzene. The analytical procedures for the various fractions obtained from the small distillation and the vapor sample from the loop are outlined in Section 2.1.2.2.

2.1.2.1 Physical Properties

The physical testing of samples of the working fluids from the AEC degradation test loops #2, #3, and #4 has been continued during this quarter. Results still have not shown any significant change to indicate that the fluid is being degraded. There is some scatter of data, but there has been no continued trend of change of a particular property with time.

The physical property data for the biphenyl-biphenyl ether eutectic samples from loop #2 are given in Table 2.1.5. The kinematic viscosities show only small

TABLE 2. 1-4 LOOP #4 CYCLE POINT COMPARISON

POINT	P (PSIA)		T (°F.)	
	PROPOSED	ACTUAL	PROPOSED	ACTUAL
1	.90	1.3	296.7	267
2	79	75	300	272
3	78.5		556	539
4	73		650	655
5	68		642	655
6	68	74	650	655
7	1.0	1.3	636.5	638
8	.98	1.3	334	325
9	.98	1.3	316	
10	.90	1.3	310	292

Table 2.1-5 - Physical Properties for Fluid Samples from Degradation

Loop #2

Time Hours	Viscosity, cs			Refractive Index @ 180° F	Specific Gravity @ 77° F	Freezing Point ° F
	@ 100° F	@ 210° F	@ 300° F			
0	2.64	1.02	0.64	1.5606	1.0563	54
100	2.61	1.00	0.64	1.5609	1.0604	54
200	2.66	1.03	0.63	1.5609	1.0591	52.5
400	2.65	1.03	0.64	1.5606	1.0584	54
750	2.64	1.01	0.65	1.5604	1.0602	54
1000	2.65	1.01	0.65	1.5608	1.0553	54
1250	2.60	1.02	0.63	1.5608	1.0551	52

changes through 1250 hours and there is similar scatter of data for refractive index and specific gravity. There has been no definite trend in the variations found in the data. The freezing point is determined using a freezing point curve procedure. These data also show some variation, but there is no observable trend in the data.

The samples of biphenyl from loops #3 and #4 have been tested and the resultant data are given in Tables 2.1.6 and 2.1.7. Again there is some scatter of the data points, but there is no definite trend to indicate there has been major degradation of the fluids. The data for loop #3 in Table 2.1.6 is essentially for two separate fluid changes to that test loop. The first covers the period to 1025 hours. At that time, a major air leak was noted in this loop and the fluid rapidly degraded to a yellow color. The leak was repaired and the yellow fluid was drained from the loop. A new charge of biphenyl was introduced into the loop and the loop was restarted. The data from 1200 hours to 1900 hours are for this charge of working fluid.

In conclusion, there have not been any major changes seen in the physical properties of the biphenyl after up to 1500 hours. The biphenyl-biphenyl ether eutectic has physical properties after 1250 hours which are comparable to those of the new eutectic mixture.

Table 2.1-6 - Physical Properties for Fluid Samples from Degradation

Loop #3

Time Hours	Viscosity, cs		Refractive Index @ 180° F	Specific Gravity @ 200° F	Melting Point	
	@ 210° F	@ 300° F			°C	°F
0	1.00	0.62	1.5839	0.9869	69.4-69.8	156.9-157.6
100	0.99	0.61	1.5837	0.9823	69.6-69.8	157.3-157.6
200	1.01	0.61	1.5840	0.9871	69.6-70.0	157.3-158.0
400	1.01	0.63	1.5839	Insufficient sample	69.1-69.5	156.4-157.1
700	1.03	0.60	1.5837	Insufficient sample	69.3-69.8	156.7-157.6
1025	1.05	0.64	1.5844	0.9782	69.3-69.7	156.7-157.5
New	1.01	0.62	1.5848	0.9689	69.8-70.0	157.6-158.0
1200	1.03	0.64	1.5848	0.9775	69.6-70.0	157.3-158.0
1400	1.02	0.63	1.5848	0.9776	69.8-70.2	157.6-158.4
1700	1.01	0.65	1.5853	0.9783	69.5-69.9	157.1-157.8
1900	1.02	0.64	1.5857	0.9776	69.4-69.8	156.9-157.6

