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PROGRESS REPORT

For the Period

February 1, 1969 - October 31, 1969

LIQUID METAL BEARINGS TECHNOLOGY FOR LARGE,
HIGH TEMPERATURE SODIUM ROTATING MACHINERY

AEC CONTRACT AT (30-1) -3930

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NWO 3930-6
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**MECHANICAL TECHNOLOGY INCORPORATED
PROGRESS REPORT**

on

**LIQUID METAL BEARINGS TECHNOLOGY FOR LARGE,
HIGH TEMPERATURE SODIUM ROTATING MACHINERY**

For the Period

February 1, 1969 - October 31, 1969

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**Contract AT(30-1)-3930
U.S. Atomic Energy Commission
December, 1969**

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I. INTRODUCTION

The purpose of the program, currently in progress under Contract AT(30-1)3930 is to develop the design data and instrumentation needed for reliable design, optimization, and experimental evaluation of the sodium lubricated bearings for the high capacity sodium pumps as well as other auxiliaries of the sodium circulation systems of sodium cooled, fast breeder reactors. To this end, the program was planned to generate the following:

- a. Extension of turbulent flow bearing theory to incorporate fluid inertia effects, followed by preparation and experimental verification of accurate bearing design data and procedures applicable to the large, highly turbulent, sodium lubricated bearings.
- b. Accurate and reliable instrumentation with which proximity and film pressure measurements may be made directly in the high temperature sodium environment.

Specifically, the authorized program tasks are as follows:

- Task I - Program management.
- Task II - Development of the turbulent-inertial lubrication theory and experimental verification of the theory using a low viscosity, non-corrosive lubricant.
- Task III A - Preparation of a design data handbook for large, hydrodynamic bearings.
- Task III B - Preparation of a design data handbook for large, hydrostatic bearings.
- Task IV A - Development and evaluation of film thickness probes for liquid sodium bearing tests, including the amplification and read-out system.
- Task IV B - Development of film-pressure probes for liquid sodium bearing tests.
- Task IV C - Long duration (1000 hours) test of the rugged, extended range (0.10 inches) proximity probes and the film pressure probes in liquid sodium at high temperatures up to 1200 F.

- Task V - Design and procurement of a 12 inch diameter, hydrodynamic sodium lubricated bearing test rig.
- Task VI A - Conduct evaluation tests of the 12 inch diameter hydrodynamic bearings in liquid sodium at elevated temperatures up to 1200 F and compare the bearing performance characteristics with the design handbook data.
- Tasks VI B & C - Screening, selection, and evaluation of surface materials for high temperature sodium bearings.

During the period covered by this progress report, the principal effort was in the following areas:

1. Completion of the design handbook on hydrodynamic sodium bearings (Task III A).
2. Completion of the development of the proximity (film thickness) probes, including short term (100 hours) tests in liquid sodium (Task IV A).
3. Completion of the development of the film pressure probes (Task IV B).
4. Commence preparation for the 1000 hour tests of the proximity and film pressure probes in liquid sodium (Task IV C).
5. Completion of the design of the sodium bearing test rig and continued procurement of the test rig components (Task V).

11. SUMMARY OF PROGRESS

The progress by task during the period covered by this report **is** described in Section III of this report. Following **is** a brief summary of this work.

1. The development of the turbulent-inertial lubricant theory and its initial verification using non-corrosive, low viscosity lubricants were completed in 1968 and described in Topical Report **NYO 3930-2**, issued in January 1969. During the current period, the analysis was programmed for plain and grooved bearings and a design data handbook was prepared covering partial arc bearings, axial grooved bearings, shrouded step bearings and tilting pad bearings. This design handbook was prepared (Topical Report **NYO 3930-5**), and submitted for patent and technical approval.
2. During the earlier work, the effort on the proximity transducer had been directed towards detail design and experimental evaluation of the transducer components. During this reporting period, the work comprised:
 - a. Finalization of the proximity transducer assembly detail design.
 - b. Evaluation of prototype transducer with a conducting medium in the probe-target gap.
 - c. Development of the electronic system.
 - d. Evaluation of core and target materials.
 - e. Evaluation of the transducer-electronic system in a high temperature sodium environment.

This development effort was concluded near the end of the report period with the successful testing of two transducers of the final design in sodium to temperatures in excess of 1100 F.

3. During the earlier work, the effort on the film pressure transducer had comprised detail design and comparative evaluation of **two** transducer types (a) a purely dynamic response transducer for installation in

the rotor to scan the pressure around the full bearing circumference and, (b) a static and dynamic response transducer for mounting in the bearing to monitor local bearing film pressures. The latter transducer was selected for use in the sodium bearing tests to be conducted later under Task VI. During the present reporting period, the design of this transducer was finalized and evaluated at temperatures up to 1200 F. Eight complete transducers were fabricated for use in the bearing tests. The pressure transducer uses the standard Wayne-Kerr electronic amplification system.

4. During the earlier work, the specifications of the sodium bearings test rig were defined and the design of the test system was made, including conduct of the rotor-bearing dynamics, stress, and thermal analyses. During the current period, all design and analyses were completed, the major components were ordered and installation of the test equipment was conducted. The test rig support structure was designed, fabricated, and installed in the test facility. The sodium circulation (oxygen indicating and control) loop was procured and installed. All the major process and test rig controls and equipment components were also received and installed in the control room.
5. Near the end of the current reporting period, the additional tasks comprising the design handbook on hydrostatic bearings, the 1000 hour test of the proximity and film instrumentation as well as the screening, selection and evaluation of bearing surface materials were authorized and work on these tasks was initiated.

111. DISCUSSION OF PROGRAM PROGRESS

Following is a description by task of the work conducted during this reporting period.

