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QUARTERLY PROGRESS REPORT NO. 12
ORGANIC RANKINE CYCLE TECHNOLOGY PROGRAM

AVIATION DIVISION
SUNDSTRAND CORPORATION

PREPARED UNDER
CONTRACT AT(04-3)-651
FOR THE
SAN FRANCISCO OPERATIONS OFFICE
U.S. ATOMIC ENERGY COMMISSION

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Report

QUARTERLY PROGRESS REPORT NO. 12

ORGANIC RANKINE CYCLE TECHNOLOGY PROGRAM

COVERING THE PERIOD 1 JANUARY, 1969
to 1 APRIL, 1969

APRIL 15, 1969

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PREPARED UNDER
CONTRACT AT (04-3)-651
FOR THE
SAN FRANCISCO OPERATIONS OFFICE
U. S. ATOMIC ENERGY COMMISSION

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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. Ron Anderson, Division of Space Nuclear Systems, USAEC, Washington, D.C., administers the program, while Mr. R. E. Niggemann serves as Project Engineer at Sundstrand. Mr. J. Petersen is the Contract Program Manager for Sundstrand. Messrs. T. J. Bland, L. W. Sibert, L. J. Suit and J. L. Martz are the significant contributors to this report.

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1.0 INTRODUCTION AND SUMMARY

The Organic Rankine Cycle Technology Porgram 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 the eutectic mixture of biphenyl and biphenyl ether.

c. The Condensate Pump Investigation

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

d. The Boiler Investigation

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

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

a. Working Fluid Investigation

Loop #1, with the eutectic mixture of biphenyl and biphenyl-ether as the working fluid at a boiler outlet temperature of 700°F, was the only loop to be operated during this reporting period. The loop suffered a severe over-temperature resulting in extreme fluid degradation and the rupture of a weld. The test was subsequently terminated with an accumulated total of 6367 hours operation.

The eutectic continued to show excellent stability up to the time that final shutdown occurred. Total degradation, linearly extrapolated to 10,000 hours, is only 0.126 percent. This is higher than previously reported because new improved analytical methods have resulted in the discovery of additional high boiling point degradation products.

b. Bearing Investigation

Successful testing of the plain journals has been performed and calibration data are complete.

One successful run has been made with the floating pad bearings, but a full speed rub occurred after four minutes operation. No significant damage resulted.

c. Pump Investigation

The pump test rig has been run during the reporting period. Investigation of the head-flow characteristics for the high flow rate jet condenser pump has been completed.

d. Boiler Investigation

No testing was performed on the boiler rig this reporting period. All experimental work has been completed and the final report is being published.

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 at 650°F, 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.

At 6000 hours the 700°F eutectic loop showed degradation rates approximately the same as those for 700°F biphenyl (at 3000 hours) with values of .126 percent and .133 percent, respectively, when linearly extrapolated to 10,000 hours. It should be realized however, that the data for the eutectic were obtained by new chromatographic methods with the ability to detect previously undetected degradation products. Consequently, the values for the 700°F biphenyl and indeed, all other test loops may be somewhat low.

The new data shows the 700°F eutectic degradation to be significantly higher than that at 650°F (although these latter values may be low), but the quantity is still so small that no deleterious effects would be expected in systems operating for many tens of thousands of hours.

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

2.1.1 Test Loop Status

One of the four fluid investigation loops has operated during this reporting period. Loop #1, the 700°F eutectic ran early in the report period, but suffered a severe over-temperature which ended its usefulness. There was no activity on Loops #2, 3, or 4 during this report period. The sampling schedule for Loop #1 is shown in Table 2.1.1-1.

2.1.1.1 Loop #1

Loop #1 is the 10,000 hour eutectic loop having a 700°F boiler outlet temperature. The loop was put into operation on 5-16-68. During this report period the loop experienced eleven shutdowns. The majority of these were caused by electrical interruptions.

Table 2.1.1-1 Sampling Schedule for the Working Fluid Investigation

LOOP NO. 1 BIPHENYL - BIPHENYL ETHER EUTECTIC @ 700°F					
HOURS	SAMPLES TO DATE	PHYSICAL PROPERTIES	CHEMICAL ANALYSIS LIQUID	CHEMICAL ANALYSIS VAPOR	RESERVE SAMPLE
0		X	X		X
250			X	X	X
500		X			X
750			X	X	X
1000		X			X
1250			X	X	X
1500		X			X
1750			X	X	X
2000		X			X
2250			X	X	X
2500		X			X
2750			X	X	X
3000		X			X
3250			X	X	X
3500		X			X
3750			X	X	X
4000		X			X
4250			X	X	X
4500		X			X
4750			X	X	X
5000		X			X
5250			X	X	X
5500		X			X
5750			X	X	X
6000		X			X
6250			X	X	X
6500		X			X
6750			X	X	X
7000		X			X
7250			X	X	X
7500		X			X
7750			X	X	X
8000		X			X
8250			X	X	X
8500		X			X
8750			X	X	X
9000		X			X
9250			X	X	X
9500		X			X
9750			X	X	X
10000		X	X	X	X

On March 3, 1969, the loop was being restarted after a shutdown the previous night. It had not reached steady-state and consequently was not in its off-design, over-temperature protection mode, when flow unaccountably decreased, allowing the boiler to overheat. The flow steadily decreased, unnoticed, and the constant, unmodulated heaters were sufficient to drive the salt bath temperature above 1300°F. The small amount of eutectic which did enter the boiler tube was degraded and the pressure in the condenser and the whole loop, due to non-condensable gas degradation products, rose to approximately 150 psia. This high pressure deformed the large duct areas of the regenerator and condenser, and opened up a weld seam, relieving the pressure. Because of the resulting extreme degradation (which increases by an order of magnitude for approximately every 70°F above 700°F)and also the loop rupture, it has been decided to terminate the test. A total of 6367 hours were accumulated on the loop and the operating history is shown in Figure 2.1.1-1.