Table 2. 1-7 - Physical Properties for Fluid Samples from Degradation

Loop #4

Time Hours	Viscosity, cs		Refractive Index @ 180° F	Specific Gravity @ 200° F	Melting Point	
	@ 210° F	@ 300° F			° C	° F
0	1.02	0.63	1.5841	0.9832	69.6-70.0	157.3-158.0
100	1.02	0.63	1.5845	0.9852	69.6-70.0	157.3-158.0
200	1.00	0.62	1.5841	0.9850	69.7-70.1	157.5-158.2
500	1.01	0.64	1.5851	0.9829	69.8-70.3	157.6-158.6
1500	1.03	0.62	1.5853	0.9757	69.5-69.7	157.1-157.5

2.1.2.2 Chemical Analysis

Vapor Sample - The gas is analyzed by gas chromatography using a molecular sieve column for carbon monoxide, hydrogen, methane, and nitrogen and a silica gel column for the detection of carbon dioxide, ethene, and propane.

Liquid Sample - The sample is distilled to give two fractions - low boilers and a residue which contains the unchanged working fluid and any higher boiling products which may have formed in the loop.

The low boilers are dissolved in chloroform and analyzed by gas chromatography. A column of polyethylene glycol 1500 on teflon has been used to detect quantities of benzene down to 8 parts per million by volume in the chloroform solution.

The working fluid - high boiler residue is normally dissolved in chloroform and analyzed by gas chromatography on an Apiezon L column. This procedure will detect about 50 parts per million of the terphenyl isomers in the sample.

The working fluid high boiler mixture has been distilled further for several samples in an attempt to concentrate the high boilers. This has not yielded any detectable amounts of these products, however. A possible problem may be that the polynuclear aromatics are all somewhat volatile and the small quantities present in these samples sublime with the unchanged

working fluid. This procedure will be tried on random samples, but it will not be incorporated as a standard analytical procedure.

The analytical data for the three loops are discussed separately in the following sections.

2.1.2.2.1 Loop #2

Vapor samples from this loop which uses the biphenyl-biphenyl ether eutectic mixture as a working fluid have been run for samples taken at times up to 1600 hours. The analytical data are given in Table 2.1.8. Hydrogen and methane constitute the major amount of expected degradation products. The amount of carbon monoxide and carbon dioxide has been constant since the 300 hour sample. The nitrogen showed an increase for the 1600 hour sample. The reason for this increase is not readily apparent. The sample bottle could leak slightly allowing air to enter, but oxygen was not detected in this sample. It could indicate a very minute leak in the system, probably in the low pressure liquid feed to the pump.

The total recovery of gaseous products has been good for this loop as it approaches 90% or more in all samples except at 1000 hours which was unexplainably low.

The analysis of liquid samples from this loop have not produced any detectable amounts of expected degradation product, specifically benzene and terphenyls, after 1000 hours of operation.

Table 2. 1-8 - Composition for Vapor Samples from Loop 2

Time Hours	Vapor Composition, Mole %						
	Hydrogen	Methane	Ethane	Nitrogen	Carbon Monoxide	Carbon Dioxide	Total %
100	44.5	2.0	-	45.5	2.0	1.6	95.60
300	70.65	2.74		12.65	1.61	8.78	96.43
500	65.82	4.36	0.03	11.01	1.74	9.48	92.44
1000	48.36	3.69	0.08	9.70	1.95	9.21	72.99
1600	57.45	4.14	0.15	16.80	2.20	7.72	88.46

Based on these observations, a maximum amount of these two products has been calculated based on our limits of detection. For the low boilers, the calculation was made by the following equation:

$$V_{\text{OH}} = 8 \times 10^{-6} \times V_{\text{soln}}$$

$$V_{\text{OH}} = \text{Maximum Volume of Benzene}$$

$$V_{\text{sol}} = \text{Volume of chloroform solution of low boilers.}$$

Detection limit is 8 parts per million. This may be converted to the weight by converting the limit to parts per million by weight and using the weight of the low boiler solution.

$$W_{\text{OH}} = 8 \times \frac{0.8787}{1 \times 10^6 \times 1.4916} \times W_{\text{soln}}$$

$$W_{\text{OH}} = \frac{5}{1 \times 10^6} \times W_{\text{soln}}$$

$$W_{\text{OH}} = \text{Weight of benzene in grams}$$

$$W_{\text{soln}} = \text{Weight of low boiler solution in grams.}$$

The results of this calculation are included in Table 2.1.9. The amount of benzene is quite small and amounts to about 5 ppm. The terphenyls may be as much as 150 ppm (total of three isomers with a 50 ppm detection limit each). This indicates we need to improve the limits for detection of the high boiling compounds.

