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Multidirectional Turbulence Probe Development

Phase 1: Unidirectional Turbulence Sensor Development

U.S. ENVIRONMENTAL PROTECTION AGENCY

WATER POLLUTION CONTROL RESEARCH SERIES

MULTIDIRECTIONAL TURBULENCE PROBE DEVELOPMENT

PHASE I
UNIDIRECTIONAL TURBULENCE SENSOR DEVELOPMENT

by

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for

ENVIRONMENTAL PROTECTION AGENCY

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ABSTRACT

Development of a unidirectional-turbulence probe was undertaken to investigate the feasibility of a small-diameter strain-gaged diaphragm-type pressure transducer and a self-adjusting depth compensation air reservoir for use in the follow-on development of a small (1/2-inch diameter) multidirectional-turbulence probe. A unidirectional probe has been developed which is capable of monitoring water velocities over a range of 0.5 to 5 ft/sec in turbulence frequencies of 0 to over 100 Hertz and which will automatically operate in water up to 10-feet deep.

Sealing inadequacies in both the air reservoir membrane and the pressure diaphragm permit mositure entry into the air volume covering the strain gages. This has given rise to balance drift and circuitry ground problems that have resulted in the placing of limitations on the water exposure and turbulence monitoring times for the unidirectional probe. These problems also suggested that the concepts cannot be immediately incorporated into a multidirectional probe design.

The undirectional turbulence probe was released to the Environmental Protection Agency for use and further evaluation with recommendations for analysis of data obtained with the probe. This report was submitted in fulfillment of Contract Number 14-12-827 under the sponsorship of the Environmental Protection Agency.

CONTENTS

FIGURES

SECTION I

CONCLUSIONS

1. Reliable water-velocity monitoring with the undirectional probe can be expected over a range of approximately 0.5 to 5 ft/sec. The actual output voltages, with 3 volts bridge excitation, corresponding to these velocities are approximately 0.1 to 10 millivolts, a range of 100 to 1. The device is at least partially successful. Acceptability of the threshold velocity of 0.5 ft/sec or slightly less will have to be determined by the Environmental Protection Agency.

2. Using a collapsible air-reservoir membrane for automatic-depth compensation appears to be a workable concept in itself. Modifications in the membrane's size and geometry should produce even better compensation than that found acceptable for the undirectional probe.

3. Based on the diaphragm's high natural frequency (6600 Hz) indicated by calculation, the unidirectional probe should have excellent frequency response in the relatively low range desired, i.e., 100 Hz or less.

4. A probe to be used for long periods of immersion will have to have a thicker air-reservoir membrane and possibly a thicker sensing diaphragm, therefore, both these members will have to be larger in order to maintain their response sensitivity. The twin concepts of a thin-air reservoir membrane for compensation response and a thin membrane-like diaphragm for velocity response appear, in the case of the unidirectional probe, to have a very negative effect on the water tightness of the air environment of the strain gages. Water, at least in vapor form, seems to be penetrating these two membranes causing wide drift in the zero balance of the unidirectional probe (20 to 30 millivolts with 3 volts bridge excitation) and drastically reducing the integrity of the circuitry's insulation to ground (from 33×10^6 ohms resistance to less than 200,000 ohms over three days of immersion).

5. The unidirectional probe is a useful device even with the drift and ground problems described above. The differential output of the probe with a given impinging water velocity is only slightly different (2 to 5 percent lower) with a high output balance point than with a zero voltage balance point.

6. The diaphragm and air reservoir membrane designs as embodied in the unidirectional probe are not suitable for direct incorporation into a multidirectional turbulence probe design. The problem of output drift observed with only the one diaphragm on the unidirectional probe can only be multiplied in a multidirectional probe where three or more diaphragms may be required. In the latter case corrective balancing procedures would be likely to become so ponderous as to be impractical.

SECTION II

RECOMMENDATIONS

The unidirectional probe should be used in laboratory and possible field tests both to provide further information on the functionality of the concepts involved and to generate, through use, more specific performance requirements for the probe. Specific instructions for operating the probe are provided in Appendix B. These instructions should be closely followed to avoid damage to the probe.

It is suggested that the performance of the unidirectional probe be first monitored either directly with a sensitive oscilliscope or with amplification and subsequent oscilliscope or chart recording display. With this procedure a period of familiarization will take place in which the probe's capabilities will be more clearly defined and the type of water environment to be subjected to analysis will be indicated.

As described in Appendix C, characterization of the water turbulence monitored by the probe may be best obtained by spectral density analysis. One method of obtaining such an analysis is to convert the probe's signal from analog to digital form for analysis by one of several digital computer techniques. Another method is to use Battelle's graphic level recorder and frequency analyzer which provides a quasi-rms amplitude spectrum down to about 2.5 Hz in frequency.

Two procedures can be followed to apply this analysis device to the probe's output. Battelle personnel could bring the equipment to the area where the probe is in use and perform direct spectral density analyses. Another method would be to have the probe's output amplified to a minimum-nominal voltage of 1-volt root mean square (this is a gain of 10,000 for a minimum signal of 0.1 millivolt or 0.5 ft/sec) for recording on a magnetic tape compatible with a Hewlett Packard Model 3960 tape recorder with a carrier center frequency of 27 kilohertz at 15 in/sec or 5.4 kilohertz at 3 in/sec. This tape can then be sent to Battelle's-Columbus Laboratories where its information can be processed on the graphic level frequency analyzer and/or digitized for additional processing with Battelle's autocorrelation or Fourier transform computer programs.

Following the familiarization and preliminary analysis procedures described above, a re-evaluation of the concepts employed in the unidirectional-probe design and usage should be made with the purpose of formulating the direction of further development on a multidirectional probe.

SECTION III

INTRODUCTION

As part of the mission of the Environment Protection Agency is to conduct research directed at the expansion of scientific and technical knowledge relating to pollution control, the need exists for appropriate instrumentation and analysis procedures to characterize the relationship of bacteria growth to turbulence in streams of the United States.

The overall objectives of the research reported herein are to develop a device for monitoring the magnitude and direction of three-dimensional water turbulence, under laboratory and field conditions, and to devise procedures for analyzing the data obtained by this device. Existing devices for this purpose are limited in low velocity sensitivity, which is the case with conventional diaphragm-type dynamic pressure transducers, are not suitable for the field requirements of ruggedness and resistance to fouling, a problem with hot wire anemometers, or do not facilitate highly localized three-dimensional measurements, most devices are unidirectional.

Past research at Battelle has produced significant advances in miniature diaphragm type low-pressure transducers. This type of transducer features the electronic output from strain gages mounted on the back of a diaphragm which is strained by the pressure differential to be measured. Knowledge of this art combined with the inherent fouling resistance of a diaphragm transducer suggested the development of a device featuring an array of sensitive diaphragm-type dynamic (stagnation) pressure transducers mounted on a small common housing for the purpose of measuring three-dimensional turbulence.

To obtain a multidirectional probe using the diaphragm transducer concept, a two phase development program was begun. In the first phase the problems of design, fabrication, and operation of a diaphragm transducer capable of meeting Environmental Protection Agency requirements would be investigated by developing a unidirectional probe around a single diaphragm transducer. The second phase would be the extension of the first phase experience into the design of a multidirectional device. To meet the specific needs of the Environmental Protection Agency, a number of requirements have been placed on such a device. These requirements along with certain problems related to the concept and the requirements are outlined in the following discussion. The actual developments of Phase I are described in the sections following the discussion section.

SECTION IV

DISCUSSION

Size and Turbulence

The entire housing size for the multidirectional probe has been tentatively set at 1/2-inch diameter or less. This limit arises from the need to measure what might be somewhat inaccurately called microturbulence. Turbulence or current eddies can occur on the truly microscopic scale. Since the output of the device is an integration of the dynamic pressures acting on the monitoring surface (the diaphragm), the minimum coherent eddy size that can be identified can be no less than the diaphragm diameter. The multidirectional device permits the identification of a turbulence vector, i.e., the magnitude and direction of an eddy, the size of which is limited to something greater than the total probe diameter. The problems caused by the need for a miniature device are discussed below.

Sensitivity

The most immediate requirement is sensitivity. The monitoring of average water velocities over a range of from 0.1 to 5 ft/sec is desired. In terms of equivalent stagnation pressure this range is from 0.000067 to 0.168200 psi. The low pressure is an extreme requirement for any diaphragm transducer but particularly so for one that is miniaturized. The above low pressure acting on the 1/2-inch housing cross section would only produce a force of 0.00021 ounces or 5.9×10^{-3} grams.

Frequency Response

Another requirement placed on the device is that it respond to water turbulence frequencies of at least 100 Hz. Given the requirement of small size, any resulting diaphragm automatically has a very high natural frequency (several thousand Hertz). There is, however, one liability associated with this requirement. The diaphragm must be unrestrained or undamped on the side not in contact with the turbulent water, i.e., it must be free to respond to the turbulence. To allow this response then, the back of the diaphragm must be exposed to a relatively low viscosity environment such as air. This necessity has one advantage in that air is highly desirable as a medium in which the strain gages are to function.

Static Pressure Compensation

Since the diaphragm is to respond, that is deflect, in proportion to the fluctuating pressure of water impinging on its outside surface, some relatively stable or known reference pressure must be maintained on its back side. A sealed fixed volume of air behind the diaphragm would essentially provide such a reference pressure but there are two negative features borne with this practice. The probe is to operate in water depths up to 100 feet. At any given depth the diaphragm, with a fixed air pressure on its backside, would deflect under the static water pressure in addition to the dynamic pressure. This static pressure could be subtracted from all readings but this would be cumbersome. However, the main drawback with a fixed backside pressure system is that a low-pressure sensing diaphragm is not strong enough to withstand a static-pressure differential of more than a foot or so of water. Therefore, it is imperative that the air pressure on the backside of the diaphragm be within approximately 0.5 psi of the static water pressure outside the diaphragm, which at the 100-foot depth in water is approximately 43.3 psi.

Readout and Analysis

For the device to be of use, a means for monitoring, interpreting, and analyzing its electronic output signals must be provided. The main problem in monitoring the signals is the detection of those weak signals produced by low-water velocities. There are practical limits to the minimum signal that can be discerned by conventional electronic equipment.