2.1.2 Sample Analysis - Physical and Chemical

This section of the report covers the actual data obtained for the periodic samples from the single loop still in operation during the quarter. The biphenyl-biphenyl ether eutectic was used as the working fluid in that test loop with a turbine simulator inlet temperature of 700°F. Regularly scheduled samples were taken through

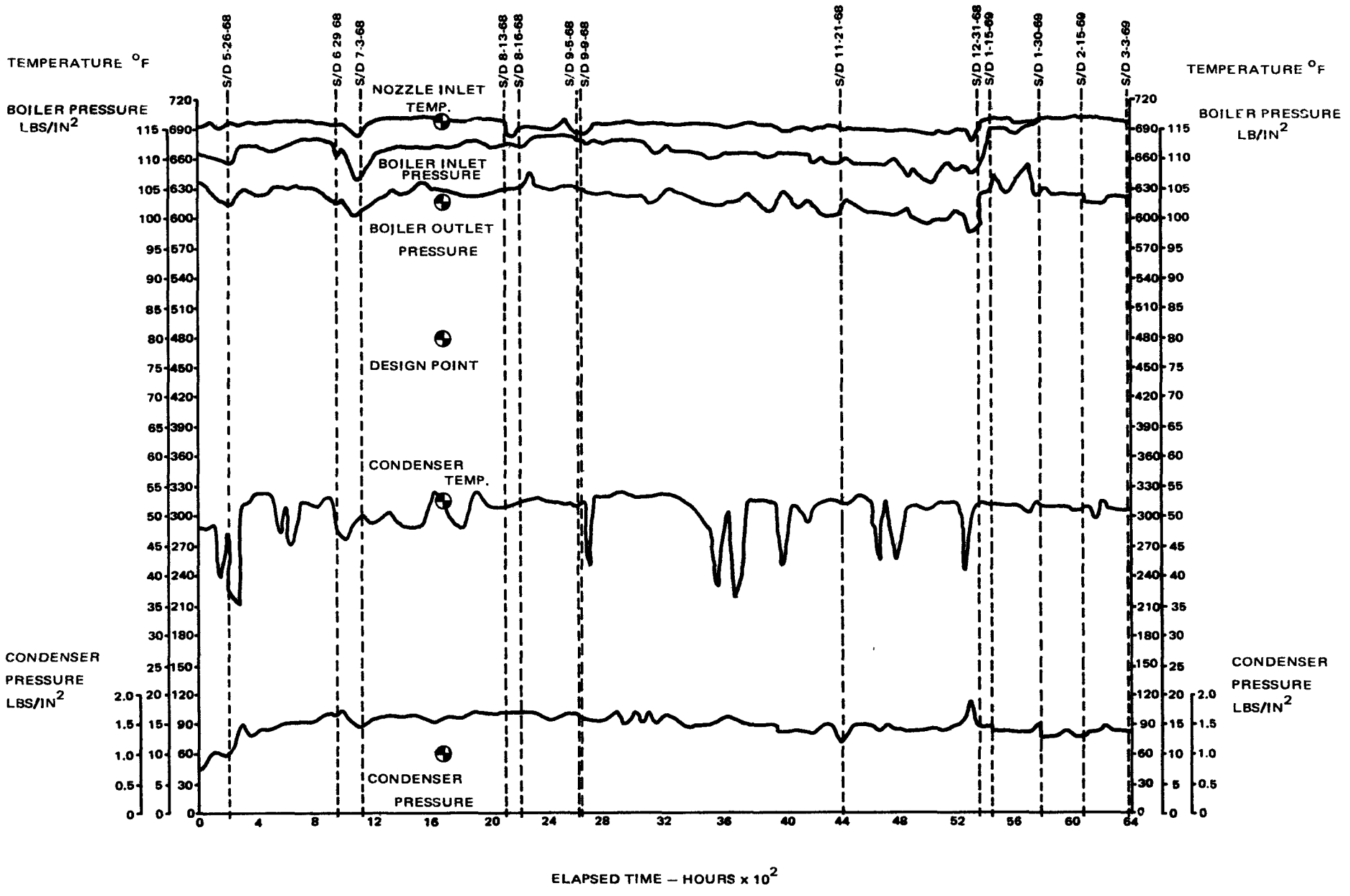


Figure 2.1.1 - 1 Operating History of Loop No. 1

6250 hours, just prior to an overheat condition which resulted in failure of the loop. The fluid was still in excellent condition after 6250 hours in the test loop, prior to failure, with only a very small amount of degradation.

2.1.2.1 Physical Properties

The physical properties for the samples of biphenyl-biphenyl ether eutectic from the thermal stability loop are given in Table 2.1.2-1. There was no evidence of significant change in the physical properties of the fluid through the 6250 hours of operation at the 700°F inlet temperature.

Following the severe overheat condition of approximately 1300°F encountered at 6367 hours, gross changes were found in all of the physical properties. There was a sharp increase in viscosity and smaller increases in the refractive index and the specific gravity. This was probably due to the formation of higher molecular weight degradation products. The presence of these products in the fluid also resulted in a decrease in the freezing point to less than -40°F.

