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PRELIMINARY DESIGN AND TEST OF A PROPOSED TURBINE-DRIVEN OSCILLATOR FOR EBR-II

by

J. H. Cole,* J. R. Karvinen, and C. C. Price

EBR-II Project
Argonne National Laboratory
Argonne, Illinois - Idaho Falls, Idaho

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ABSTRACT

This report describes the design and water test of a reaction-turbine-driven rotary oscillator for possible use in EBR-II. The water test verified that the new oscillator has a much greater frequency range than that of the existing oscillator rod. Continued development is recommended.

Only a 6-in. section rotates during oscillator operation. This would minimize effects of bowing due to temperature differentials and eliminate the resonance problem associated with mechanical oscillator rods. Simplicity of design should result in a more reliable and less expensive oscillator, if the concept is developed for reactor installation. The greater frequency range should yield more useful kinetic data than is presently obtained. In addition, noise-signature analyses during the rotation of this oscillator should help establish the feasibility of using remotely sensed turbine flowmeters in reactor subassemblies.

I. INTRODUCTION

The role of EBR-II as the primary fast-flux irradiation facility has taken on added significance with the recent decision to accelerate the AEC's Liquid Metal Fast Breeder Reactor (LMFBR) Program. To obtain the maximum useful information for the Fast Flux Test Facility and subsequent LMFBR demonstration plants, the EBR-II plant factor must be optimized as much as possible. Likewise, it is essential to develop techniques for improving the efficiency and effectiveness of data acquisition for experiments and for studies of the reactor's operational characteristics.

The development of a new reactor oscillator is consistent with these objectives. Reactor dynamics tests are performed regularly on EBR-II to determine its dynamic characteristics and ensure that the reactivity feedback structure or system transfer function of the reactor does not show significant short-term changes. Two types of devices, the oscillator rod and drop rod, are used in these tests.

A recent study was conducted to determine if an improved design could be developed, using the energy in the flowing coolant sodium to drive the neutron-absorbing section of an oscillator.[1] The conclusion was affirmative. Both vertical and rotary configurations were investigated. The most promising concept was a reaction-turbine-driven rotary oscillator. The concept was designed in sufficient detail to permit the fabrication of a full-size model of the turbine-oscillator section, which was tested in water. Test results verify that the oscillator has an operating range from 0.1 Hz to above 20 Hz. Lower frequencies can be achieved by adding a braking system.

The remainder of this report describes the design and test of the turbine-driven oscillator.

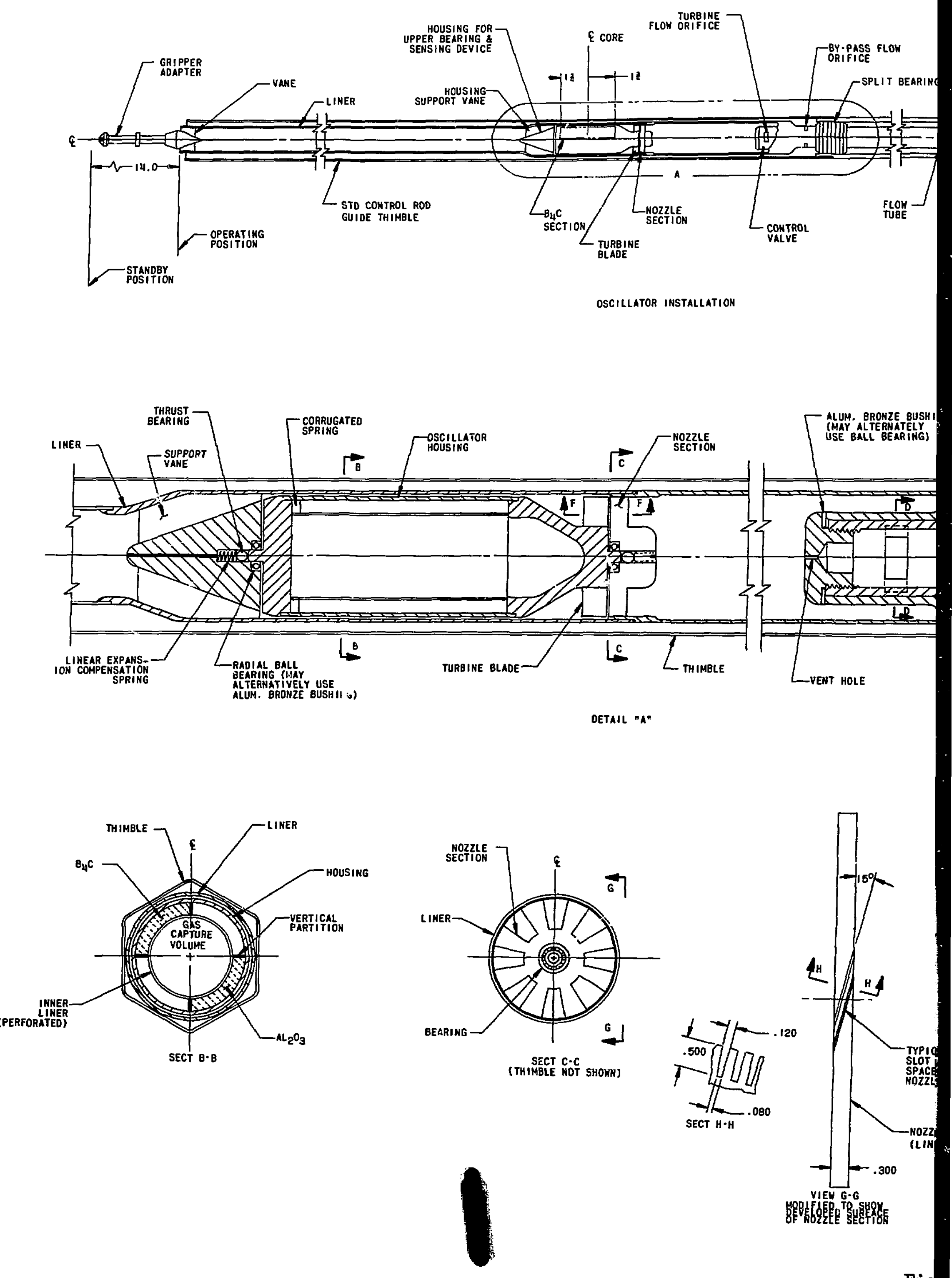
II. DESCRIPTION OF TURBINE-DRIVEN OSCILLATOR

A. Reactor Configuration

Figure 1 shows how the turbine-driven oscillator would be installed in the reactor. The oscillator is designed to fit into a standard control-rod-guide thimble. The mechanical portion of the system that fits into the thimble consists of four major components: liner, turbine-rotor, control valve, and flow tube.

During operation of the oscillator, it is positioned as shown in Fig. 1. During periods of nonuse, it is drawn up 14 in. into the axial reflector to increase the life of the neutron-absorbing material and increase reactor efficiency.

The nonrotating flow tube forms the lower section of the oscillator system. Rotation of the flow tube is prevented by a slotted fitting attached to the bottom end. The slot fits over a lock pin in the thimble. Two guide bearings are located near the bottom of the tube, and between them is an orifice that forms a passageway to the inside of the tube. When the oscillator system is in the raised position, the lower bearing is beneath the



GRIPPER ADAPTER
VANE
LINER
HOUSING SUPPORT VANE
HOUSING FOR UPPER BEARING & SENSING DEVICE
℄ CORE
TURBINE FLOW ORIFICE
BY-PASS FLOW ORIFICE
SPLIT BEARING
14.0
A
STD CONTROL ROD GUIDE THIMBLE
OPERATING POSITION
STANDBY POSITION
B_4C SECTION
TURBINE BLADE
NOZZLE SECTION
CONTROL VALVE
FLOW TUBE
OSCILLATOR INSTALLATION
THRUST BEARING
CORRUGATED SPRING
OSCILLATOR HOUSING
NOZZLE SECTION
ALUM. BRONZE BUSHI
(MAY ALTERNATELY USE BALL BEARING)
LINER
SUPPORT VANE
B
C
F
D
LINEAR EXPANSION COMPENSATION SPRING
RADIAL BALL BEARING (MAY ALTERNATIVELY USE ALUM. BRONZE BUSHING)
TURBINE BLADE
THIMBLE
VENT HOLE
DETAIL "A"
THIMBLE
LINER
B_4C
HOUSING
GAS CAPTURE VOLUME
VERTICAL PARTITION
INNER LINER (PERFORATED)
AL_2O_3
SECT B-B
NOZZLE SECTION
LINER
BEARING
G
SECT C-C
(THIMBLE NOT SHOWN)
.120
.500
.080
SECT H-H
15°
H
TYPIC
SLOT
SPACE
NOZZL
NOZZ
(LIN
.300
VIEW G-G
MODIFIED TO SHOW DEVELOPED SURFACE OF NOZZLE SECTION