Given sufficient strength so as to be readable, the output signals may have to be interpreted (processed) in preparation for analysis. The electronic output from the diaphragm strain gages is in direct proportion to the stagnation pressure which is a square function of the actual water velocity. To obtain a direct indication of the water velocity impinging on a diaphragm, the magnitude of the output signal must be reduced to its square root. However, since a function of the velocity squared is required for one type of turbulence analysis (power spectral density) the probe's signal may be used directly.

Two different methods of calibration and signal processing can be employed for the multi-directional probe. The simpler method would be to interrogate and calibrate the particular sensing diaphragm(s) associated with each primary axis on an axis-by-axis basis. With this type of calibration, the device would be used in a passive manner with signal information being processed in an after-the-fact program. A much more sophisticated approach would be to electronically process the signals from all the diaphragms on a real time basis. The resulting signal from the electronic logic unit would be the velocity, in terms of magnitude and direction of the water impinging on the whole probe. Such an electronic package would undoubtedly be complex in conception, fabrication and calibration, but it would permit better control of a laboratory setup and might be amenable to a more direct analysis procedure.

The type of analysis applied to the velocity data will evolve with usage. For preliminary analyses, random phenomena characterization techniques would best be used. These are described in Appendix C. These results coupled with specific Environmental Protection Agency experimental requirements will dictate the required analysis techniques and hardware.

Summary

The environmental and performance criteria require the use of a small-diameter, thin, strain-gaged, diaphragm-type, differential pressure transducer(s).

An air environment is required behind the diaphragm(s) to promote its frequency response.

The air pressure behind the diaphragm must be close to the ambient water pressure at operational depths in order to prevent diaphragm collapse.

A self-pressure adjusting air volume would be greatly preferrable to one that requires external measurement and adjustment control.

Electronic instrumentation, calibration procedure, and analytical methods must be developed to permit meaningful monitoring and subsequent characterization of the water turbulence.

SECTION V

DEVELOPMENT PHASE I

Since many of the technical problems are initially encountered in the small, depth compensated, pressure-sensing diaphragm concept, it was decided to devote an initial phase in the probe's development to the proving out of the critical points contained in this design concept. This portion of the development was designated Phase I. Development within Phase I would center around the design, fabrication, and testing of a unidirectional turbulence probe containing one diaphragm. The performance objectives and specifications for this probe are:

1. A 3/8-inch maximum-housing diameter with a removable orifice tip
2. Detect water velocities within the range of .1 to 5 ft/sec
3. Have a frequency response of up to 100 Hz
4. Operate in water depths up to 10 feet
5. Evaluate the system for application to a multi-directional probe

To meet the requirements placed on either the multidirectional or uni-directional probe, significant departures from existing diaphragm design and manufacturing practices must be undertaken. These departures can only be guided by approximating engineering calculations and heavy extrapolations on experience.

The final design of the unidirectional probe evolved through several engineering conceptual arrangements, discussions with Dr. Walter M. Sanders,III of the Southeast Water Laboratory, and through improvements discovered during its fabrication and testing. This evolution is partially documented in the monthly progress reports to the Southeast Water Laboratory. The resulting form of the probe is shown in a partially disassembled condition in Figure 1 and assembled in Figures 2 and 3. Complete drawings of the probe details, assembly, and assembly instructions are contained in Apendix A. Only the salient features of the design will be discussed here.

The heart of the device is the strain-gaged diaphragm. This assembly is shown in Figure 4 and Drawing A-4 of Appendix A. The diaphragm derives its sensitivity from its extreme thinness (0.00075 inch) and its arrangement of silicon semiconductor strain gages. These gages have a very high gage factor which permits the reading of very low strain levels. The arrangement shown, particularly the notches at the rim, enable placement of the gages in areas of highest possible reverse strain on the diaphragm's inner surface. The fully mounted diaphragm is shown in Figure 5.

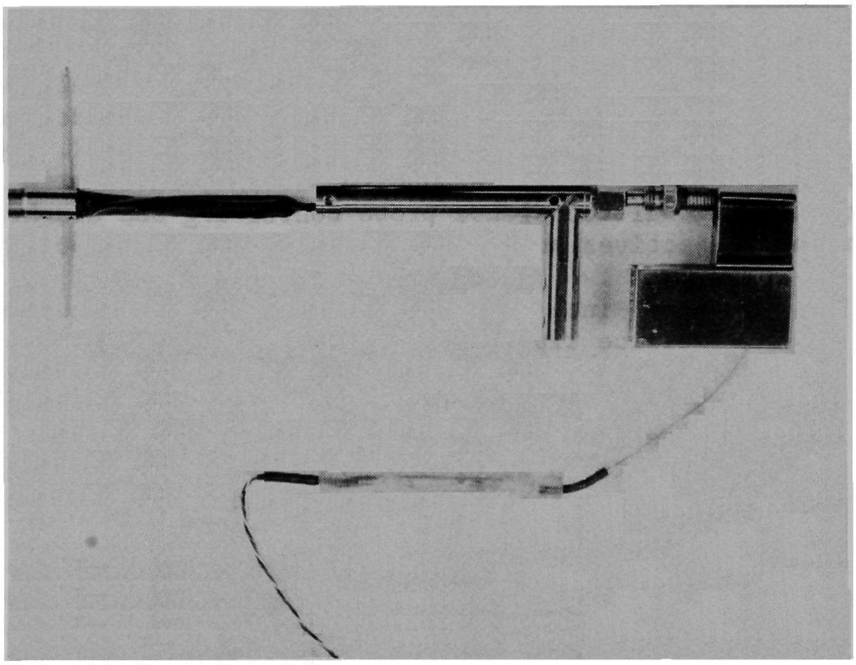


FIGURE 1. PARTIALLY ASSEMBLED PROBE

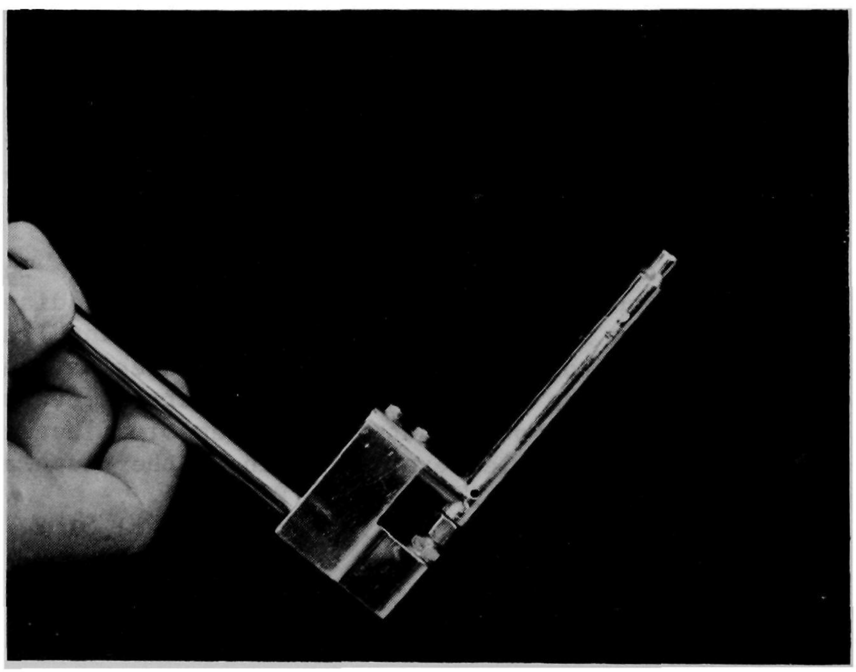


FIGURE 2. UNIDIRECTIONAL PROBE

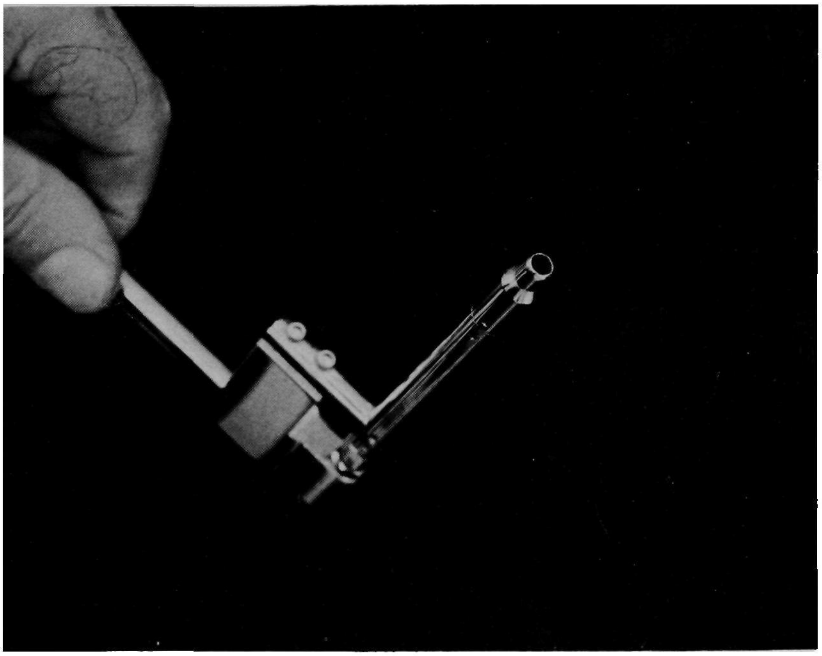


FIGURE 3. ORIFICE END OF PROBE

FIGURE 4. DIAPHRAGM WITH STRAIN GAGES

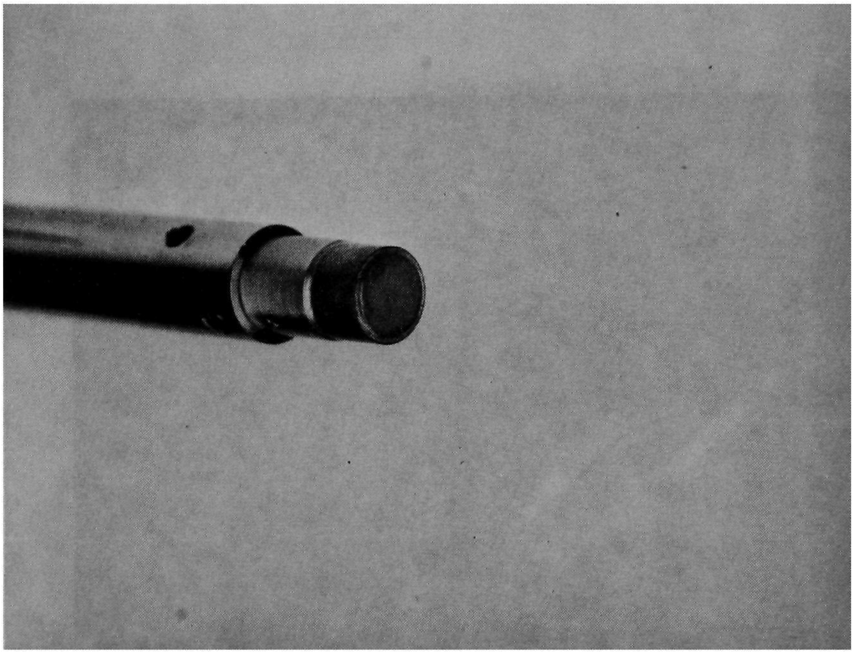


FIGURE 5. MOUNTED DIAPHRAGM

The gages are wired and connected in a Wheatstone bridge circuit whose diagram is presented in Drawing A-15 of Appendix A. The actual bridge connections and temperature compensation and balancing elements are made on a special mounting strip physically located in the wire leads just outside of the probe body proper. This location of the connections permits electronic adjustments and checking of the individual bridge elements without a complex disassembly of the device. The strip is partially protected inside a hard plastic sheath which can be seen in a horizontal position at the top of Figure 1.