Table 2.1.2-1 Physical Properties for Liquid Biphenyl – Biphenyl Ether Eutectic From Loop No. 1

Time Hours	Viscosity, CS			Refractive Index @ 180°F.	Specific Gravity @ 77°F.	Freezing Point °F.
	@ 100°F.	@ 210°F.	@ 300°F.			
0 [1]	2.64	1.02	0.64	1.5606	1.0563	54.0
0 [2]	2.64	1.02	0.66	1.5612	1.0620	54.0
250	2.63	1.07	0.64	1.5609	1.0641	54.0
750	2.62	1.01	0.65	1.5610	1.0605	53.5
1250	2.71	1.02	0.65	1.5610	1.0593	53.5
1750	2.64	1.05	0.64	1.5609	1.0596	53.5
2250	2.62	1.01	0.62	1.5610	1.0534	53.0
2750	2.69	1.00	0.64	1.5610	1.0585	53.0
3250	2.64	1.04	0.64	1.5612	1.0537	53.5
3750	2.66	1.08	0.65	1.5612	1.0556	53.5
4250	2.60	1.00	0.62	1.5612	1.0592	54.0
4750	2.59	1.05	0.63	1.5612	1.0557	53.0
5250	2.61	1.00	0.65	1.5611	1.0551	53.5
5750	2.64	1.06	0.65	1.5613	1.0572	53.0
6250	2.70	1.02	0.65	1.5613	1.0575	53.5
6367	5.14	1.62	0.92	1.5922	1.0797	<-40

1 NEW FLUID AS RECEIVED

2 FLUID FROM LOOP NO. 1 AFTER FLUSHING OUT BIPHENYL FROM EARLIER TESTING

These data confirm that this organic fluid is quite acceptable from a stability standpoint at the 700°F inlet temperature. It also confirms that extremely high temperatures, such as the 1300°F encountered in the test loop, will cause rapid breakdown of the fluid. This temperature extreme should not be encountered in an actual working system.

2.1.2.2 Chemical Analysis

The analyses of the permanent or non-condensable gases in this thermal stability loop have been made using the same gas chromatographic techniques outlined in an earlier report. Molecular sieve and silica gel columns have been used for this purpose. The samples from the test loop have been analyzed through 6250 hours of normal operation and these data are tabulated in Table 2.1.2-2. The amount of hydrogen decreased somewhat from earlier samples for no readily apparent reason. The amount of carbon dioxide increased to some degree during the same time period.

The sample taken after the 1300°F overheat condition contained more hydrogen, methane, and carbon monoxide in addition to about 46 percent of air which probably leaked into the system during cooling following the

Table 2.1.2-2 Composition for Vapor Samples From Loop 1 -- Eutectic

Time Hours	VAPOR COMPOSITION, MOLE %								
	Hydrogen	Methane	Ethane	Propane	Nitrogen	Oxygen	Carbon Monoxide	Carbon Dioxide	Total
250	31.68	4.25	0.23	0.05	37.7	1.93	10.80	11.03	97.62
500	28.58	5.27	0.28	0.03	37.9	2.21	11.48	11.15	96.87
1000	15.94	4.48	0.26		49.0	2.26	7.80	13.06	92.80
1250	25.98	5.13	0.31		40.7	1.78	8.75	13.89	96.54
1500	23.89	5.61	0.36		45.0		9.27	13.94	98.07
2250	18.47	4.66	0.31	0.10	36.0	3.50	6.51	12.31	99.86 [1]
2750	21.57	6.32	0.43	0.09	42.5	2.06	8.69	17.15	98.81
3250	20.31	7.49	0.53	0.16	42.76	1.97	7.99	16.76	97.97
3750	15.37	7.13	0.49	0.10	47.32	1.64	6.39	18.16	96.50
4250	20.94	6.66	0.46	0.08	52.42	1.74	3.79	14.92	101.01
4750	28.70	7.69	0.66	0.10	41.94	2.00	4.06	16.75	101.90
5250	11.89	7.45	0.69	0.11	47.22	2.00	4.56	21.51	95.43
5750	10.27	6.86	0.80	0.12	46.85	2.72	2.71	21.78	92.11
6250	15.97	7.53	0.80	0.18	42.21	2.09	3.29	24.83	96.90
6367	30.58	9.71	0.09		36.99	9.04	10.65	1.09	98.14

[1] Includes 18.0% of argon detected in this sample.

overheat condition. The nitrogen-oxygen ratio is slightly greater than that for air, probably due to the reaction of some of the oxygen with the fluid at the elevated temperature.

The gradual buildup of non-condensable gases in the test system is of considerable importance. The increase of these products has been determined by the procedure derived in Reference 1. This calculation assumes ideal gas behavior for all of the non-condensable products, uniform vapor temperature during sampling, and an assumption that all of the thermal stability loops involved in this study had a similar initial free volume available for non-condensables. The volumes of the non-condensable gases in the thermal stability loop have been calculated by this procedure for the different time periods. The volumes of the non-condensable products as a function of time are plotted in Figure 2.1.2-1. The upper curve represents the total non-condensable gases in the test loop and includes nitrogen, oxygen, carbon monoxide, and carbon dioxide. The lower curve includes only hydrogen, methane, ethane, and propane, the expected thermal degradation products. The carbon monoxide and carbon dioxide are not included as fluid

