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Final Report

THE DEVELOPMENT OF AN IMPROVED BIAXIAL (TWO COMPONENT) WATER METER

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ABSTRACT

An improved biaxial water meter has been developed to record water movements in lakes. The basic sensors of the water meter are two four-bladed propellers, mounted orthogonal to each other, with shafts in a horizontal plane. Propellers are of fiberglass, are nonmoisture absorbing, and should be unaffected by algae. For water flow parallel to the axis of a sensor, the average starting speed is somewhat less than 2 cm sec^{-1}; at 6 cm sec^{-1} the propeller turns at 90% of its pitch speed; and at speeds above 18 cm sec^{-1} the propeller is turning at 100% of its pitch speed. Three four-bladed propellers were tested—the pitch of all three was 4.79 (± 1%) revolutions per meter of water flow. The linearity of response was excellent up to highest speed total (4 ft sec^{-1} or 1.3 m sec^{-1}) which was a higher speed than any expected in use.

The water meter was tested for water flows at all azimuth angles in 10-degree steps. The response more nearly approached the cosine curve than we have seen for any water sensor to date—for the complete 360 degrees of azimuth the average error was usually less than ± 3% of axial flow, with a peak error of -10% for 20° to 30° of the circle. This is markedly superior to most commerical flow meters.

Each propeller shaft drives a gear reducer through a magnetic coupling so that the gear reducer may be in an air environment rather than water. The gear reducer drives a potentiometer which makes 1.00 revolution for the passage of say 1 km of water. The data from the two potentiometers is recorded

sequentially on a battery driven miniature recorder that needs chart changing only once per month. The water meter is equipped with a compass driven potentiometer so that the azimuth orientation of the UV Water Meter is routinely recorded also.

The water meter is designed for suspension from a buoy cable, or for tower mounting or lake bottom mounting.

1. INTRODUCTION

1.1 NEEDS OF THE IFYGL

For the International Field Year of the Great Lakes, one of the most important measurements that needs to be made is the determination of the three components of water flow at various places and at various depths in the lake. At all depths, excepting near the surface, two components of the water flow will probably be adequate; but near the surface the vertical flow may be needed. At the suggestion of the Water Movements Subcommittee of IFYGL, one of the authors submitted a proposal[1] to IFYGL on February 1, 1968, for the development of an improved biaxial water meter and a triaxial water meter. The proposed water meters would be similar to the unit developed some two years earlier by the present two authors and Mr. Floyd Elder who at that time was with the Great Lakes Research Division. All units were a follow-up of the UVW air flow meter that one of the authors had developed about 1964.*

1.2 DEVELOPMENT OF THE FIRST MODEL (PRIOR TO CURRENT CONTRACT)

The design and construction of the first UVW Water Meter (1967 model) is briefly discussed by Michelena et al. (1968). Figure 1 shows this UVW Water Meter with six-bladed, 10-in. diam propellers. Figure 2 shows the speed calibration of one of the sensors of this meter. Note that the starting speed with the Rulon bearings was somewhat greater than 0.5 ft/sec. Note, however, that above 1.4 ft/sec the calibration is linear, and, if projected toward the

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*Gill UVW Anemometer, Model 27002. R. M. Young Co.

zero, passes through 0:0. This means that at a speed above 1.4 ft/sec there is a linear relationship between the rpm of the propeller and the water speed—the friction of the bearings having become negligible compared to the applied torque. By reducing this bearing friction the starting speed could be lowered, and the region of linearity increased to reach below 1.0 ft/sec. In Figure 3 the response of one of the sensors to water flows at various angles to the axis of that sensor is shown for the complete 360° of arc. Two things are noteworthy from this figure: (1) for 290° of arc (220° through 360° to 150°) the propeller response is within ± 10% of a true cosine response; and (2) for the other 70° of arc the response error may be much greater reaching -22% at one point. The large dip in the curve is due to slowing down of the water as it passes one of the sensors before reaching the sensor whose output is being measured; the enlargement of the curve (200° to 230°) is due to channeling of the flow past the measuring propeller. Both of these distortions to flow past the measuring sensor would probably be reduced if the system were designed such that water passing one propeller did not pass by another propeller; and the support piping was of smaller diameter.

1.3 PROPOSED IMPROVEMENTS OVER FIRST MODEL

In the submission of February 1, 1968, the following improvements in the UVW Water Meter were proposed:

(1) Try to reduce the magnitude of error in the cosine response to ± 10% (or less) for a larger angle, and try to reduce the width of the marked distortion to less than 40°.

(2) Try to reduce the starting speed to water flows of 0.2 ft/sec or less.

(3) Adapt the system for either buoy or tower installation.

(4) Provide choice of either digital or analog output for wave movement studies.

2. DESIGN AND DEVELOPMENT OF THE UV WATER METER

2.1 DESIGN OF A NEW SENSING HEAD

Careful consideration was given to the design of each and every part of the new sensing head, so as to: (1) improve its cosine response, (2) reduce the mechanical friction of the system, and (3) make for reliable, efficient operation. The bearings, made of Rulon in the first unit, had considerable friction, though this is the material used in many instruments and pieces of equipment where shafts must turn in water. Manufacturers of precision ball bearings were contacted with regard to bearings that might be used in fresh water lakes and where algae might be present. One of the manufacturers had experience with such bearings. The bearings and bearing lubricants that he suggested were adopted for our operations.

Another source of extra friction in the first unit was in the linkage between the shaft rotating in water and the tachometer generator rotating in an air environment. Two horseshoe-type magnets had been used in this application, one on the end of the stainless steel shaft exposed to the water, the other on the end of the tachometer generator, and with a brass wall between. The axial pull of the two magnets thus increased the thrust load and the friction of both bearings. To overcome or greatly reduce this load, it was decided to use two concentric magnets, the inner magnet being a short cylinder with the poles located on its periphery; the outer magnet being a circular ring magnetized with its poles on the inside surface. The small inner magnet was attached to the end of the stainless steel propeller shaft which was immersed in water. The ring magnet was cemented to a light aluminum cup which was mounted on, and concentric with, the drive shaft of the gear reducer. We selected two magnets that had an air gap of 1/16 in. (.062 in.) between them. This permitted us to fabricate a cup-shaped barrier of brass having a wall thickness of .032 in. and a radial clearance of .015 in. on each side, water on one side, and air on the other side. With care in the installation of the system, it was quite easy to locate the two magnets such that there was no axial pull one on the other and therefore no extra friction from this means of coupling from the water chamber to the air chamber.

In the first UVW Water Meter each propeller turned a tachometer generator through the magnetic coupling. Thus, a voltage directly proportional to the instantaneous rate of turning of the propeller was generated, and the polarity of the voltage indicated the direction of water flow. This type of recording is excellent where one is concerned with the instantaneous flow velocities in waves. However this system is not well suited to accurately recording the transport of water past a point day by day and month by month. A system which totalizes the revolutions of the propeller (and thus the transport of water past the propeller) is much preferable to a system which measures the speed of the propeller (and thus the instantaneous water flow rate). [Example: Suppose two identical flowmeters such as that shown in Figure 1 were exposed side by side in a broad river, one flowmeter having a tachometer generator output, the other a mechanical counter. At the end of a 24-hr period the analog trace from the first sensor showed this flow to be within the limits 1.5 to 2.5 ft/sec with an average of 2.0 ± 0.1 ft/sec. Then the transport of water must have been (86,400 x 2.0) ft/day = 173,000 ft/day ± 5%. The other sensor recorded 247,608 revolutions/24 hr, and, with a pitch of .704 ft/rev ± 0.5% would mean a passage of 174,500 ft/day ± 0.5%. Thus in this illustration we can expect a tenfold improvement in accuracy in recording water transport when using the totalizing technique instead of the analog trace technique.]

For the transducer system in this new sensor, the writers selected a gear reducer whose output would drive a precision potentiometer. The potentiometer has a 360° mechanical rotation angle (continuous rotation) and a 342° electrical angle (95% of 360°). The output from this potentiometer could be recorded on an inexpensive Rustrak recorder; a multichannel Brush recorder, or could be monitored sequentially by a remote measuring and recording system. For the first unit a gear reducer of a 1000:1 was selected. One revolution of the potentiometer shaft would then represent the transport of .210 km of water when the propeller had a pitch of .210 m/rev (1.45 rev/ft—Figure 18). By recording on a Rustrak recorder, the number of transits of the trace across the paper in any one hour, multiplied by .210, would give the flow in kilometers per hour. The slope of the curve would give the speed of the water at any given time; the sign of the slope would give the direction of flow.

For the calibration of each sensor (that is, the relationship between the rate of rotation of the propeller and the water speed), it is necessary to be able to measure the propeller speed quite accurately. Likewise, in determining the cosine response of the sensor, it is again necessary to know the instantaneous speed of rotation of the shaft quite accurately. For this work we used a photo-transistor-chopper circuit rather than the gear-reducer-potentiometer system. This chopper circuit gave us five impulses per revolution of the shaft.

The assembly drawing of the sensing head is shown in Figure 4. Photographs of the U and V sensing heads are shown in Figures 5 and 6. Brass and stainless steel are the two metals used throughout in these heads. Both metals are suitable for underwater installations and are compatible electrolytically.

2.2 USE OF FOUR-BLADED AND SIX-BLADED PROPELLERS

Model airplane propellers are an inexpensive source of quality propellers of various pitch, diameter, and material. Most of them are of the two-bladed or three-bladed variety, ranging from 6 to 12 in. diam. Different plastics are used, some of which are water absorbing. Many of these propellers are of nylon, but, unfortunately, in our tests we found that such propellers absorbed water and their pitch was altered markedly. Accordingly, we conducted a search for propellers which would not absorb water (and thus would not change their shape). Fiberglass propellers should be impervious to water; stronger than most plastics; and should be unaffected by algae. We located one source of two-bladed, 11-in. diam fiberglass propellers. Samples of this type of propeller were placed in a water bath for about two weeks and their dimensions and weight were measured before and after water exposure. It was found that there was a slight increase in weight due to water absorption, but no detectable change in shape. Accordingly, these propellers were adopted for our study.

In model aircraft propellers the leading face of the propeller is curved and the trailing face almost flat. Accordingly, one would anticipate that the response for the propeller for air or water moving in one direction would be different for that moving in the opposite direction. This is borne out in wind tunnel tests. To overcome this weakness and still use these inexpensive quality propellers, one can combine two or three propellers to form four-bladed or six-bladed compound units—with alternate faces being curved, flat, curved, flat, etc. To form a four-bladed propeller, the backside of the core of two two-bladed propellers was milled away to half its normal thickness; the two halves were then turned back to back and cemented together to form the propellers as seen in Figure 5. This four-bladed propeller is then symmetrical on both its faces and should equally react to water moving in one direction or the other, parallel to its axis. All four blades are in the same plane, as contrasted to the case in the first model of the instrument shown in Figure 1.

Each six-bladed propeller was made by cutting three two-bladed propellers into 60° pie-shaped units and assembling them as shown in Figure 7 and the right of Figure 6. The propellers were cemented together as well as being fastened to the hub by six close-fitting screws.

2.3 USE OF PROPELLER HUB EXTENSION

From wind tunnel tests of the UVW anemometer it was found that when shaft extensions were used, improved dynamic response resulted. With this shaft extension there was an improvement in the cosine response in the region 90° ± 30°, and, 270° ± 30° of Figure 3. Likewise, the angle where the propeller did not turn was reduced from about 90° ± 4°, and 270° ± 4° to about 90° ± 2°, and 270° ± 2°. It was expected that a similar situation would occur in the water meter, so shaft extensions 5 in. long and 5/8 in. diam were prepared (Figure 5) and tested in the tow tank.

2.4 TESTING TO DETERMINE VERTICAL SEPARATION OF SENSING HEADS

In Figure 3 there is considerable distortion to the cosine response of the propeller, (1) as the water flows over the support housing of the instrument, and, (2) as the water flows over one propeller before it arrives at the propeller whose output is being recorded. In the region 195° to 235° enhancement of water flow is due to channeling of the water by both the vertical support pipe (Figure 1) and the large diameter transducer housing of the sensor under test. To reduce this affect in the new sensor, Figure 5, the support housing has been reduced from 2 in. diam to 1-1/8 in. diam. In the region 155° to 195° the marked decrease in water flow is due largely to interference of flow by the other propeller. In order to determine the effect of flow over one propeller on the measurement by another propeller, we fabricated two support structures, one with the U and V sensors separated by a vertical height of 3 in., the other by a vertical height of 12 in.—the latter is shown in Figure 5. Test results are given in the next section.

2.5 SELECTING THE RECORDING SYSTEM FOR THE UV WATER METER

In order that the complete two-component flowmeter system be a compact package that could be suspended from a buoy at a depth of say 200 ft and left there unattended for a month or more, the recording system must be small, battery operated, and with a low power consumption. As indicated in Section 2.1 a gear-driven potentiometer was selected as the basic transducer. A single channel, Rustrak Recorder with a 0-100 μA movement was selected as the recorder. The chart drive and tapping bar is powered by a self contained synchronous motor driven by a miniature tuning fork and electronic power supply drawing only 10 mA of current from a 12-V battery. Manufacturers specification claim a variation in speed of ± 0.5% over a recorder temperature range of 0°F to 150°F (150°F span) where the input voltage is 12.0 ± 2.4 V, and; ± 0.1% if recorder temperature is maintained at 72°F, and input voltage 12.0 ± 2.4 V. For our normal submerged installations the temperature is likely to change very slowly, by not more than 10°F/mo, over the range 36°F to 66°F (1/5 of 150°F span), and the battery voltage is likely to vary less than that specified. So we expect the chart speed to vary by little more than ± 0.1%/mo (3/4 hr/mo)—a very satisfactory figure. A chart speed of 1 in/hr was selected; with chart rolls 63 ft in length each roll will last a full 31 days, so monthly chart changes will be expected.

Another reason for choosing a Rustrak Recorder was that it utilizes the tapper-bar, pressure-sensitive paper technique for recording. By freeing the meter needle of any pen friction for at least 6 sec out of each 12-sec print-out cycle, one can use a sensitive meter without amplification (0-100 μA, 4600 ohm coil, .46 V full scale). By avoiding the inking problem of a pen-and-ink system, the chances of getting recorded data month after month is probably increased five fold by the use of the tapper-bar, pressure-sensitive paper technique.

The orientation of the UV Water Meter suspended by flexible cable from a buoy is sure to vary from month-to-month and even day-to-day, and from installation to installation, by the complete 360° of azimuth. It thus becomes necessary to provide some means of recording the azimuth orientation of the UV sensor. The simplest, reliable system at reasonable cost appeared to be to use a compass needle—potentiometer arrangement in which the compass needle would be free to rotate at all times excepting when a reading was needed. At such a time a solenoid would depress the compass needle onto the potentiometer winding. We found that just such a system had been developed by Plessey of England and could be purchased for use in our equipment. Specifications of the units we purchased are given in the Appendix.

To record the three outputs, (U, V, and C (compass)) sequentially on one recorder (and four outputs for the UVW Water Meter) it is necessary to switch these circuits in succession. To avoid electrically operated relays drawing appreciable power, it was decided to use a nylon cam and four microswitches as shown in Figure 8. This cam is on the primary shaft of the chart drive motor; it makes one revolution in 3 min. As indicated by the figure each of four parameters is sampled for about 45 sec during each 3-min cycle, with each sample composed of three or four dots (1 print-out each 12 sec). When the recorder is used for a UV Water Meter, it is intended that the W switch be connected to the U switch, so that the U signal will record about 50% of each cycle and the V and C signals each about 25% of time. With double the print-outs for the U signal there will be no problem in distinguishing the U and V signals. What might be a representative record from a UV Water Meter is shown in Figure 9. Each crossing of the chart by the U and V signals will represent the passage of .75 km of water (1 rev of fiberglass prop per .21 m of water flow, and 3600:1 gear reducer). The positive or negative slope of U and V signals indicates the direction of flow. The compass is calibrated so that 45 chart divisions = 360°, as shown (8°/div). For the period 12 noon to 1 p.m. the flow was U = 1.45 km ((.12 + 1.00 + .82) x .75 km); V = -.30 km ((.05 + .35) x .75 km); and the sensor orientation 296° magnetic (240° + 7 x 8°).

The cost of American-made gear reducers in the size range needed (3/4 in. diam; 1000:1 to 4000:1 reduction) is almost prohibitive—the 1000:1 reducer we purchased cost $137.00; and is not available at speed ratios greater than 1500:1. Most other U.S. manufacturers do not make reducers this small in diameter; and their prices are just as exorbitant. After purchasing the initial speed reducer we located a source of Japanese-made gear reducers of almost comparable quality having speed ranges of 10:1, 20:1, 30:1, 60:1, 100:1 up to 1800:1 at less than $10.00 each. By using two gear reducers of 60:1 in series, costing $13.60 ($6.80 each), of 0.78 in. diam we have a gear reduction of 3600:1 at a reasonable cost which will result in 1 rev of the potentiometer shaft for the passage of .75 km of water flow. (This was the best combination of gear reducers we could find to give us 1 rev of the potentiometer shaft for the passage of some convenient length of water between 0.4 and 1.2 km.) With a probable peak flow rate of 0.8 m/sec (2.9 km/hr) the recorder pen will make a corresponding maximum of about 3.8 transits across the chart roll per hr—about the maximum rate for convenient abstraction of data.

For the self-contained gas tight system design of the UV Water Meter it was desirable not to use lead-acid storage batteries due to their gaseous emission on discharging, and the possibility of acid spillage when exchanging batteries. It was desirable to choose batteries that would maintain 70% or more of their rated output when the environment temperature dropped to near 32°F. Nickel-cadmium, sealed and rechargeable batteries would be excellent for this work but are very expensive. Conventional dry batteries (zinc-carbon) will probably be adequate when replaced monthly. The cell space provided in the recorder-battery compartment is suitable for either the zinc-carbon or the nickel-cadmium types of batteries. With very light load, mercury cells are suitable down to 39°F (temp. of maximum density of water). Because of their constancy of voltage output they were selected for the potentiometer circuit shown in Figure 8.