Fig

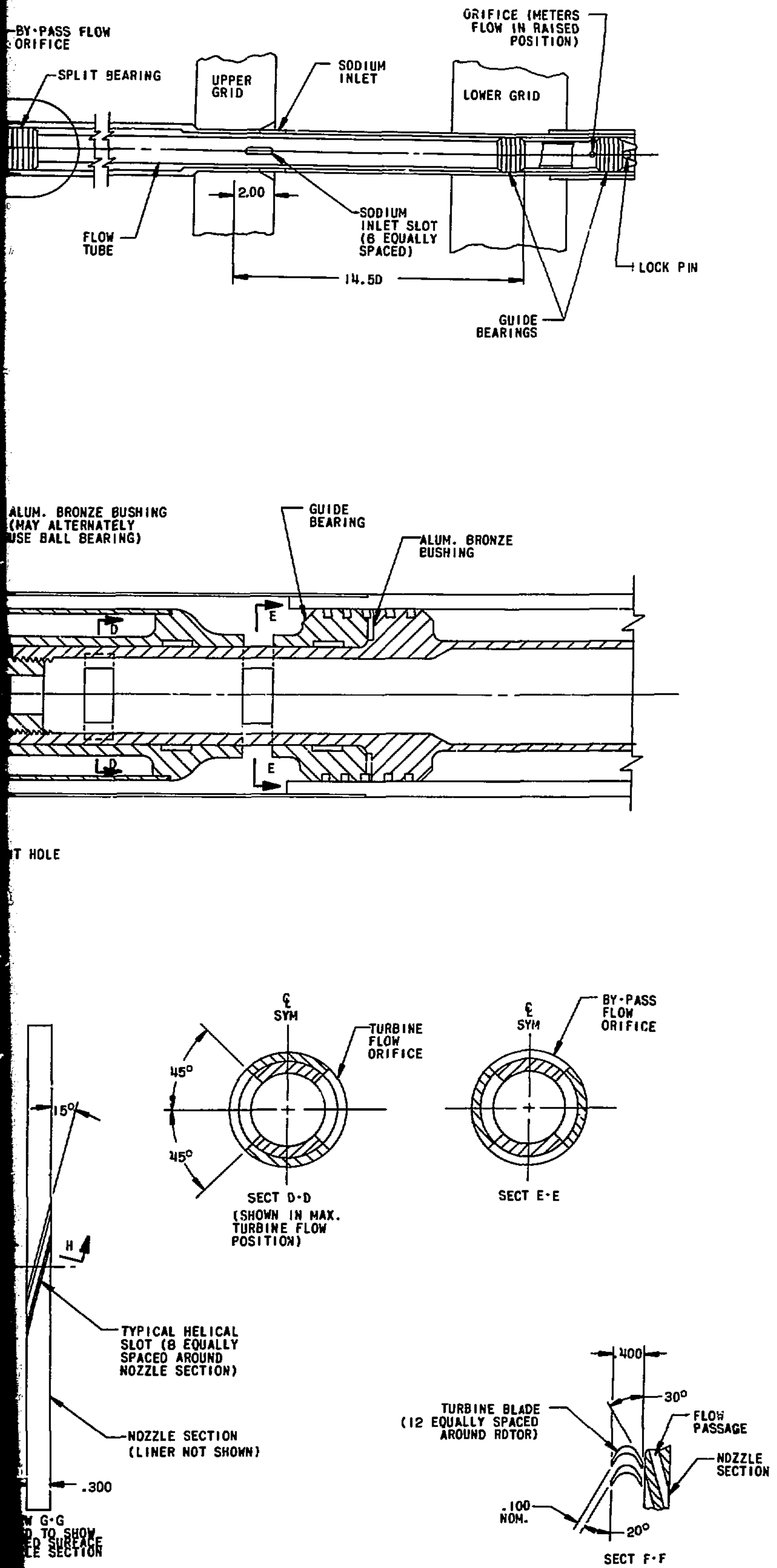


Fig. 1. Turbine-driven Oscillator for Reactor Installation

sodium inlet in the guide thimble so as to prevent reverse flow into the reactor low-pressure plenum. The other guide bearing is just above the inlet. The orifice thus meters flow through the system in the raised position, preventing an excessive temperature difference at the top of the thimble. The orifice also permits sodium to drain from the tube when the system is removed from the reactor. One-half of a split bearing is attached to the upper end of the flow tube. Above this bearing, the tube terminates in the nonrotating portion of the control valve.

The liner is a cylindrical piece that extends from the gripper adapter, enclosing the turbine-rotor and attaching to the rotating section of the control valve. The top of the liner is attached by vanes to the gripper adapter.

Sodium enters six equally spaced slots in the flow tube and flows upward through the control valve, which then divides the coolant flow into two parts: turbine flow and bypass flow. The openings in the control valve are designed so that the total of turbine flow and bypass flow remains nearly constant for all positions of the valve, to ensure that an excessive temperature difference does not occur at the outlet of the guide thimble. The division of flow, and thus the turbine speed, is controlled by rotating the gripper adapter. The rotation is transmitted to the valve by the cylindrical liner.

The turbine-rotor combination is mounted inside the liner. In the operating position, the neutron-absorbing material inside the rotor is located symmetrically with respect to the horizontal midplane of the core. The housing for the upper bearing of the turbine-rotor is attached by support vanes to the liner. The housing for the lower bearing is part of the nozzle section, which is also attached to the liner. Rectangular outlet slots are located in the liner just above the turbine-blade section to permit turbine flow to pass back into the annular region between the thimble and liner. The remainder of the liner surrounding the oscillator is perforated so that an intermixing of flow between the two annular spaces can occur, thus ensuring cooling of the rotating oscillator.

A cross section of the oscillator is shown in Section B-B of Fig. 1. The neutron-absorbing material is a 90° section of a hollow cylindrical segment of B_4C and has a mass of 38.2 g. An identically shaped piece of Al_2O_3 is placed 180° away to balance the section. A perforated inner liner supports the segments internally, and vertical partitions provide support at the edges. Corrugated springs fit over the segments of B_4C and Al_2O_3 to permit expansion of the segments under maintenance of compressive loads. The void space within the cylindrical housing and end fittings provides a capture volume for the helium given off by the B_4C as a result of neutron capture. On the basis of calibration measurements of the existing oscillator rod, the estimated peak-to-peak reactivity worth of the turbine oscillator would be approximately 5.5 Ih.[2]

The rotating oscillator section was made as short as possible to minimize the effects of any bowing caused by a temperature difference in the section. This reduces the possibility of the housing rubbing against the liner.

The oscillator is mounted in stainless steel ball bearings to reduce low-speed friction. However, a ball-sleeve bearing configuration may be preferable to provide tolerance for fluid contamination and rotor misalignment.

Although a propeller-blade turbine was considered, the impulse type was selected because of its higher efficiency and starting torque. The impulse type also minimizes axial thrust on the rotating section.

B. Water-test Model

The reactor-installation configuration was redesigned somewhat to facilitate construction of a test model of the turbine-rotor section. Figure 2 is the assembly drawing of the arrangement for testing in water.

A 22-in. section of hexagonal tubing houses the model. End fittings permit inlet and outlet water connections to be made. Since flow for the test assembly can be controlled by external valving, the liner surrounding the turbine is not required to rotate. Two threaded inlets are located in the bottom fitting. The center inlet is for turbine flow and the angled inlet is for bypass flow. The bottom adapter guides the center flow into the nozzle section of the turbine and diverts the bypass flow around the nozzle. The top adapter has a larger diameter than the cylindrical tube sections to keep the tube system centered within the hexagonal housing.

Figure 3 is a detailed drawing of the turbine wheel. The geometry is based on calculations contained in the Appendix. Figures 4 through 8 are photographs of the actual components in various stages of assembly.