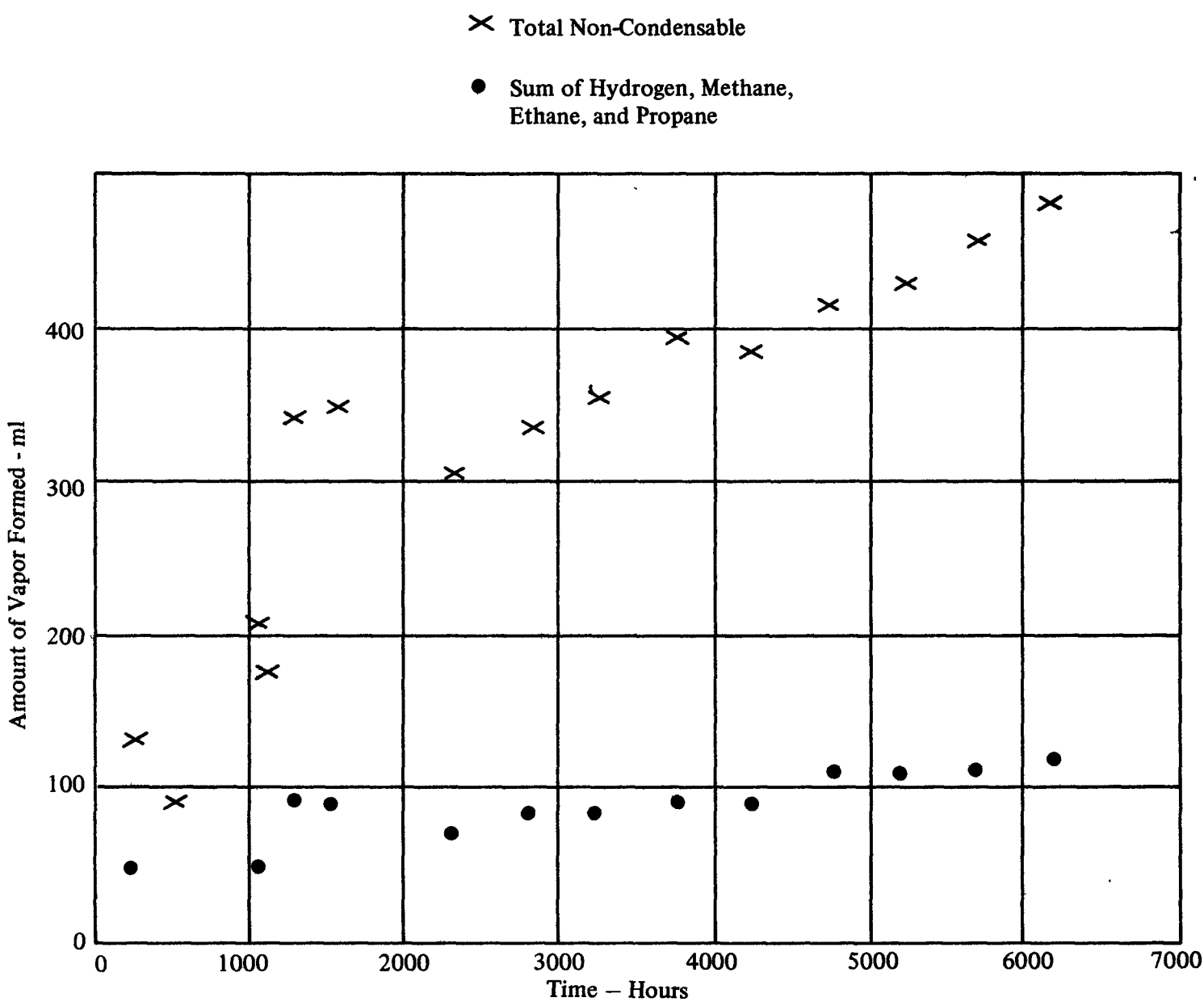


Figure 2.1.2-1 Accumulation of Non-Condensable Vapors in Loop No. 1

thermal degradation products because it is believed that nearly all of these gases are the result of air oxidation of the fluid based on the results found in earlier thermal stability loops using biphenyl. Major amounts of these oxides were found in all of the biphenyl loops where they could not be thermal degradation products.

The analysis of the liquid samples has been further modified with respect to the high boiling components. General procedures used are outlined below.

1. Benzene Analysis. This analysis is made on the fluid sample, with no dilution by gas chromatography, on a lithium chloride column. Quantities of 0.001% of benzene can be detected by this procedure.
2. Phenol. This product is determined by gas chromatography using an OV-1 silicone column. About 0.002% phenol in the sample can be detected.
3. High Boilers, i.e. any product boiling at temperatures higher than that of the biphenyl-biphenyl ether eutectic. The products include terphenyls, diphenoxybenzenes, biphenylyl phenyl ethers, quaterphenyls, various ether

products with four aromatic rings, and other similar higher molecular weight compounds. The general method of analysis was very similar to that described in an earlier report. The sample was distilled to concentrate the high boiling products in a small volume of fluid. This concentrate was then analyzed using a lithium chloride column in a gas chromatograph. Earlier work reported in Reference 2 used a lithium chloride column which did not provide adequate resolution or detection of significant quantities of products with boiling points greater than para-terphenyl.

A new improved lithium chloride column has been procurred and was used to analyze the most recent samples of biphenyl-biphenyl ether eutectic from the final thermal stability loop. It was found that much better resolution was obtained and many more peaks were found. These results are discussed in the following paragraphs.

The samples from 5500 and 6000 hours were analyzed using these three procedures. The results from these tests are given in Table 2.1.2-3 as are earlier results for

Table 2.1.2-3 Analytical Data for Liquid Samples from Thermal Stability Loop 1 - Biphenyl - Biphenyl Ether Eutectic, 700°F

Time Hours	Benzene %	Phenol %	Total Terphenyls %	Diphenoxybenzene Detected %	Biphenylyl Phenyl Ether Detected %	Unknown Peaks Estimated %
1000	.0013	.0020[1]	.0029	–	–	.0029[2]
2000	.0038	.0025	.0031	–	–	.0036[2]
3000	.0068	.0040	.0047	–	–	.0062[2]
4000	.0092	.0020[1]	.0048	–	–	.0059[2]
5000	.0128	.0020[1]	.0058	–	–	.0077[2]
5500	.0135	.0051	.0081	.0023	.0029	.0302[3]
6000	.0161	.0060	.0083	.0046	.0062	.0347[3]