Self-adjusting depth compensation is probably the second most critical feature of the device. It is accomplished by placing a reservoir of air behind the diaphragm enclosed in a collapsible membrane. This reservoir is exposed to the ambient water pressure under which it accordingly compresses or expands, depending on its previous condition, until the pressure inside and outside the air volume are balanced at the ambient static water pressure. In this manner the diaphragm sees no pressure differential from its outside to its backside due to the operational water depth. This is shown schematically in Figure 6.

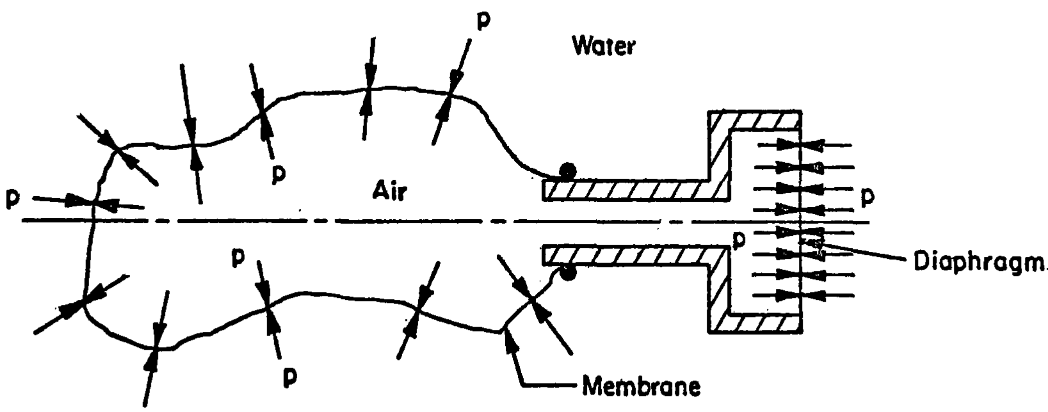


FIGURE 6. SELF-ADJUSTING DEPTH COMPENSATION

In this concept the membrane must be highly flexible so that it will not support water or air pressure but will act only as a divider between the air and the water. The flexibility is achieved by fabricating a very thin membrane, 0.002- to 0.004-inch thick, in a geometry that is susceptible to collapse. The membrane is shown in Figure 7 and Drawing A-9 in Appendix A.

The other features of the probe are evident in the assembly Drawings A-1 through A-3 in Appendix A.

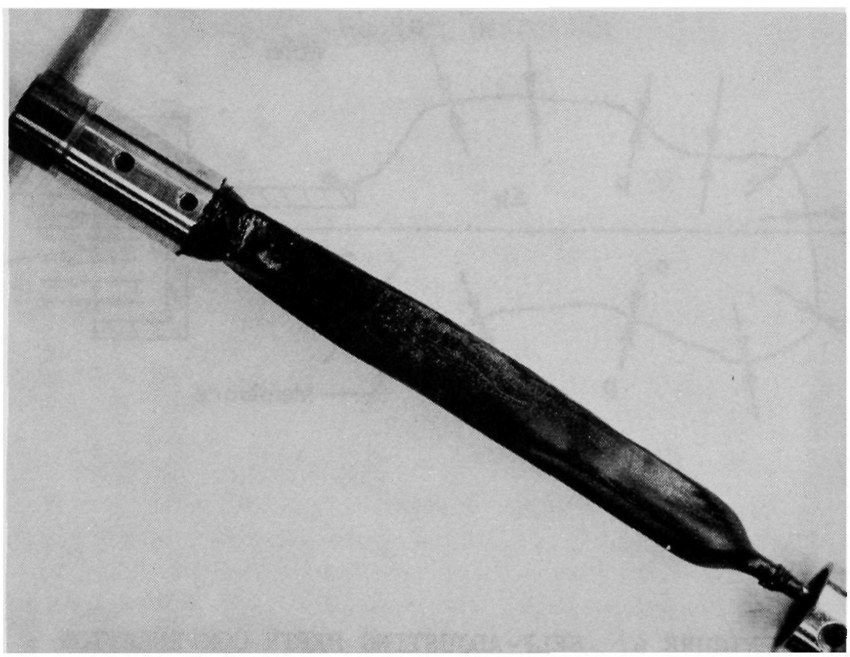


FIGURE 7. AIR-RESERVOIR MEMBRANE

SECTION VI

PERFORMANCE

Throughout the design, fabrication, and calibration processes of Phase I, various characteristics of the unidirectional probe were noted and, in some cases such as calibration, these were quantified. A discussion of those characteristics that have a bearing on the operation of the device follows.

Sensitivity

The device, though sensitive, is not sensitive enough to produce a practical readable electronic signal at the specified minimum velocity of 0.1 ft/sec. Though the minimum or threshold signal that can be discerned will depend on the actual electronic equipment used, conventional amplifying and signal processing equipment will operate on minimum signals of 0.1 millivolt or slightly lower. As presented in the "Calibration" portion of this report (see Figure 13) 0.1 millivolts is the probe output expected at approximately 0.5 ft/sec water velocity. No operational equipment will function on the 0.0036 millivolt signal produced by a water velocity of 0.1 ft/sec, therefore, the functional water velocity detection range of the unidirectional probe is approximately 0.5 to 5 ft/sec.

Linearity

The device displays excellent linearity throughout its range with deviations of less than 1 percent of the full scale output (9.1 millivolts at 5 ft/sec) observed during calibration. There was also no measurable hysteresis encountered in the static calibrations.

Drift

The one major negative characteristic of the device is its lack of balance stability. Balance stability, in the case of the probe is its ability to maintain the same output reading over a period of time in which there is no change in the velocity of the medium to which the probe's diaphragm is exposed, e.g., with a lack of balance stability the probe, when lying in a pool of motionless water, would show a gradual change in its output voltage over a period of time. In the development of the unidirectional probe two types of drift have been observed, one type occurs when the probe is in air, and the other occurs when the probe is under water.

When the probe has been resting in undisturbed air on a laboratory bench with 3 volts excitation, its electronic output over a period of days has drifted back and forth over a range of ±9 millivolts. While this range is high (double the operational range), the rate of this drifting has been relatively low apparently never exceeding ±0.030 millivolts/min. A sample of this drifting in room air has been recorded and is presented in Figure 8.

While the range of drift is excessive, its existence is not entirely unexpected. The extreme thinness of the diaphragm coupled with the highly strain-sensitive semiconductor gages renders the diaphragm assembly susceptible to all of the negative factors normally affecting diaphragm transducers plus factors unique to this assembly. The most common source of drfit is environmental temperature effects on the transducer components. Temperature compensation elements have been added within the bridge circuitry. In this manner subsequent temperature excursions have been limited to less than 1 millivolt over the environmental temperature range of 32 to 100 F. Normally a diaphragm transducer can be temperature compensated to produce a much lower excursion than this but again the coltish nature of this unique diaphragm assembly is manifest. In any event the temperature excursion does not appear to be the source of the wide drift range. A clue to the true source of drift may be contained in the performance of the probe when it has been immersed in stagnant (no flow) water.

In this case, the drift has consistently gone up scale, i.e., in the direction seen with a positive impinging water velocity. The initial drifting observed when only the diaphragm was exposed to 2 inches of water is shown in Figure 9. The drift over a long term was observed when the entire probe was immersed in 10 inches of water, this is shown as the upper curve in Figure 10. The lower curve on this figure shows the long term drift accompanying the immersion of only the rear, i.e., reservoir, portion of the probe in 1-1/2 inches of water.

Prior to each of the water immersion experiments shown on Figures 9 and 10, the probe had been dry for some time, indeed, prior to the experiments of Figure 10 the assembly had been baked in an over (curing of the reservoir seal prior to the 10-inch immersion and drying up after the 10-foot support tube leak prior to the 1-1/2 inch immersion). The baking, at 195 F, prior to the 1-1/2 inch immersion may have affected the distribution of the air reservoir's wax coating. When dried, the balance of the probe is less than +8 millivolts.

The resistance between the strain-gage bridge and ground was checked during the water immersion experiments. Prior to immersion, the resistance was immeasurably high. Immediately after immersion, the resistance to ground was 33 x 10^6 ohms. With increasing immersion time the resistance continued to decrease; on the 1-1/2-inch immersion, the resistance was 13 x 10^6 ohms on the second day and fluctuating at 200,000 to 20,000 ohms on the third day.