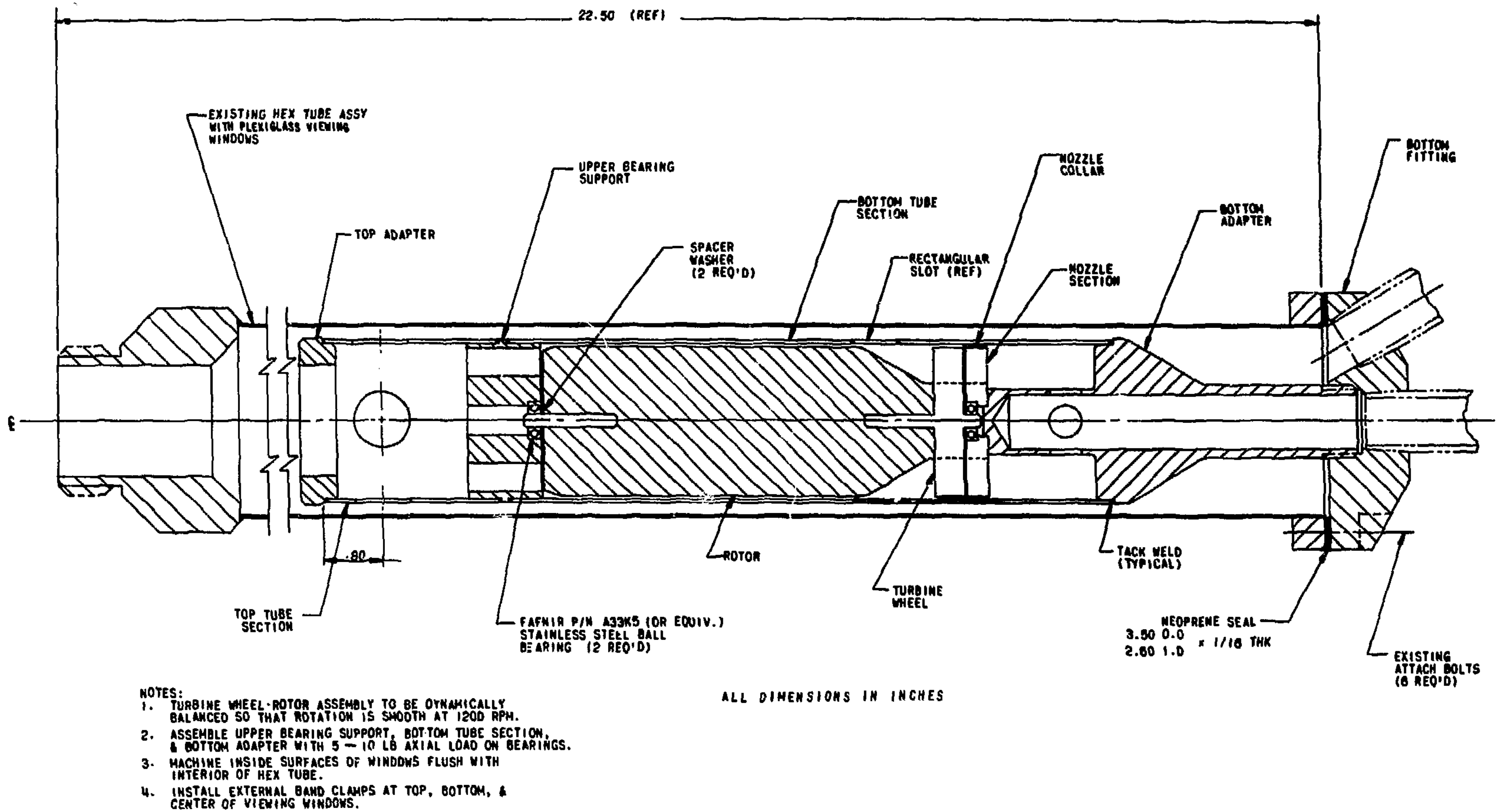


Fig. 2. Water-test Model of Turbine-driven Oscillator

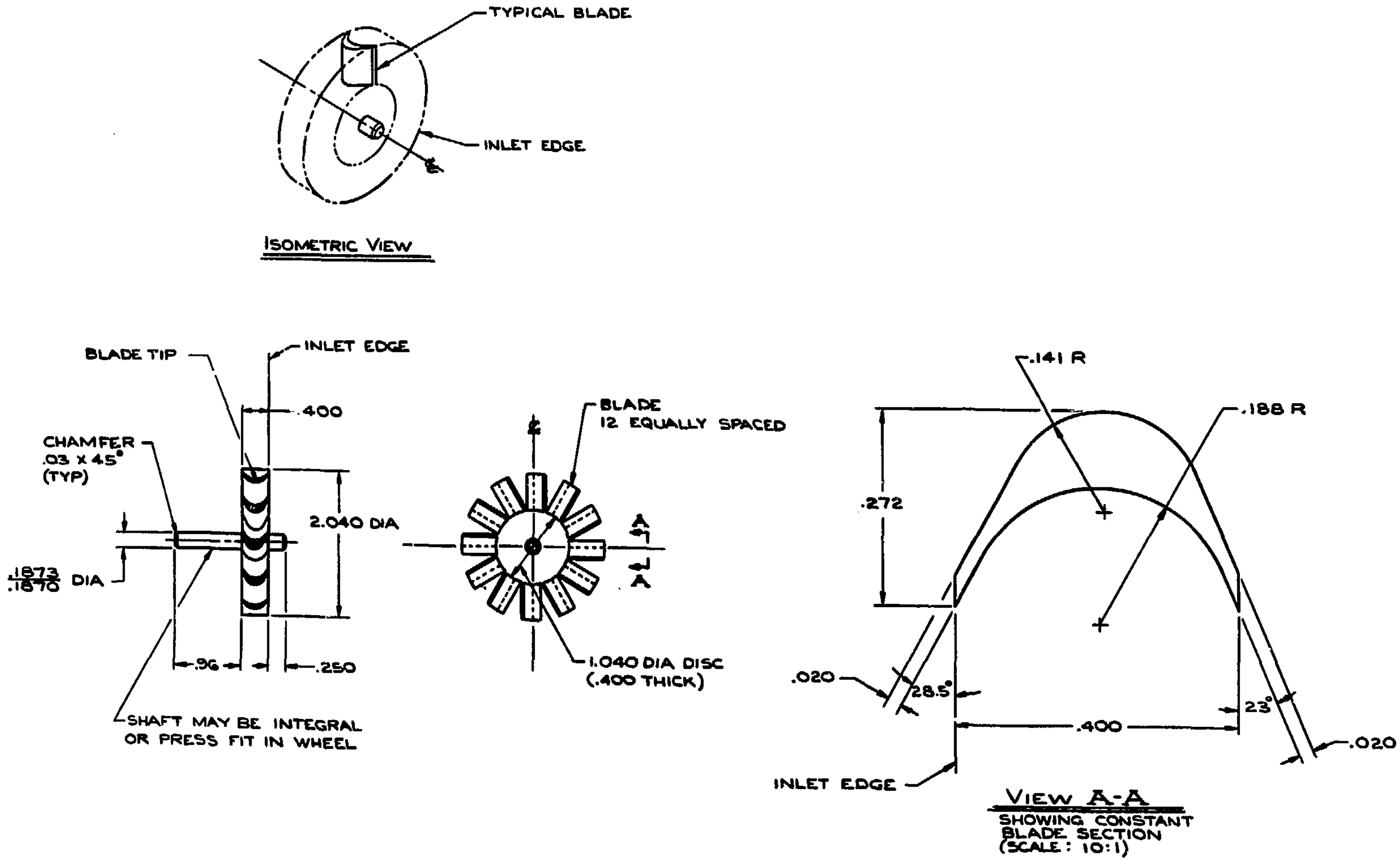


Fig. 3. Turbine Wheel for Oscillator

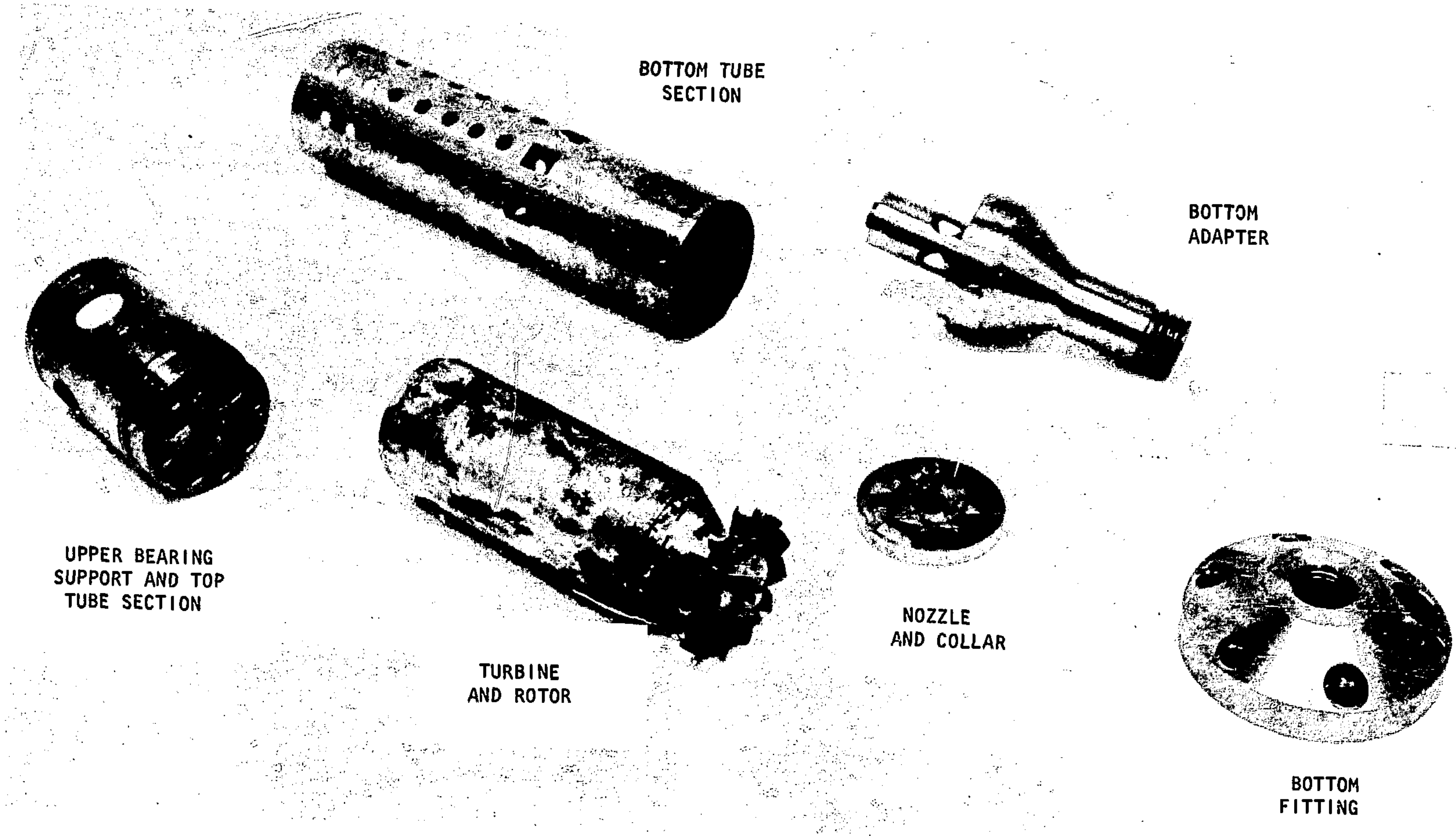


Fig. 4. Internal Components of Water-test Oscillator

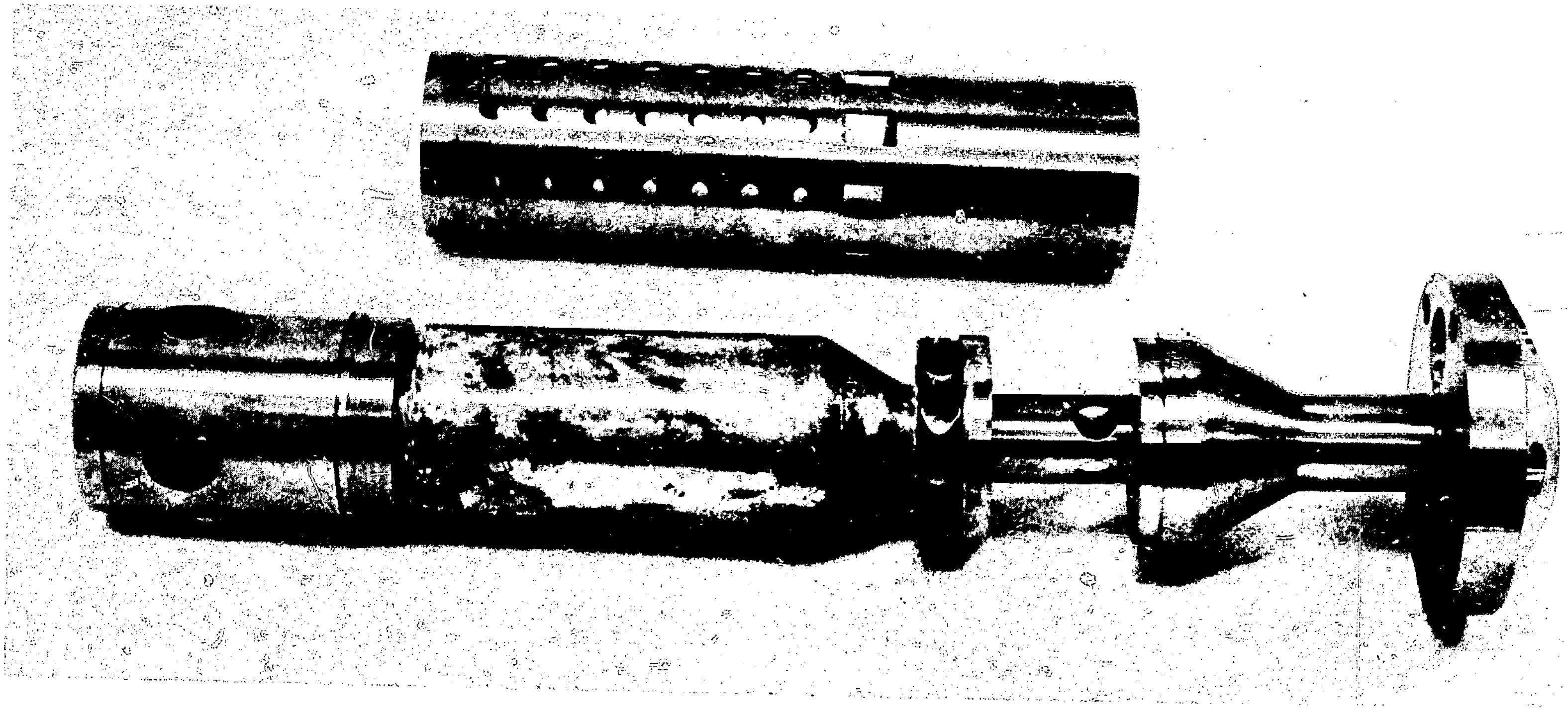


Fig. 5. Partial Assembly of Internal Components of Water-test Oscillator

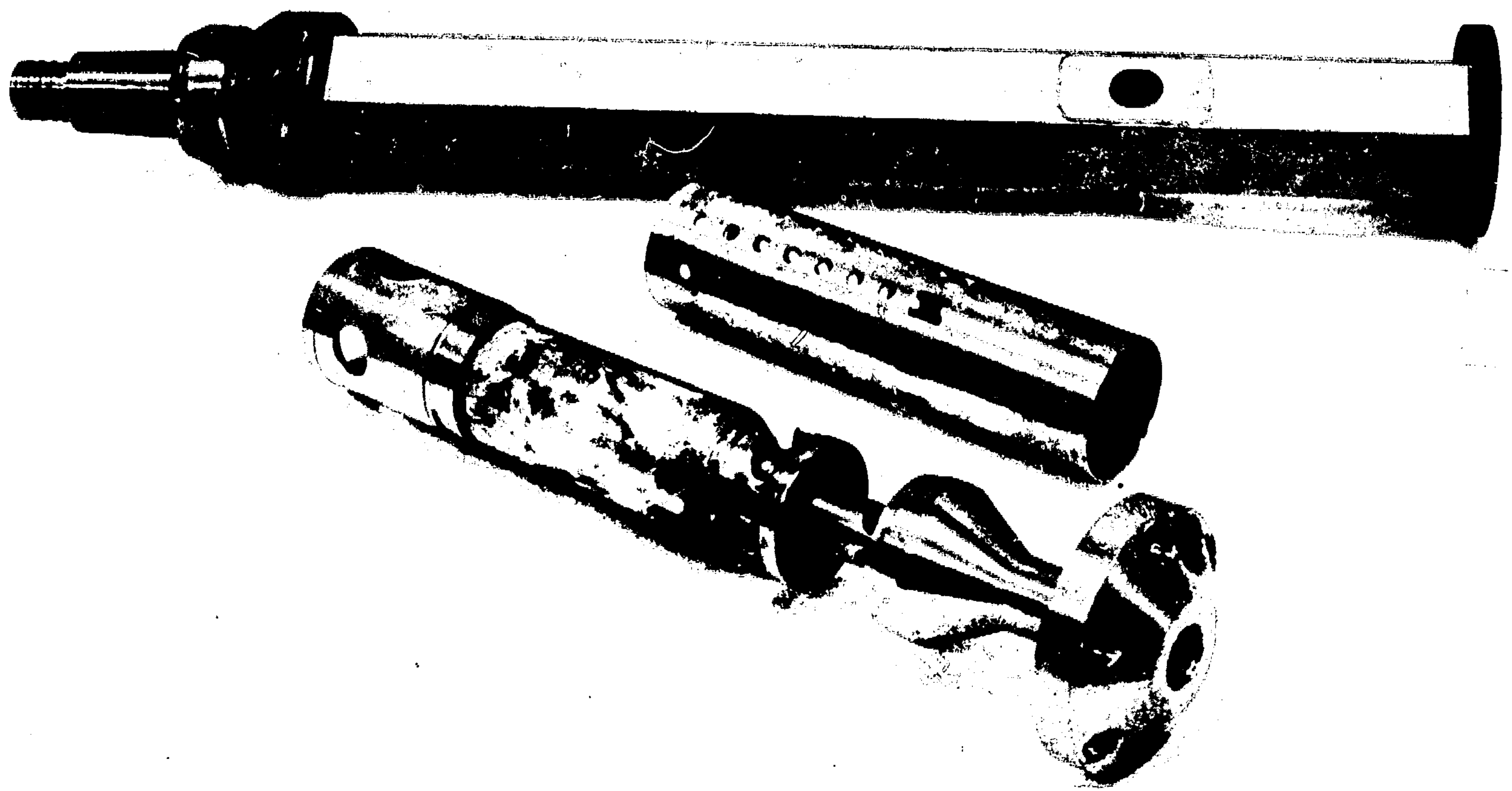


Fig. 6. Water-test Oscillator with Housing

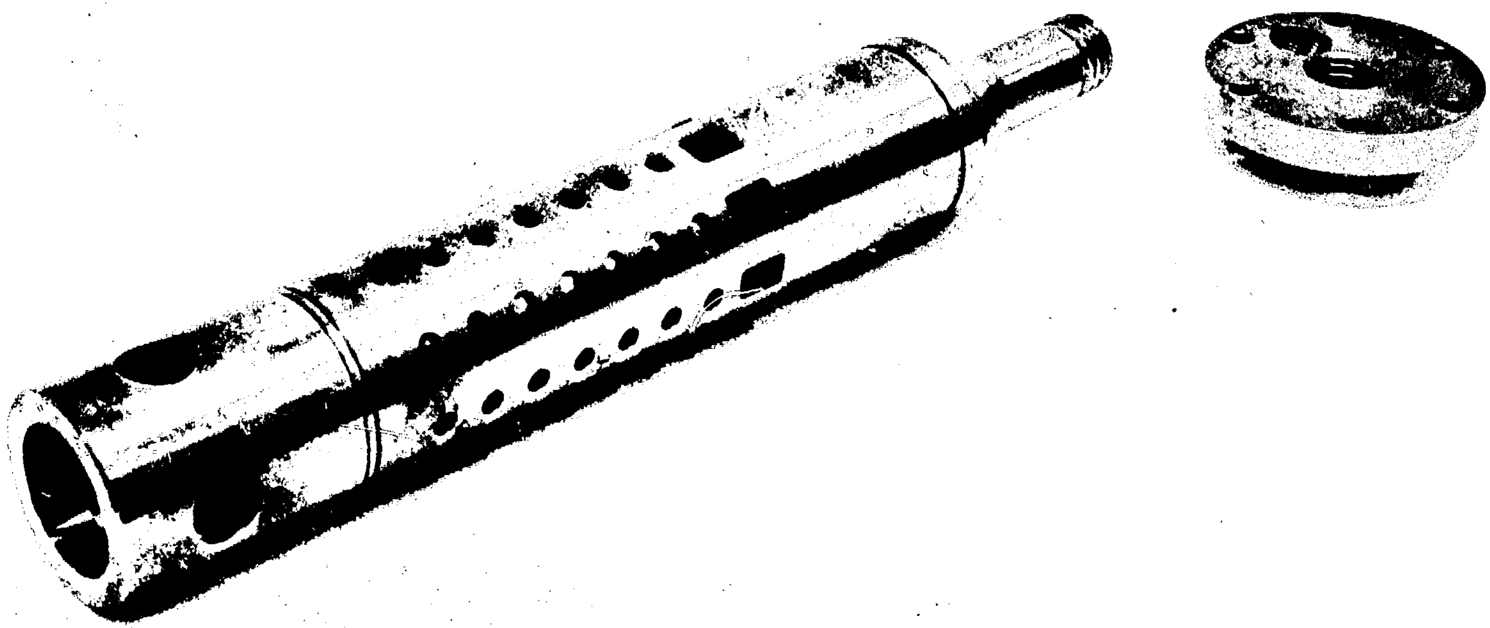


Fig. 7. Complete Assembly of Internal Components of Water-test Oscillator

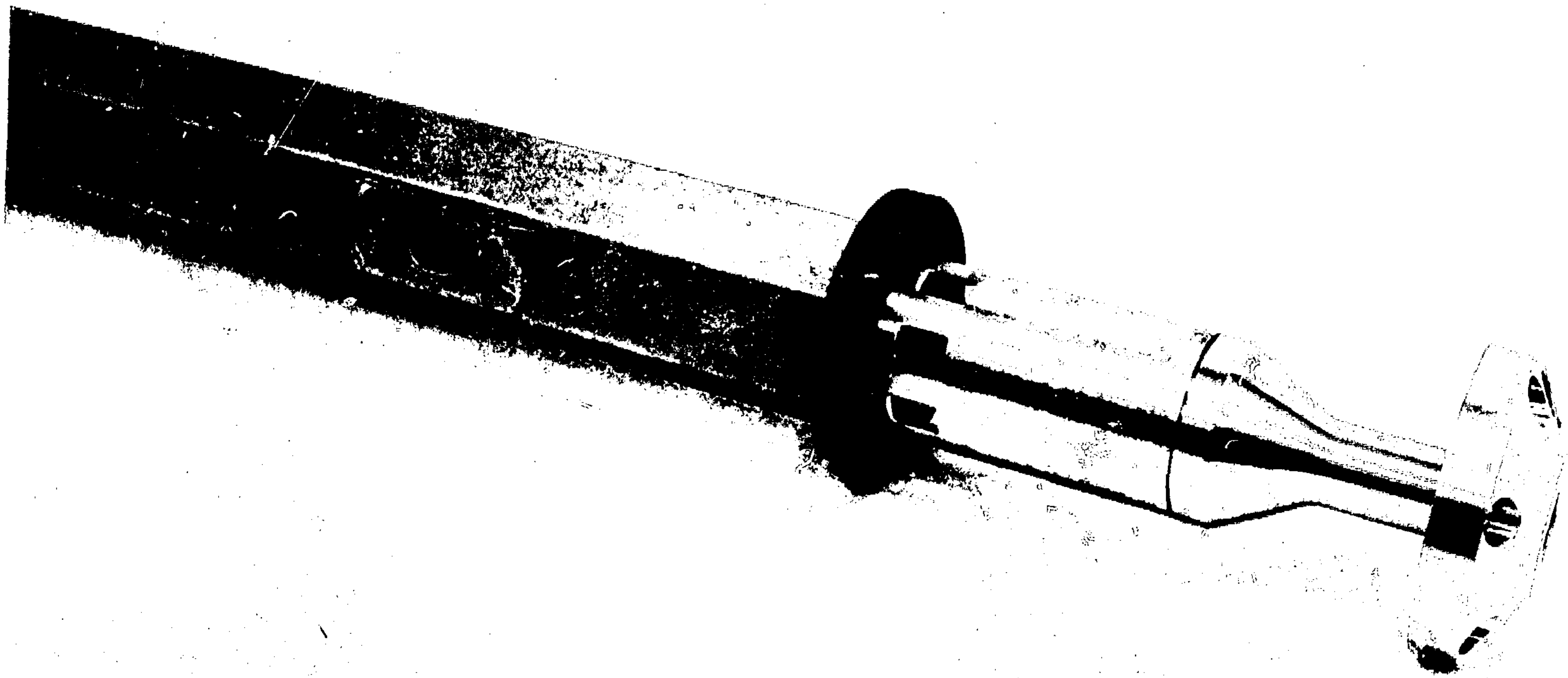


Fig. 8. Water-test Oscillator Partially Inserted in Housing

When the test model is assembled, one of the rectangular slots in the bottom tube section aligns with a plexiglass window in the hexagonal tube assembly, exposing a section of the rotor just upstream from the turbine wheel. A