2.6 THE COMPLETE ASSEMBLY

The proposed complete assembly of a UV Water Meter is shown in Figure 10. The wire rope suspending one or more water meters below the buoy is shown on the left of the drawing. A welded bracket of thin wall stainless steel supports the UV Water Meter about 30 in. out from the cable. The latter hangs freely from the support bracket, there being no exposed electric cables to tangle with the supporting wire (or plastic rope). When servicing the equipment the water meter is easily separated from the support bracket, and the support bracket is easily removed from the wire rope.

The batteries and recorder are housed in a cylindrical chamber at the base of the system as shown in Figures 10 and 11. The batteries and recorder are rigidly fastened to the base plate. A magnetically operated reed switch attached to the recorder permits opening of the power circuit when the unit is completely assembled but not ready for lowering into the water by placing a horseshoe magnet on the top of the recorder-battery case (Figure 11).

The support bracket, snaps, swivel, etc., are all of nonmagnetic material so as not to interfere with the operation of the compass. Since the Rustrak Recorder has a strong permanent magnet in the meter movement it is necessary to widely separate the compass from the recorder. This is the reason for locating the compass as remote from the recorder as conveniently possible as seen in Figure 10. With a .30-in. separation between the compass and the wire rope the latter should not affect the compass readings. If it does a nylon or polypropelene rope may be necessary.

A pair of weights on opposite sides of the vertical shaft are provided to permit adjusting the system to vertically when it hangs freely in the water.

3. TOW TANK TESTING OF UV WATER METER

3.1 DESCRIPTION OF FACILITY

The performance of the UV Water Meter was determined by towing the instrument in the Ship Model Towing Tank belonging to the Department of Naval Architecture and Marine Engineering, located in the basement of the West Engineering Building of The University of Michigan. The water tank of this facility has dimensions of 360 ft x 22 ft x 11 ft in depth. Water depth at the time of these tests was about 8 ft. A rectangular carriage, about 26 ft x 20 ft spans the tank and is supported by four flanged wheels riding on railroad-type rails on each side of the channel. Electric drive motors, control and measuring equipment, operating personnel, and test equipment are all accommodated on this carriage (see Figures 12 and 13). Electric power to the carriage system is supplied by sliding contacts in a way similar to that used to power electric trains. The complete system was precision designed and precision constructed. This resulted in a very smoothly operating carriage whose speed is accurately controlled and accurately measured. The speed is continuously variable from about 0.03 to 20 ft/sec. In the speed range .03 to 4 ft/sec the accuracy of measuring a steady speed is about ± .002 ft/sec. The top speed in any of our tests was about 4 ft/sec—greater than any flow rates the instrument is likely to encounter.

3.2 TEST PROCEDURES

To obtain calibration data for our UV Water Meter each of the U and V sensors were equipped with a photo-chopper transducer as explained in Section 2.1. These sensors provided five equally spaced on-off pulses per revolution of the propeller shaft. The pulses were counted on a Hewlett Packard electronic counter (instrument to extreme right and on lower shelf of Figure 12(b)) for a period of 10, 20, 30, 60, or 120 sec, depending on the carriage speed. At lowest carriage speeds a minimum of about 20 pulses (4 revolutions of propeller shaft) were acceptable for a measurement, usually counts were in the range 60 to 500 for a measurement.

The UV Water Meter was mounted on the floor of the carriage (see Figure 13(b)) about the center line of the tow tank, with the propellers located about mid-depth of the water in the tank, not less than 3 ft below the surface and not less than 3 ft above the floor of the tank (see Figure 14). The support shaft was vertical (within ± 1°), and angular positions (relative to the center axis of tow tank) were adjusted (by protractor, see Figure 13(b)) to within ± 1° for the various angles.

To obtain the starting speed of a sensor and its speed calibration, the sensor position was set at 0° (axis of its shaft parallel to the axis of the tow tank, and so that when the carriage is in motion water passes through the propeller before it passes over the vertical supporting shaft), and the carriage operated at one of several steady speeds. A typical set of carriage speeds was: .03, .04, .06, .08, .10, .12, .14, .16, .18, .20, .25, .30, .35, .40, .45, .50, .60, .80, 1.00, 1.20, 1.40, 1.60, 1.80, 2.00, 2.50, 3.00, 3.50, and 4.00 ft/sec. At each speed setting the propeller speed reading was not recorded until the propeller speed was found to be steady (e.g., the same number of impulses registered on electronic counter for two successive 1-sec or 10-sec periods). For such a calibration the carriage made about 7 or 8 transits of the tank, with observations being made going in each direction. This necessitated reorienting the sensor 180° in azimuth a corresponding number of times—prior to each reversal in carriage motion.

To determine the response of each propeller to water flow from directions other than parallel to its axis of rotation (sometimes called the "cosine response" curve) each sensor was tested at 10° increments of azimuth angle from 0° to 360°. In this testing the carriage speed was adjusted to, and maintained at, 2.00 ft/sec for all azimuth angles. This speed was maintained steady for about 80% of the length of the tow tank. After a reading at a particular azimuth angle was obtained, the angle was changed by 10° (± 1°); 1-sec counts were observed until the reading became steady; then a 10-sec count was obtained; the angle changed by 10°; and the process repeated. In this way the propeller rotation rate measurements should be quite reliable.

3.3 ANALYSIS OF TOW TANK MEASUREMENTS

The conventional calibration data for Propeller #1 is presented in Figures 15 and 17; and that of Propeller #2 in Figures 16 and 18. Both of these propellers are of the four-blade type as discussed in Section 2.2. As can be seen from Figures 15 and 16 there is a linear relationship between the rate of turning of the propellers and the speed of the water past them. There is no distortion of the propeller blades up to 4.0 ft/sec—the maximum speed the sensors are likely to encounter.

The same data as given in Figures 15 and 16 is plotted in a different way in Figures 17 and 18, in order to determine:

(a) The speed range above which bearing friction becomes insignificant.

(b) The pitch of the propeller.

From Figure 18 we see that *at water speeds above 0.5 ft/sec the friction of the bearings (and magnetic coupling, etc.) has become negligible*, and at these higher speeds *Propeller #2 makes 1.45 ± .01 revolutions per ft of water flowing past it*, or, if we count the number of revolutions of the propeller in a given period and divide by 1.45 we have the transport of water, in feet, during the specified period. From Figure 18 we can also see that the *starting speed of Propeller #2 is less than .06 ft/sec* (*≤ 2 cm/sec*).

From Figure 17 we see that the pitch of *Propeller #1 is 1.48 ± .01 revolutions per ft* of water flowing past it. The starting speed is in doubt (due to observer recording carriage speeds only to nearest 0.1 ft/sec up to 1.8 ft/sec on our initial run, instead of to the nearest 0.01 ft/sec), but it is less than 0.1 ft/sec, and *probably ≤ 0.06 ft/sec* (*≤ 2 cm/sec*).

For both Propellers #1 and #2 the propellers are recording 90% or more of true water speed when the water speed is 0.2 ft/sec (6 cm/sec) or stronger.

NOTE: Since the flow past the propeller is a simple multiplication factor (1/1.45 for Propeller #2) times the number of revolutions turned by the propeller one is fully justified in drawing a straight line calibration in Figures 15 and 16 for speeds above 0.5 ft/sec, and, an extension of this line below 0.5 ft/sec will pass through 0.0, the intersection of the x and y axes.

From Figure 19 we see that the presence of the shaft extension apparently has little or no effect on the calibration of a four-bladed propeller (Propeller #3) when the propeller is aimed directly into the water flow.

From Figures 17, 18, and 19 we see that the three, hand assembled, four-bladed propellers have almost identical calibration: #1, 1.48 rev/ft of water; #2, 1.45 rev/ft of water; and #3, 1.46 rev/ft of water—an average of 1.46 ± 1% rev/ft of water. This is as good as could be expected from run-of-the-mill toy propellers.

From Figure 20 we see that Propeller #3 made fewer revolutions per ft of carriage travel when the water passed over the support structure before reaching the propeller than when there was no obstructions to water flow. As was expected, the supporting pipe of the water meter caused a drag on the water flow so that the propeller made about 4% fewer revolutions than for unobstructed flow (1.40 rev/ft of water in Figure 20 compared with 1.46 rev/ft in Figure 19).

In Figures 21 and 22 the corresponding calibration curves for a six-bladed propeller for flow angles $\alpha = 0^\circ$ and $\alpha = 180^\circ$ are given. As in the case of the four-bladed propellers there was:

(1) A specific number (1.42 ± .01) of revolutions per ft of water passage when the water speed was 0.5 ft/sec or higher.

(2) When the flow direction was reversed ($\alpha = 180^\circ$) the drag of the support structure reduced the flow past the propeller by about 4% (from 1.42 rev/ft to 1.36 rev/ft)—the

same proportion as for the four-bladed propeller.

In Figure 23 is plotted the data on the starting speeds (forward flow) for the three four-bladed propellers and the one six-bladed propeller; also their relative responses at water flow rates up to 0.5 ft/sec. These curves show:

(1) The friction loss of the six-bladed propeller was indistinguishable from that of the four-bladed propeller.

(2) The starting speed of the six-bladed propeller (.05 to .06 ft/sec) was not significantly better than that of the four-bladed propellers (.05 to .07 ft/sec).

From this calibration data the six-bladed propeller does not seem to demonstrate any superiority over that of the four-bladed propeller.

In Figures 24 through 29 the cosine response of both four-bladed and six-bladed propellers is shown, (a) for differences in vertical spacing of the U and V shafts, and (b) for shafts with, and without, end extensions.

By comparing the response of Propeller #1 in Figures 24 and 26 in the region 160° through 180° to 270° we see the marked improvement in sensor response when the vertical separation between the U and V sensors was increased from 3 in. to 12 in. There was a similar improvement, but not so marked, in the case of the V sensors as shown in Figures 25 and 27. Since the better cosine response with a vertical separation of 12 in. was expected, this separation was accepted for the future design of the instrument.

By comparing Figures 26 and 28 we see the improvement in cosine response when the shaft extension is used. This improvement is noteworthy for flow angle α between 60° to 120° and especially in the region $\alpha = 170°$ to 190°. In this latter critical area the error in indication is reduced to almost one half its former value. *Comparing Figure 28 with Figure 3 the very great improvement of the new sensor with slimmer support, U and V sensors offset by 12 in. in the vertical, and, the use of shaft extensions is clearly evident.*

In Figures 28 and 29 the cosine response of a four-bladed propeller and a six-bladed propeller, both with shaft extensions, are compared. From these graphs there seems to be no clear cut superiority in cosine response of one sensor over the other. From this one calibration the four-bladed propeller seems to be slightly superior in the region of $\alpha = 165°$ to 230°, but the six-bladed propeller seems to be superior in the region $\alpha = 140°$ to 165°. Neither propeller is perfect in the region $\alpha = 230°$ to 360°.

From the above comparisons (Figures 21, 22, 23, 28, and 29) *we must conclude the six-bladed propeller is not significantly superior to the four-bladed propeller from any of our tests.* The four-bladed propellers are simpler to construct; stronger; cheaper; and more repeatable in pitch (being the same as that of the two-bladed propellers from which they are fabricated) than the six-bladed propellers. Accordingly the four-bladed propellers are recommended for this work.

4. ACKNOWLEDGMENTS AND EXPLANATIONS

When the proposal was made by Messrs. Gill and Elder it was expected Mr. Elder would be able to actively participate in the instrument development. However, he had a full commitment with Great Lakes Research Division until March 31, 1969, when he accepted a position with the Canadian Center for Inland Waters. Accordingly he was unable to assist in the instrument development.

Prof. Gill directed the design and development of the improved UV Water Meter ably assisted by Mr. Eduardo Michelena, a graduate student in oceanography. This continued until early June, 1969 when Prof. Gill had to take sick leave for some weeks due to acute rheumatoid arthritus. He assisted Mr. Michelena part-time in September and October, 1969 but was obliged to take sick leave again, from November 1, 1969 to mid-August, 1970, after the termination date of the contract. In view of his illness, and of other commitments of Mr. Michelena, the complete assembly and the field testing of the instrument has not been possible. However, Mr. Michelena was able to conduct most of the tow tank tests needed, analyze the data, and prepare curves and graphs for the final report. The two of us, Messrs. Gill and Michelena have prepared this report, between August 15 and December 15, 1970. We sincerely regret we could not complete the proposed development and testing of the water meters as outlined in the proposal.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCERNING BASIC SENSOR

Referring to the Proposed Improvements as set forth in the original proposal and repeated in this report, Section 1.3, we have:

(1) Developed a sensor with improved cosine response, having reduced the drag and interference errors in the region 180° ± 30° from + 6% and - 22% to + 3% and - 5% (see Figures 3 and 28).

(2) Developed a sensor with a starting speed of 2 cm/sec or less— apparently as low as any commercial flowmeters in use today. There is no problem in the sensor maintaining excellent linearity over the range of water flows expected 0-0.8 m/sec, as it has been tested to speeds of 1.2 m/sec without loss of linearity.

(3) Developed a self-contained UV Water Meter, suitable for either buoy or tower installation, and requiring chart and battery changing but once per month.

(4) Not developed the system for wave movement studies. (However Mr. Elder has modified one pair of sensors with tachometer generators for exactly this purpose, and used them for about two months in the fall of 1970. The instrument appeared to function very well. Upon removal from the water in early December, 1970, water had entered one air chamber (we should have used "marine wire" for critical wiring) and one of four outside bearings was slightly "rough.")

Accordingly all of the proposed improvements in the basic sensor have been accomplished.

5.2 CONCERNING COMPLETE UV WATER METER

The design of the complete system has been accomplished. Testing of most of the components has been accomplished, with the exception of the recorder-battery compartment, and the magnetic compass compartment. Assembly of the complete system does not appear to be very difficult but it has not been accomplished. Testing of the complete system has not been accomplished, of course.

5.3 CONCERNING UVW WATER METER

Early in the development of the UV Water Meter the Water Movements Sub Committee pointed out that the development of the UVW Water Meter was not nearly as important as the UV Water Meter. Accordingly only cursory consideration has been given to the measurements of the W component, all energy being concentrated on the UV instrument.

5.4 RECOMMENDATIONS

Three or more of the complete instruments should be assembled and tested as outlined in the proposal under "Lake and stream testing," before the system is accepted for use in the IFYGL Program. The weakest two links in the system are thought to be the especially treated ball bearings supporting the sensor shafts, and the Rustrak Recorder. These two items are more likely to give trouble than any other components. It is likely more suitable bearings will be found or designed; and it is hoped that a more easily serviced and more reliable recorder than the 1968 model of Rustrak will be found.

REFERENCES

1. Gill, Gerald C., and Floyd C. Elder, proposal to the "U.S. National Committee for the International Hydrological Decade, National Research Council" for the "Development of an Improved Biaxial (Two Component) Water Meter and a Triaxial (Three Component) Water Meter." Univ. of Mich., Feb. 1, 1968.

2. Michelena, Eduardo, Floyd C. Elder, and H. K. Soo, "A Triaxial Flowmeter for Wave Motion Measurements," Proc. 11th Conf. Great Lakes Research, 1968, pp. 424-436, International Assoc. Great Lakes Research.

APPENDIX

SOURCES OF SUPPLY OF MAJOR COMPONENTS
(Numbers refer to Figure 4)

Dynamic Gear Co., Inc.
Amityville, Long Island, N.Y.
(Part #68132 - Speed reducer, Cat. #SR086-1000, Size 8, 1000:1 ratio)

Herbach and Rademan, Inc.
401 East Erie Ave.
Philadelphia, Pa. 19134
(Micro reduction gearhead, Cat. #VI-004, ratio 60:1)

Maurey Instrument Corp.
4555 West 60th St.
Chicago, Ill. 60629
(Part #68135 - Potentiometer, Cat. #75-M96-6, servo-mount, wirewound, 2000ohm)

Miniature Precision Bearings, Inc.
Precision Park
Keene, N.H. 03431
(Part #68115 - Ball bearing, their part #D940 with special Dicronite LT4 dry lubrication)

R. M. Young Co.
32 Enterprise Drive
Ann Arbor, Mich. 48103
(Part #68111, 68112, 68113, 68114)

Stackpole Carbon Co., Electronics Division
St. Mary's, Pa.
(Part #68126 - Cylindrical magnet, their ceramagnet A, code 61-650-1, exc. .250 long, and MMF 4 poles inside;
Part #68127 - Annualar magnet, their ceramagnet A, code 61-502-1, exc. .250 long, and MMF 4 poles outside)

Plessey Canada Ltd.
300 Supertest Rd.
Downsview, Ont.
(Compass - compass assembly, Part #M020C)

Gulton Industries, Inc.
Rustrak Instrument Div.
Municipal Airport, Manchester, N.H. 03103
(Rustrak Recorder, 0-100 microampere range, 12 volt D.C. chart drive)

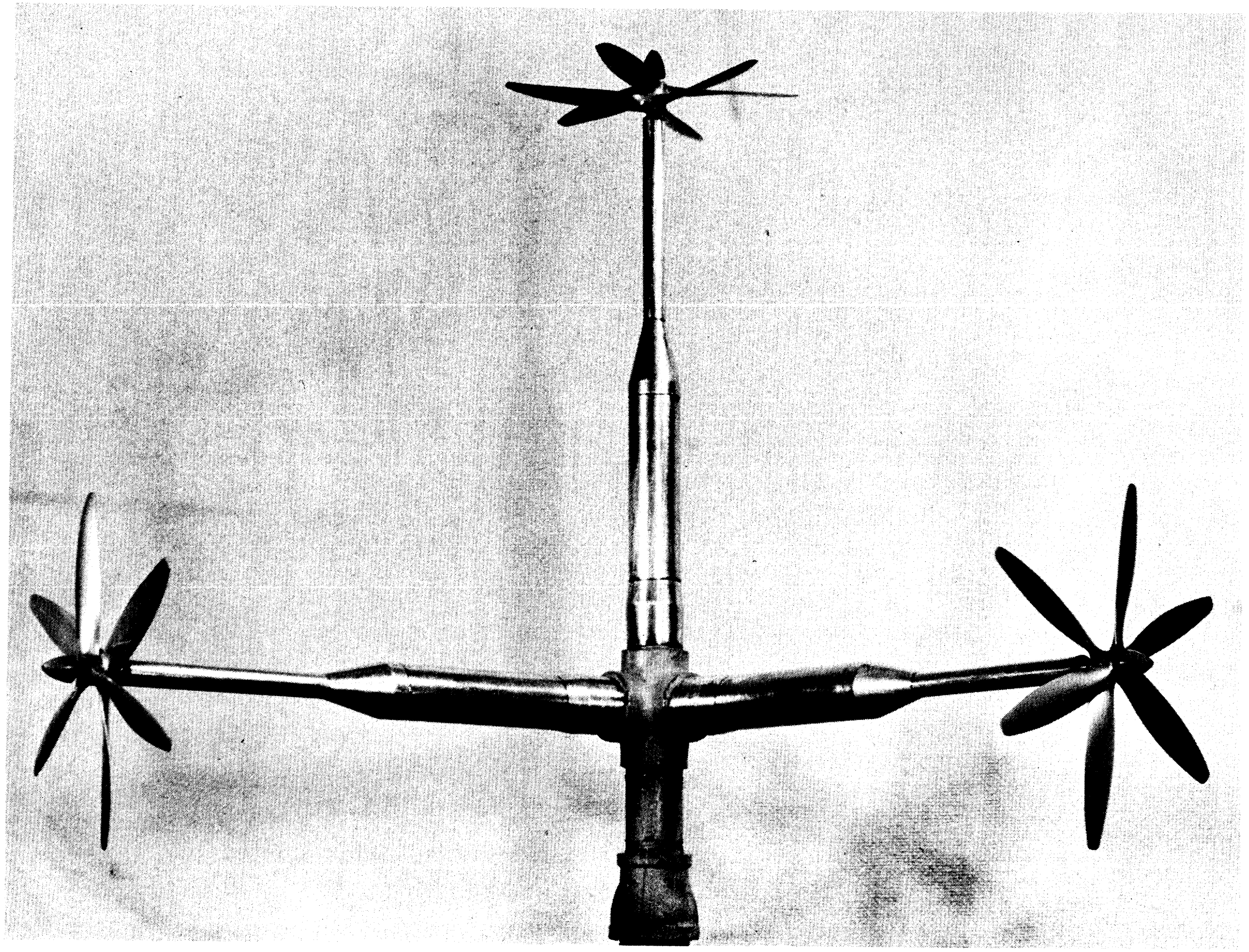


Figure 1. UVW Water Meter (1967 model). (Propellers 10 in. in diameter; distance from tip of hub to intersection point of three axes = 20 in.)