TABLE 2.1.9

ANALYTICAL DATA FOR LIQUID SAMPLE - 1000 HOURS, LOOP 2

Weight of Fluid Sample	14.9238 grams
Low Boilers, grams	0.0050*
Weight of Solvent, grams	16.2657
Maximum Benzene, grams based on detection limit	0.00008 (0.0005%)
Maximum Terphenyl, o-, m-, and p-, based on detection limit	0.00224 (0.015%)

*- From distillation. Contained some liquid which was not dissolved in chloroform - probably moisture.

2.1.2.2.2 Loop #3

The analytical data obtained for the vapor samples from this loop which uses biphenyl as the working fluid are included in Table 2.1.10 for up to 2500 hours. This is actually only a maximum of about 1500 hours on a single batch of fluid as new biphenyl was charged to the loop at about 1000 hours. The only expected degradation products found have been hydrogen and methane. All samples have contained a major quantity of nitrogen indicating that air has leaked into the system at some time. However, it has been quite constant since the loop was restarted at 1000 hours. The presence of large amounts of carbon monoxide and carbon dioxide in the samples is consistent with this observation.

The overall recovery of products in the vapor samples from loop #3 has not been too good. It is believed that the probable cause of this is the presence of low boiling oxidation products which are not detected by the presently used molecular sieve and silica gel columns.

This is the only loop where we have found any detectable quantities of degradation products other than gaseous materials. The sample at 933 hours was found to contain a measurable amount of benzene - 70 ppm by weight in the chloroform solution of low boilers. For this sample, this corresponds to about 0.013% in the fluid. Data for this sample are given in Table 2.1.11. This sample was prior to the fluid change at 1026 hours.

Table 2. 1-10 - Composition of Vapor Samples from Loop 3

Time Hours	Vapor Composition, Mole %					
	Hydrogen	Methane	Nitrogen	Carbon Monoxide	Carbon Dioxide	
100	30.6	1.37	57.7	0.32	3.36	93.35
300	20.0	1.21	63.9	0.36	1.85	87.32
500	10.2	1.09	67.2	0.39	1.43	80.31
950	0.25	0.11	73.6	1.90	5.37	81.23
1200	0.95	0.04	48.44	6.38	15.19	71.00
1500	4.67	0.14	41.54	6.33	14.79	67.47
2000	11.23	0.64	38.92	8.42	17.41	76.62
2500	6.45	0.79	45.02	6.56	13.24	72.10*

*Included 0.04 mole % ethane

TABLE 2.1.11

ANALYTICAL DATA FOR LIQUID SAMPLE - LOOP 3, 933 HOURS

Sample Weight, grams	10.6928
Low Boilers, grams	0.0498*
Solvent, grams	20.4204
Benzene in Solution PPM by Weight	70
Benzene in Sample, grams	0.00143
Benzene in Sample, Weight %	0.013

*- Low boilers were solid and contained a large amount of biphenyl which was carried over into the trap.

The reason benzene was found in this sample may be that there was definitely an air leak in this loop. Air is known to catalyze the degradation of biphenyl.

The most recent liquid sample from loop 3 did not contain any detectable amounts of benzene. A calculated value for the maximum amount of degradation products is given in Table 2.1.12 as determined by the method described for loop 2.

The amount of degradation is quite small based on these data. No terphenyls have been detected in any fluid sample from loop 3 to the present time.

2.1.2.2.3 Loop #4

Vapor samples have been obtained from loop 4 which uses biphenyl as the working fluid and analyzed to produce the data in Table 2.1.13. Hydrogen and methane are again the major products of thermal degradation found. Appreciable amounts of carbon monoxide and carbon dioxide have also been detected as indicated by the data. It is of interest to note that there was a marked decrease in hydrogen between the 200 hour and 1000 hour sample. The loop was shut down between these two samples due to mechanical problem in the coolant circuit.