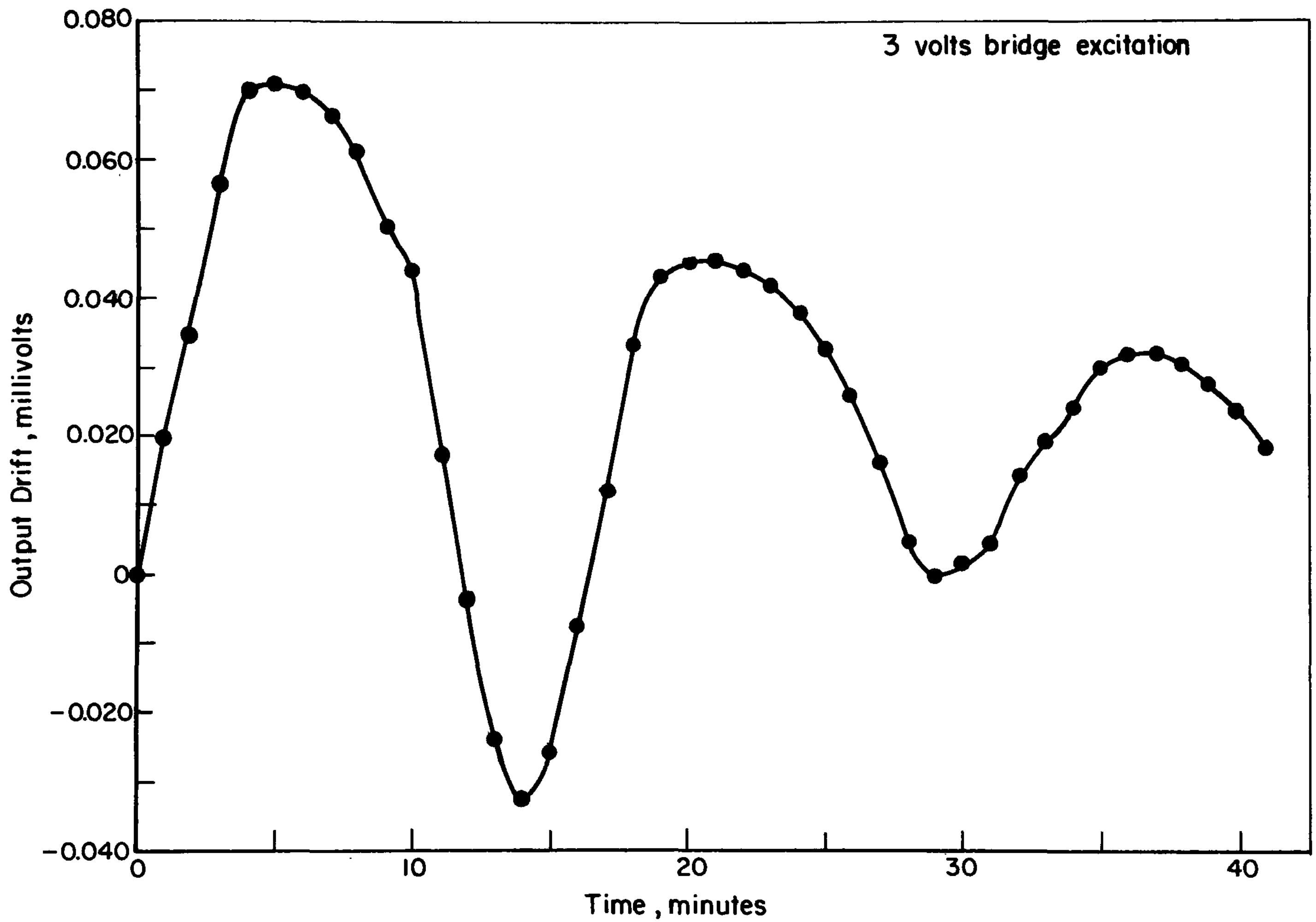


FIGURE 8. DRIFT IN AIR

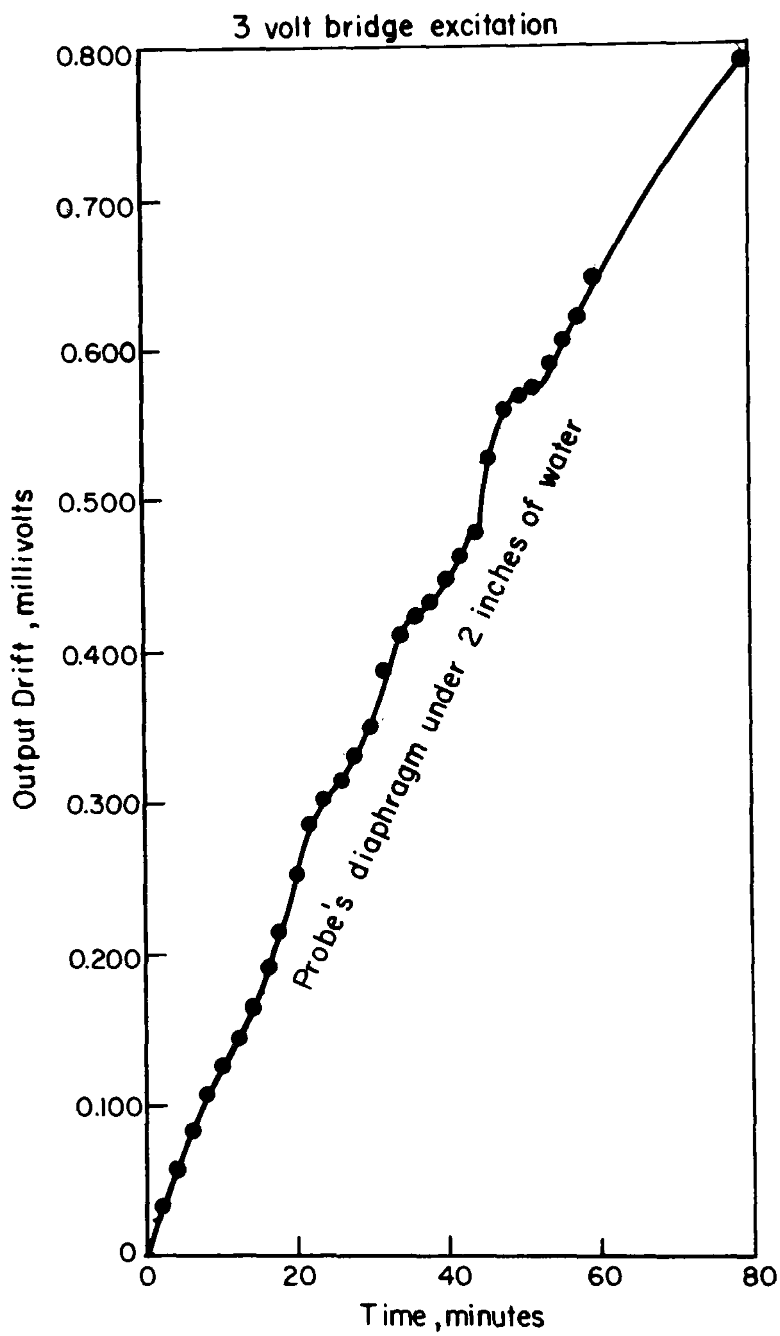


FIGURE 9. INITIAL DRIFT IN WATER

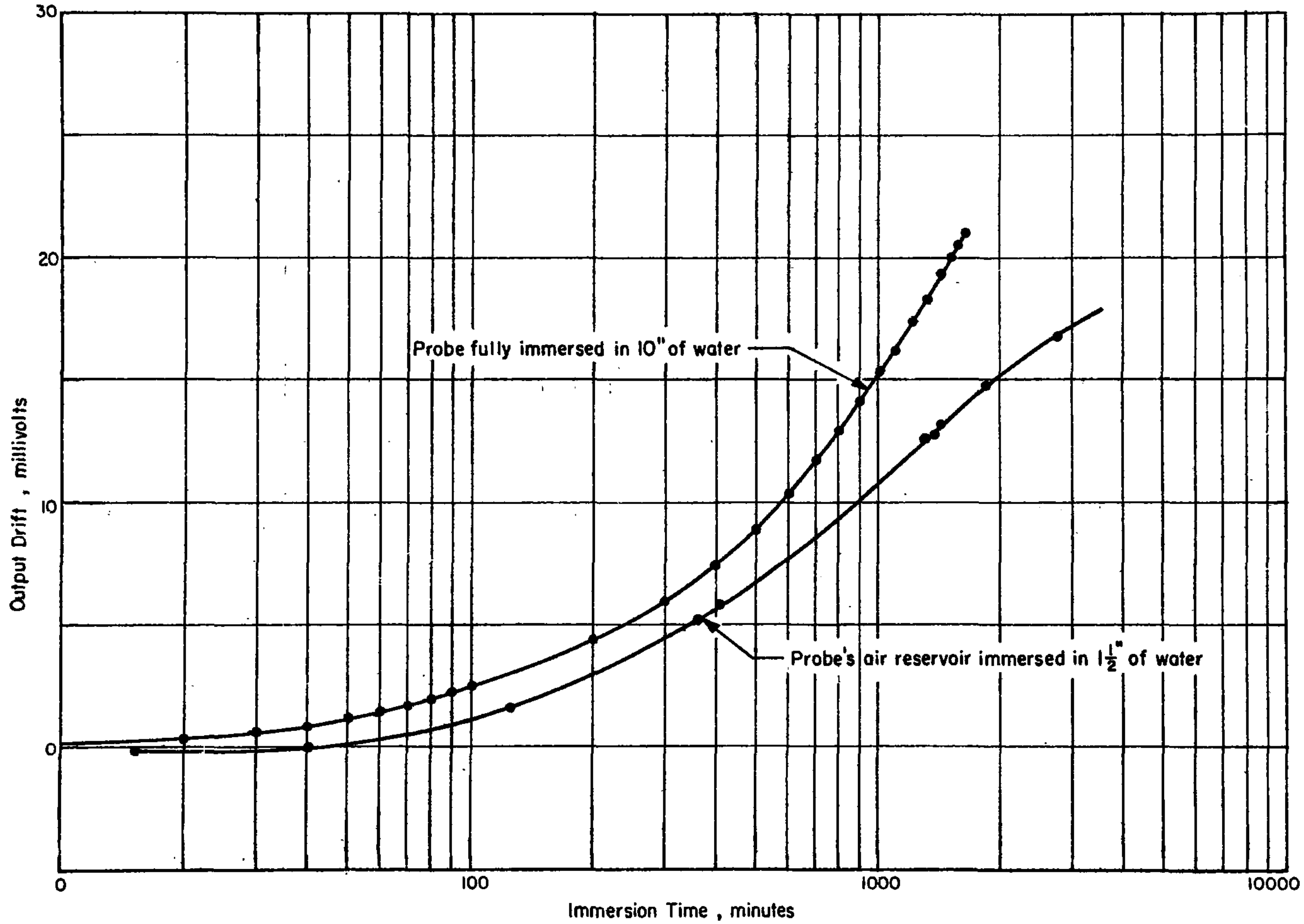


FIGURE 10. LONG TERM DRIFT IN WATER

The key to the above described behavior seems to be exposure to water. It is a well recognized fact that contact with water vapor causes problems with any strain gage installation but this is particularly true with semiconductor gages. Water vapor appears to be getting through the neoprene reservoir membrane and even possibly the diaphragm. The requirement of thinness in both parts introduces the likelihood of molecular porosity. Whether the upward drift of the 1-1/2-inch immersion (still in progress at this writing) will produce a vapor pressure equilibrium or a condensate ground is not clear at this point.