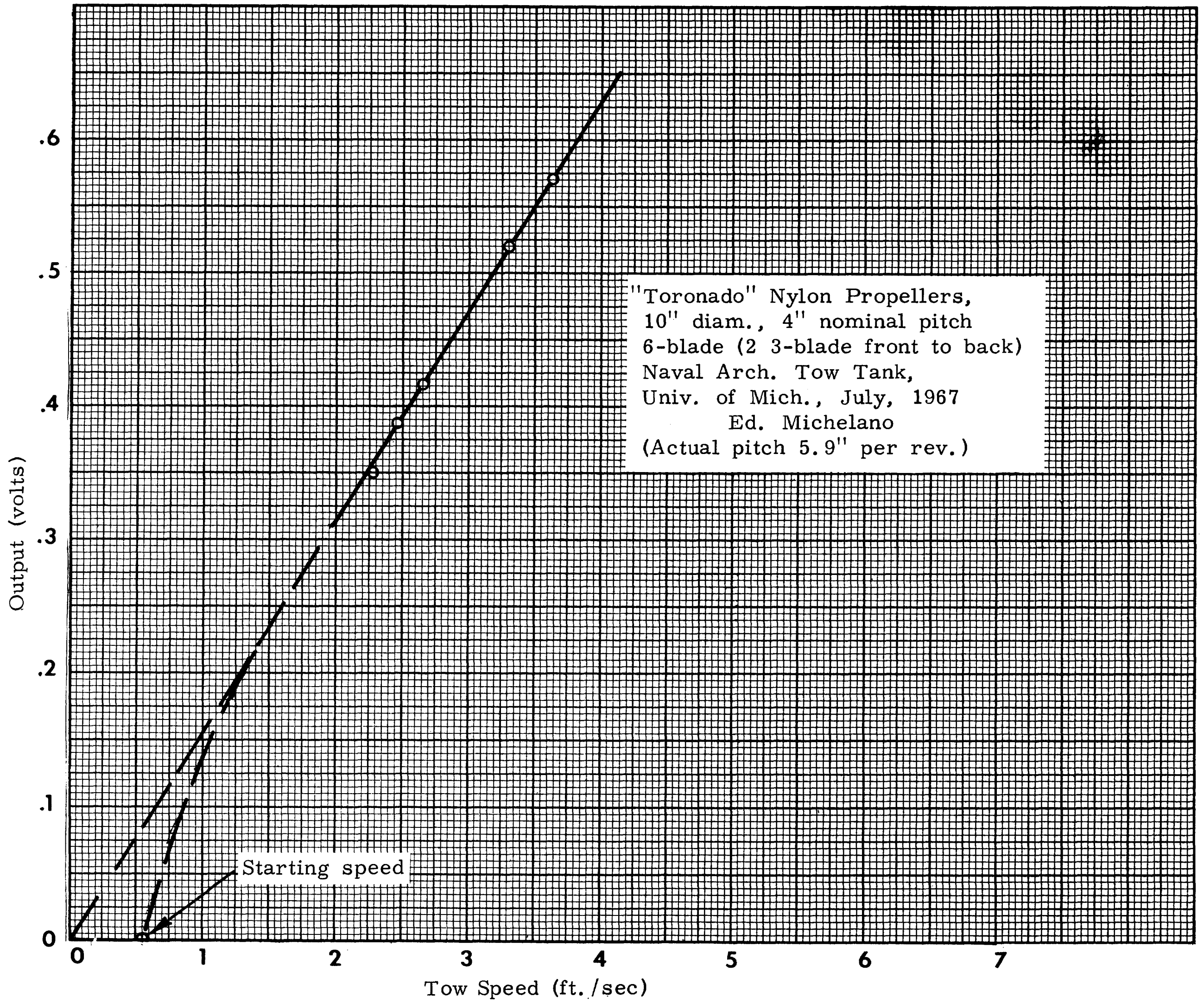


Figure 2. Speed calibration of one sensor of UVW Water Meter (1967 model).

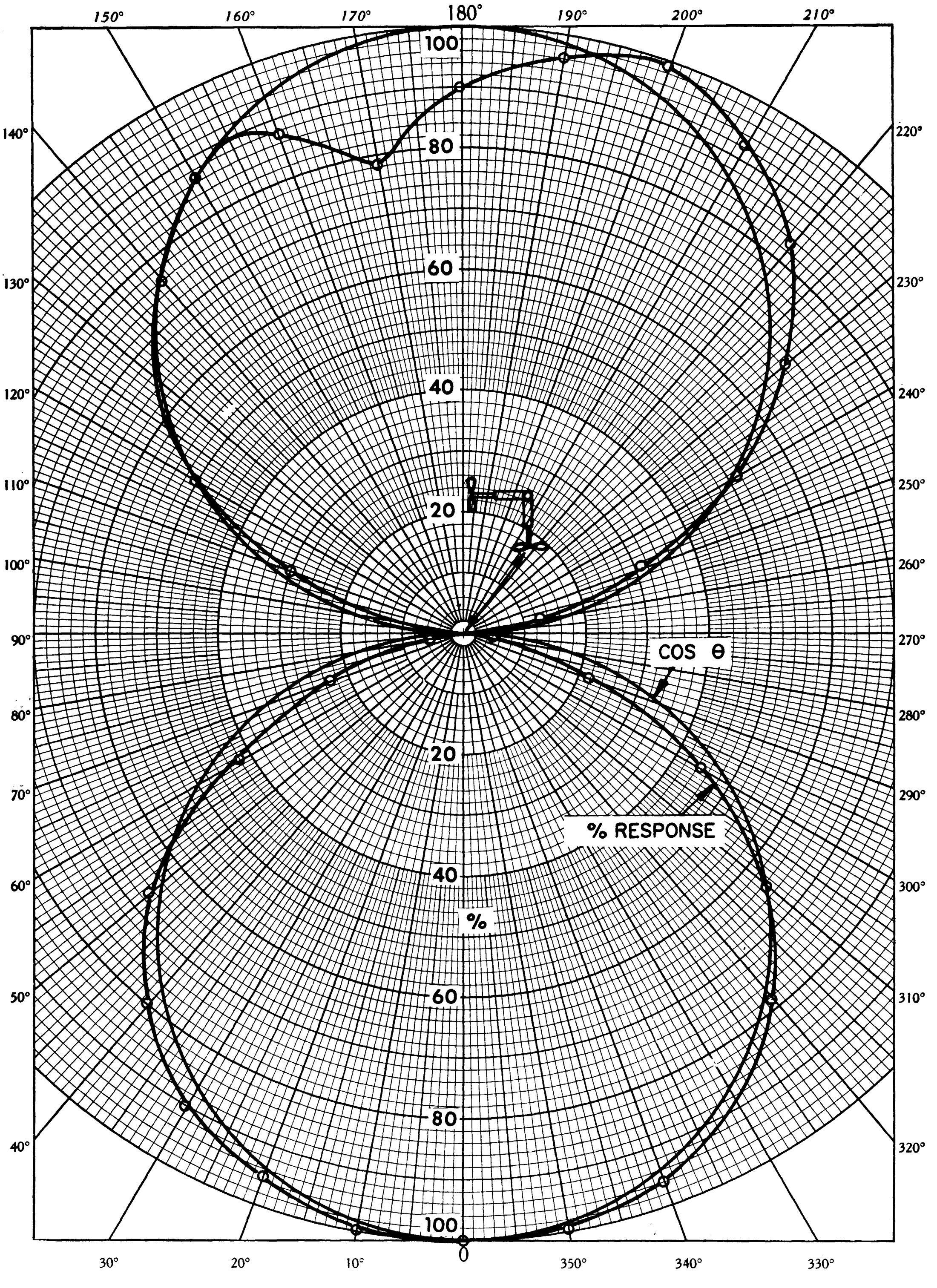


Figure 3. Response of one six-bladed propeller (two three-bladed propellers) as UVW Water Meter rotated in 10° steps through 360°. (Tank carriage speed adjusted to 4 ft sec^{-1} prior to each test.)

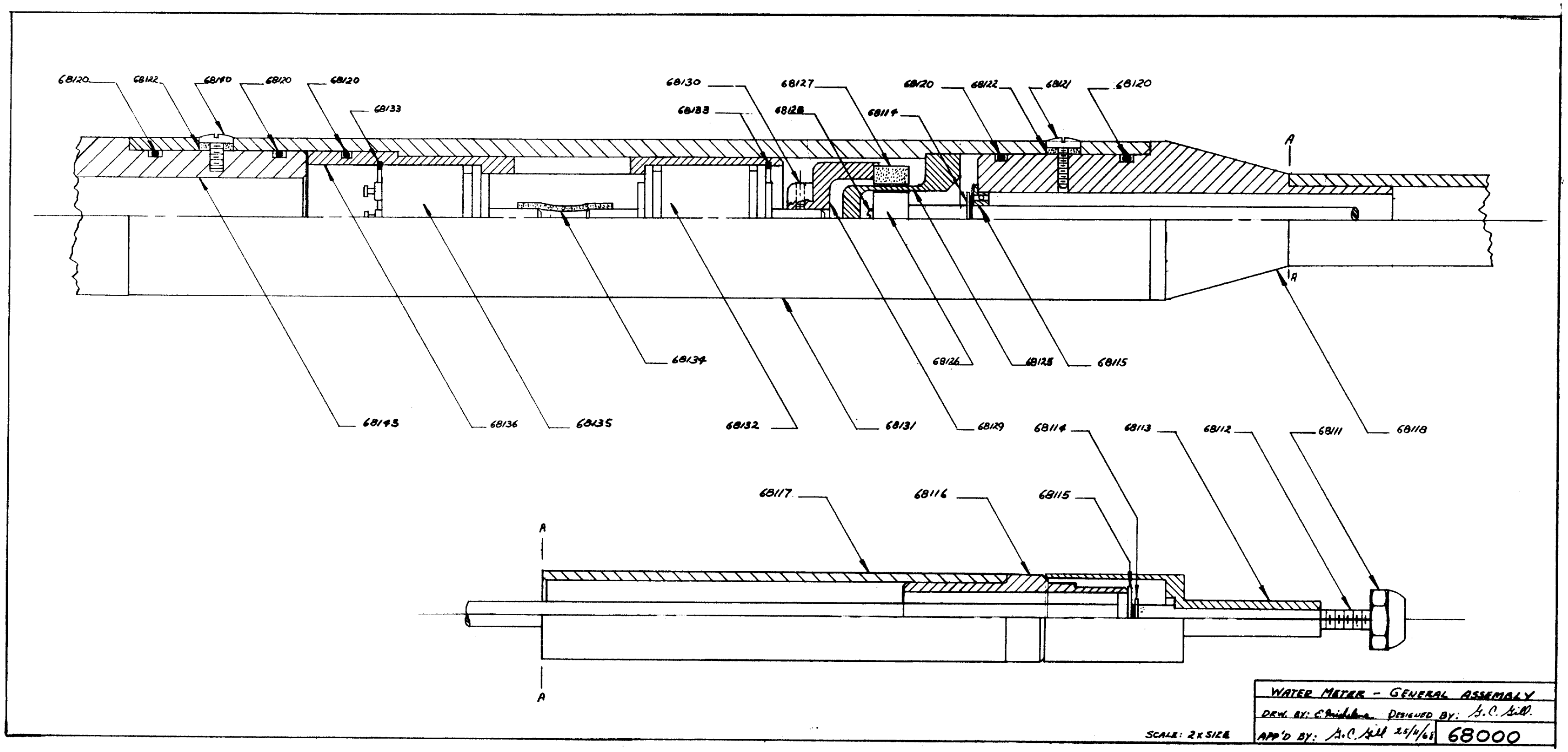


Figure 4. Sensing head of each U and V water component—cut away drawing.

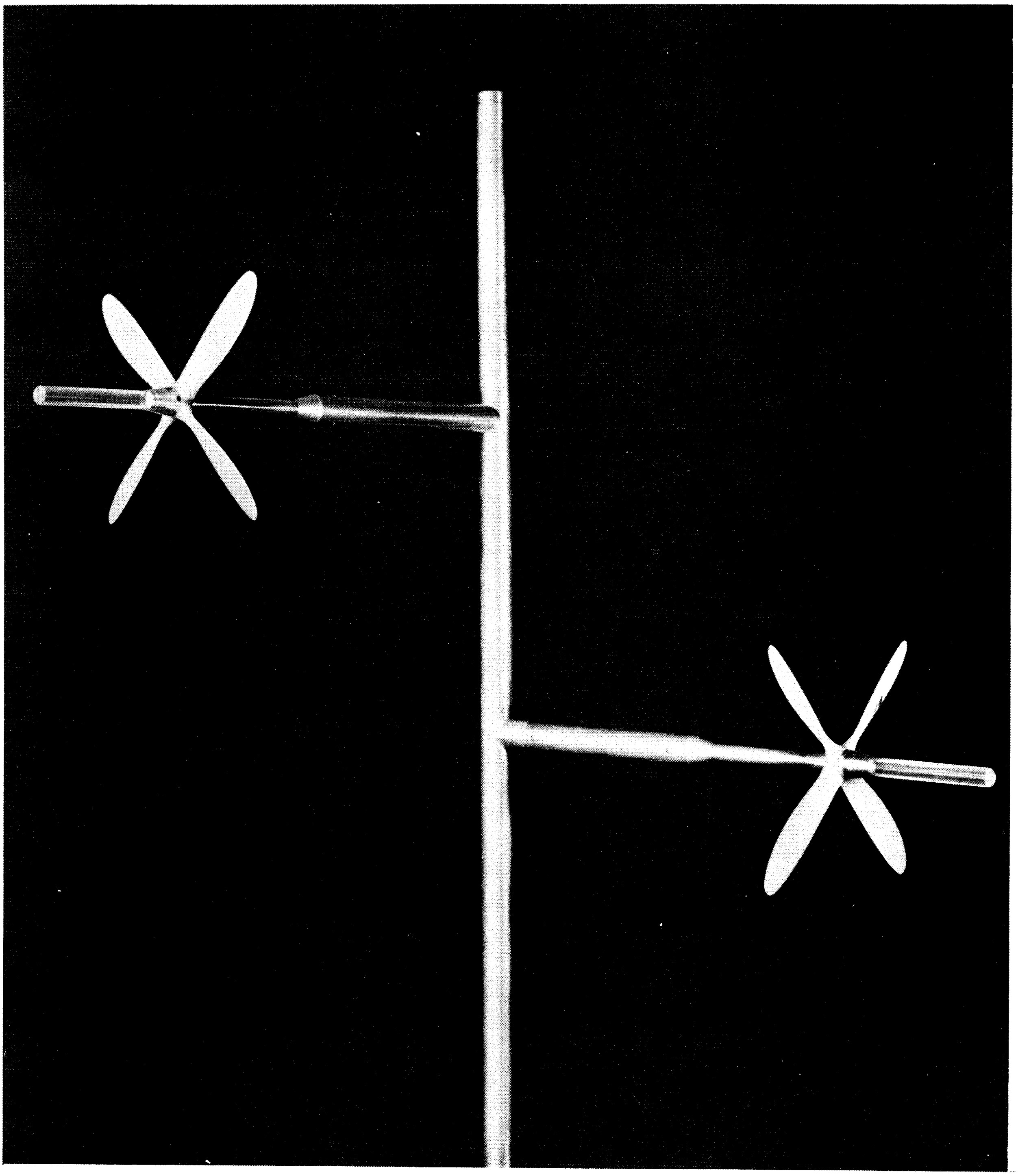


Figure 5. Four-bladed U and V sensors with hub extension and with 12-in. vertical separation of sensors.