Task I - Program Management and Reporting

Letter-type monthly progress reports were issued and a quarterly progress report covering the period November 1, 1968 through January 31, 1969 was prepared and issued (Report No. NYO 3930-4). A technical progress and contract review meeting was held at MIT on September 25, 1969, attended by representatives of RDT (Special Technology Branch) and NYO.

Task II - Fluid Inertia Investigation

This task has been completed and described in Topical Report NYO 3930-2, which was distributed in January, 1969.

Task III A - Design Handbook. Hydrodynamic Bearings

The technical effort under this task was completed and the draft of the topical report was prepared and issued to the Commission for patent and technical approvals.

The object of this task was to prepare rational design data, based upon the turbulent-inertial lubrication analysis developed in Task II, for use in the design of hydrodynamic journal bearings of large, sodium lubricated rotating machinery.

The design data was generated for the following bearing types:

1. Four axial grooved bearings.
2. Shrouded step bearings.
3. Tilting pad bearings.

These are illustrated schematically in Fig. 1. In addition, the data for the individual 80° bearing arcs was obtained and provided also in the design

handbook to permit bearing designers to obtain performance of other bearing types (e.g. preloaded lobe bearings).

a. Shrouded Step Bearing Optimization

In the preparation of the design data, optimization studies were conducted for the shrouded step bearing to establish, on the basis of maximum load and static stiffness, the optimum geometrical parameters such as groove length, width, and depth ratios.

A fixed design was sought such that, irrespective of the overall pocket dimensions, the step depth ratio (δ/C where δ is the step depth and C the radial clearance), the pocket width ratio (B_p/B where B_p is the pocket width and B is the total width of the bearing), and the pocket length ratio (l_p/l where l_p is the length of the pocket and l is the sum of the pocket and land lengths) remain constant. The design had to be near optimum in the sense that it provided high stiffness for journal bearings using four equal pads around the circumference. This meant that the bearings should have a high static radial stiffness and be consistent with the following restraints:

- Provide satisfactory load capacity of high eccentricity
- Preserve adequate land area for good start-up capability
- Have low attitude angle for good stability
- Be suitable for use over large ranges of Reynolds number (up to 60,000) and bearing clearance ratios (up to 0.003 inch/inch)

The optimization studies were conducted for a "standard" set of operating conditions and ranges of the parameters about this standard, as noted below :

(see next page)

TABLE 1
STANDARD OPERATING CONDITIONS AND VARIATIONS
CONSIDERED IN THE OPTIMIZATION STUDIES

	<u>Minimum</u>	<u>Standard</u>	<u>Maximum</u>
Reynolds Number	5000	20,000	60,000
Clearance Ratio	1×10^{-3}	2×10^{-3}	3×10^{-3}
Length to Diameter Ratio	0.5	0.7	1.0
Pad Extent	52°	80°	—

The complete optimization study is described in the Topical Report **NYO 3930-5**. Typical curves from this study are reproduced here from Report **NYO 3930-5**, in Figs. 2, 3, and 4.

The optimum bearing configuration that evolved from this study has the following geometrical factors:

Pocket Depth Ratio	1.5
Pocket Width Ratio	0.6
Pocket Length Ratio	0.7

Fig. 5 shows the load parameter vs. eccentricity ratio for an 80°, L/D = 0.7 pad having the above geometry.

A study was also made to determine the extend to which shrouding of the pocket, i.e., the use of circumferential end seals around the pocket will increase load capacity over an unshrouded step bearing. The results showed that, with each design optimized, the shrouded step bearing has an advantage of about 50 percent in load capacity over the unshrouded step design.

b. Design Data

Design tables were generated and included in Topical Report **NYO 3930-5**

for the following combinations of parameters:

L/D Ratio: 0.5, 0.7, and 1.0
 Reynolds Number: Laminar, 5000, 10,000, 20,000, and 60,000
 Clearance Ratio: Non-inertial (i.e. very small values of C/R),
 0.002, and 0.004

The data for the combinations of the above parameters was provided for each of the three bearings illustrated in Fig. 1. Also, the data was presented in each case for two directions of the static load vector: (a) through the center line of a pad and, (b) midway between pads (or midway between pivots in the case of the tilting pad bearing). Complete tabulations of the steady state parameters (load, attitude angle, friction, and flow) were prepared in each case, as functions of eccentricity ratio. Fig. 6 is a typical data table, and Figs. 7, 8, and 9 are typical plots of the data.

Several numerical examples were also worked out and provided in Topical Report NYO 3930-5 to illustrate the utilization of data. Tables were also added to describe the effects of changes in bearing parameter (e.g., Reynolds number and clearance ratio) on the performance of the bearing to further facilitate utilization of the handbook.

Task III B - Design Data Handbook, Hydrostatic Bearings

This task was authorized at the end of this reporting period and was started in late October, 1969. During the following quarter, the hydrostatic bearing geometry selections will be made and the programming of the analysis will be conducted.

Task IV A - Proximity Instrumentation

Non-contact proximity sensors are used to measure the locus of the journal within the bearing clearance. Such measurements are required for experimental determination of the eccentricity ratio and attitude angle for steady-state loading, as well as for measurements of shaft orbits due to dynamic loads and to determine stability thresholds. For accurate measurements of this type it is necessary for the sensors to exhibit very low DC drift, including the minimal drift due to temperature change. The sensors are used also to measure the motion of the rotor axis in response to dynamic loading, such as that due to unbalance. Accurate measurements of this type require moderate frequency response, low noise (at least in the frequency range of interest) and a linear relationship between output signal and displacement is extremely helpful for straightforward interpretation of the results.