The hydrogen probably escaped from the loop through the palladium plate during the shutdown. Other gases could not permeate the plug and remained in the loop. The relatively large amounts of nitrogen, carbon monoxide, and carbon dioxide indicate there has been air in the system at

TABLE 2.1.12

ANALYTICAL DATA FOR LIQUID SAMPLE - LOOP 3, 2000 HOURS

Sample Weight, grams	18.3063
Low Boilers, grams	0.0093*
Solvents, grams	16.4144
Maximum Benzene, grams based on detection limit	0.00008 (0.0005%)
Maximum Terphenyl, o-, m-, and p-, grams based on detection limit	0.00275 (0.015%)

*- Contained some liquid which was not dissolved in chloroform
probably moisture.

Table 2. 1-13 - Composition of Vapor Samples from Loop 4

Time Hours	Vapor Composition, Mole %						
	Hydrogen	Methane	Ethane	Nitrogen	Carbon Monoxide	Carbon Dioxide	Total
100	69.4	1.92	-	2.46	0.80	1.54	76.12
200	67.9	6.02	-	4.29	2.99	0.92	82.12
1000	13.27	16.62	0.52	27.50	17.63	4.97	86.69*
1240	7.05	9.32	0.28	36.74	10.94	2.69	80.12**
1600	18.12	34.67	0.60	12.77	15.91	1.13	83.20

*This includes 6.18% oxygen found in sample

**This includes 13.1% oxygen found in this sample

some time. It does not appear that there is any major leak in this loop, however, as the nitrogen level is decreasing. Oxygen was found in two of the samples, at 1000 hours and 1240 hours. This may be due in part to a leak in the sample bottle. However, it is present in too high a quantity with respect to nitrogen to be due entirely to this source. It appears there was some oxygen in the loop at those times. There was no oxygen detected at 1600 hours. Overall recovery of products has been fair. The unknown products may be due to unidentified oxidation products such as discussed for loop 3. It appears that there has been oxygen in this loop, so this is a feasible explanation.

The analysis of liquid samples from this loop at 1000 hours show no detectable amounts of benzene or terphenyls. This in contrast to the sample from loop 3 at 933 hours where benzene was found. The maximum amount of benzene and terphenyls was again calculated and is given in Table 2.1.14.

In conclusion it does not appear that there has been any significant degradation of the biphenyl or biphenyl-biphenyl ether eutectic based on these analytical results. Both fluids are very nearly of the same quality as when they were when put into the loops.

TABLE 2.1.14

ANALYTICAL DATA FOR LIQUID SAMPLE - LOOP 4, 1000 HOURS

Sample Weight	11.7988
Low Boilers, grams	0.0072
Solvent, grams	12.8322
Maximum Benzene, grams based on detection limit	0.00006 (0.0005%)
Maximum Terphenyl, o-, m-, and p- grams based on detection limit.	0.00177 (0.015%)

2.2 Bearing Investigation

Simultaneous consideration of the thermal degradation and the melting point of both pure biphenyl and the eutectic mixture of biphenyl and biphenyl ether led to the decision that the eutectic mixture would be used as the lubricant for the bearing investigation. This will greatly simplify the operation of the test loop since problems associated with the high melting point of the biphenyl will no longer exist.

The ultimate objective of the bearing test program is to define a bearing system suitable for operation in an organic Rankine Cycle Space Power System producing from one (1) to ten (10) kilowatts of useful electrical power. Investigation will be made of bearing stability, power loss and load capacity for a rig employing a rotor representative of that of a 5 kwe unit.

Four (4) configurations are to be tested, with an ultimate design lifetime of 10,000 hours. The configurations are an angular contact ball bearing, a plain journal and a floating pad hydrodynamic bearing, and a hybrid tilting-pad hydrostatic/hydrodynamic bearing.

2.2.1 Bearing Test Rig and Test Loop

The manufacture of the bearing test rig is nearing completion, and delivery is expected within a few weeks.

The test loop components have all been received including the 24,000 RPM motor, the reaction torque meter, the reservoir, Viking facility pump, chromalox circulation heater and valves.

The test rig loop and cabinet will be assembled prior to receipt of the test rig.

2.2.2 Bearings

The M-50 tool steel angular contact bearings have been received and two types of ball retaining cages are in the process of being manufactured.

The first type of cage is a free machining steel (SAE 4130) cage which will be electroplated with silver (AMS 2410). This type of cage was recommended by the Marlin Rockwell Company and great success has been achieved with the use of silver plating in other situations involving poor lubrication.