1. Based on detection limit for this product.

2. Includes estimate for combined dimethoxybenzene, biphenylyl phenyl ethers, and possibly other unresolved peaks.

3. Includes numerous high boiling peaks which had not been detectable with earlier lithium chloride column.

the 1000, 2000, 3000, 4000, and 5000 hour samples. It is immediately evident that the data are not directly comparable as the earlier runs did not utilize the newer column for detecting the numerous components seen in the new samples. The earlier chromatogram had only seven peaks which were not well resolved. The new lithium chloride columns permitted the separation of twenty-two distinct peaks of which only seven have been identified. These are:

ortho terphenyl
meta terphenyl
para terphenyl
o-biphenylyl phenyl ether
p-biphenylyl phenyl ether
o-diphenoxy benzene
m-diphenoxy benzene

For the purpose of simplicity, these have been grouped in general classes such as terphenyls in the table. Each class includes all of the identified isomers of that class.

The remainder of the peaks were all placed in a single "unknown" class at the present time. It is believed these are primarily compounds containing four aromatic rings in their structures such as the quaterphenyls, 4P3E type polyphenyl ethers, etc. These peaks have

not been identified up to the present time and such identification may be quite difficult due to a general lack of pure standards for these types of compounds.

The quantitative data estimated for the unknown peaks in Table 2.1.2-3 is based on data obtained for the p-terphenyl and m-diphenoxybenzene. It is felt these values may be higher than actual concentrations because the sensitivity of the flame ionization detector used in these analyses is increased by the increasing number of carbons and hydrogens in the chemical structure, and the four ring structures would have an increase of six carbons and four hydrogens over the three ring products. This would cause greater response with the detector for the four ring compounds than for the three ring compounds. It definitely should be realized that these are calculated estimates for the unidentified peak compounds.

The overall degradation of the eutectic has been calculated using the data from Table 2.1.2-3 and the following postulated reactions for formation of the products:

$$3\ C_{12}H_{10} \longrightarrow 2\ C_{18}H_{14} + H_2$$

Biphenyl — Terphenyl — Hydrogen

$C_{12}H_{10} + H_2 \longrightarrow 2\ C_6H_6$

Biphenyl — Benzene

$2\ C_{12}H_{10}O \longrightarrow C_{18}H_{14}O_2 + C_6H_6$

Biphenyl Ether — Diphenoxybenzene — Benzene

$C_{12}H_{10}O + H_2 \longrightarrow C_6H_5OH + C_6H_6$

Biphenyl Ether — Phenol — Benzene

$C_{12}H_{10}O + C_{12}H_{10} \longrightarrow C_{18}H_{14}O + C_6H_6$

Biphenyl Ether — Biphenyl — Biphenylyl Phenyl Ether — Benzene

$2\ C_{12}H_{10} \longrightarrow C_{24}H_{18} + H_2$

Biphenyl — Quaterphenyl

$2\ C_{12}H_{10}O \longrightarrow C_{24}H_{18}O_2 + H_2$

Biphenyl Ether — 4 Ring Aromatic Diether

$C_{12}H_{10} + 19\ H_2 \longrightarrow 12\ CH_4$

Biphenyl — Methane

$C_{12}H_{10} \longrightarrow 12C + 5\ H_2$

Biphenyl

$2\ C_{12}H_{10} + 17\ O_2 \longrightarrow 24\ CO + 10\ H_2O$

$2\ C_{12}H_{10} + 29\ O_2 \longrightarrow 24\ CO_2 + 10\ H_2O$

Table 2.1.2 - 4 Amount of Eutectic Degraded at Various Times to Form the Observed Degradation Products

Time	1000	3000	5000	5500	6000
Benzene	8.32×10^{-4}	4.35×10^{-3}	8.19×10^{-3}	4.91×10^{-3}	4.98×10^{-3}
Phenol	2.13×10^{-3}	4.44×10^{-3}	2.13×10^{-3}	5.42×10^{-3}	6.38×10^{-3}
Terphenyls	1.89×10^{-3}	2.98×10^{-3}	3.78×10^{-3}	5.28×10^{-3}	5.40×10^{-3}
Dimethoxybenzenes	2.28×10^{-3}	4.42×10^{-3}	6.06×10^{-3}	1.74×10^{-3}	3.50×10^{-3}
Biphenylyl Phenyl Ethers				1.77×10^{-3}	3.78×10^{-3}
Unknown High Boilers (est.)	2.28×10^{-3}	4.42×10^{-3}	6.06×10^{-3}	1.876×10^{-2}	2.16×10^{-2}
Methane	3.37×10^{-5}	6.43×10^{-5}	7.94×10^{-5}	9.17×10^{-5}	9.75×10^{-5}
Ethane - Propane	4.82×10^{-6}	1.28×10^{-5}	1.71×10^{-5}	1.85×10^{-5}	2.02×10^{-5}
Hydrogen	3.95×10^{-4}	1.33×10^{-3}	1.74×10^{-3}	1.39×10^{-3}	1.64×10^{-3}
Sub-Total	7.57×10^{-3}	1.76×10^{-2}	2.20×10^{-3}	3.901×10^{-2}	4.750×10^{-2}
Carbon Monoxide	6.22×10^{-5}	1.03×10^{-4}	1.12×10^{-4}	1.15×10^{-4}	1.18×10^{-4}
Carbon Dioxide	9.33×10^{-5}	1.55×10^{-4}	1.98×10^{-4}	2.50×10^{-4}	2.67×10^{-4}
Total	7.72×10^{-3}	1.786×10^{-2}	2.231×10^{-2}	3.938×10^{-2}	4.778×10^{-2}
% of Original Charge to Loop	0.013	0.030	0.037	0.066	0.079

The loop was originally charged with twenty-two pounds of the biphenyl-biphenyl ether eutectic. Using this fact and the analytical results in Table 2.1.2-3, it is possible to estimate the amount of high boiling products in the loop at any given time of analysis. From these quantities of degradation products and the aforementioned reaction equations, it is possible to estimate the amount of eutectic which has been degraded to form the observed products. Table 2.1.2-4 contains these data calculated for the thermal stability loop. There is a definite break between the older data and the most recent samples, as was expected, due to the inclusion of the additional high boilers detected. There was still less than 0.1% degradation of the eutectic after 6000 hours at the 700°F turbine simulator inlet temperature.