It should be noted that the sensitivity of the probe does not seem to be seriously affected when the zero balance is as high as the 20 to 30 millivolts range. Satisfactory static and dynamic experiments were performed with the zero balance at these levels. It should also be noted that the drift rate of the submerged probe is always less than 0.020 millivolts/min.

Depth Compensation

Depth compensation does take place in the unidirectional probe. As described in the "Calibration" section of this report submersion in ten feet of water produces less than one millivolt of shift. This indicates a relatively minor pressure differential across the diaphragm, whereas without the compensation the diaphragm would have seen a pressure differential great enough to cause its permanent deformation.

Frequency Response

A simple calculation of the diaphragm's natural frequency yields the value of 6627 Hz. This frequency is sufficiently higher than the required maximum response frequency of 100 Hz that a considerable amount of inaccuracy in the assumption that the diaphragm is a simple circular plate with rigidly clamped edges can be tolerated. This margin of better than 60 to 1 between the theoretical natural frequency and the required response frequency also indicated that no checking of the probe's performance in this area is required, consequently no specific frequency response experiments have been performed.

SECTION VII

CALIBRATION

Several calibration and performance checking experiments were applied to the unidirectional probe. In all of the experiments the Wheatstone bridge on the device was supplied with three volts potential from a constant current source and its output was read directly on a voltmeter sensitive to $\pm 10^{-5}$ volts.

Static Calibration

This procedure consisted of applying an essentially static water pressure to the outside of the diaphragm while maintaining atmospheric pressure on the air reservoir. The experimental setup is shown schematically in Figure 11.

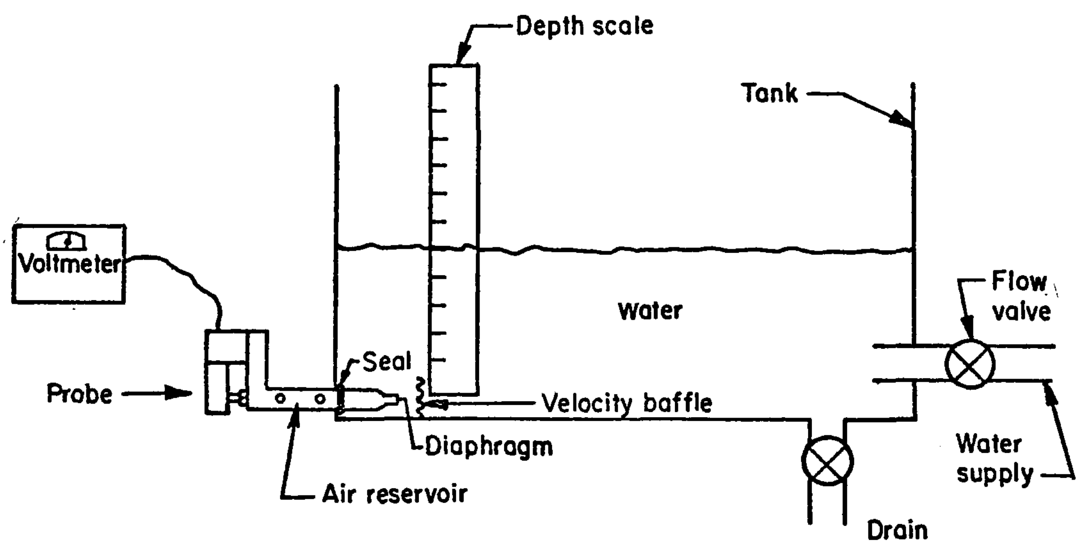


FIGURE 11. STATIC CALIBRATION EXPERIMENT

The experiment was begun with a half inch of water (0.01806 psi), measured from the ceterline of the diaphragm, covering the diaphragm. This static water pressure was then varied by filling the tank to a depth of six inches (0.21667 psi) above the diaphragm centerline and then draining back to a half-inch depth. The output of the probe was recorded at every half-inch increment of depth. The elapsed time for each cycle, from one-half to six and back to one-half inch, was approximately 15 minutes. The results of three of these cyclings are presented in terms of output versus water level in Figure 12.

The deviation was slight, i.e., if the actual experimental points were plotted on the above graph they would fall within the thickness of the plotted line. The slope of the output curve is

$$1.964 \, \frac{\text{millivolts}}{\text{inch } H_2O} = 54.388 \, \frac{\text{millivolts}}{\text{psi}} \, ,$$

or with the input voltage normalized,

$$0.655 \, \frac{\text{millivolt/volt}}{\text{inch } H_2O} = 16.129 \, \frac{\text{millivolts/volt}}{\text{psi}} \, .$$

If these static pressure results are converted into an equivalent water velocity by interpreting the static pressure as a velocity stagnation pressure through the formula,