The plastic cage which was finally chosen for the ball bearing configuration is a glass fibre filled Teflon called Armalon (Du Pont). The choice of this rather than Duroid was based mainly on mechanical strength. Duroid does have slightly superior lubricating properties due to the presence of the Molybdenum Disulphide filler, but the Barden Company, which has experience with both materials, was sceptical about the ability of Duroid to withstand the loads

and speeds which will be met in the investigation.

As far as a design life of 10,000 hours is concerned all the bearing manufacturers expressed great doubt on the capability of ball bearings. The major problem which is expected to be met is race and cage wear rather than fatigue failure.

The floating pad bearing is being manufactured and few problems are expected with the tungsten carbide plating process. Some doubt was expressed about good bonding at the edges of the pads but it is expected that a corner break will resolve that problem.

There are no problems associated with the manufacture of the plain journal bearing.

The analysis of the hybrid tilting-pad bearing is almost complete, with the exception of the complete hydrodynamic characteristics. The magnitude of the developed hydrodynamic pressure under the pad must be calculated to determine whether a check valve is required in the inlet line. If the hydrostatic supply flow is interrupted when the rig is at full speed the hydrodynamic operation of the bearings can be investigated, with the additional possibility of actually measuring the pad pressure via the hydrostatic inlet.

It is expected that these bearings will be ready for manufacture in a few weeks and no problems are expected.

2.3 Condensate Pump Investigation

The intent of the pump investigation program is to experimentally define the optimum pump configurations to fully cover the power range from one to ten kilowatts of net electrical output. Three types of pumps have been selected and sized for the flow and application at which efficient operation is most likely for the particular pump. The working fluid will be the eutectic mixture of biphenyl and biphenyl ether.

2.3.1 Pump Test Rig and Test Loop

All components of the pump test rig and test loop are on order or in house. The major components of the test rig, the motor, torque ring and the first pump, are shown in an exploded view in Figure 2.3.1.

The motor is a one HP water-cooled induction motor capable of 24,000 RPM. The motor is directly coupled to the pump impeller with a close fitting viscoseal (the viscoseal is not shown in the photographs). A magnetic pick-up will be used to determine the shaft speed.

FIGURE 2.3.1 EXPLODED VIEW OF TEST RIG

A Lebow torque ring couples the pump and motor housing together and senses the reaction torque on the impeller shaft. Sensitivity of the torque and speed readouts allow power consumptions of two watts to be detected.

2.3.2 Pumps

The pump shown in Figure 2.3.1 is the first pump to be tested and is a partial emission type with two discharge ports and diffusers. It is anticipated that by using two discharge flow paths the off-design performance of the pump will be improved over a single discharge flow path. The inlet to one of the diffusers is shown in Figure 2.3.2 along with the impeller in position. The impeller is shown separately in Figure 2.3.3. This pump, when operated in series with a jet-pump, could be used in a 1 to 5 kilowatt Rankine power system.

Two other pumps have been designed and are being manufactured. Pump #2 is a centrifugal pump with an integral axial inducer and is shown in Figure 2.3.4. This pump could be used in a 5 to 10 kilowatt Rankine power system. Pump #3 is shown in Figure 2.3.5. This pump is designed for a jet condenser system in which a high by-pass flow is used to enhance condenser performance and in turn provides a high suction pressure at the pump inlet. The pump is sized for a 5-6 kilowatt Rankine power system.

DIFFUSER INLET

FIGURE 2.3.3 PUMP IMPELLER

Figure 2.3-4 - Centrifugal Pump With Axial Inducer

Figure 2.3.5 Jet Condenser Pump

A schematic of the test loop is shown in Figure 2.3.6. The fluid flows from the reservoir and passes through a jet pump or simply flows directly to the pump inlet section. The fluid is pressurized by the pump and delivered to a manual control valve which is used to control pump flow and exit pressure. The flow is then filtered and returned to the reservoir and the cycle is completed. A detailed description of the pumps, test loop, test objectives, and test procedure is given in the test plan, which has been submitted to the AEC for approval.