Figure 2.1.2-2 is a plot of the amount of unchanged eutectic mixture as a function of time. There is a non-linearity as expected. Even based on the worst points, there should be less then 0.2 percent degradation after 10,000 hours. This amount of degradation would not appreciably affect the performance of the fluid itself. The non-condensable gas accumulation will have to be considered to minimize back pressure in an actual turbine system.

It was reported previously that there was a distinct anomaly in the rates of production of hydrogen and high boilers from Loop 1 (700°F eutectic) and Loop 2 (650°F eutectic). Further consideration has resulted in the resolution of the problem. There were errors in two of the numbers involved. Firstly, the evolution of benzene and terphenyl ethers from Loop 1 should have read 2.2×10^{-8} lbs/hour (not 2.2×10^{-7} lbs/hour), this gives a value of the same order of magnitude as that for Loop 2. In addition the evolution rate for terphenyls for Loop 2 should have read 5.0×10^{-2} lbs/hour (not 3.11×10^{-2} lbs/hour).

If one now considers the difference in detection limits for the terphenyls in Loops 1 and 2 and normalizes the results to 85 parts per million detection capability, then the values 6.25×10^{-2} and 5.0×10^{-2} lbs/hour for Loops 1 and 2 respectively are obtained. The values are now of the same order of magnitude but slightly higher for the 700°F eutectic, as expected.

2.1.2.3 Conclusions and Recommendations

The total degradation found in the biphenyl-biphenyl ether eutectic after 6000 hours operation in the test loop with a 700°F turbine simulator inlet temperature was less than 0.1 percent. This is quite small and shows the fluid's thermal stability to be very good.

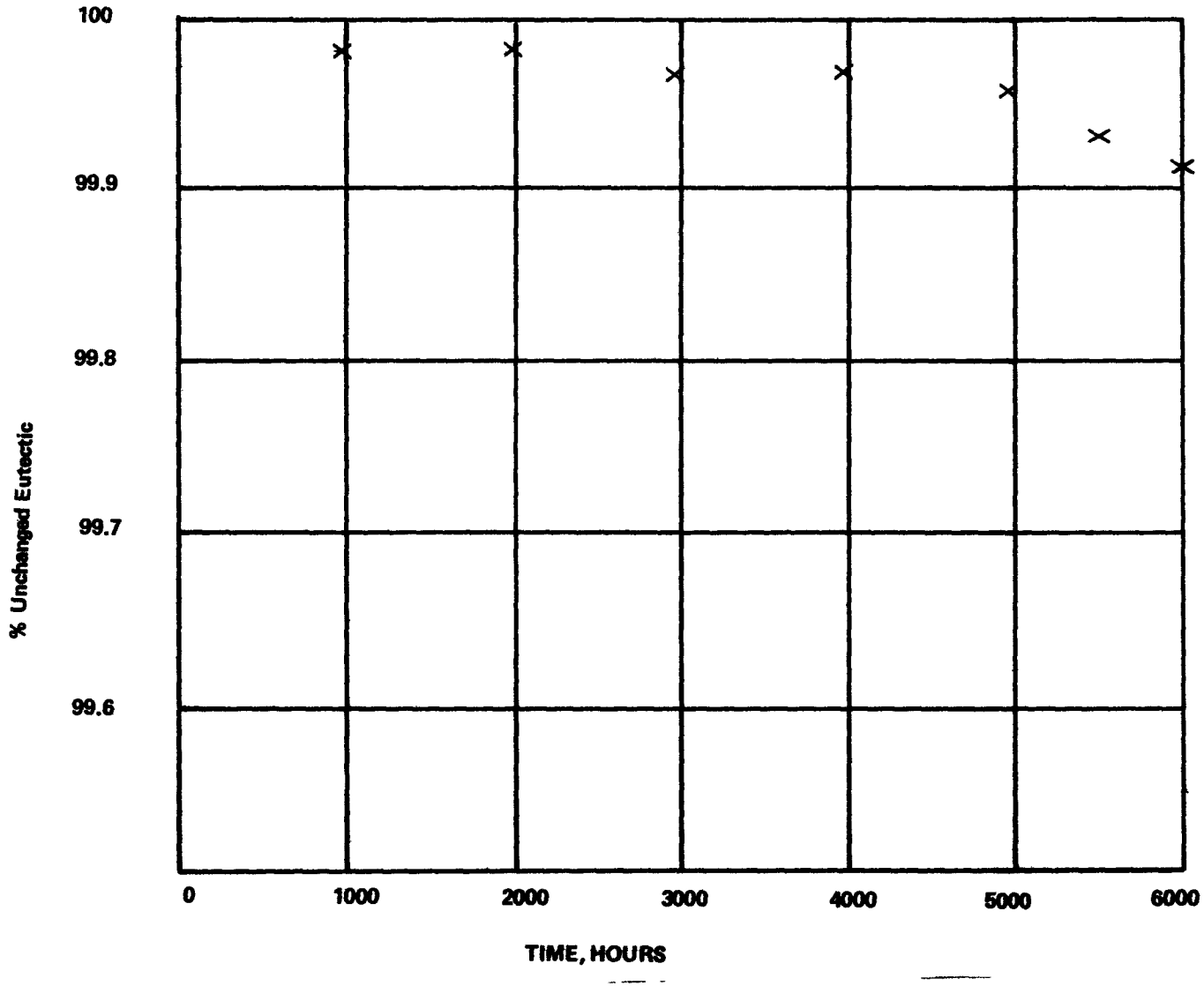


Figure 2.1.2-2 Decrease in Amount of Eutectic in Loop 1 as Function of Time

It is recommended that several of the retained samples from the 700°F eutectic loop and from the 650°F eutectic loop, and possibly the two biphenyl loops (700°F and 650°F), be opened and subjected to analysis by the revised procedures for high boilers. This would define more positively the overall degradation. This additional work would delay the final report somewhat, but it is felt the added information would enhance the final value of this work.