The following target specifications were established for the proximity sensors at the onset of the program:

environment	-----	sodium
Temperature	-----	50 to 1100°F
Operating range	-----	0.004 to 0.040 in.
linear range*	-----	0.030 in.
sensitivity	-----	0.1 volt/mil
probe and leadwire temperature sensitivity*	-----	10^{-6} in/°F
readout equipment temperature sensitivity	-----	10×10^{-6} in/°F max.
DC drift*	-----	10×10^{-6} in/hr. max.
readout equipment line voltage sensitivity	-----	10^{-6} in/volt max.
noise	-----	30×10^{-6} in. equiv.

During the previous reporting period the effort on the proximity transducer development was directed toward the detail design and experimental evaluation

* when wired in "push-pull"

of the transducer components. The effort during this reporting period has been in the following areas:

- 1) Finalization of the proximity transducer assembly detail design.
- 2) Evaluation of prototype transducer with a conducting medium in the probe-target gap.
- 3) Development of the electronic system.
- 4) Evaluation of core and target materials.
- 5) Evaluation of the transducer-electronic system in a high temperature sodium environment.

This development effort was concluded near the end of the report period with the successful testing of two transducers of the final design in sodium to temperatures in excess of 1100°F.

Final Transducer Design

As a result of the component testing carried out during the last reporting period and the testing of the prototype probe assemblies, which included evaluation of various hermetic sealing welds, accomplished early in this report period, the design of the final transducer was established. Final manufacturing detail and assembly drawings based upon the formentioned design were completed. The assembly drawing of this finalized design is shown on Figure 10.

Four transducers were manufactured to these detail drawings for further evaluation. Two were utilized for various additional tests described later in this section and were finally subjected to elevated temperature Na testing. The remaining two were maintained as spares. A photograph of two of the four transducers prior to installation of the hermetic sealing diaphragms is shown in Figure 11.

Effect of Liquid Metal in Probe-Target Gap

Experiments were conducted on the prototype transducers with various conductors inserted into the gap between the transducer face and the target. Aluminum, copper, mercury, and cerrobend were used in the initial evaluations. However, most of the tests utilized mercury. These tests showed that the presence of a conductor in the gap had a significant effect on the transducer system sensitivity.

Two variables were investigated in the experiments with a conducting medium in the gap. These were bridge frequency and the bridge output phase referenced to the bridge input voltage (phase detection). From the results of these experiments and parallel analysis it was determined that the probe sensitivity in a function not only of the gap medium permeability but also of its electrical resistivity. The test results further showed that:

- 1) Reduction in bridge input frequency reduces the change in sensitivity caused by inserting a conductor into the probe-target gap.
- 2) For every condition of temperature and gap medium there **is** an optimum phase detection angle for maximum sensitivity.

It was also postulated that a phase detection setting could be established that would result in no change in sensitivity between say air and sodium if ~~so~~ desired. However, since the transducers are ultimately intended for use in a purely sodium environment, the absolute change in sensitivity between air and sodium **is** not important, thus the determination of this peculiar phase angle was not ~~persued~~. The important result was the fact that by proper selection of phase detection, large sensitivities could be achieved with liquid metal in the probe-target gap.

In order to provide the necessary flexibility of the transducer system **it was** established that the electronic network must have both variable bridge frequency selection and variable output phase sensitive detection selection.

Development of Electronic System

Most of the proximity transducer development work had been accomplished using a modified Daytronic 300D Strain Gage Amplifier-Indicator. This particular unit had been selected for use in the development phase early in the program after a thorough evaluation of several commercially available carrier amplifier systems. The basic unit, however, was not entirely suitable for the proximity transducer application. Its major shortcomings were:

- 1) The bridge frequency was fixed at 3kHz which ~~was~~ higher than desirable for use with proximity transducers intended for liquid metal service. **Also**, the rest of the circuitry was not compatible with lower frequency operation.

- 2) The bridge frequency generator was not sufficiently stable for the proximity transducer application.
- 3) The unit did not have an adjustable phase sensitive detector.
- 4) The unit did not possess the compatible components necessary to complete the bridge. (These were added externally in the development phase.)
- 5) The unit limited bridge balance range.

A specification was prepared for an electronic system that was completely compatible with the proximity transducer electrical characteristics and had mechanical and operational features consistent with the needs of the operator.

Some of these other features include:

- 1) The ability to operate the probes in either quarter or full bridge (singly or in push-pull, with compatible internal quarter bridge components).
- 2) Frequency lock between amplifiers to eliminate transducer system cross talk due to small frequency differences.
- 3) Resettable phase, balance, and gain controls in which the settings are directly relatable to voltage, phase angle, etc.

A prototype electronic system was built to these specifications by Encore Electronics Inc. at Saratoga Springs, New York and was delivered in July. The unit (shown in Figure 12) was subjected to extensive acceptance testing and was found to meet or exceed all specification requirements. Seven additional units are currently being assembled for use with the large sodium bearing test rig.

Evaluation of Core and Target Materials

Early in the development of the transducers, a search was made to select an optimum core material. Because of their curve point, electronic and high temperature properties, the Hipercor alloys were the initial choice. Both Hipercor 27 and Hipercor 50 were considered and the former selected because of its superior ductility. The initial tests conducted with Hipercor 27 cores have been discussed in earlier reports. While much of the test data obtained with the Hipercor 27 cores was satisfactory, the temperature stability tests

revealed a thermal hysteresis which, while it was repeatable, made the transducer sensitivity sensitive not only to temperature, but also to thermal history. A typical inductance vs. temperature plot is shown in Figure 13 for a probe with Hiperco 27 core at open and closed gaps, which shows the hysteresis loop.