continuous line is spirally scribed around the rotor in this area with different letters stamped at intervals along the line. The letters and line are filled with blue dye to permit the rotational speed to be measured by a stroboscope aimed at the window.

The water-test rotor is solid aluminum and has approximately the same mass as the actual oscillator rotor. Other internal components are made of stainless steel and could be used in a sodium test. The rotor could be easily replaced by a hollow stainless steel version. The hexagonal section and end fittings would, of course, have to be redesigned for sodium compatibility; also, a different speed-readout system would be required.

III. TEST RESULTS

The water-test model of the turbine-driven oscillator was assembled and installed in a water system as diagrammed in Fig. 9.

With the assembly mounted vertically in a holding fixture, water was directed into the two inlets in the bottom fitting. The sum of turbine and bypass flows was held constant at 23 gpm while the turbine flow was varied.

Figure 10 is a plot of turbine speed versus flow through the turbine section. The plot is nearly linear between 8 and 17 gpm. The maximum speed attained was 1420 rpm, which would correspond to an oscillator frequency of 23.7 Hz. Only one data point was taken below 7 gpm, because the stroboscope reflections from the window became too intense for reading at the lower frequencies.

Some of the data points in Fig. 10 deviate slightly from a smooth curve. This is probably the result of changes in water pressure when other functions connected to the same water system were used intermittently during the test. Although a surge tank was installed to minimize these effects, there were still noticeable fluctuations in pressure that directly affected the manometer and stroboscope readings.