2.2 BEARING INVESTIGATION

The bearing test program is designed to allow accurate measurement of the operating parameters of various bearing configurations which are lubricated with the working fluid of an organic Rankine cycle power system.

Four bearing configurations are being tested, supporting a rotor representative of that to be found in a system capable of producing 5 kw of electrical power.

The investigation will permit the definition of bearing types suitable for a 1 to 10 kwe power system with a design lifetime of 10,000 hours.

The four configurations are an angular contact ball bearing, a plain journal and a floating pad hydrodynamic bearing and a hybrid, hydrostatic-hydrodynamic tilting pad bearing.

2.2.1 Bearing Test Rig

Minor problems associated with the rig occurred during the reporting period while testing journal bearings, notably, drive motor power supply failures, lip seal failures and the presence of liquid in the housing causing high starting torques. All problems were overcome successfully.

After the first run with floating pad bearings it was decided to modify the end caps to accommodate additional proximity probes so that the rotational speed of the pads could be measured.

2.2.2 Bearing Test Results

One set of angular contact ball bearings has been tested. After 25 hours of design operation, and subsequent disassembly, a fatigue failure was discovered in one bearing and severe wear in both.

Attempts at running the hybrid tilting pad bearing, hydrostatically, have not been successful.

The plain journal bearings have been run for film thickness measurements and test rig calibration tests are now completed. Further details are reported in Section 2.2.2-1.

One test has been performed with the floating pad bearings during the reporting period. Further details may be found in Section 2.2.2-2.

2.2.2.1 Plain Journal Bearing

Further testing of the plain journal bearing was conducted during the quarter. A series of atmospheric pressure tests, using a lip seal, was completed at different temperatures. On evacuation of the housing, however, several lip seal failures occurred and it was realized that the seal frictional torque would be a function of the differential pressure across it, thus making the values taken at atmospheric pressure useless for vacuum calibration tests. Consequently it was decided to change to a close clearance seal at this location which could not touch the quill shaft under any condition. This resulted in a high air inleakage through the seal but the vacuum pump was of ample capacity to cope with the additional leakage.

A final series of tests were conducted for calibration of the windage losses. During the first runs the primary of the jet pump, which had been used to scavenge the housing, was closed off. Unfortunately the additional restriction in the housing drains prevented the housing from draining properly, resulting in the accumulation of liquid in the housing. This was evidenced by high starting torque and short run down times. The problem was cured by connecting the vacuum pump to the loop reservoir. This maintained a positive pressure differential sufficient to ensure adequate drainage from the housing. Under these conditions of satisfactory drainage, series of windage calibration tests were run at different pressures and temperatures.

Full details of these tests will not be reported in full here, complete results will appear in the final report currently being prepared.

A total of sixty-seven starts and stops were accumulated on the journal bearings, and no damage occurred. Slight polishing of the bearing surfaces resulted from these wear cycles, whereas the journals themselves (flame plated tungsten carbide) showed no sign at all of any damage. A photograph of the condition of the journals at the end of testing appears in Figure 2.2.2-1. These

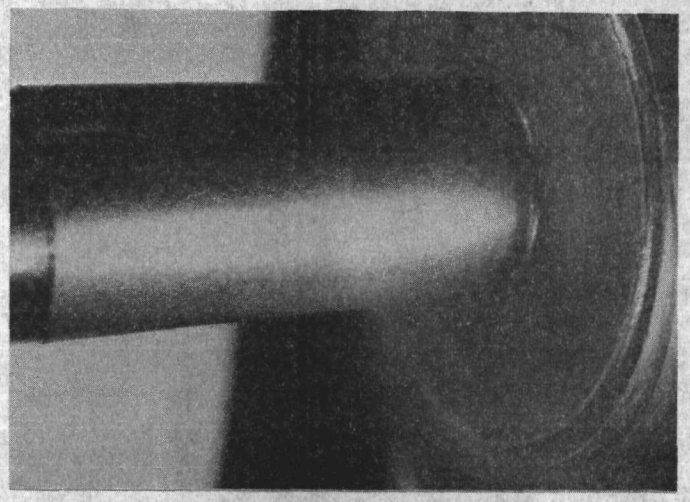
journals were also used for the tilting pad bearings with a total accumulation of 121 start and stop wear cycles.