Similar tests run on 410, 416, and 430 SS cores revealed no such hysteresis loop as can be seen on a typical curve shown in Figure 14. The 400 series cores did show greater temperature sensitivity than did the Hiperco 27 cores as is witnessed by the difference in slopes of the curves in Figures 13 and 14. Although the transducers made of 400 series stainless do possess a greater temperature sensitivity, it is repeatable and smooth (as compared to Hiperco 27 which possesses two inflection points in its temperature sensitivity characteristic). Since all the 400 series cores tested has similar inductance characteristics, the final selection of 430 was based upon superior corrosion resistance.

Concurrently with the evaluation of the several core materials, materials for use as transducer targets were also evaluated. Similar results were obtained using Hiperco 27, 410, 416 and 430 as were obtained in the core material tests. It should be noted, however, that the core material had the dominant influence on transducer performance.

For the bearing test rig application, the major problem with the probe target is not its electromagnetic characteristics, but is the problem of physically attaching it to the rotor. The rotor is made of 316 SS which has a thermal expansion coefficient much larger than that of the 400 series stainless target materials considered. If the target were shrunk onto the rotor it would become over stressed at the elevated operating temperatures. Furthermore, no magnetic material having a thermal expansion coefficient suitably close to 316 SS has been found. Thus, other mechanical means of fastening the low expansion alloy targets to the rotor have to be incorporated. Several mechanical designs were evaluated, but all the ones considered to be feasible were necessarily complex and expensive to fabricate.

In order to reduce the rotor fabrication costs an alternate target material and manufacturing technique were evaluated. This alternate utilized 431 stainless

steel applied to the 316 shaft by plasma spray technique. 431 was selected because it is commercially available in powder form and has the required electromagnetic characteristics.

Sample targets were made for evaluation in air and the test results indicated that a coating thickness of .030 inches was thick enough to produce adequate transducer sensitivity, yet was thin enough to survive the several imposed temperature cycles to 1000 F with no coating distress. Additional targets of .030 inch thick 431 Plasma sprayed stainless on 316 substrate were made for evaluation in high temperature sodium. These targets were used in the transducer tests described in the following section.

The inspection of the sodium test apparatus in which the transducers and targets were tested revealed an increase in the thickness of both the plasma sprayed 431 SS probe targets and other plasma sprayed 431 SS samples which had been inserted into the apparatus and subjected to the same environment as the probe targets. Microscopic examination of metallurgical cross sections of the coated samples indicated that some oxides were present in the form of thin layers in the plasma sprayed 431 stainless coatings. Those specimens which were exposed to high temperature (to 1100 F) sodium showed voids where the oxides had apparently been dissolved away. Since the coatings are normally in a stressed condition as a result of the spraying operation, it is believed that the loss of these oxide layers relieved the residual stresses and caused the dimensional changes that were measured. There was also some evidence that the Na attack of the oxides had degraded the bond between the 431 SS coating and the 316 SS substrate.

Because of this, the targets in both the calibration fixture and bearing test rig will be made of solid 410 SS rather than coatings. 410 stainless was chosen over 430 because it is a castable grade which lends itself to the manufacture of the solid target design in the bearing test rig.

Tests in High Temperature Sodium

The final phase of the proximity transducer development program was the testing of the final transducer design and the completed prototype transducer electronic package with the transducers and targets in a high temperature

. sodium environment.

The existing AEC owned fixture for calibrating the transducers in high temperature sodium was modified to accept the final probe envelope and to conduct the tests with transducers arranged in push-pull. The calibration fixture which is shown in Figure 15 consists of a small pressure vessel which is partially filled with sodium. The probes are inserted into the vessel from the bottom and look at two movable targets which are supported on Inconel flexures. The targets are accurately positioned and moved by means of micrometers located on top of the vessel.

The static sodium system used to supply sodium to the test fixture was assembled utilizing components from the AEC owned NaK bearing test system. A photograph showing the entire test apparatus is shown on Figure 16.

The analysis of the test data that has been conducted to date has shown that the probes have a high sensitivity throughout the test range (400 to 1000 F) both in sodium and in air or nitrogen. Moreover, when used in push-pull, a near linear range of about 50 to 60 mils can be achieved. Analysis of the high temperature calibration test data also indicated that the probe/electronic system has a characteristic (displacement vs. output curve shape) which is independent of both temperature and gap medium (air, N_2 , Na). Only the sensitivity is effected with increasing temperatures resulting in increased sensitivity, as expected. Also, the presence of liquid metal in the gap caused slightly higher sensitivities than does air or N_2 . Typical normalized calibration curves for the measurement system are shown in Figures 17 through 20. In particular, the following extremely desirable features should be noted from these curves: large linear range, similarity of curve shape, symmetry about centered position, and large sensitivity.

Analysis of the test data taken in air, N_2 , and Na at temperatures to 1107 F will continue into the first couple of weeks of the next period. The results will be reported in detail in the Topical Report covering the proximity transducer system development which will be issued early in the next quarter.

Task IV B • Pressure Instrumentation

The objective of this task is to develop the instrumentation, suitable for the use in high temperature sodium environment, that is needed to measure the pressures in the bearing film. The target specifications that were set for this pressure measurement system are as follows:

Primary Sensor

Environment----- Sodium
 Temperature----- 50 to 1200 F
 Pressure Range----- 0 to 500 psig
 No. of Pressure Cycles----- 5×10^8

High Temperature Leadwire

Environment----- Sodium
 Temperature----- 50 to 1200 F
 Pressure Range----- 0 to 500 psig
 Length----- to 20 feet
 Minimum Bend Radius----- 0.5 inch

Detector

Environment----- Air or Inert Gas
 Temperature----- 50 to 200 F

System

Operating Range----- 0 to 500 psig
 Sensitivity----- 10 mV/PSI
 Linearity----- $\pm 5\%$ Full Scale
 Line Voltage Sensitivity----- $\pm 10\%$ No Effect

As has been discussed in previous progress reports, a hermetically sealed capacitance probe that senses the elastic deflection of a stainless steel diaphragm has been selected for the high temperature sodium application.