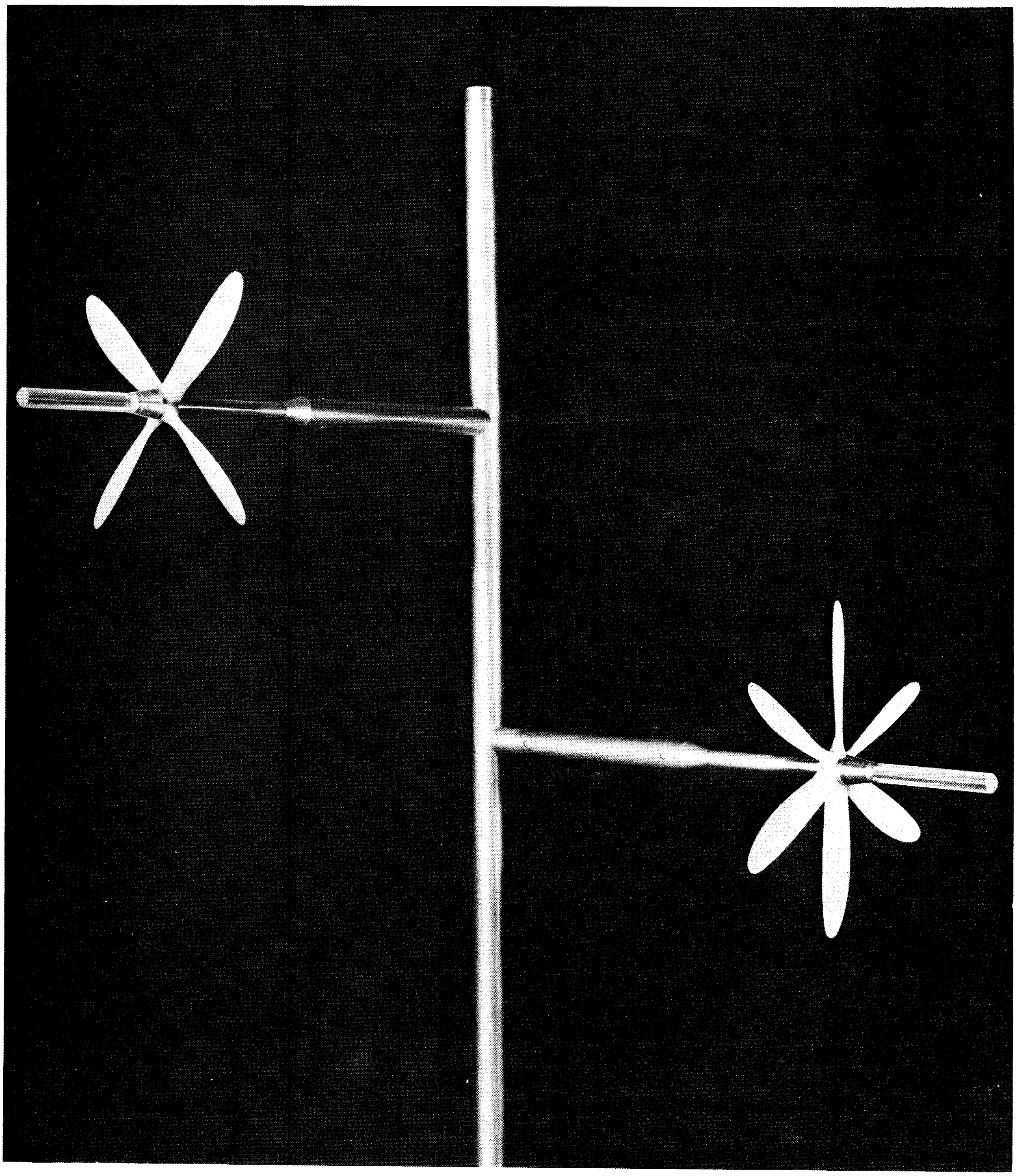
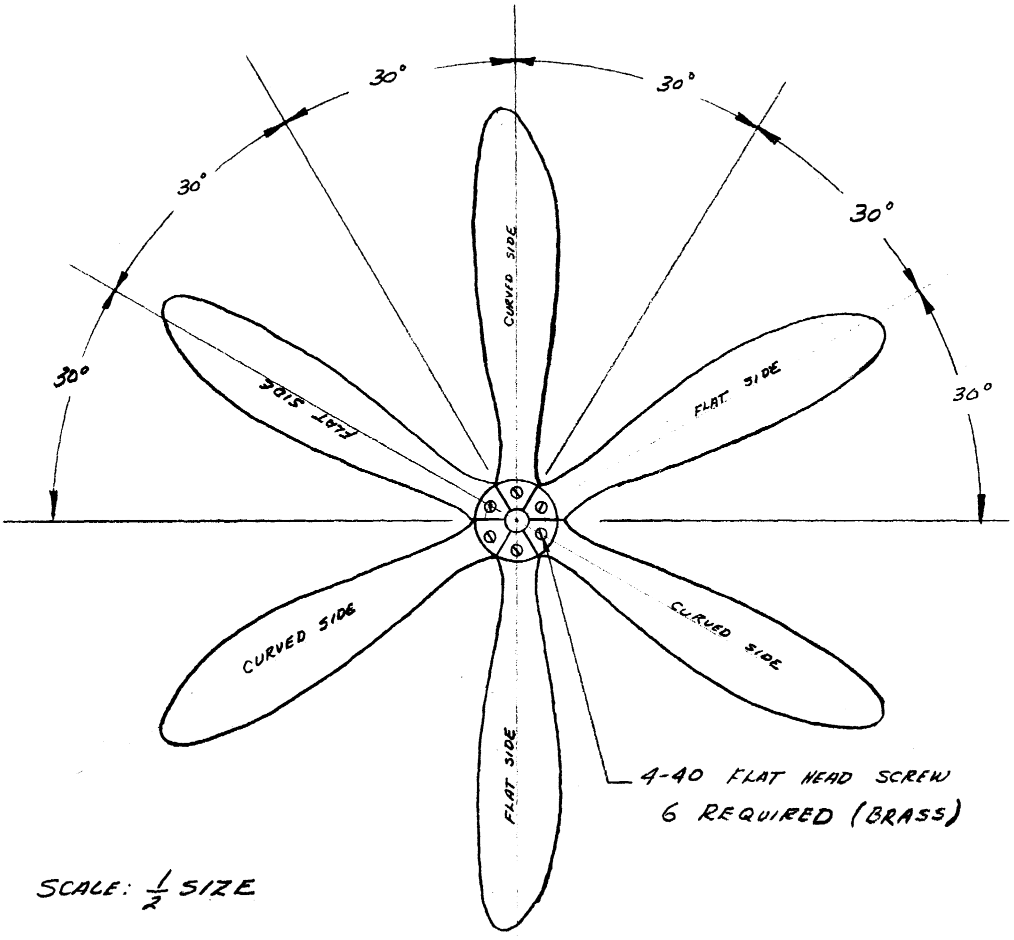


Figure 6. U and V sensors with hub extensions, one sensor with four-bladed propeller; other sensor with six-bladed propeller.



① EACH OF 6 BLADES FROM TWO BLADED FIBERGLASS PROP. FK-11-7 $\frac{3}{4}$

② ASSEMBLE BLADES WITH FLAT AND CURVED SIDES AS INDICATED TO MAINTAIN ALL AROUND SYMMETRY.

③ EPOXY BLADES TOGETHER AT HUB DURING ASSEMBLY

④ REMOVE ALL MARKINGS ON BOTH FLAT SURFACES OF PROP. HUB

Figure 7. Assembly drawing of six-bladed propeller—made from three two-bladed propellers.

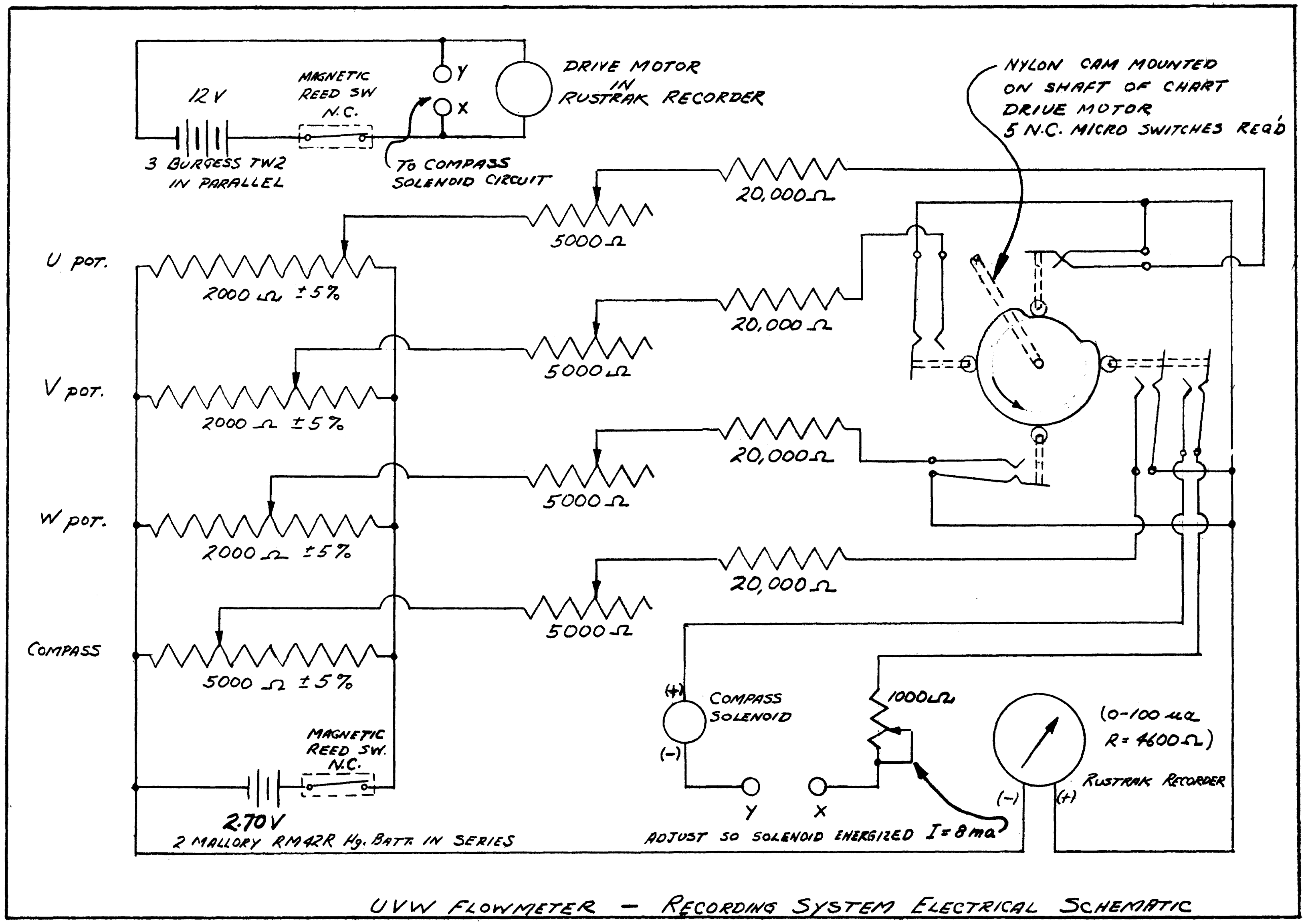


Figure 8. Wiring diagram of recording system for UV and UVW Water Meters.

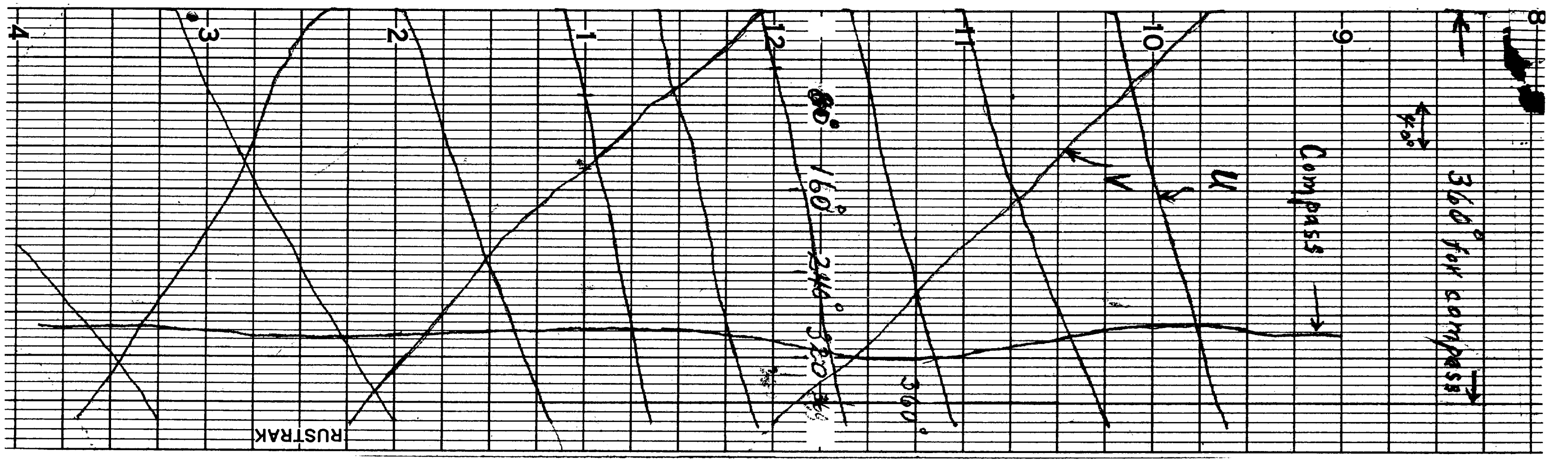


Figure 9. Mock-up of representative Rustrak record from a UV Water Meter. Each trace is shown as a solid line—actual trace would be series of dots instead, making almost an unbroken line.

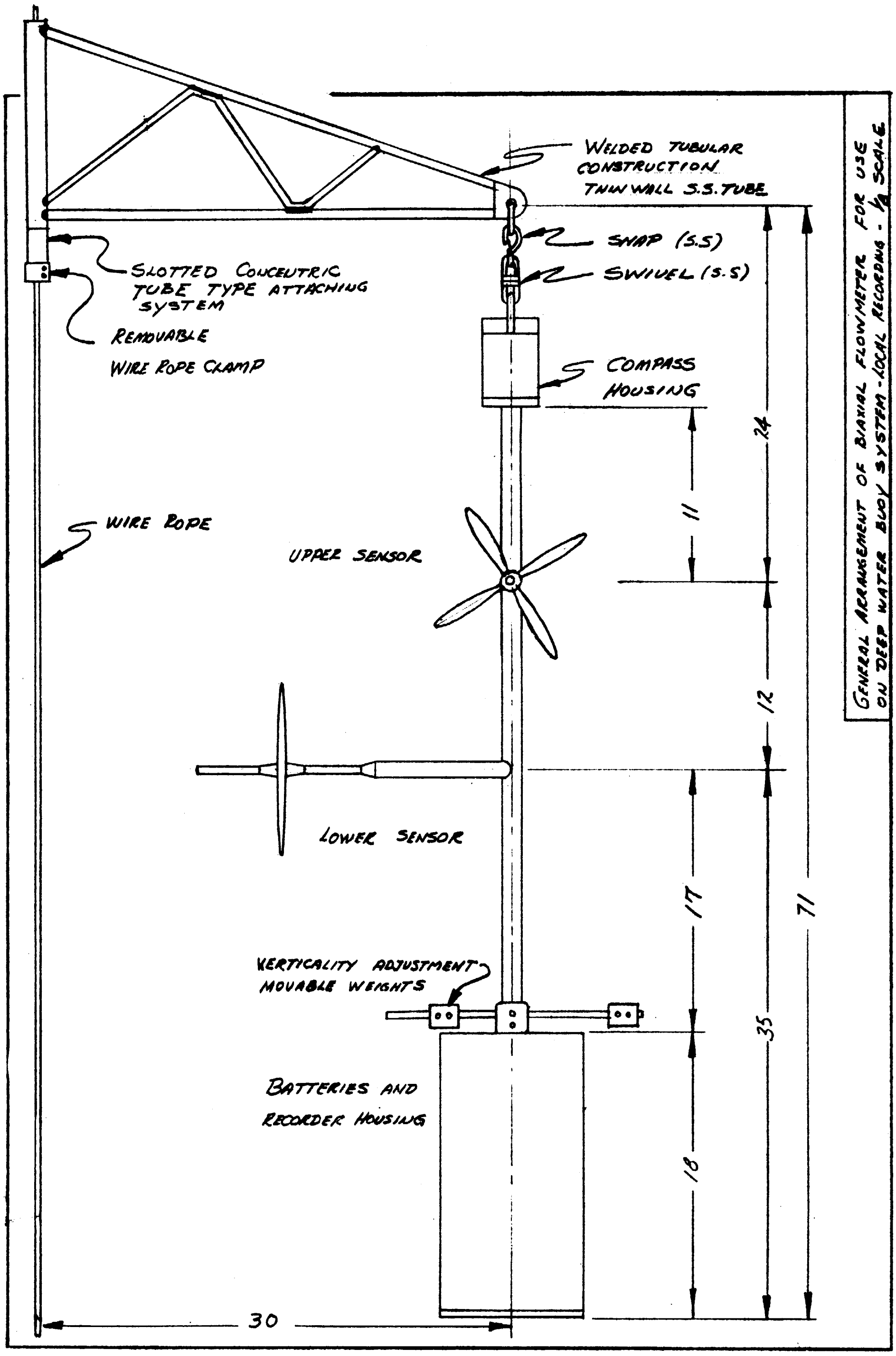


Figure 10. Complete UV Water Meter system attached to buoy cable.