$$P_s = P_v = \frac{V^2}{2g} \, ,$$

and

$$V = \sqrt{2gP_v} = 8.02496 \, P_v^{1/2} \, , \ \text{ft/sec} \, ,$$

where

P_s = static pressure, feet of H_2O

P_v = stagnation pressure, feet of H_2O

g = acceleration due to gravity, 32.2 $\frac{\text{ft}}{\text{sec}^2}$,

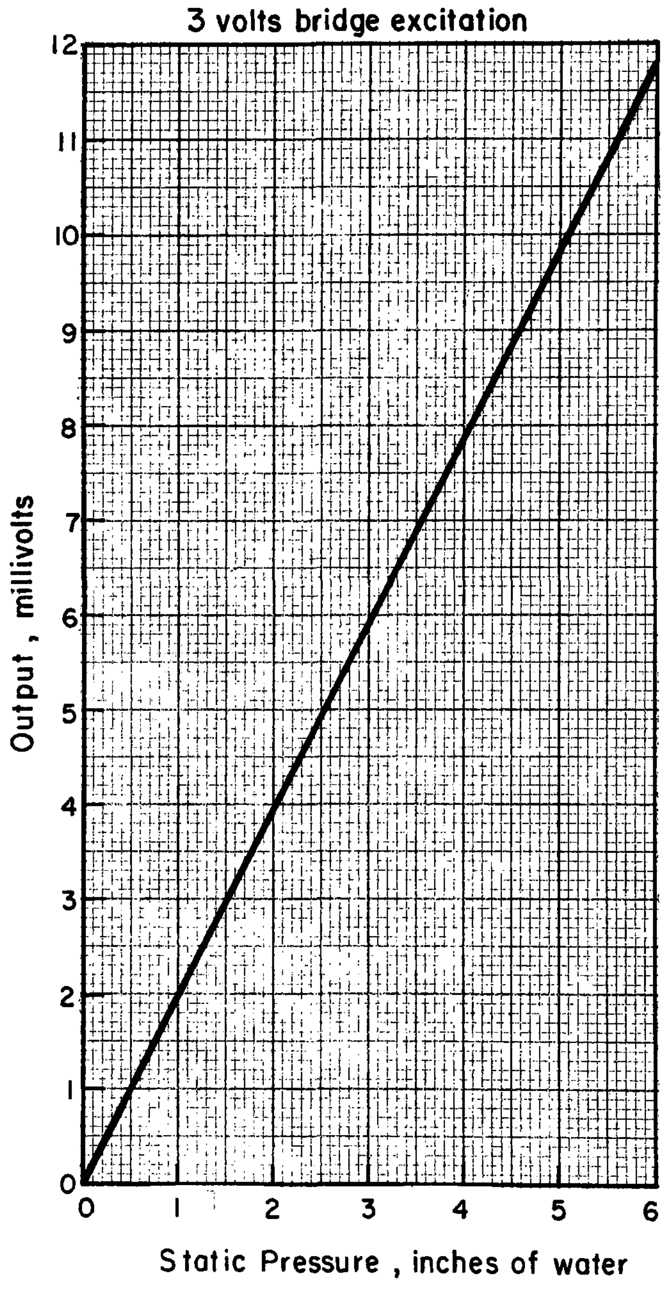


FIGURE 12. STATIC CALIBRATION, PRESSURE

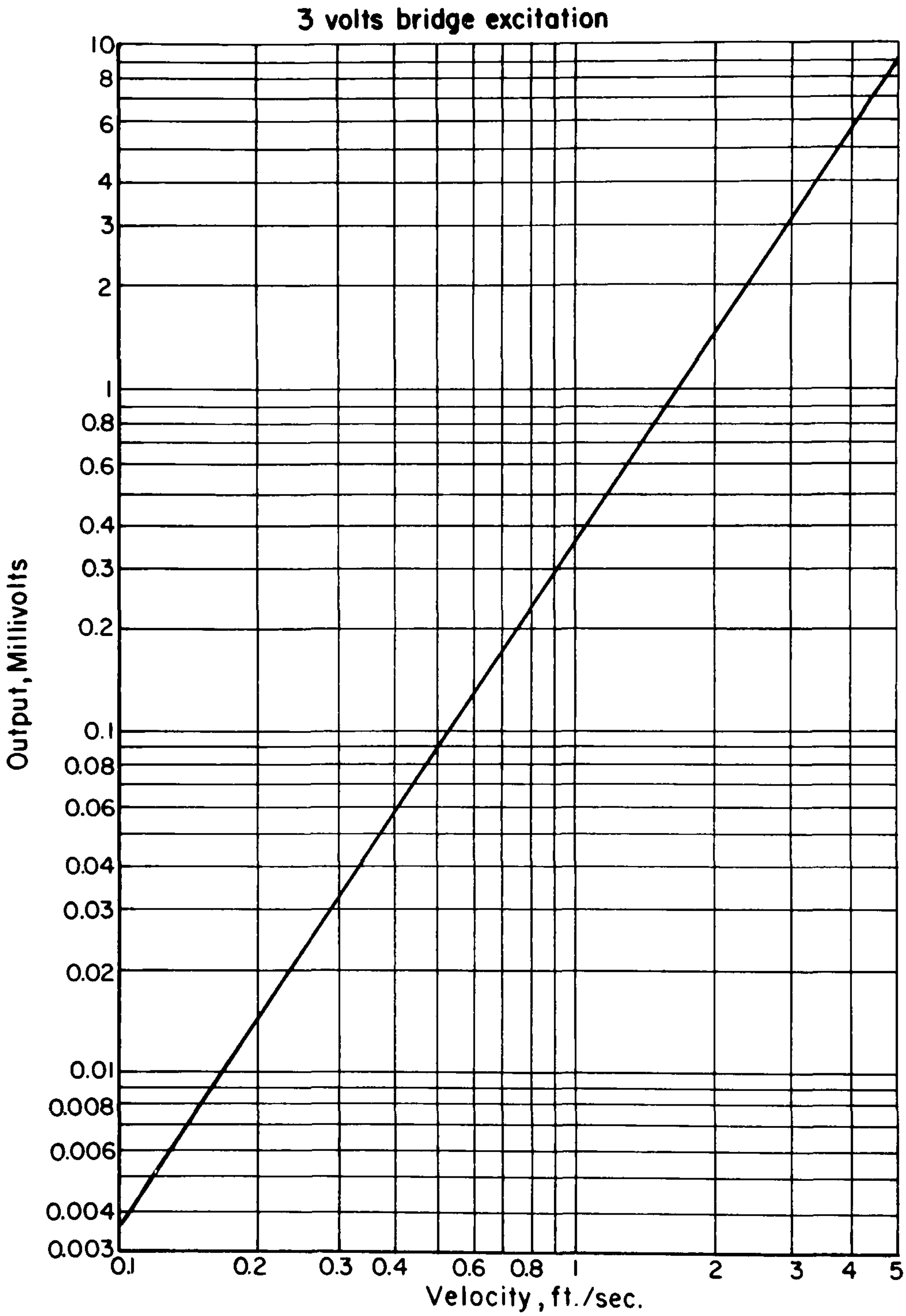


FIGURE 13. STATIC CALIBRATION, VELOCITY

then Figure 13 represents the relationship between the electronic output and the velocity of the water impinging on the probe's diaphragm. The slope of this curve is

$$365.960 \ \frac{\text{microvolts}}{\text{ft}^2/\text{sec}^2} \quad \text{or} \quad 121.987 \ \frac{\text{microvolts/volt}}{\text{ft}^2/\text{sec}^2} \ .$$

Flow Performance

The procedure described here is not strictly one of calibration but the probe was subjected to it in order to approximately check the static calibration results. The probe was pointed into the center of the opening of a 0.815 inch internal diameter pipe discharging water at various flow rates. The apparatus of this procedure is shown in Figure 14.

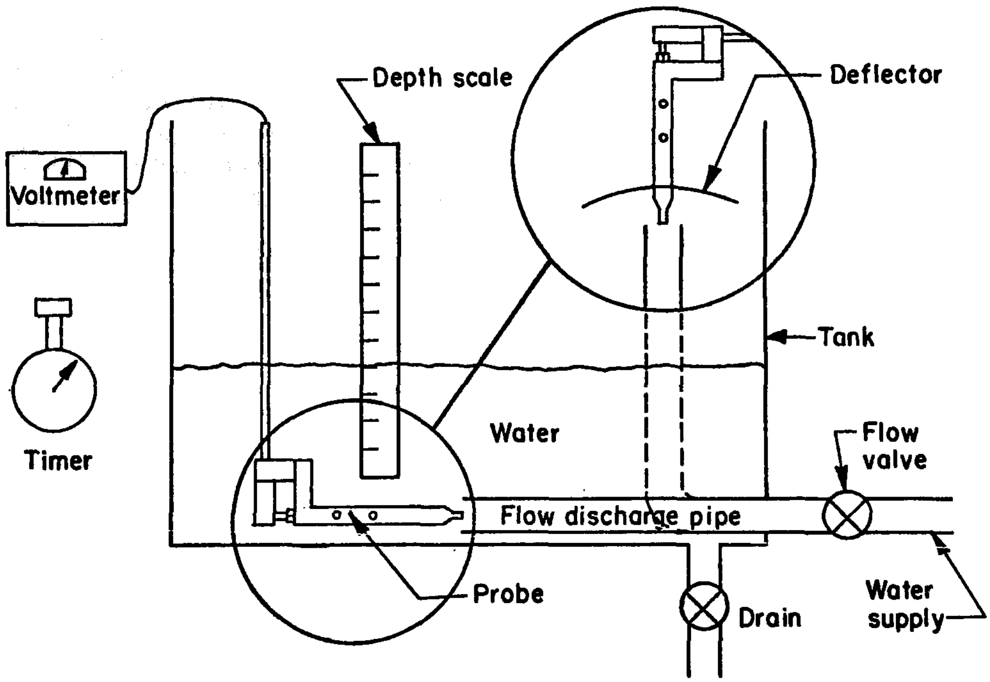


FIGURE 14. FLOW PERFORMANCE CHECK

An individual run in this checking procedure consisted of opening the control valve until the desired approximate flow rate was established. The actual average flow rate was checked by timing the rise of the water level, and thus the volume change, in the tank. The probe output during this period was monitored through the voltmeter and an approximate average value was recorded. The tank is 24 inches in diameter and the timing was done over 4-inch and 8-inch level changes depending on the flow rate used. The timing periods varied from 97 to 287 seconds.

The procedure does not provide an accurate calibration for several reasons; chief among these is that the apparatus itself is not calibrated. For example, the exact velocity profile of the water discharging from the pipe is not known and can only be defined within theoretical limits. A uniform velocity-flow profile is one limit and a laminar-flow profile would be the other. A brief calculation of Reynolds number for the average velocity of 1 ft/sec yields 5,600 which is just above the upper limits for the laminar-flow region as normally encountered in engineering applications, therefore, the flow is very likely to be turbulent. A theoretical determination of the correct turbulent-flow profile is not feasible as it would entail too many doubtful assumptions. It must suffice to state that the velocities at the center of the pipe discharge will be greater than those predicted by uniform flow and less than the peak value (twice that of the average uniform flow) predicted by a laminar-flow assumption. Additional factors such as a fluctuating pressure source, approximation of the average voltmeter readings, and probe output drift with time also detract from the quantitative accuracy of the results using this procedure.

The results of numerous runs using the procedure are presented as individual points in Figures 15 and 16. In these figures the average volumetric-flow rate is plotted against the velocity at the center of the pipe discharge as indicated by the probe and its static calibration shown in Figure 13. Lower flow velocities were not run due to the difficulty of obtaining accurately measurable flow volumes in reasonable periods of time.

Depth Compensation

An extension tube and wiring were fitted onto the probe's existing two feet of support tube in preparation for depth-compensation tests. The immediate probe portion of the assembly was then immersed beneath the surface of Battelle-Columbus' diving pool and allowed to stabilize for six minutes. The probe was then immersed in increments to a depth of ten feet and the resulting deviations recorded. A total of eleven minutes elapsed while moving the probe from the depth of two inches to the ten-foot depth. The resulting point-by-point deviations are shown in Figure 17.

The maximum deviation of less than 1 millivolt took place at the ten-foot depth (4.33 psi). This shift is comparable to that observed when the diaphragm alone was subjected to 1/2 inch of water pressure (0.01805 psi) during the static calibration shown on Figure 12. After a short period at the ten-foot depth, the support tubing developed a leak which grounded the electronics and the probe was removed for repair. No further compensation tests were performed.