2.4 Boiler Investigation

The design of a boiler for an organic Rankine cycle power system requires knowledge of the heat transfer and stability characteristics of the evaporation process over the entire length of the boiler tube. These characteristics are intimately related to the complex two-phase hydrodynamic flow patterns that exist as a result of the boiling process. In addition, the overall boiler pressure drop is also a parameter of importance. The pressure drop should be kept as low as possible to minimize power system performance penalties without sacrificing stability and heat transfer requirements. The theoretical and empirical equations used to define these areas of interest are at best, unconfirmed and limited in scope. In addition, the uncertainty of these equations is magnified by the necessity of modifying these

LEGEND

- RECORDED
- NON RECORDED
- SHUTDOWN
- T TEMPERATURE
- P PRESSURE
- Δ P PRESSURE DIFFERENTIAL

PUMP TEST LOOP SCHEMATIC

Figure 2-3-6

15	FACILITY PUMP
14	BOTTLE-1 GAL VACUUM
13	HEATER IMMERSION 5KW
12	FLOW METER
11	FILTER- 5 INPT-1 PSI MAX 10GPM 66PS 35
10	GAGE DIFFERENTIAL PRESSURE 0-25 PSID
9	TRANSDUCER DR GAGE PRESSURE 0-150 PSI TRANS
8	TORQUE RING 6-40 IN OZ
7	VARI-DRIVE 75W MOTOR & GENERATOR
6	MOTOR 400W 220V 400 CYCLES
5	CHAMBER VACUUM
4	PUMP TEST
3	PUMP JET
2	CONTROL HEATER 8KW SCR
1	RESERVOIR TO GAC

<p>TYPE</p> <p>PUMP LOOP SCHEMATIC</p> <p>AEC PROGRAM (ORGANIC)</p>			
<p>DATE</p> <p>99167</p>	<p>REV</p> <p>NO</p>	<p>REV</p>	
<p>SCALE</p> <p>100 FT</p>	<p>CAC</p>	<p>10 SHEET</p>	

equations to account for the effects of swirl generators such as spiral wires or twisted tapes. Therefore, the objective of these tests is to produce sufficient data to define and eliminate the areas of uncertainty existing in predicting boiler tube performance and to establish reliable design criteria.

The working fluid previously specified for this boiling investigation has been changed from biphenyl to a eutectic mixture of biphenyl and biphenyl ether.

2.4.1 Boiler Test Loop and Hardware Status

All hardware required for the test loop, with the exception of the boiler tube wall thermocouples, has been received and the loop is presently under construction.

The boiler tube thermocouples, which have a promised 10 day delivery time, will be ordered subsequent to the verification of the acceptability of four sample thermocouples previously received.

A cavitating venturi, which was not previously shown on the loop schematic, will be added to the test loop just downstream of the boiler feed pump. The venturi will enable the system flow rate to be independent of minor changes or fluctuations in downstream pressures.

2.4.2 High Heat Flux Boiler Tube

Experimentation with different braze alloys and brazing procedures was conducted to develop an acceptable method for joining a copper jacket to the stainless steel boiler tube. Although favorable results were not achieved, the results did indicate that a satisfactory joint could be achieved if the dimensions that control the gap between the stainless steel tubing and copper could be tightly controlled.

An alternative to the tightly controlled gap dimensions would be the development of a technique to supply sufficient filler metal to the variable gap that exists between the tubing and the copper. However, due to limitations in time and funding, it was decided not to undertake the effort to develop the necessary fixturing to solve this problem.

An acceptable brazing procedure was developed for this application and is described as follows: vacuum braze with AMS 4772 copper braze alloy. Braze at 1800°F for 10 minutes without a flux. Metal grit blast and then acid etch the materials prior to brazing.

Vacuum casting of the copper around the tube is not being given further consideration because of the high cost of the graphite molds and the uncertainty in the

acceptability of the results of this procedure.

Therefore, a high heat flux boiler tube will not be manufactured and tested because of the unsuccessful attempt to develop a relatively cheap and simple method for fabricating a copper finned stainless steel boiler tube.

2.4.3 Heat Source Study

Hittman Associates, under subcontract to Sundstrand, has successfully completed a detailed design study of a 25 K_{WT} Po²³⁸ heat source designed for the low heat addition temperature requirements of the organic Rankine cycle. This design employs a reentry body for the entire heat source and uses a superalloy for isotope encapsulation. This design study is reported in "24.5 K_{WT} Radiosotope Fueled Organic Rankine Cycle Heat Source Study for Space Power" 9/6/67.