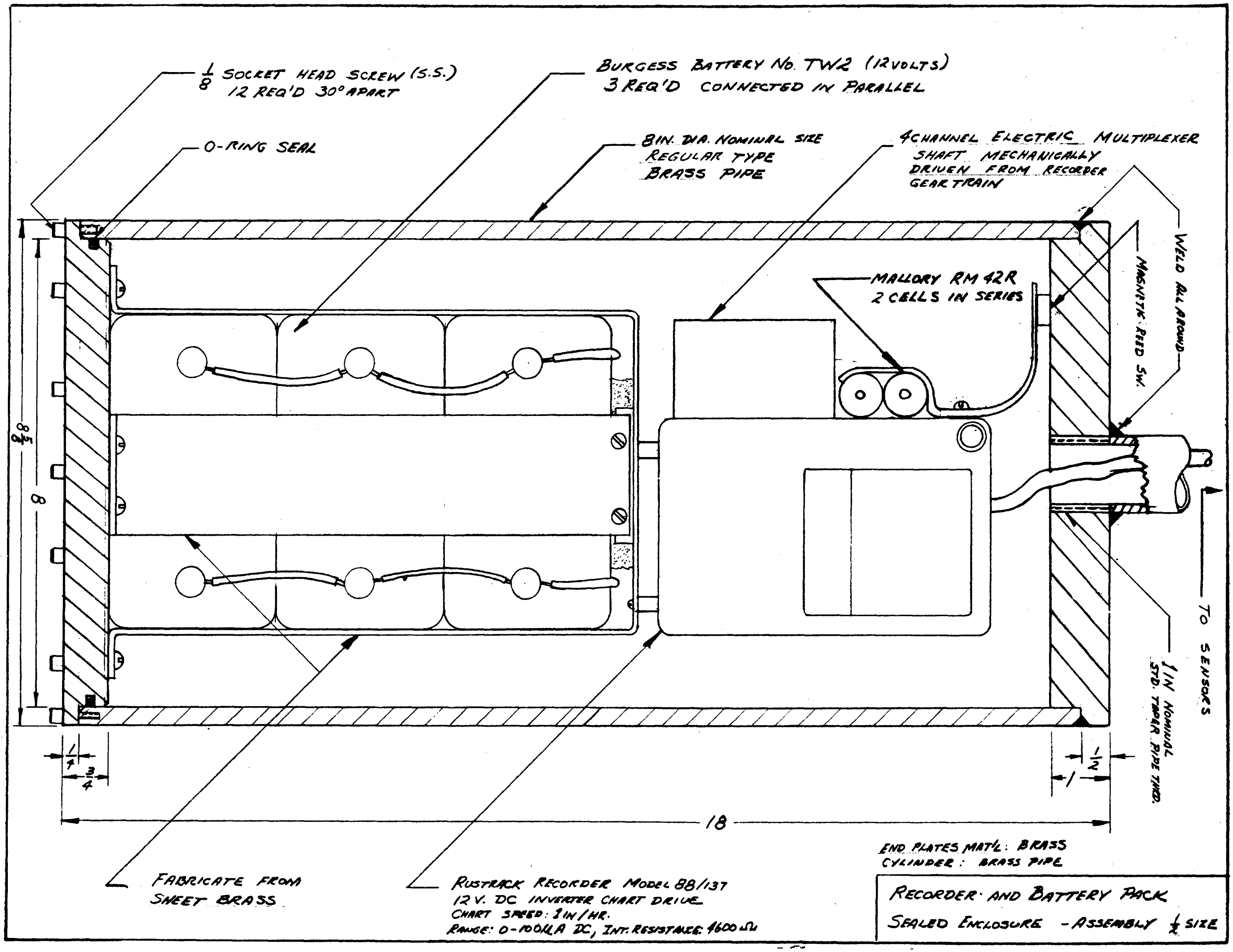
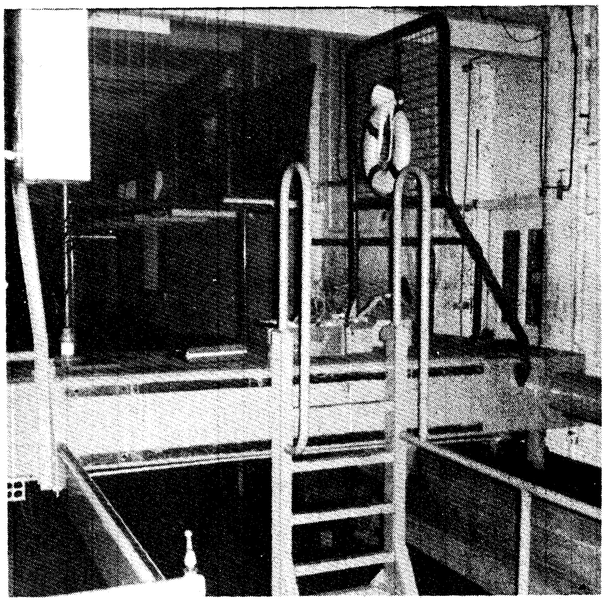
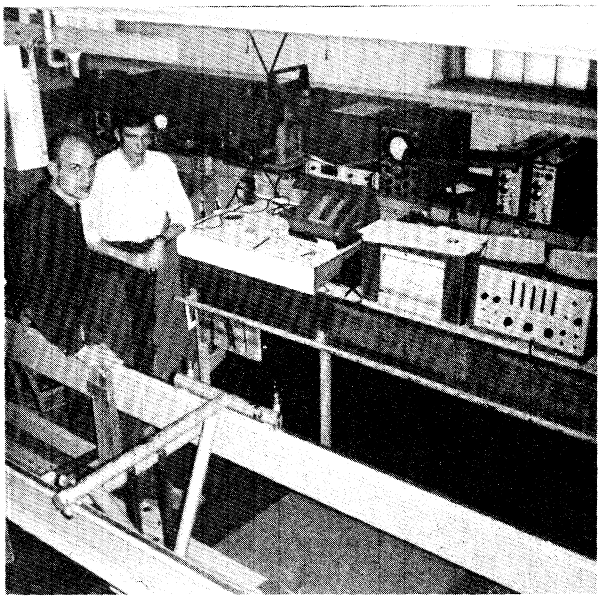


Figure 11. Recorder and battery case. Unit is water-tight when in use.

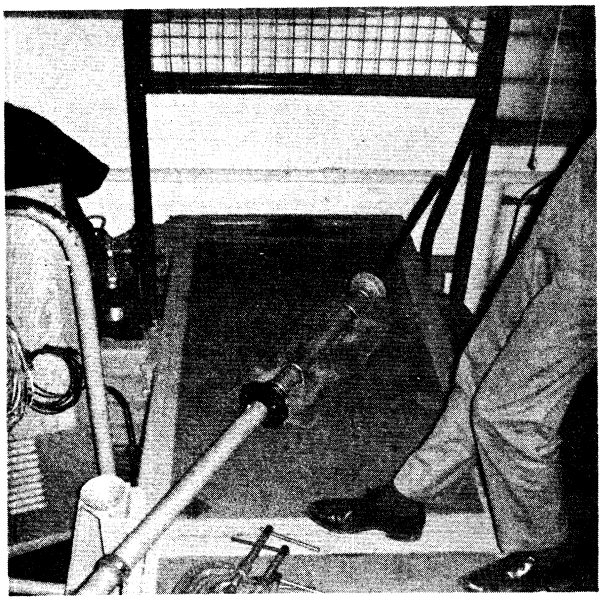


(a) Forward end of heavy carriage that moves back and forth the length of the tow tank. Ladder is attached to the strong frame of carriage and moves with it.

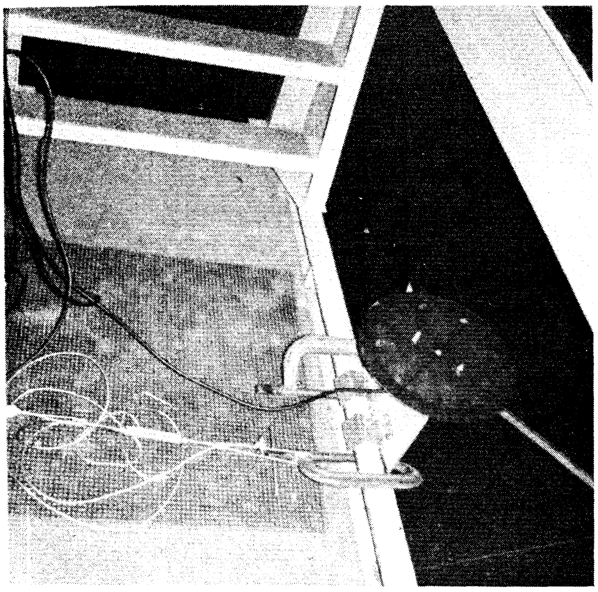


(b) Main portion of carriage with operators at left; speed measuring and control module behind them; and electronic counter and strip chart recorder for use with UV Water Meter in center right of photo. UV Water Meter bolted to floor about 6 ft ahead of operator's feet.

Figure 12. Views of tow tank carriage.



(a) Test frame (pipe with floor flanges and rectangular flat plate) for UV Water Meter lying on floor of carriage prior to lowering into water and attaching to right edge of floor.



(b) Test frame fastened to floor with large C-clamps. Frame axis vertical, with 360° protractor now bolted to upper floor flange--for use in cosine response tests.

Figure 13. Mounting of UV Water Meter test frame on floor of carriage prior to tests.

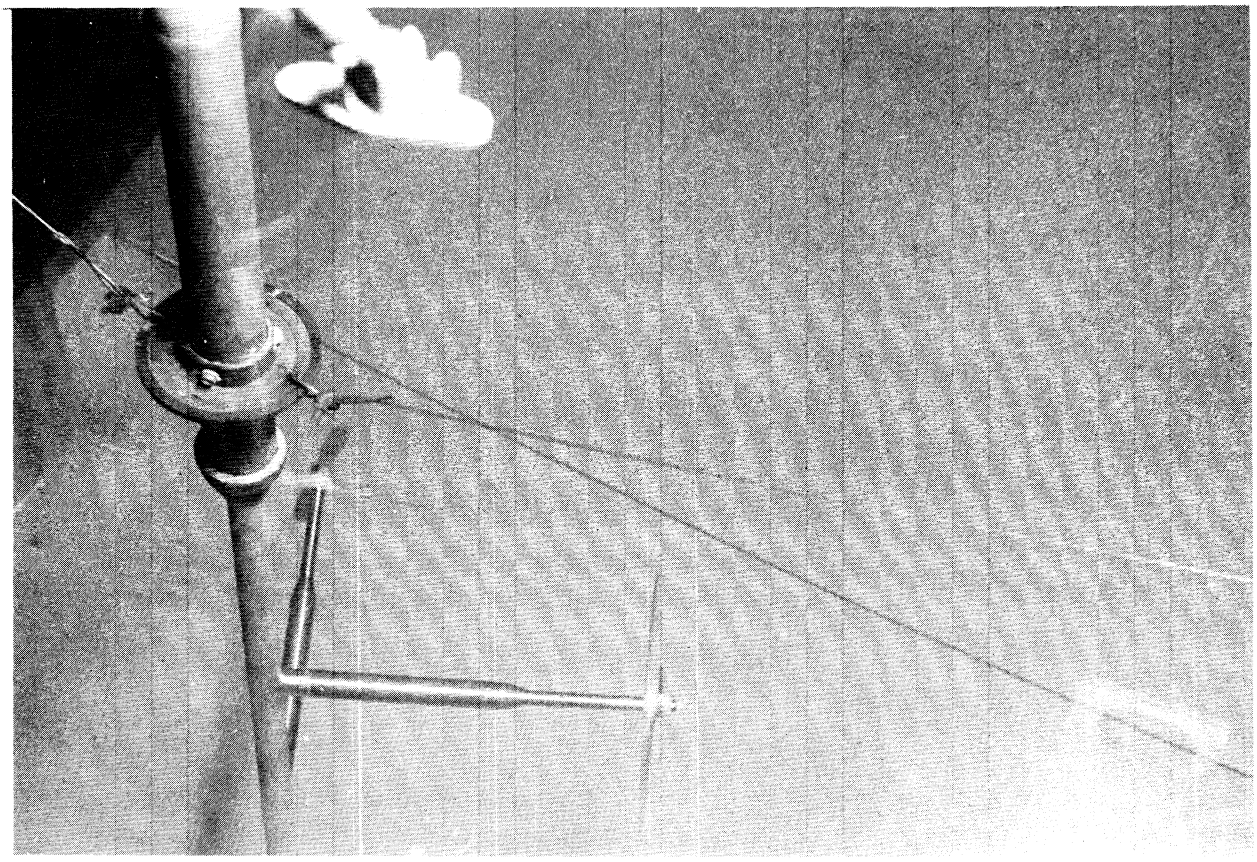


Figure 14. Upper left of photo shows lower portion of test frame with guy lines for maintaining frame in vertical position. Lower left of photo shows U and V water sensors 3 ft and 4 ft below the water surface ready for carriage movement.

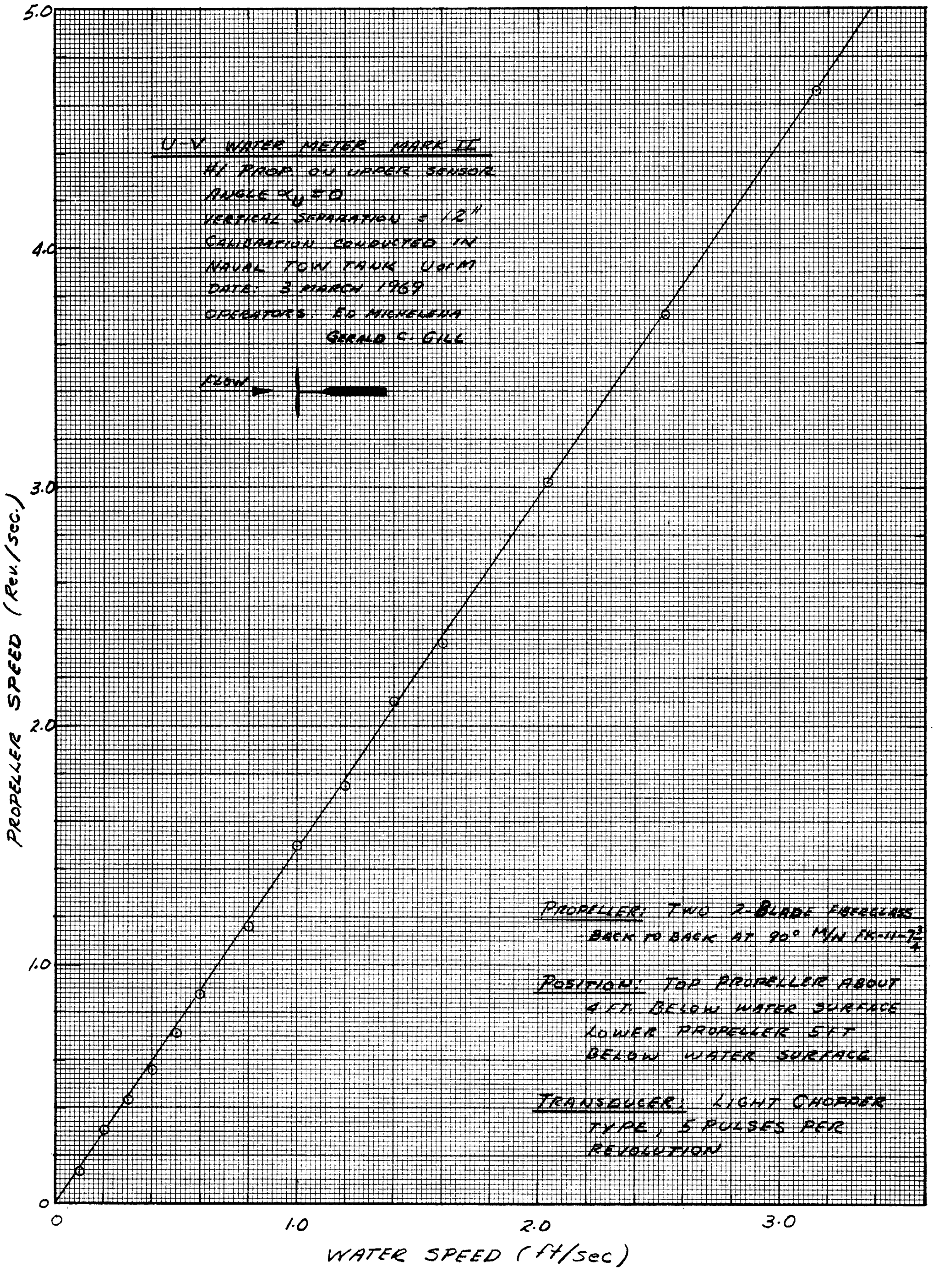


Figure 15. Speed calibration of four-bladed propeller, Prop. #1.