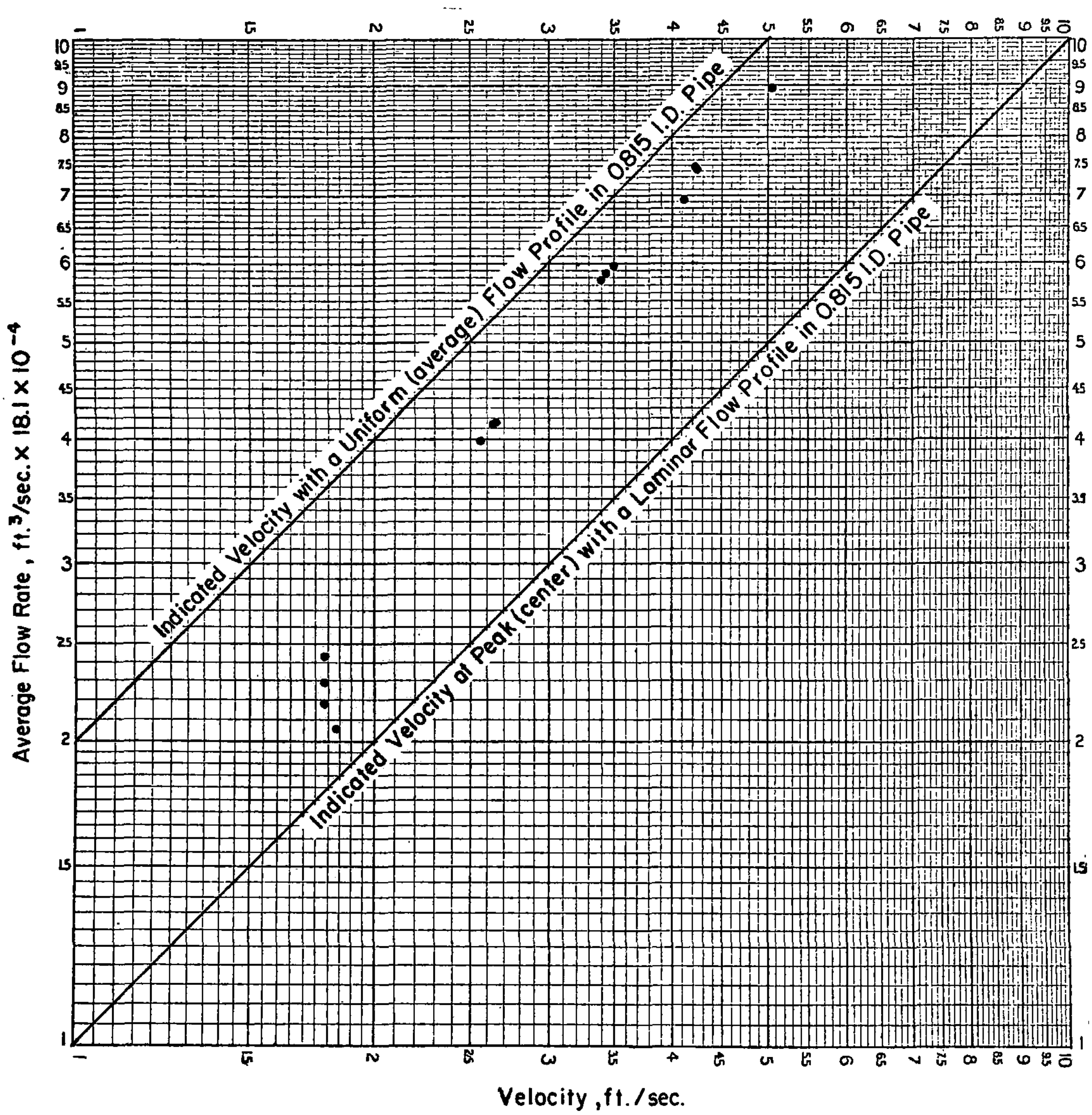


FIGURE 15. DYNAMIC PERFORMANCE PROBE HORIZONTAL

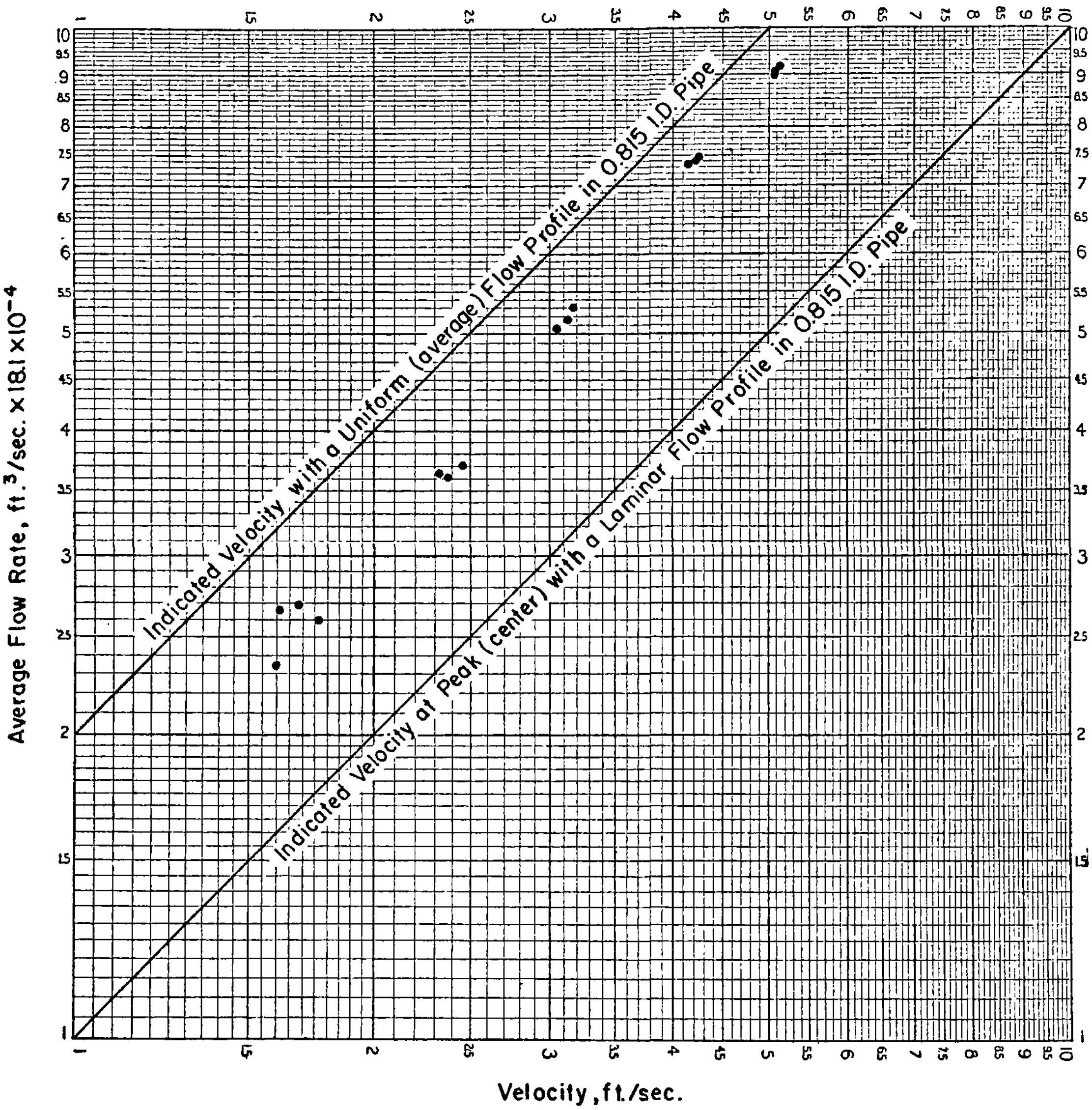


FIGURE 16. DYNAMIC PERFORMANCE PROBE VERTICAL

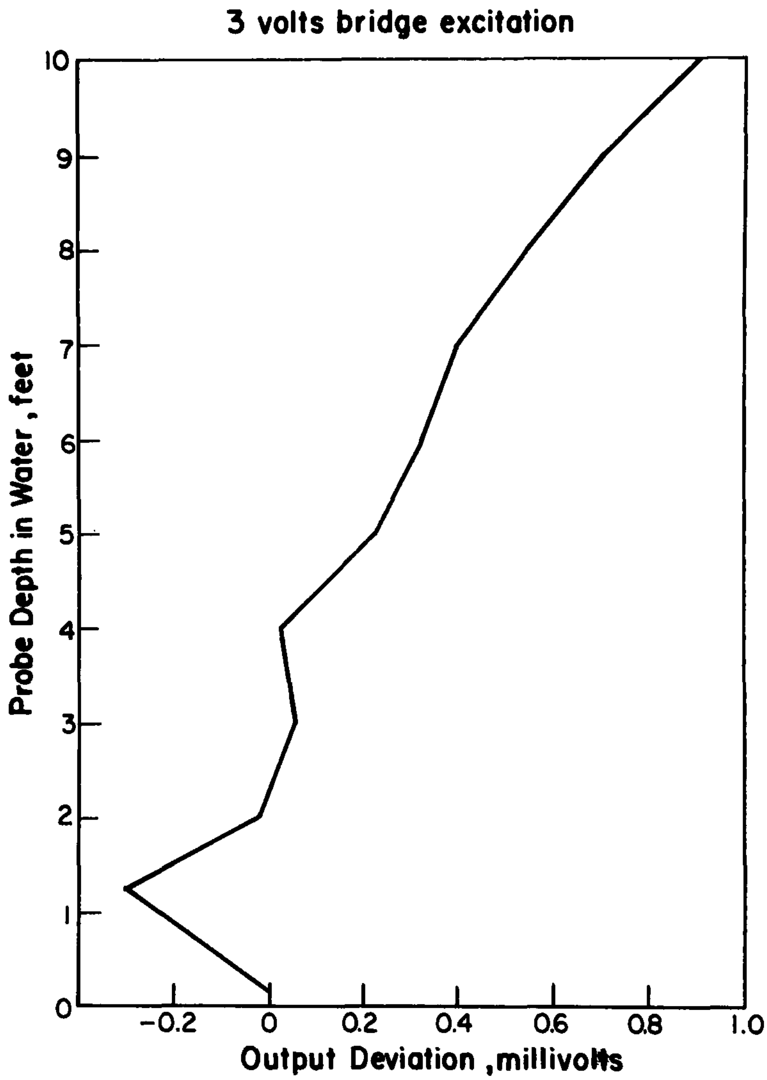


FIGURE 17. DEPTH COMPENSATION DEVIATION

SECTION VIII

ACKNOWLEDGMENTS

The majority of the fabrication and laboratory calibration experiments on the unidirectional probe were performed by Battelle's senior technician Mr. Donald H. Lyons.

Attachment of the semiconductor strain gages, compensation, and wiring of the Wheatstone bridge were performed by the Sensotec Division of Comtel.

The final air reservoir neoprene membrane used was fabricated by The Oak Rubber Company.

The design of the unidirectional probe was assisted by Mr. Nelson A. Crites, Mr. James E. Sorenson, Mr. Milton Vagins, and Mr. Jack J. Groom, all of Battelle Columbus Laboratories.

All documentation covering the development of the unidirectional probe is contained in Battelle Laboratory Record Book Number 27668.

This report was prepared by Mr. Thomas J. Atterbury, Mr. James E. Sorenson, and Mr. Jack J. Groom.

The support of this project by the Environmental Protection Agency, and the direction of Dr. Walter M. Sanders III, are acknowledged with sincere thanks.