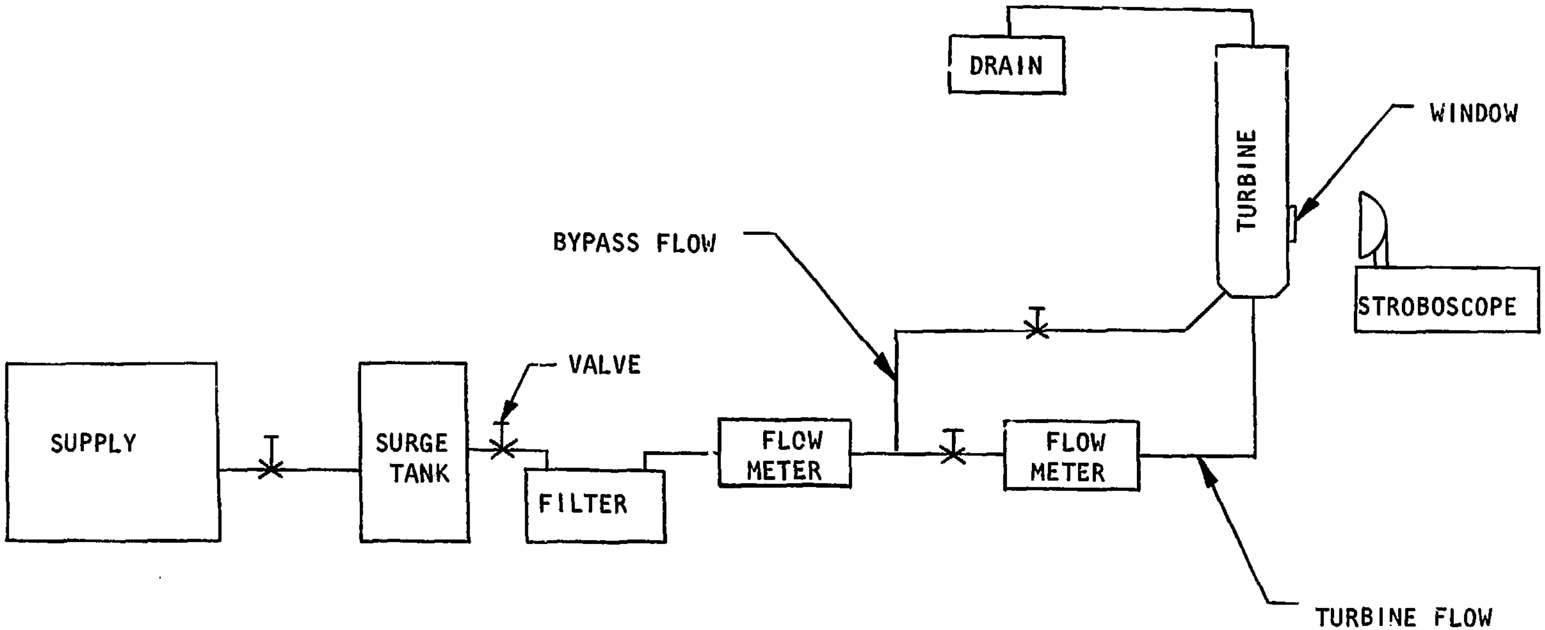


Fig. 9. Diagram of Setup for Water Test of Turbine-driven Oscillator

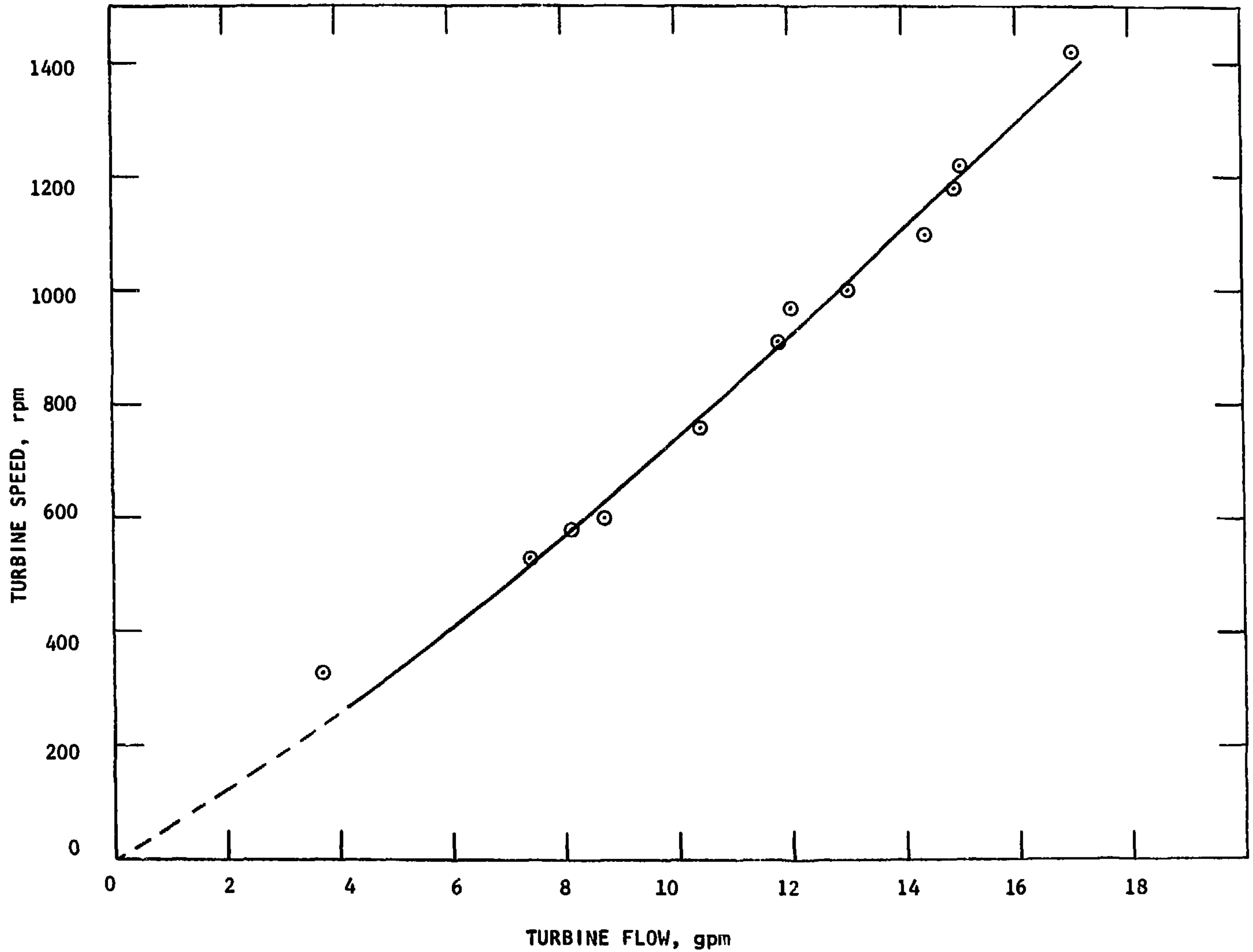


Fig. 10. Speed vs Flow for Water-test Model of Turbine-driven Oscillator

Several low-speed measurements were made to determine minimum operating speed. The turbine ran smoothly down to 0.1 Hz. Below that, its operation became erratic. There was a slight misalignment of the bearing in the nozzle section, resulting in a slight rotor wobble and corresponding bearing friction.

Since it was desirable for water to lubricate the bearings, the bearing grease was washed away with a solvent prior to assembly. Small contaminant particles in the solvent were thus introduced into the bearings and produced additional bearing friction at low speed. Slightly smoother low-speed operation was observed in a separate test with grease-lubricated bearings, although high-speed performance was unaffected.

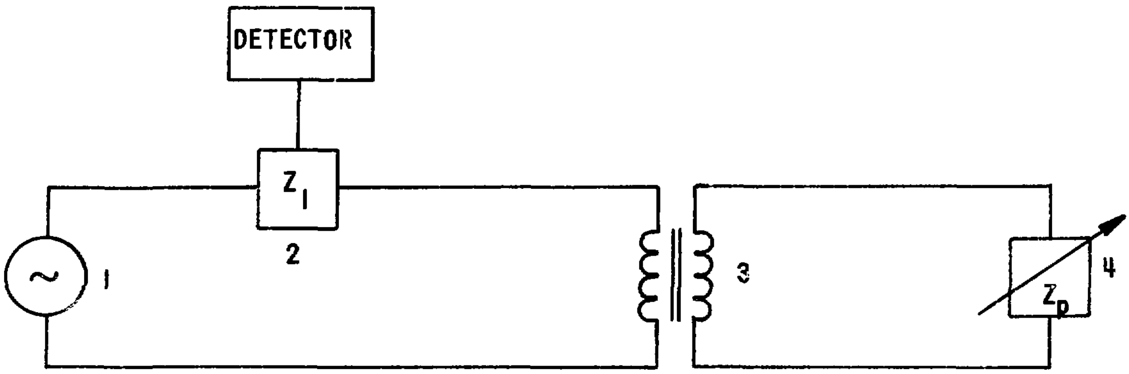
Measured flow at 1200 rpm was considerably less than indicated by the calculations in the Appendix. To facilitate manufacture of the nozzle section, straight milling cuts were made rather than spiral cuts, resulting in a nozzle-outlet area of 0.272 in.^{2} as compared to 0.356 in.^{2} used in the calculations. Also, the nozzle's mean outlet radius was increased by the straight cuts. When the calculations are modified for these values, the measured and calculated rates are very close.