During the period covered by this report, the design and development of the static/dynamic pressure transducer which is used in connection with the Wayne-

Kerr capacitance system was completed. This **is** the transducer that will be used in the bearing tests under Task VI of the program and eight transducers have been constructed. In addition, the design of a shaft mounted dynamic pressure transducer used in conjunction with the Boersma capacitance system was completed. This latter transducer type will not be used in the bearing tests and completed prototypes have not been produced.

The target specifications for the pressure measurement system that were established at the beginning of the program have been met with two exceptions by the transducers which were built and tested during this report period. One exception **is** the design pressure range, which had been set at 0 to 500 psig. During the course of development this pressure range was reduced to 0 to 120 psi to be more compatible with pressures anticipated in the first bearing tests to be conducted under Task VI of the program. Pressure ranges in excess of 120 psi are achieved by using a thicker sensing diaphragm which can readily be accommodated with the current design. The sensitivity, however, would be lower than with the 120 psi diaphragm, with a correspondingly lower accuracy during the critical, early bearing tests **of** Task VI.

The other exception **is** the system sensitivity which had been set at 10 mv/psi. The transducers used in conjunction with the Wayne-Kerr capacitance system have a sensitivity of 2.5 mv/psi which **is** completely adequate because of the extremely low noise level (less than 0.2 mv) of the capacitance system.

Early in the period covered by this report, detailed layouts **of** the mechanical design of the final shaft mounted dynamic and the bearing mounted static/dynamic pressure transducers were made. Although the dynamic transducer incorporates the Boersma capacitance system and the static/dynamic transducer incorporates the Wayne-Kerr capacitance system, the design of the two probes was such that many of the critical components are interchangeable.

In the case **of** the shaft mounted dynamic pressure transducer, the Boersma capacitance system was used because its capacitance detector **is** physically small enough to be mounted in the rotor. With this arrangement, a slip ring assembly **is** used to carry the high frequency power to the rotating detector and to carry the DC pressure signal out.

The design of the shaft mounted dynamic pressure transducer was completed, and experiments were run on the transducer capacitance system/slip ring assembly to-determine the quantity of slip ring induced noise into the transducer output signal. The experimental apparatus consisted of a 30 - 680 Boersma capacitance detector mounted in a 6 inch diameter test shaft at a radius of 1.5 inches from the rotating axis to simulate its installation in the bearing test rig. A 200 pf capacitor to simulate the transducer was attached to the detector and the detector was driven by the Boersma carrier frequency generator through the slip ring assembly.

With the apparatus operating at 1800 RPM, the measured noise in the output signal was equivalent to less than 1% of full scale transducer output. A part of this noise was caused by the stray magnetic field around the drive motor which induced noise directly into the shaft mounted capacitance detector. In the noise tests, the drive motor was located about 18 inches from the detector, whereas in the bearing test rig the drive motor is located several feet away. For this reason, drive motor stray field should not present a problem in the bearing test rig. The remainder of the noise was high frequency resistive brush noise that is readily removed by a low pass filter.

Based upon the results of these tests, it has been concluded that the rotating detector and slip ring arrangement is suitable for obtaining bearing dynamic pressure data from a rotating shaft and that if noise levels below 1% are required, low pass filtering can readily be incorporated.

The static/dynamic transducer utilizing the Wayne-Kerr Electronic System incorporates a so-called guard shield inserted between the center electrode of the coaxial lead and the ground shield. The guard shield is kept at the potential of the center electrode. As a result, changes in capacitance between the guard shield and the center electrode do not cause instrument output. Only at the probe end is the center electrode exposed to ground, and at this location the proximity of a grounded surface is sensed.

To insure stability and to obtain ruggedness, the probes and diaphragms form a completely welded structure. To permit in-line calibration or differential pressure measurements on the static/dynamic probe, the side of the diaphragm

towards the displacement probe can be vented to atmosphere or a reference pressure can be applied. The transducer lead is of the swaged type. It is hermetic, very rugged, fully weldable (e.g., TIG or electron beam welding) and it can be made up to 10 feet long. At the termination of the swaged lead, a flexible high temperature cable can be connected,

Detail drawings of the static/dynamic pressure transducer were completed and components for ten transducers were machined. From these components, four experimental transducers were assembled and electron beam welded. The primary purpose of these experimental transducers was to establish the detailed welding procedures (penetration depth, current, speed, etc.) and the stress relieving requirements after welding. As a result of these experiments, the welding and annealing processes were established and other minor machining modifications were introduced to improve weld quality.

Two of the experimental static/dynamic pressure transducers are shown on Figure 21. The one shown on the left hand side of the photo is the basic transducer. It incorporates a heavy section about three-quarters of an inch behind the sensing diaphragm for mounting adaptation. This section can be threaded or can be utilized for welding the transducer in place or into a convenient fitting as was done with the transducer on the right. In this case, the transducer was welded into a standard 3/4 inch Swagelok (1210-6-125W-316) fitting.

Following the successful room temperature calibrations of three of the experimental transducers (one was made inoperable because it was sectioned to microscopically inspect the welds) the remaining six transducers were completed. Two of these transducers will be subjected to a 1000 hour life tests in sodium at temperatures exceeding 1050 F under Modification No. 2 to the current contract. The remaining four will be utilized to measure the bearing film pressures in the large sodium bearing test rig during Task VI of the program.