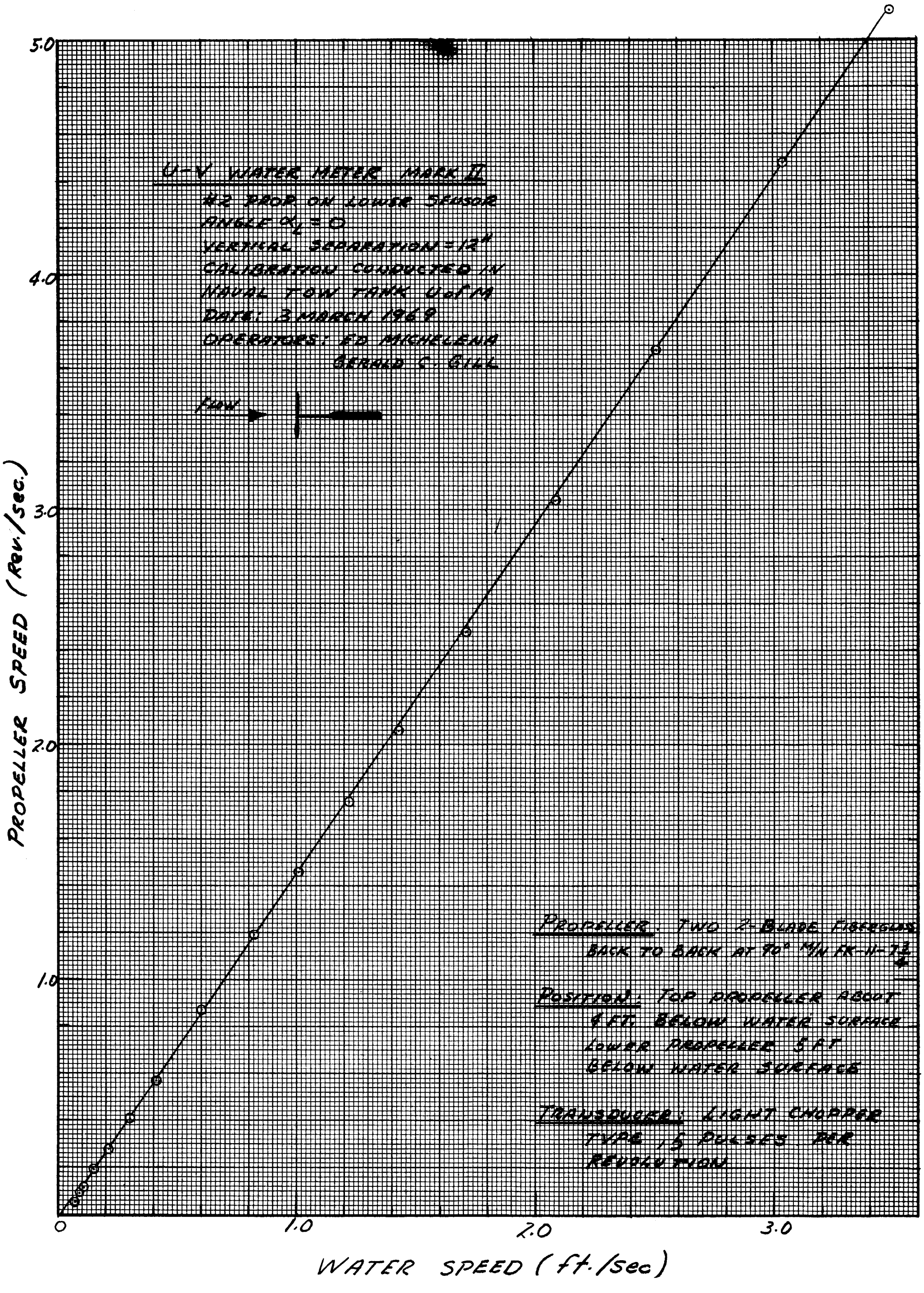


Figure 16. Speed calibration of four-bladed propeller, Prop. #2.

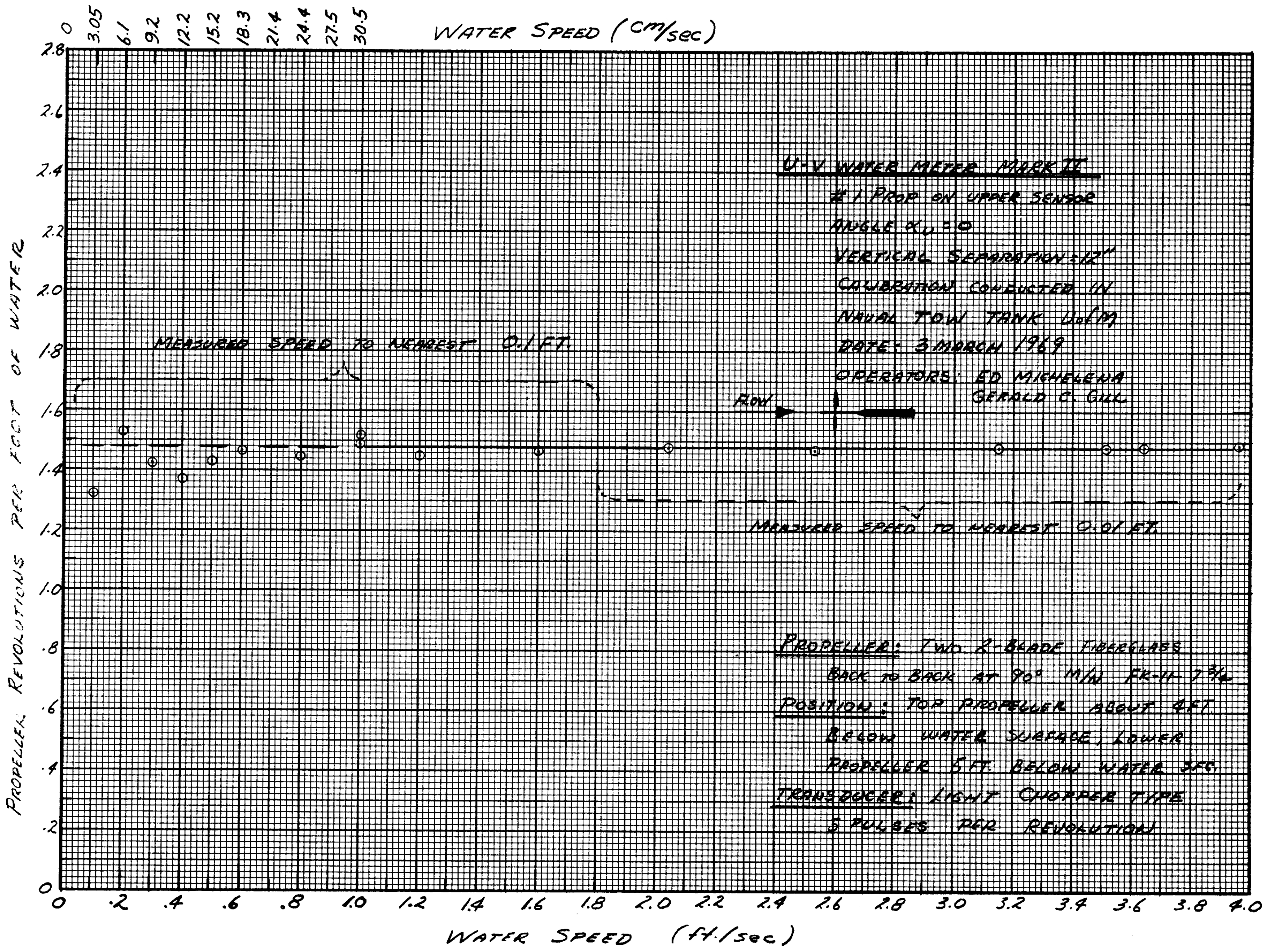


Figure 17. Determination of pitch of four-bladed propeller, Prop. #1, and its performance at water speeds below 0.5 ft/sec. No shaft extension used.

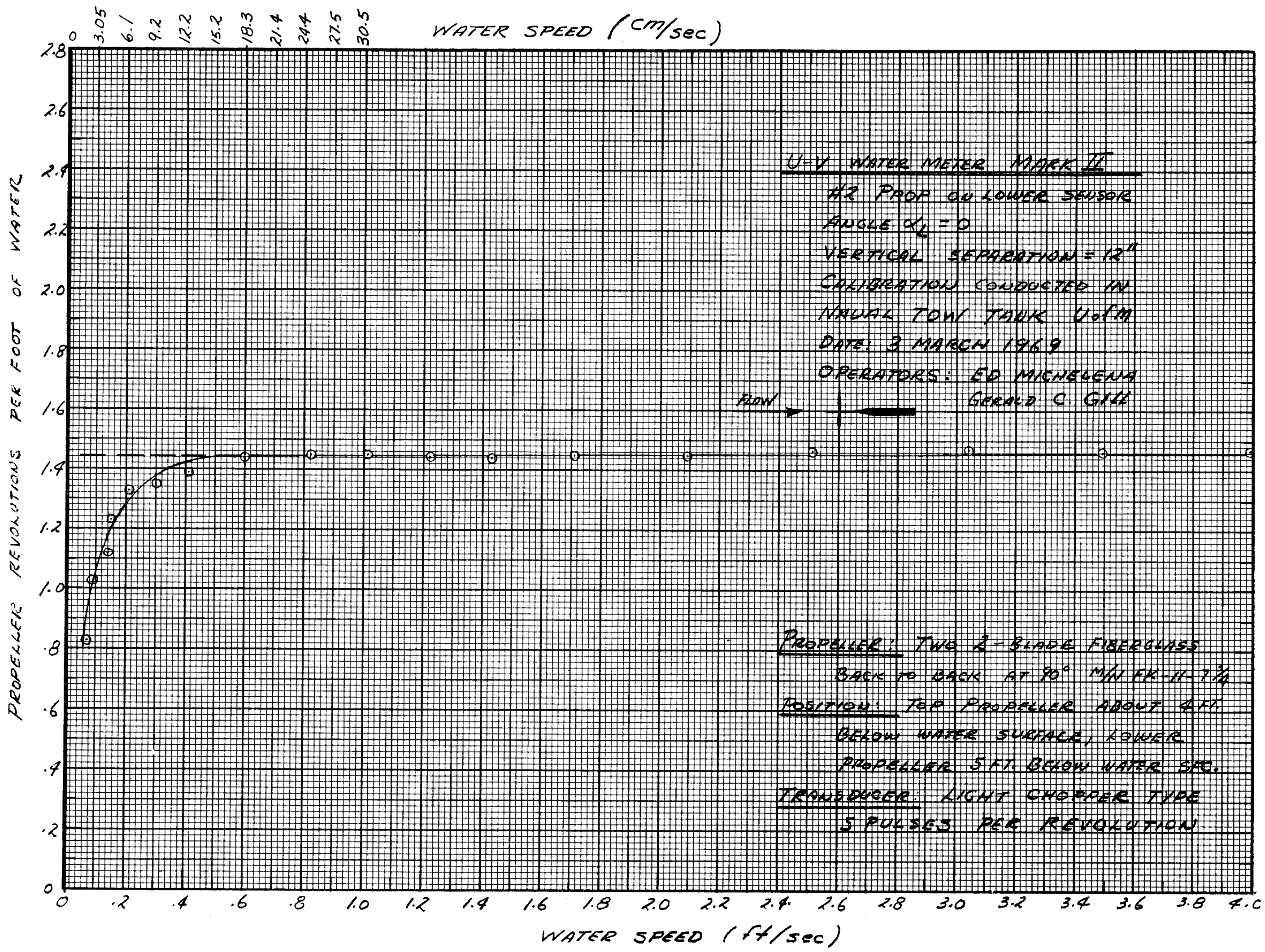


Figure 18. Determination of pitch of four-bladed propeller, Prop. #2, and its performance at water speeds below 0.5 ft/sec. No shaft extension used.

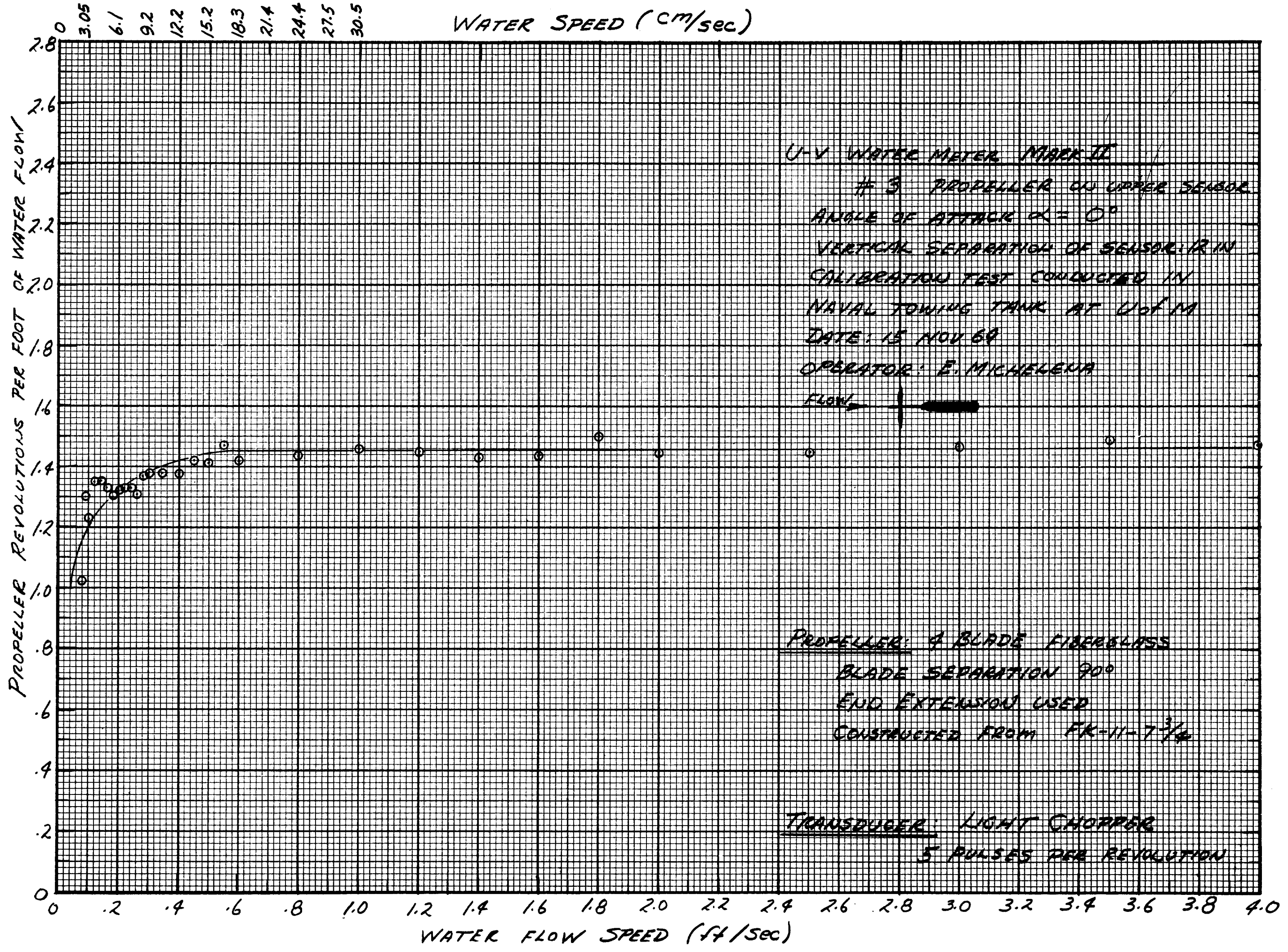


Figure 19. Determination of pitch of four-bladed propeller, Prop. #3, and its performance at water speeds below 0.5 ft/sec. Shaft extension, 5 in. in length, in use. Water flow first over sensor, thence over support structure.

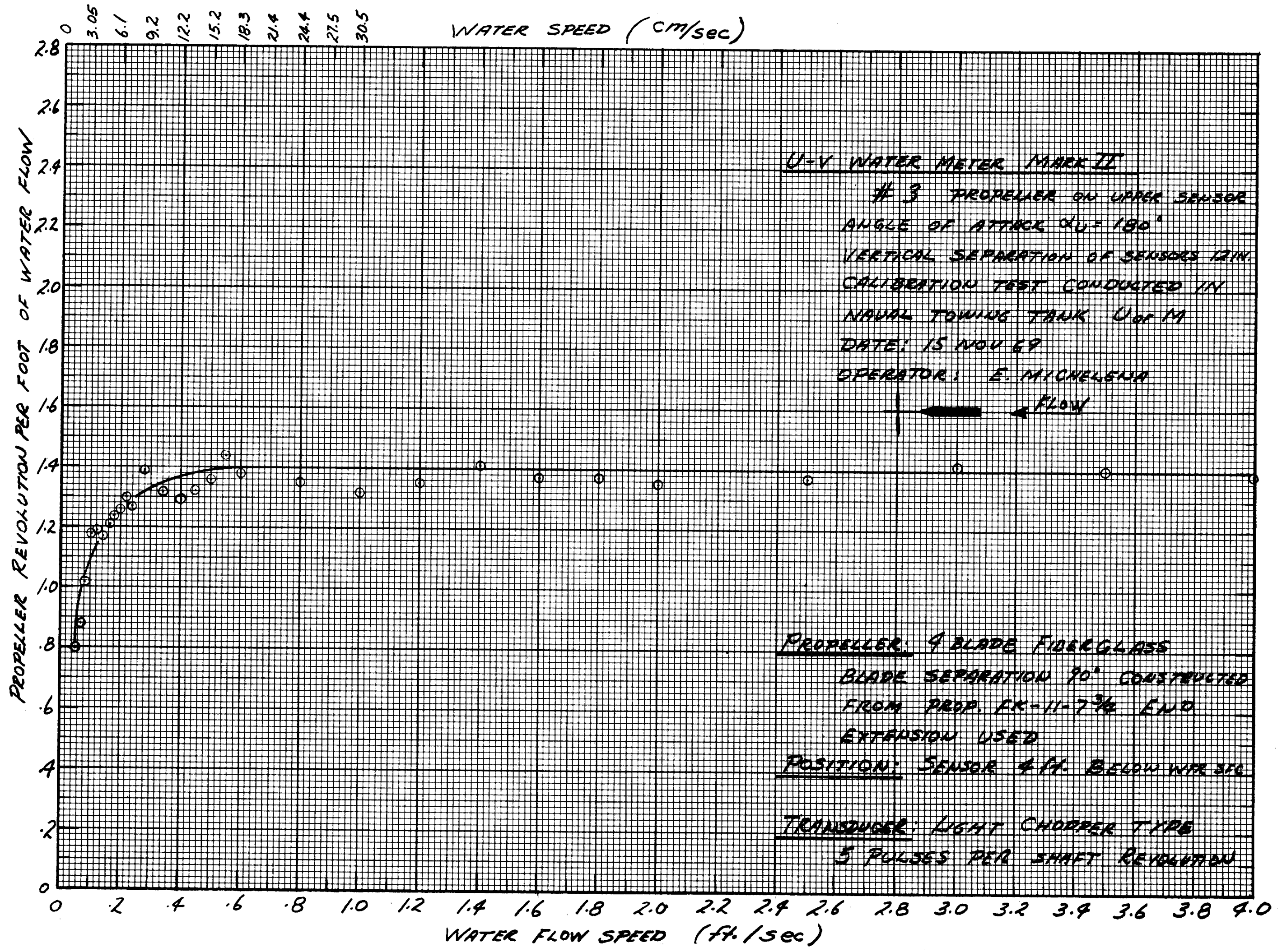


Figure 20. Repeat of test shown in Figure 19 excepting water flow reversed, that is, water flow **over** support stucture then over sensor.