The test model is thus conservative in terms of the power that can be extracted from the flowing fluid. By increasing the nozzle-outlet area to match the turbine openings, more torque becomes available. If sodium is used, the power available to the turbine will still be greater for a 0.356-in.^{2} nozzle than the power available in the water-test model. The increase in nozzle area more than compensates for the decrease in density.

IV. SENSING SYSTEM

To correlate the data obtained from operating an oscillator in the reactor, it is essential to know the angular position and velocity of the absorbing material as a function of time. This requires a system that can detect position and velocity and can transmit that information to a convenient readout location.

After consideration of a number of techniques, it was concluded that the best method for sensing the position and velocity would be a magnetically coupled circuit as represented in Fig. 11. Magnetic conductors are placed radially around the upper cap of the rotating section. During rotation,



1. CARRIER-FREQUENCY GENERATOR
2. DETECTOR IMPEDANCE
3. COUPLING TRANSFORMER
4. INDUCTIVE-TYPE PICKUP IMPEDANCE THAT INDICATES POSITION OF ROTATING ELEMENT.
   IDEALLY Z_i CAN BE ADJUSTED SO THAT CIRCUIT MOVES IN AND OUT OF A RESONANCE AS Z_p IS VARIED.

Fig. 11. Circuit for Detection and Readout of Oscillator Position

these conductors close and open magnetic paths and thus modulate a carrier-frequency signal in the circuit.

An alternative and perhaps superior concept is a recently developed design employing a rotary variable differential transformer (RVDT).[3] Fig. 12 shows the basic physical configuration, and Fig. 13 shows the electrical circuitry, which is identical to that of a linear variable differential transformer (LVDT).

As the center armature rotates with respect to the windings, the magnetic flux induced by the primary winding is coupled and uncoupled between the primary and the two secondaries. The coupling and uncoupling takes place because the shape of the armature varies the reluctance of the magnetic paths between the windings as it rotates.

Since the RVDT is entirely carrier-wave operated, it should be possible to connect and disconnect the RVDT in liquid sodium with the use of a magnetic coupling (transformer). A system using hand-wound RVDT's was tested in air and performed quite satisfactorily. A schematic of a transformer-coupled RVDT is shown in Fig. 14. The ten-turn potentiometer is for the X-Y output plotter.

Several areas require additional design work to make the system suitable for a sodium environment; these areas include (a) proper selection of high-temperature materials, (b) canning and sealing the units, and (c) evaluation of short-circuiting of the loop caused by the canning material and surrounding sodium. It appears that these problems could be overcome without too much difficulty. A logical first step in the development of the sensing system would be to test an LVDT in a sodium environment, because the LVDT is easier to build than an RVDT.

V. RECOMMENDATIONS

The results of the preliminary design study and water test indicate that the turbine-driven oscillator is a feasible concept. It is therefore recommended that the following steps be taken toward the continued development of a reactor model:

(1) Lengthen the nozzle section, which also serves as the lower bearing support, to eliminate any possibility of misalignment.