All six of the final transducers were successfully calibrated at room temperature and two were subjected to calibrations at elevated temperatures after welding them into a Swagelok fitting. Figure 22 shows the results of the elevated temperature calibrations for one of the transducers. As can be seen from the curves presented in Figure 22, the transducer is reasonably linear (within

5% full scale max.) over the design pressure range of 120 psi and that the change in sensitivity with temperature behaves in a predictable manner (increasing sensitivity with temperature as a result of the corresponding decrease in Young's modulus).- Also shown on Figure 22 is the zero drift with temperature which although small, must be factored into the calibration data when using the instrument to insure good accuracy of data. Throughout the tests, there was no evidence of any hysteresis in the transducer sensitivity and the zero shift was repeatable within .001 volts.

The detailed results of all of the tests and the transducer designs are to be included in the Topical Report covering the design and development of the pressure transducers. This report is scheduled to be issued during the next quarter.

Task IV C - Extended Duration (1000 Hour) Tests of the Proximity and Film Pressure Instrumentation in High Temperature Sodium

This task was authorized and started at the end of this reporting period. During the next quarterly period which ends January 31, 1970, the preparation for the 1000 hour tests of the film pressure and proximity instrumentation in sodium at up to 1200 F will be completed and the tests are scheduled to start in late January, 1970.

Task V - Test Rig Design and Fabrication

The objective of this task is to design and build a bearing test rig in which the theoretical and technological data gained on the other tasks can be verified in bearing tests conducted in liquid sodium at elevated temperatures. The test rig must be capable of producing data which is sufficiently accurate to check the validity of the turbulent lubrication theory including fluid inertia forces and to verify the accuracy of the design charts. To accomplish this objective, the test rig design and instrumentation must be such as to permit accurate measurement of the thickness and pressure of the lubricant film at several positions around the clearance space under all operating conditions,

The following summarizes the test rig specification requirements that were established early in the program:

Bearing type-----	Flood hydrodynamic
Bearing operation-----	Vertical and submerged
Bearing size-----	12" dia. x 12" lb. max.
Bearing C/R-----	.001 to .003
Lubricant-----	Sodium
Temperature-----	1200 F max.
Speed-----	1200 RPM max.
Unidirectional load-----	10,000 lb. max.
Rotating unbalance-----	75 in. lb. max.

These conditions were selected so that the operating conditions that the test bearings will be subjected to, will span or exceed those currently anticipated in the radial, sodium lubricated bearing of a 60,000 gpm capacity LMFBR sodium circulation system pump.

During the period covered by this report all of the test rig and test system design work was completed, most of the components have been ordered and installation of the test equipment has been initiated.

Task V A - Sodium Bearing Test Rig

The basic test rig concept which has been described in detail in the previous

quarterly reports consists of a vertical shaft (approximately 9 feet long) with the upper end supported by a large rolling element bearing and the lower end supported by the test bearing. Both the test bearing and the hydrodynamic tilting pad type loader bearing are submerged in high temperature sodium which is contained within a 42 inch diameter vessel which forms the lower half of the test rig. The containment vessel has a free sodium surface approximately 3 inches above the loader bearing (which is located above the test bearing) with the remaining space filled with nitrogen cover gas. Load is applied to the loader bearing by means of a loader mechanism which penetrates the vessel wall below the sodium level. The assembly drawings of the final test rig and loader mechanism designs are included for reference as Figures 23 and 24.

The loader mechanism design is unchanged from that shown and discussed in the previous progress report. Only minor changes in the details of the test rig have been made to accommodate subcontractor machining and fabricating processes and to accommodate detailed assembly and disassembly procedures.

During the early part of the reporting period considerable effort was expended in reviews and discussions with potential machining and fabricating subcontractors for the pressure vessel, heavy weldment, and rotor components. This was done primarily through visits to the potential subcontractors' facilities to fully acquaint the bidders with the functional and quality requirements of the components so that they could prepare realistic quotations. As a result of these reviews, a better basis of subcontractor qualification was also obtained.

Quotations have been received for all test rig components and orders have been placed for all components except the rotor, the machining of the test and loader bearings, and some of the standard hardware items. The castings for the test and loader bearings were received in October and these will be released for machining in November and scheduled for delivery in January.

The letting of the subcontract for manufacture of the rotor was delayed until completion of the proximity probe tests in high temperature sodium because of the unknown behavior of the plasma sprayed 431 Stainless Steel probe target material. As was discussed under Task IV, the sprayed target material proved to be undesirable in an elevated temperature sodium environment. Accordingly,

the rotor design was modified to incorporate mechanically fastened magnetic targets instead of the plasma sprayed targets. The detail drawings have been changed and submitted to the potential rotor subcontractors for requote. It is anticipated that the rotor subcontract will be let in November for delivery in April.

The components for the following major subassemblies have been received:

- Loader mechanism
- Cover gas seal
- Upper support bearing
- Support bearing housing

The pressure vessel components which consist of all the stationary structural and sodium containment components below the cover gas seal is scheduled for delivery in December. Installation of these components and initial assembly of the test rig is scheduled to commence in January.

Also during this report period, the final draft of the test rig assembly procedures was completed. As part of this effort the special assembly tools and fixtures required for assembly were identified. The details and manufacture of these tools and fixtures will be made during the next quarter.

Task V B - Test Rig Support System and Test Facility

During this period the test rig support structure was designed, fabricated, and installed into the test facility. The photograph included as Figure 25 shows the test rig supporting structure along with the removable assembly platforms and the oxygen control and indicating system installed in the test cell.

All basic schematics including test rig control circuitry (electrical and pneumatic) together with the control room and control cabinet layouts were finalized. All major process and rig control and equipment components have been received. Detail drawings and fabrication of the control cabinet panel fronts together with the installation of all cabinet mounted equipment was also completed. The photo, included as Figure 26, shows the control cabinets with the equipment installed in the test facility control room. The final

fluid system schematic which delineates all the sodium, nitrogen, and pneumatic circuits is **also** included as Figure 27. During the next quarter, the plumbing (shown on Figure 27) and the heater and control wiring will be completed to the points where they interface with the bearing test rig.