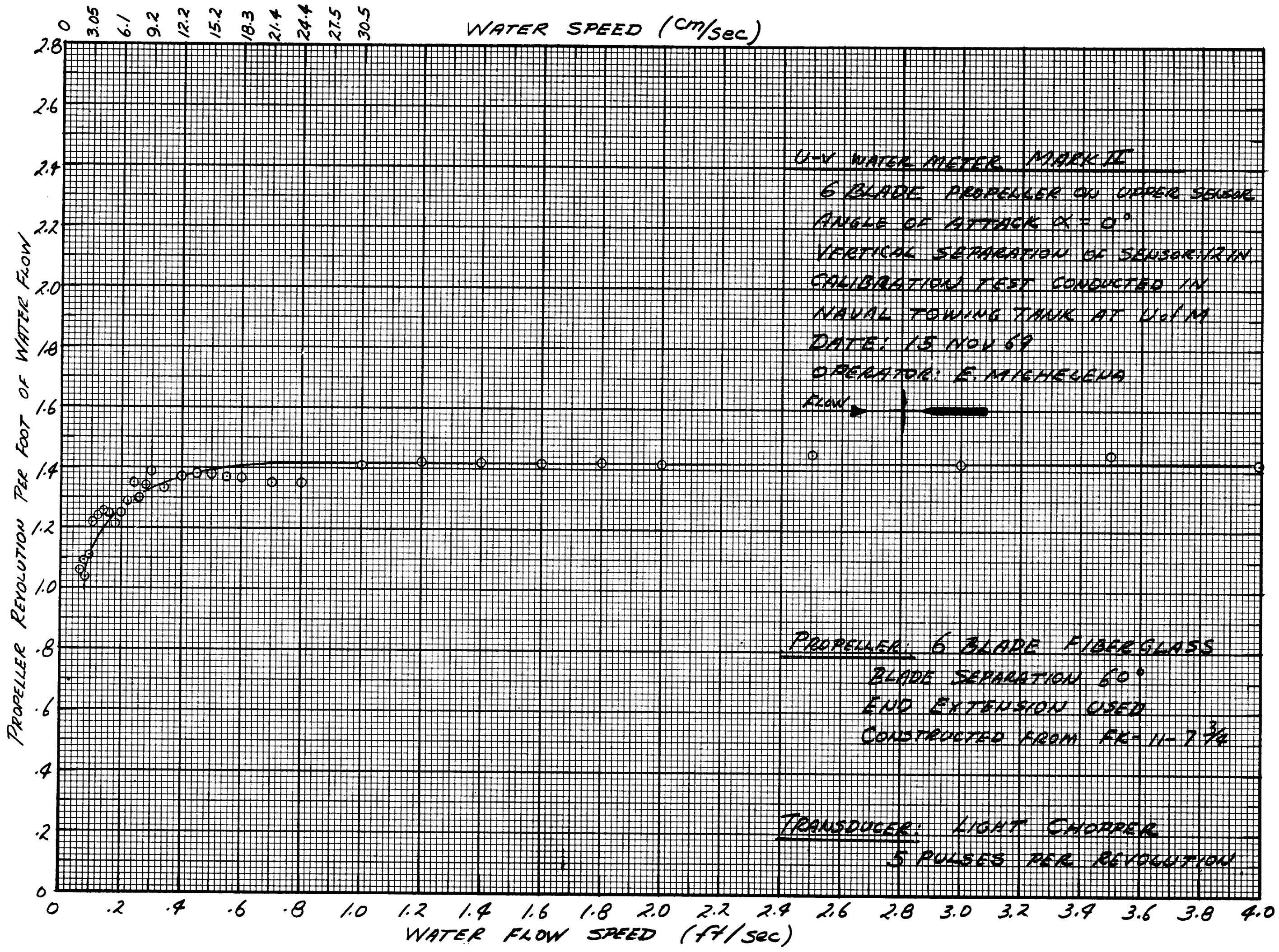


Figure 21. Determination of pitch of six-bladed propeller, and its performance at water speeds below 0.5 ft/sec. Shaft extension in use; forward water flow as in Figure 19.

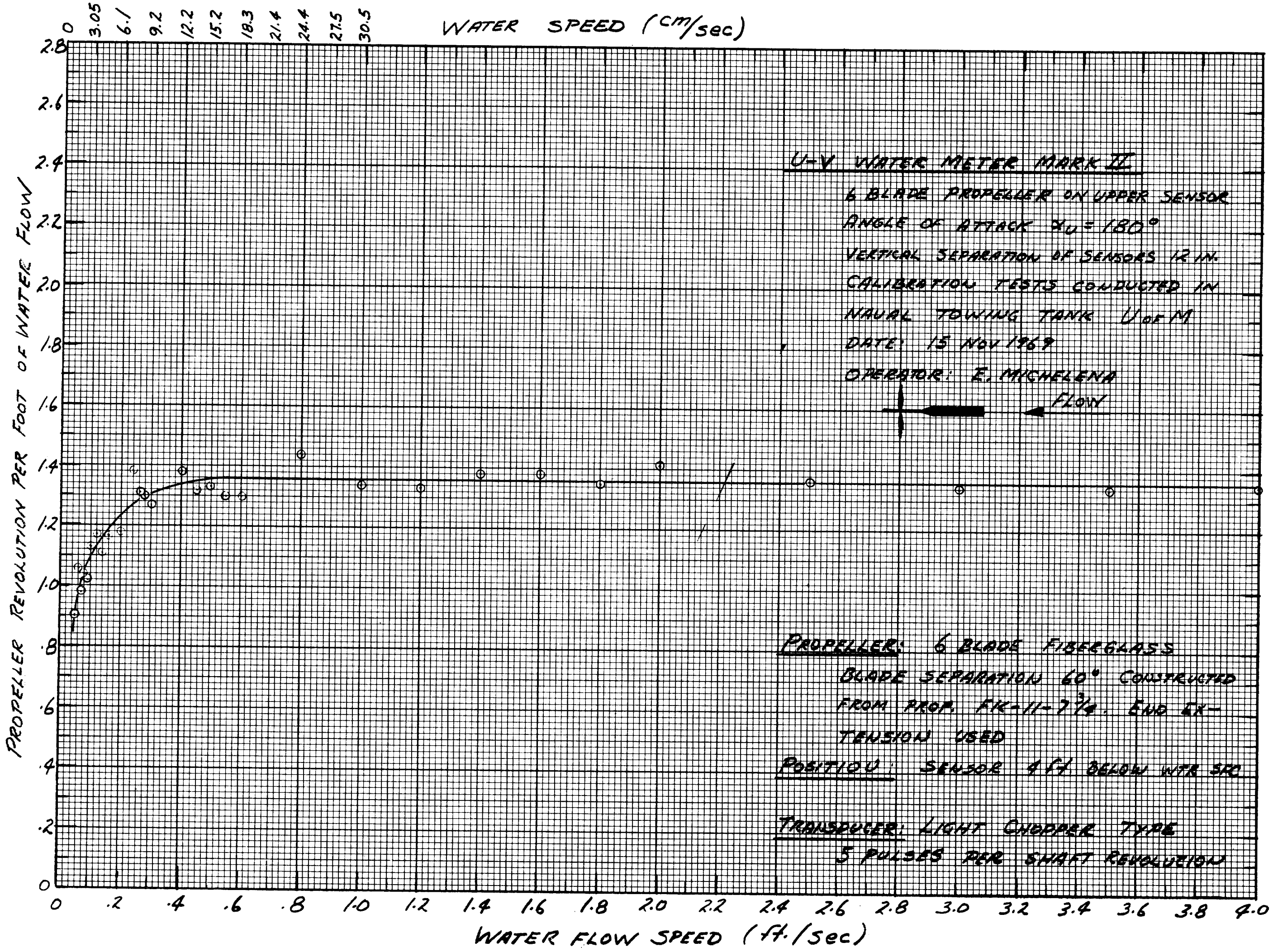


Figure 22. Repeat of test on six-bladed propeller shown in Figure 21, excepting water flow reversed.

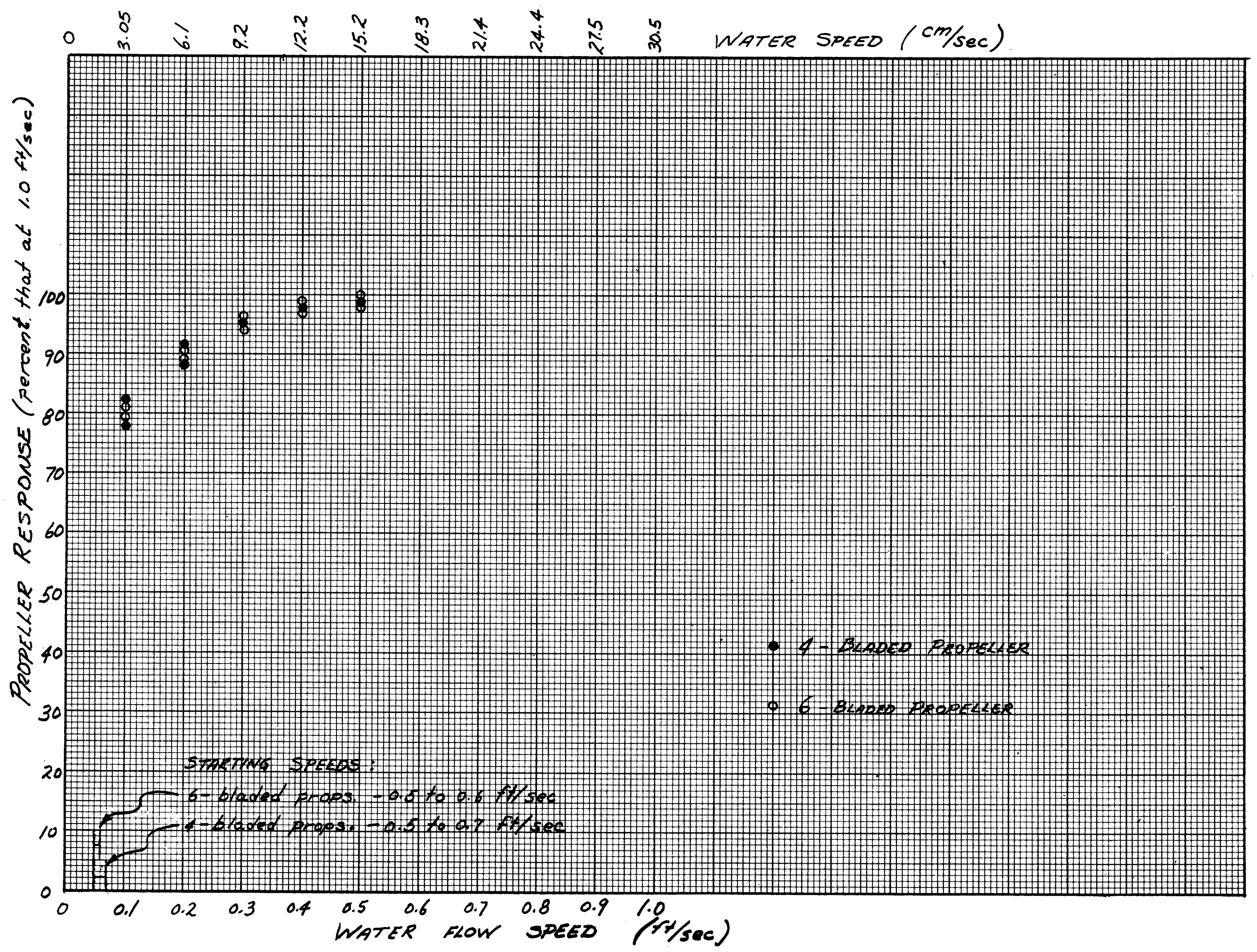


Figure 23. Comparison of starting speeds, and of low speed performance of four-bladed and six-bladed sensors.

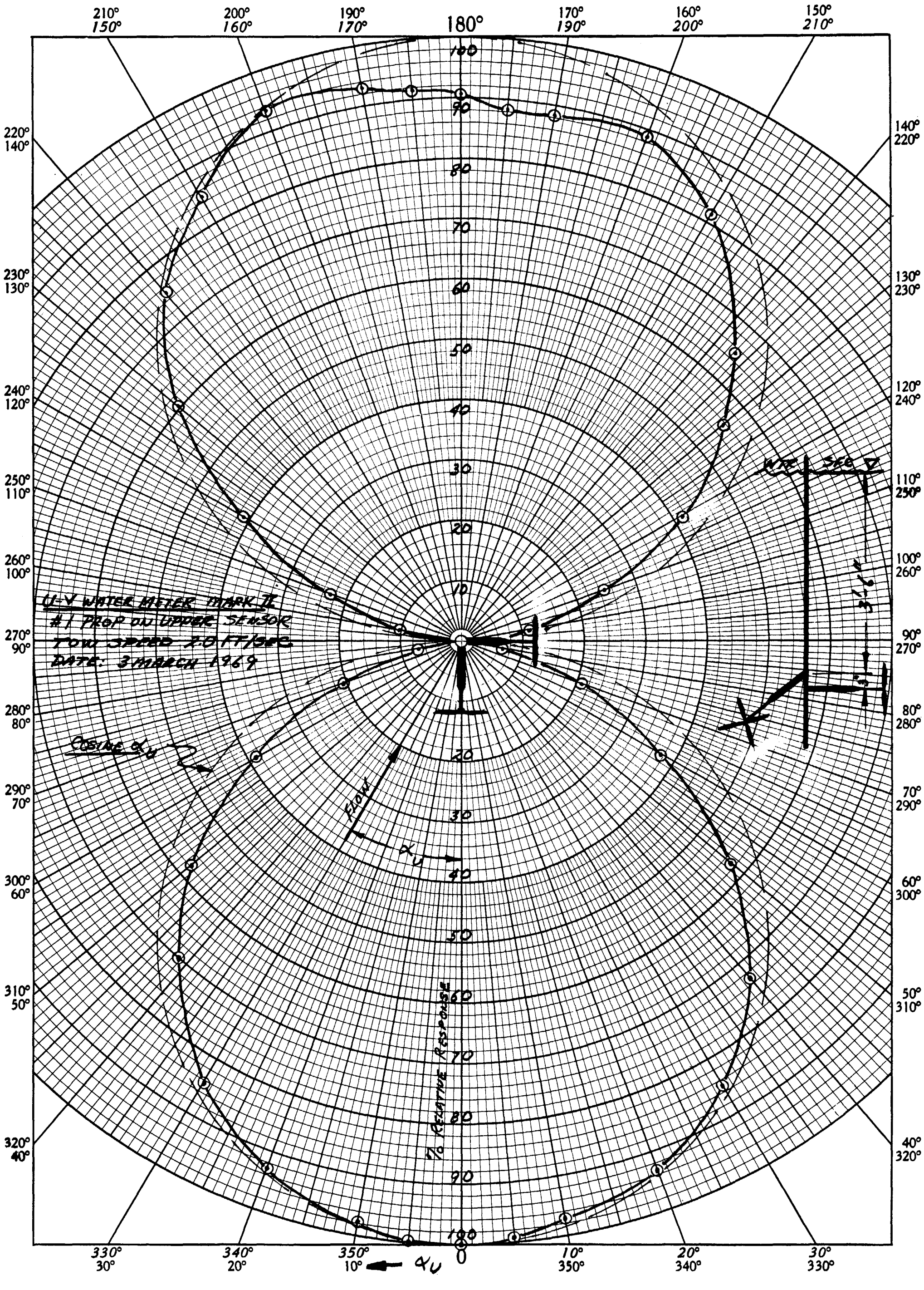


Figure 24. Response of Propeller #1 as U-component sensor as UV Water Meter rotated in 10° steps through 360°—generally referred to as "cosine response curve." Tank carriage speed of 2.00 ft sec^{-1}, vertical separation of U and V sensors, 3 in.; no propeller shaft.