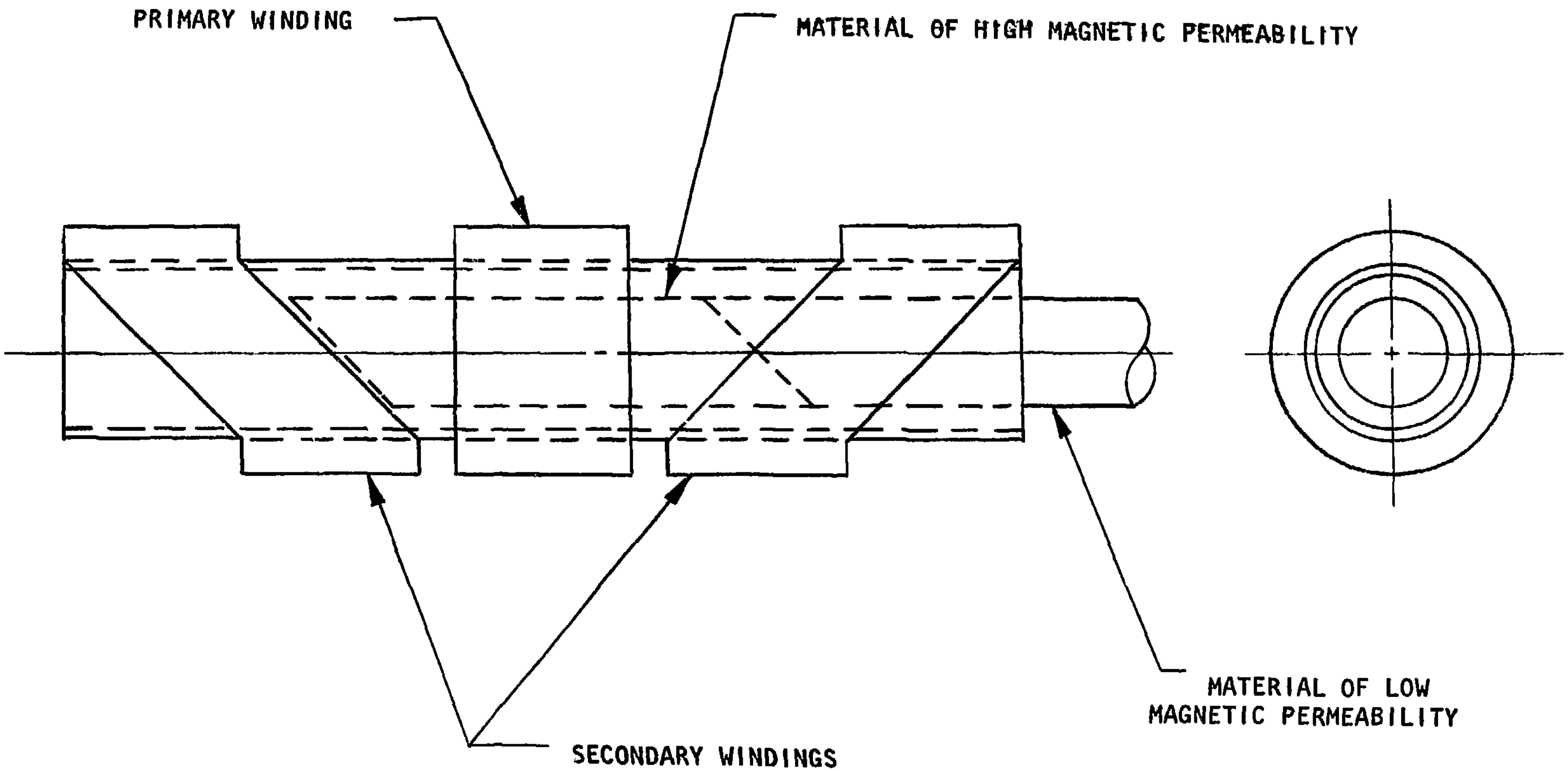


Fig. 12. Schematic Drawing of Rotary Variable Differential Transformer

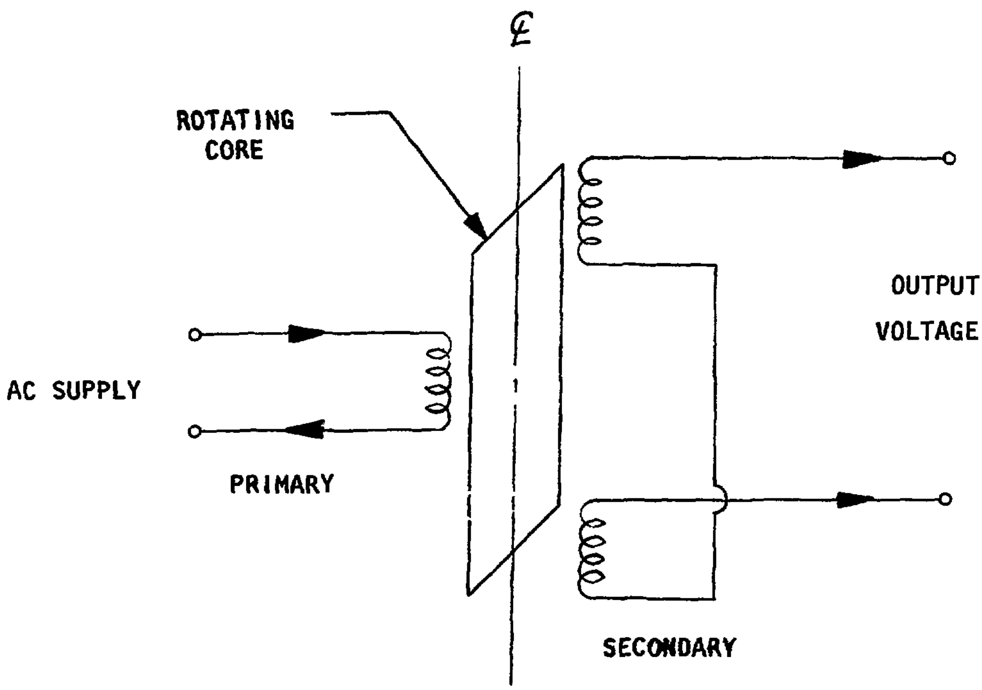


Fig. 13. Basic Electrical Circuitry of RVDT

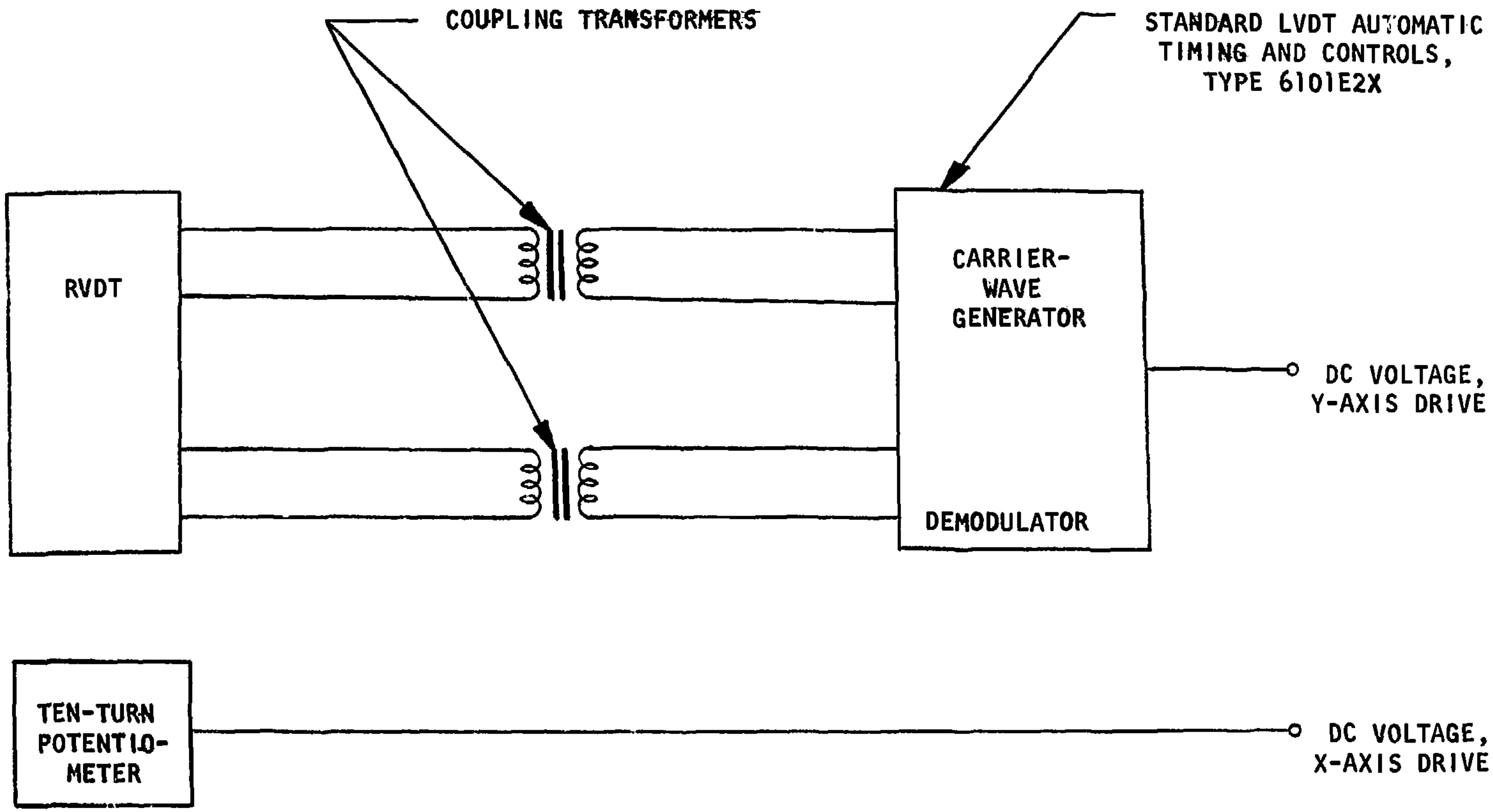


Fig. 14. Transformer-coupled RVDT

(2) Replace the ball bearings with ball-sleeve bearings and retest in water to see if improved low-speed performance can be attained. If the ball-sleeve bearings function properly, they should be used in the reactor model for superior resistance to contamination.

(3) Replace the solid aluminum rotor with a hollow stainless steel version. Incorporate the magnetic readout system and test the turbine-rotor combination in a sodium loop.

(4) Develop and test the turbine speed-control system, first in water and then in sodium. To achieve extremely low rotational speeds (less than 0.1 Hz), it may be desirable to use a braking device instead of a flow-control valve. With a brake, flow through the nozzle would be constant. Applying the brake would slow the speed. At full flow, the turbine starting or stall torque is nearly twice the running torque because of the increased fluid-momentum change. A smoothly operating brake should thus enable the turbine to rotate very slowly.

(5) Study the feasibility of installing the oscillator in the void section just above the fuel in a control subassembly and using vertical motion to control turbine speed. During oscillator operation, the subassembly would move down, shifting the fuel below the core. In the up position, the oscillator would be in the blanket and the fueled section in the core. Thus, a control-rod position would not be lost for oscillator installation.

(6) Upon successful completion of the preceding steps, develop and test a complete system in EBR-II.

(7) Investigate the possibility of replacing the neutron-absorbing material in the oscillator with a fueled section as a means of increasing the reactor loading factor.

APPENDIX

Turbine Calculations

Because of temperature considerations, the total allowable upward flow in the subassembly containing the oscillator is 24 gpm. It was on this basis that the impulse-type turbine was selected. A vane-propeller system was considered, but the blades would have been too short to be effective.

A nozzle-inlet angle, α_1, of 15° was chosen to ensure efficient design of the nozzle-and-turbine system.

The average radius, r, of the turbine is 0.9 in. With a rotational speed, n, of 20 rps, the turbine has a tangential velocity, u, of $2\pi nr = (2\pi)(20)(0.9) = 113$ ips. Using 10% overspeed as the design point, the velocity can be taken as approximately 115 ips.

For the efficiency, ν, to be at the maximum, $\nu_1 = \frac{u}{C_1} = \frac{\cos \alpha_1}{2}$, where C_1 is the absolute velocity of the fluid entering the turbine blade.

$$\nu_1 = \frac{\cos 15^\circ}{2} = 0.483$$

This yields

$$C_1 = \frac{u}{0.483} = \frac{125}{0.483} = 259 \text{ ips.}$$

A vector diagram using $C_1 = 259$ ips at 15° and $u = 125$ ips yields a blade-inlet angle of 28.5°. For this inlet angle, an outlet angle of approximately 23° is expected to give good efficiency.

The nozzle area, A_n, may be sized from the relation $Q = A_n C_1$ where

$$Q = \left(\frac{24 \text{ gal}}{\text{min}}\right)\left(\frac{231 \text{ in.}^3}{\text{gal}}\right)\left(\frac{1 \text{ min}}{60 \text{ sec}}\right) = 92.4 \text{ in.}^3/\text{sec.}$$

$$A_n = \frac{92.4}{259} = 0.356 \text{ in.}^2$$

The theoretical power, P, supplied to the turbine is

$$P = uQ\rho \ (C_1 \cos \alpha_1 - C_2 \cos \alpha_2),$$

where C_2 is the exit velocity and α_2 is the exit angle.

Assuming $C_2 \cos \alpha_2 \sim 0$,

$$P = uQ\rho\ C_1 \cos \alpha_1.$$

The following values are substituted into this expression:

$$u = \frac{125 \text{ in./sec}}{12 \text{ in./ft}} = 10.4 \text{ ft/sec}$$

$$Q = \frac{92.4 \text{ in.}^3\text{/sec}}{1728 \text{ in.}^3\text{/ft}^3} = 0.0535 \text{ ft}^3\text{/sec}$$

$$\text{Fluid density, } \rho = (0.85)(1.94)\ \frac{\text{lb-sec}^2}{\text{ft}^4} = 1.65\ \frac{\text{lb-sec}^2}{\text{ft}^4}$$

$$C_1 = \frac{259 \text{ in./sec}}{12 \text{ in./ft}} = 20.8 \text{ ft/sec}$$

$$\cos \alpha_1 = \cos 15^\circ = 0.966$$

giving

$$P = (10.4)(0.0535)(1.65)(21.6)(0.966) = 19.16\ \frac{\text{ft-lb}}{\text{sec}}$$

or

$$P = \frac{19.16}{550} = 0.0348 \text{ hp}$$

$$\text{Torque} = \frac{(\text{hp})(550)(12)}{2\pi n} = \frac{(0.0348)(550)(12)}{(2\pi)(20)} = 1.83 \text{ in.-lb}$$

This is the value of the torque at 1200 rpm. The starting torque (zero turbine speed) is approximately twice the running torque, because the fluid momentum is nearly doubled.

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