2.2.2.2 Floating Pad Bearing

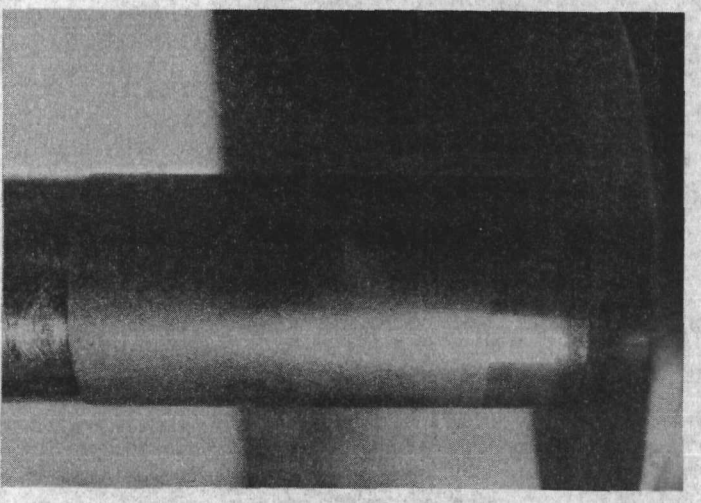
One test was performed using these bearings. The run was successful in as much as it showed that the bearings could be operated. The test was very quiet and vibration free with an operating vibration level of approximately 0.3 peak g's. After four minutes of operation at full speed the torque began to increase slightly and a sudden increase in noise level prompted a shutdown. Coast time was only 50 seconds.

Disassembly showed that a minor rub had occurred on one pad at the quill shaft end. No significant damage occurred, and photographs of the journal and pad are shown in Figure 2.2.2-1.

The small area on the pad which had rubbed was blackened in color and showed no sign of score marks. The appearance of this area pointed to the possibility that the rub was caused by a contaminant particle.

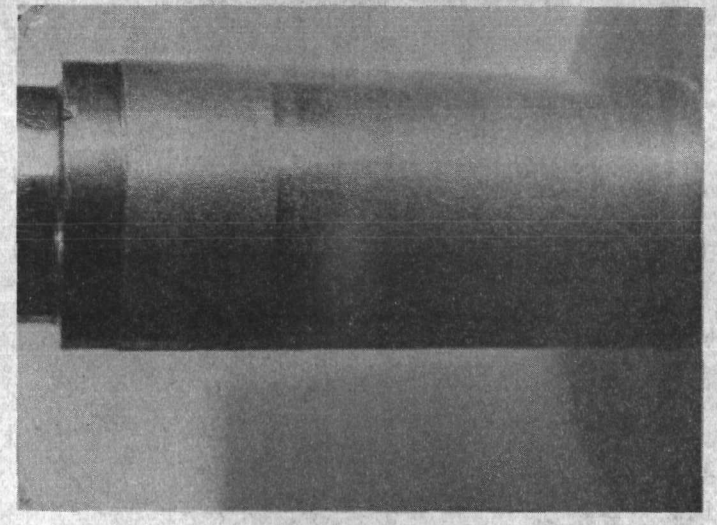


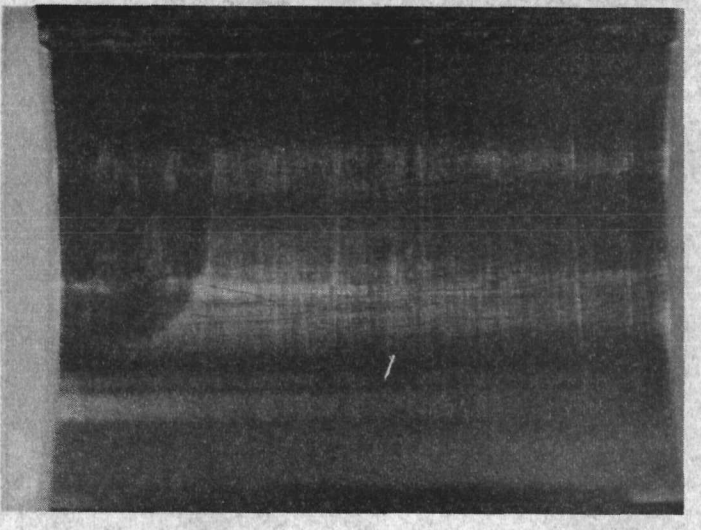
QUILL END JOURNAL



AFT END JOURNAL

A) SHOWING CONDITION OF JOURNALS AFTER 67 START AND STOP WEAR CYCLES WITH PLAIN JOURNAL BEARINGS AND 54 WEAR CYCLES WITH TILTING PAD BEARINGS.





B) QUILL END JOURNAL AFTER FIRST TEST WITH FLOATING PAD BEARING, SHOWING REGION OF SLIGHT RUB.

FLOATING PAD BEARING FROM QUILL END SHOWING DARKENED AREA ON THE LEFT SIDE WHERE RUBBING OCCURRED.

Figure 2.2.2 - 1 Showing the Condition of Journals after Completion of Journal Testing and Journal and Floating Pad After High Speed Rub.

Further testing will be performed during the following reporting period with the additional capability of counting the pads as they rotate, to enable their rotational speed to be determined. This will be accomplished by inserting proximity probes into the housing in such a position that they can detect the discontinuities on the pads.

Complete details of this testing and subsequent testing will be reported completely in the final report currently being prepared.

2.3 CONDENSATE PUMP INVESTIGATION

The pump test program is an investigation to evaluate candidate pump configurations for organic Rankine cycle power systems producing from 1 to 10 kwe. Three widely differing pump configurations have been chosen. Testing of two of these is complete while the third was cancelled for economic reasons. A pump test rig and test loop were designed to accommodate each of the configurations with a minimum of alteration.

2.3.1 Pump Configuration and Status

Testing of the mixed flow pump impeller, designed for use with a jet condenser, has been completed during this reporting period. Complete details of the results will appear in the final report currently in preparation.

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.

The objective of the boiler test program, therefore, is to produce sufficient data to define and eliminate the area of uncertainty existing in the prediction of boiler tube performance and to establish reliable design criteria.

2.4.1 Test Results

No testing has been performed during this reporting period. The final report of all experimental results has been prepared and is currently being published.

REFERENCES

1. Quarterly Progress Report, No. 9, SAN-651-65

2. Quarterly Progress Report, No. 11, SAN-651-77