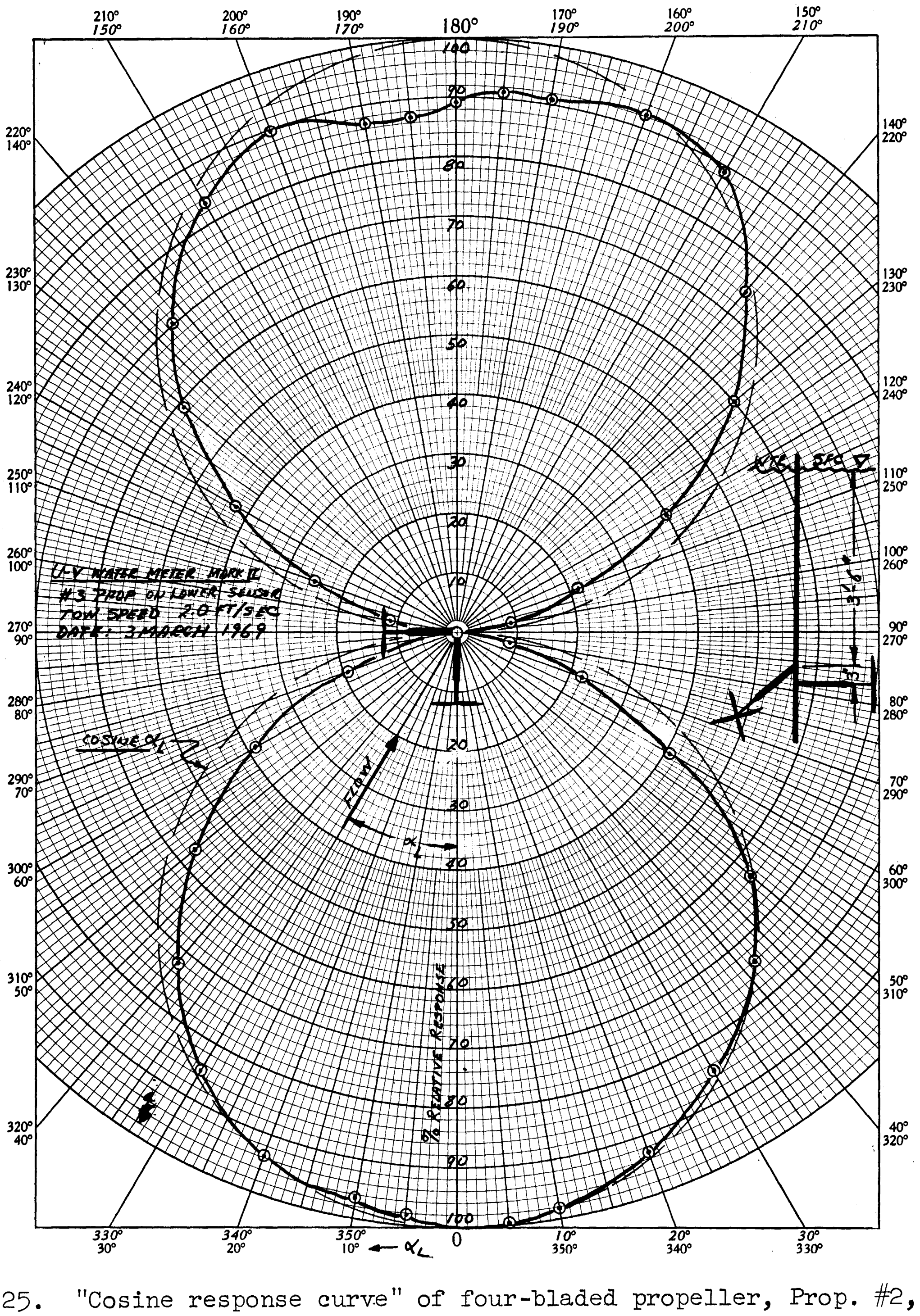


Figure 25. "Cosine response curve" of four-bladed propeller, Prop. #2, as V-component sensor; no shaft extension; 3-in. vertical separation of sensors.

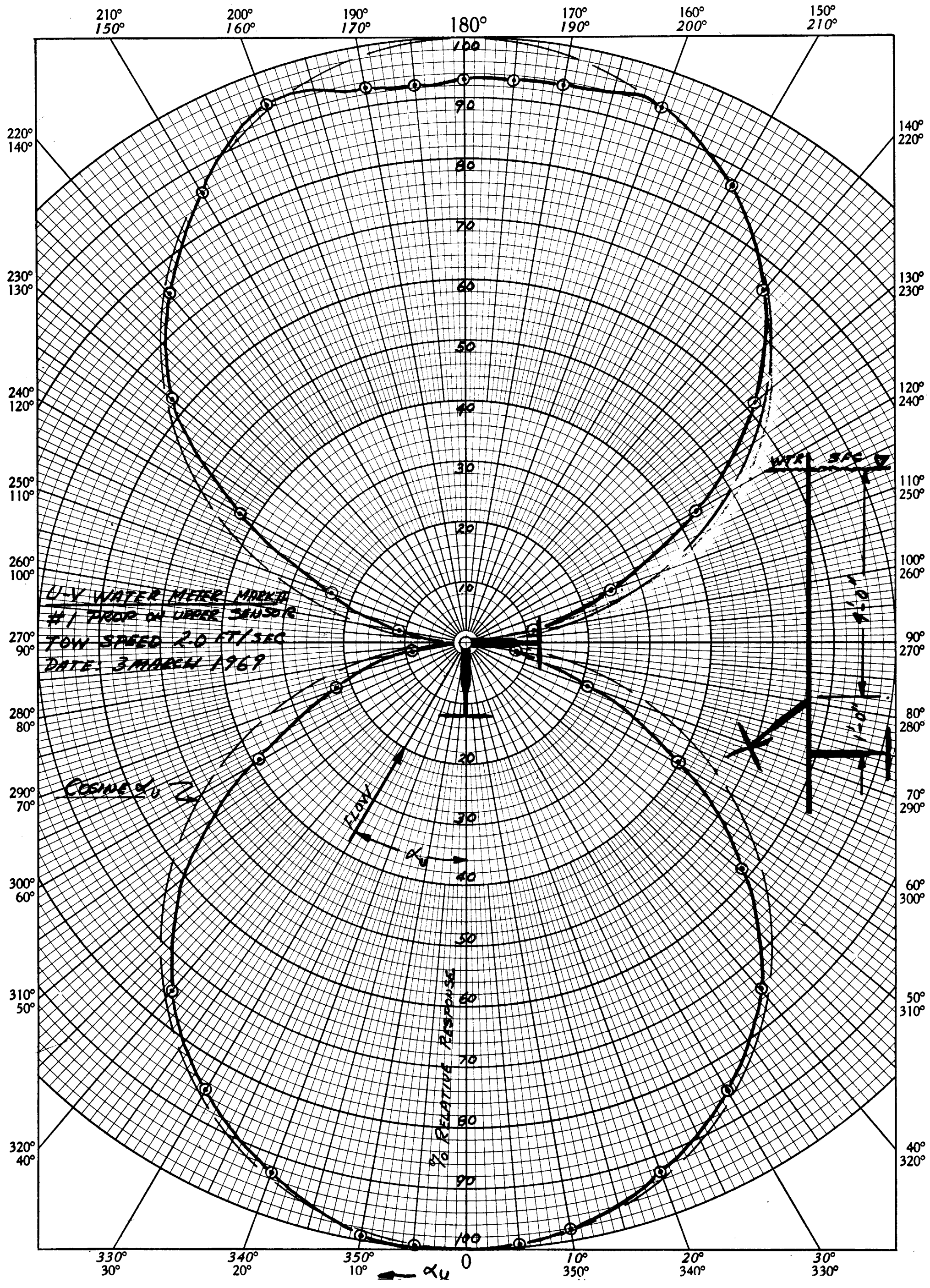


Figure 26. "Cosine response curve" of four-bladed propeller, Prop. #1, as U-component sensor; no shaft extension; 12-in. vertical separation between sensors.

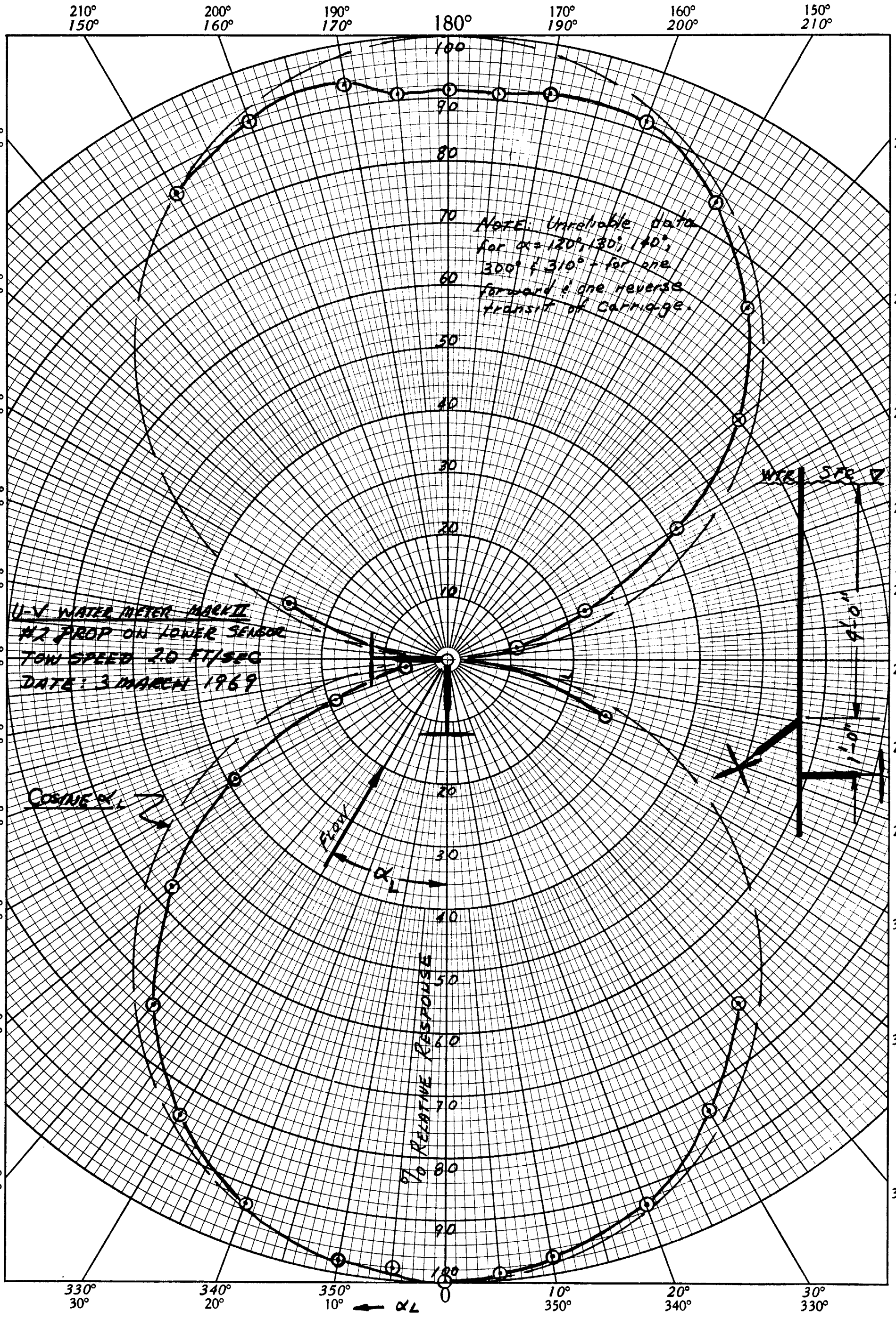


Figure 27. "Cosine response curve" of four-bladed propeller, Prop. #2, as V-component sensor; no shaft extension; 12-in. vertical separation between sensors.

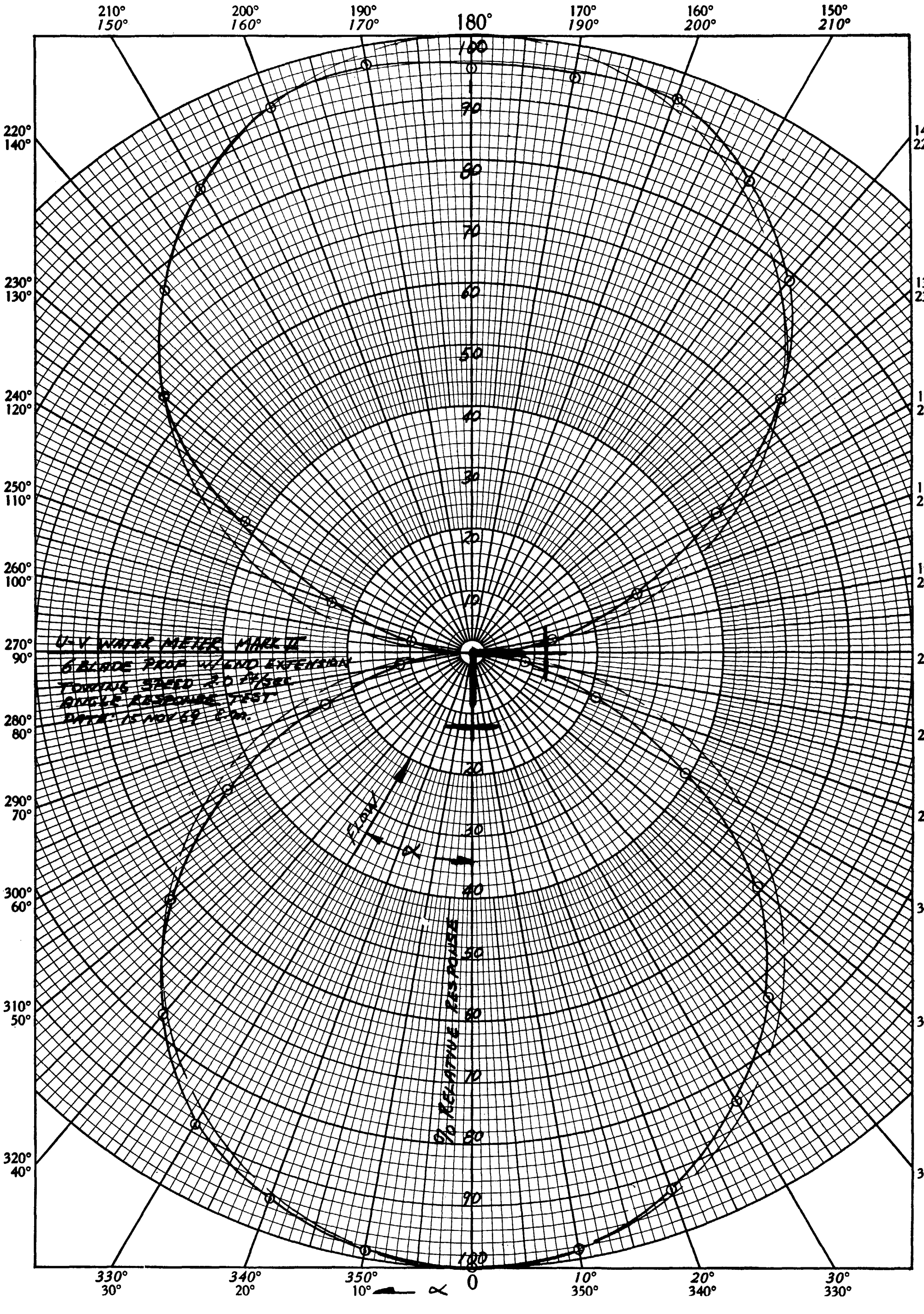


Figure 28. "Cosine response curve" of four-bladed propeller, Prop. #1, as U-component sensor; with shaft extension; 12-in. vertical separation between sensors.

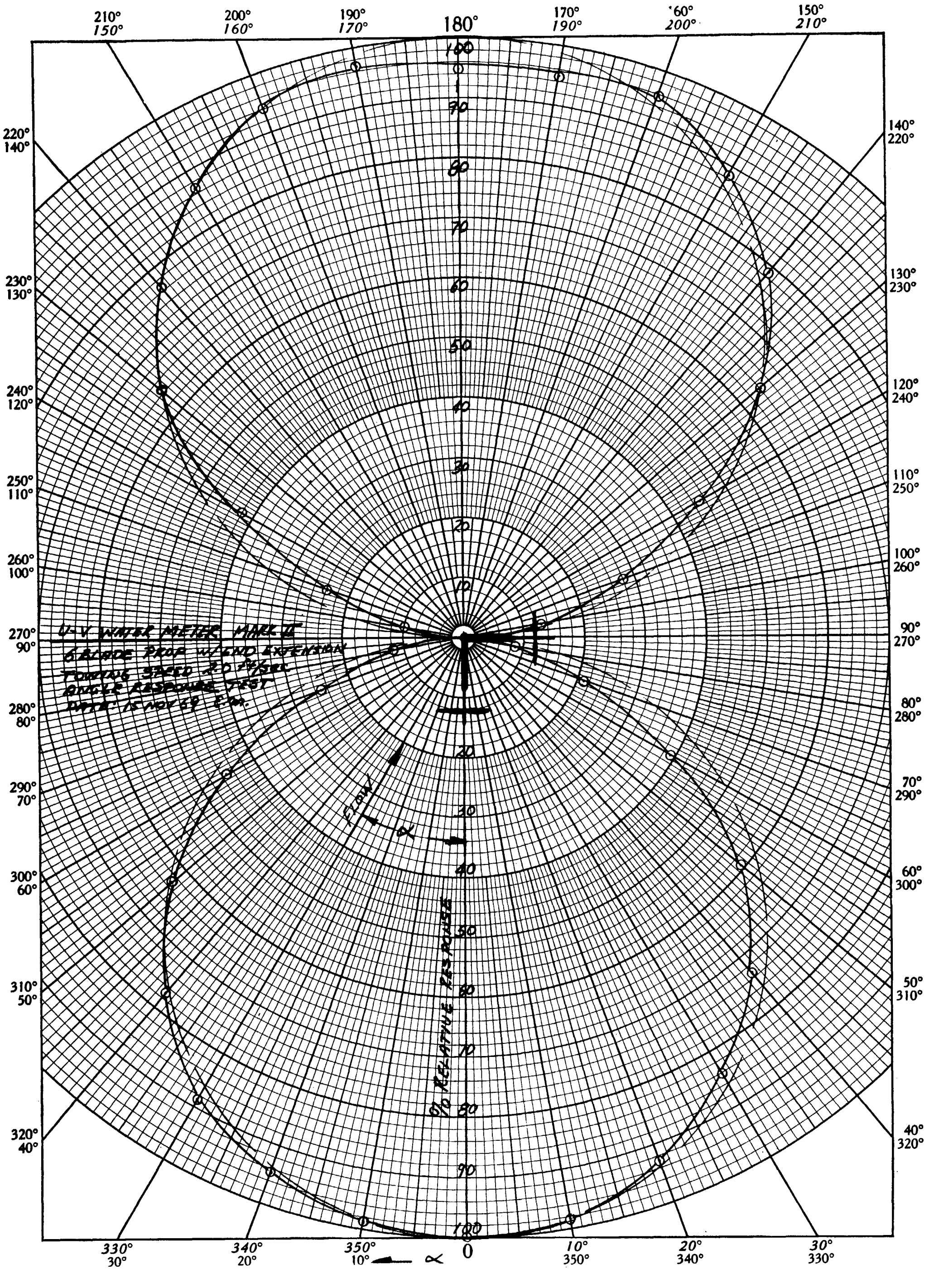


Figure 29. "Cosine response curve" of six-bladed propeller, as U- component sensor; with shaft extension; 12-in. vertical separation between sensors.