Also during this reporting period, work on the test system design topical report was initiated. The report is about **75%** completed and will be issued during the next quarter.

Task VI A - Hydrodynamic Bearing Evaluation Tests

These tests are scheduled to commence in March 1970, after the complete installation of the bearing test rig, procured under Task V.

Tasks VI B and VI C - Screening, Selection, and Evaluation of Bearing Surface Materials

These two tasks were authorized at the end of this reporting period and were started in late October, 1969. The materials selected for the evaluation are listed in Fig. 28. The initial tests will be for corrosion in sodium at up to 1200 F and will be conducted at the same time **as** the 1000 hour bearing instrumentation tests of Task IV C. These tests are scheduled to start in late January, 1970.

* Colmonoy was subsequently added to this list of materials, on the advice of RDT and LMEC. Samples of Colmonoy treated rotor and stator parts were ordered from Byron Jackson Co., for inclusion in the tests.

IV. PROGRAM STATUS

Fig. 29 is the summary chart of the program status. The schedule currently calls for completion of the technical effort by July **1970** and distribution of the last topical reports and the final summary report by October **1970**.

During the coming quarterly period, ending January **1970**, the distribution of Topical Report **NYO 3930-5**, covering the hydrodynamic bearing design handbook will be completed. Also, the drafts of the topical reports covering the instrumentation development (Tasks IV A and B) as well as the design of the test rig (Task V) will be submitted to the Commission for patent and technical approvals.

Fig. 1 Hydrodynamic Bearing Types

- REYNOLDS NO.=5000
- REYNOLDS NO.=20000
- △ REYNOLDS NO.=60000

FIG. 2 OPTIMISATION. SHROUDED STEP BEARING.
CLEARANCE RATIO=0.002. PAD EXTENT=80
DEGREES. INFLUENCE OF DEPTH RATIO ON
SINGLE PAD STIFFNESS FOR NORMAL MOTION

FIG. 3 OPTIMISATION. 80 DEGREE SHROUDED STEP
 BEARING CLEARANCE RATIO=.002. INFLUENCE
 OF WIDTH RATIO ON STIFFNESS OF A SINGLE
 PAD FOR NORMAL MOTION

- REYNOLDS NO.=5000
- REYNOLDS NO.=20000
- △ REYNOLDS NO.=60000

FIG. 4 OPTIMISATION. 80 DEGREE SHROUDED STEP BEARING. $C/R=0.002$. $L/D=0.7$. INFLUENCE OF LENGTH RATIO ON STIFFNESS

FIG. 5 SINGLE PAD LOAD VS. ECCENTRICITY CURVE
FOR OPTIMISED SHROUDED STEP BEARING
DESIGN. REYNOLDS NO.=20000, $C/R=0.002$,
 $L/D=0.7$, $BP/B=0.6$, $LP/L=0.7$, $\Delta/C=1.5$

 FLAT PAD BEARING PERFORMANCE DATA

PAD EXTENT 80.00 DEGREES

	* OPERATING CONDITIONS	
REYNOLDS	CLEARANCE	L/D
NUMBER	RATIO	RATIO
1000000	0.200-02	1.000
		RECOVERY
		FACTOR
		.1500

4 PADS EQUALLY SPACED; NO PRELOAD

LOAD OVER PAD CENTER

ECCENTRICITY RATIO	VERTICAL LOAD PARAMETER	* PERFORMANCE * ATTITUDE ANGLE (DEGREES)	SIDE FLOW PARAMETER	FRICTION PARAMETER
0000	.000	.00	.000	146.52
.200	2.002	99.97	.160	148.95
.400	4.946	89.90	.376	148.16
.600	9.880	81.15	.616	157.11
.700	13.906	75.25	.733	162.64
.800	41.563	38.89	.832	177.24
.850	61.882	31.48	.880	187.47
.900	94.993	26.00	.930	200.08
.925	123.153	23.71	.957	209.75
.950	169.375	21.58	.985	225.12

LOAD BETWEEN PADS

ECCENTRICITY RATIO	VERTICAL LOAD PARAMETER	* PERFORMANCE * ATTITUDE ANGLE (DEGREES)	SIDE FLOW PARAMETER	FRICTION PARAMETER
0000	0000	.00	.000	146.52
0200	1.768	80.68	.165	145.16
.400	5.012	69.59	.391	148.03
.600	10.179	60.13	.629	154.25
.700	14.595	54.52	.736	160.63
.800	21.752	48.97	.844	169.71
.850	28.181	45.14	.898	176.75
.900	38.834	40.47	.953	188.53
.925	47.675	37.15	.982	198.87
.950	65.979	31.66	1.011	216.88

 * LEGEND *
 * ECCENTRICITY RATIO.....ECCENTRICITY/(RADIAL CLEARANCE) *
 * LOAD PARAMETER.....W/(MU*N*D*L*(R/C)**2) *
 * FLOW PARAMETER.....Q/(N*D*L*C) *
 * FRICTION PARAMETER.....(FRICTION FORCE)/(MU*N*D*L*(R/C)) *

Fig. 6 Sample Data Table

e'

WFLAT PAD BEARING PERFORMANCE DATA

PAD EXTENT 80.00 DEGREES

REYNOLDS NUMBER 10300.	OPERATING CLEARANCE RATIO 0.00230	CONDITIONS L/D RATIO 1.000	RECOVERY FACTOR 0.1500
4 PROS EQUALLY SPACED. NO PRELOAD LOAD BETWEEN PROS

FIG. 7 STEADY STATE DATA PLOT, 4 AXIAL GROOVE BEARING

FLAT PAD BEARING PERFORMANCE DATA

PAD EXTENT 80.00 DEGREES

REYNOLDS
NUMBER
10000.

OPERATING
CLEARANCE
RATIO
0.00200

L/O
RATIO
1.000

RECOVERY
FACTOR
0.1500

4 PROS EQUALLY SPACED, NC PRELOAD
LOAD OVER PAD CENTER

FIG. 8 STEADY STATE DATA PLOT, 4 AXIAL GROOVE BEARING

PERFORMANCE COMPARISON: TILTING PAD, SHROUDED STEP, 4 AXIAL GROOVE BEARINGS
 LOAD PARAMETER VS. ECCENTRICITY RATIO. $N_{Re}=10,000$; $C/R=0.002$; $L/D=0.5$

Figure 9

Fig. 10 Proximity Probe Assembly

Fig. 11 Proximity Probes Prior to Assembly of Cap

Fig. 12 Inductive Transducer Readout

Fig. 13 Proximity Transducer Temperature Sensitivity with 27 Core.

Fig. 14 Proximity Transducer Temperature Sensitivity with 430 SS Core.

Fig. 15 High Temperature Sodium Calibration Fixture

Fig. 16 Sodium Test Apparatus

212C79 INDUCTANCE PROBE CALIBRATION

GAP MEDIUM

AIR

TEMPERATURE 80 F

DATA POINT L. DATE 08/21/69

TOTRL RRNGE 0.100
CRRRIER FREQUENCY 500
GAIN SETTING 500
BRIDGE PHRSE 0
NULL PHRSE 264
NULL MAGNITUDE 65
DEMODULATOR PHRSE 508

SENSITIVITY AT MEAN GAP
O -65.00 VOLTS/IN.

CORE MATERIAL 430STN STL
TARGET THICKNESS 0.0300 IN.
TARGET MATERIAL 431STN STL
DIAPHRAGM THICKNESS 0.0100 IN.

Figure 17

212C79 INDUCTRNC PROBE CALIBRATION

GAP HEDIUH NITROGEN TEMPERATURE 400 F

DATA POINT 26. DATE 08/21/69

TOTRL RANGE 0.100
 CARRIER FREQUENCY 500
 GAIN SETTING 500
 BRIDGE PHASE 0
 NULL PHASE 264
 NULL MAGNITUDE 65
 DEMODULATOR PHRSE 508

SENSITIVITY AT MEAN GAP
 O -76.00 VOLTS/IN.

Figure 18

212C79 INDUCTANCE PROBE CALIBRATION

GAP MEDIUM

SODIUM

TEMPERATURE 440 F

DATA POINT 27. DATE 08/21/69

TOTRL RANGE 0.100
CARRIER FREQUENCY 500
GAIN SETTING 500
BRIDGE PHASE 0
NULL PHASE 264
NULL MAGNITUDE 65
DEMODULATOR PHASE 508

SENSITIVITY FIT MEAN GAP
○ -79.00 VOLTS/IN.

Figure 19

212C79 INDUCTANCE PROBE, CALIBRATION

GAP MEDIUM SODIUM TEMPERATURE 862 F

Figure 20

Mechanical Technology Inc. Latham, N.Y.
High Temperature Capacitance Pressure Transducer For Use In Liquid Metal
Environment. Mag. Less Than 1X

Fig. 21 High Temperature Capacitive Pressure Transducer

Figure 22

High Temperature Na Pressure Transducer Calibration

Fig. 23 Liquid Metal Bearing Test Rig

Fig. 25 Test Rig Support Structure

Fig. 26 Control Room

Fig. 27 Fluid System Schematic

TEST MATERIALS

SOLIDS

Tungsten Carbide + 6% Cobalt

Titanium Carbide, 8% (Ti, Ta, Nb) C, 25Ni, 5Mo

COATINGS

Linde LC-9 (40%Cr, 60%Cr₂O₃) on 316 stainless

Linde LW-1 (Co bonded WC) on 316 stainless

Linde LC-125 (Ni-Cr bonded Cr₃C₂) on 316 stainless

Borided molybdenum

Borided type 316 stainless

Borided and titanided 316 stainless

Vapor deposited titanium carbide on M-2 tool steel

MTI nickel-chrome bonded Cr₃C₂ on 316 stainless

MTI chrome carbide on 316 stainless

MTI nickel-chrome bonded Cr₂O₃ on 316 stainless

MTI chrome oxide-chrome carbide on 316 stainless

Stellite 6 on 316 stainless

Fig. 28 Materials Selected for Corrosion Tests

TASK		TECHNICAL EFFORT				
DESCRIPTION	DATE AUTHORIZED	START DATE	COMPLETE DATE	SUBMIT DATE	APPROVE DATE	DISTRIBUTE DATE
I. PROGRAM MANAGEMENT	2/68	2/68	8/70	—	—	—
II. TURB. - INERTIA THEORY	2/68	2/68	10/68	11/68	11/68	12/68
III. A. DESIGN HANDBOOK — HYDRODYNAMIC BEARINGS	2/68	11/68	10/69	11/69	11/69	12/69
B. DESIGN HANDBOOK — HYDROSTATIC BEARINGS	10/69	11/69	4/70	5/70		
IV. A. & B. FILM THICKNESS AND PRESSURE INSTR.	2/68	3/68	9/69	12/69		
C. LONG DURATION PROBES	10/69	10/69	2/70	4/70		
V. TEST RIG DESIGN AND PRO- CUREMENT	2/68	3/68	3/70	12/69*		
VI. A. BEARING TESTS	2/68	3/70	7/70	8/70		
B. & C. BEARING SURFACE MATERIALS	10/69	10/69	7/70	8/70		

* DESIGN REPORT

Fig. 29 Summary Program Status Chart