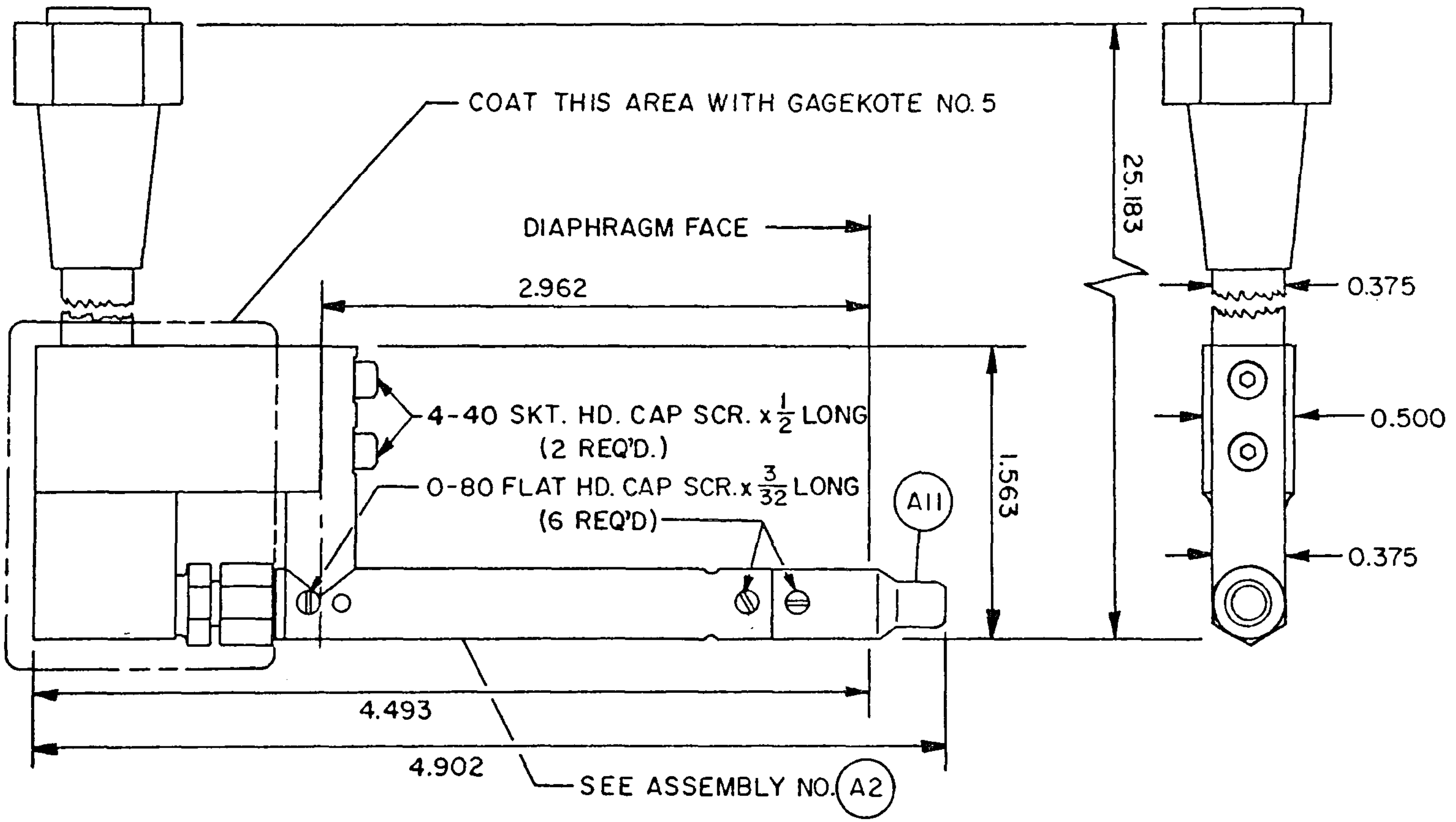
SECTION IX

APPENDICES

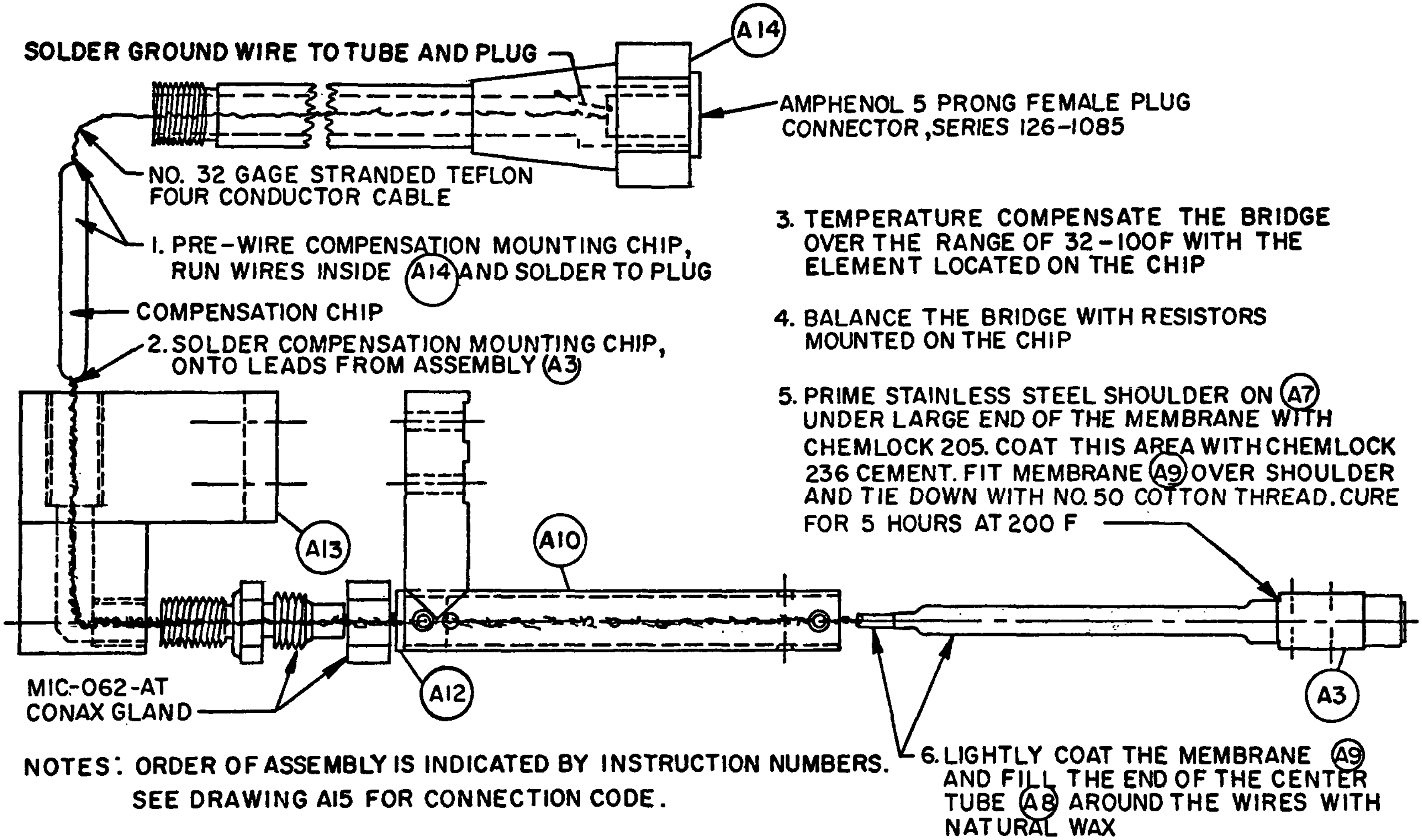
APPENDIX A

UNIDIRECTIONAL TURBULENCE PROBE DETAIL AND ASSEMBLY DRAWINGS, ASSEMBLY INSTRUCTIONS, AND OPERATIONAL CIRCUITRY

UNIDIRECTIONAL TURBULENCE PROBE ASSEMBLY



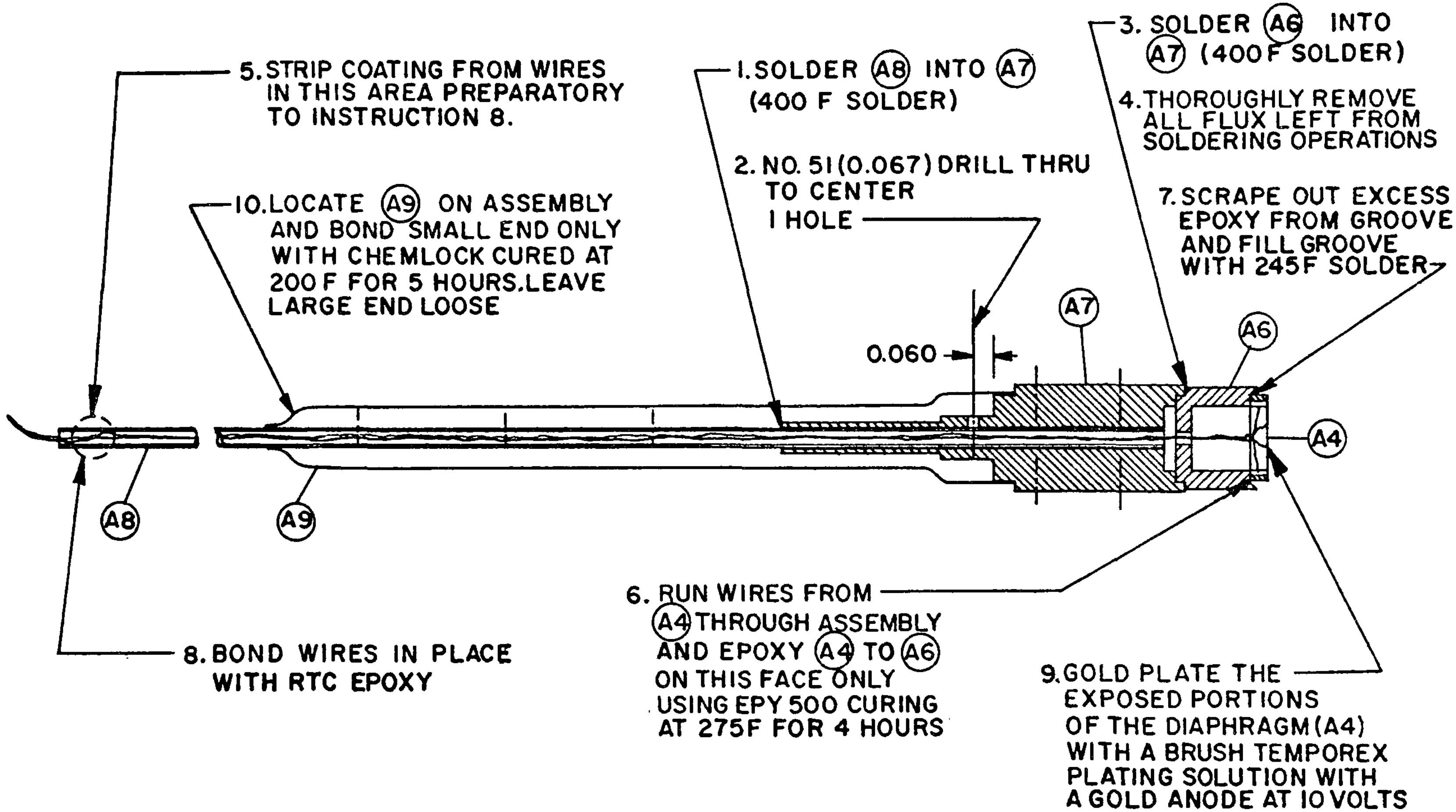
DRAWING AND ASSEMBLY NUMBER A1



COMPENSATION ASSEMBLY

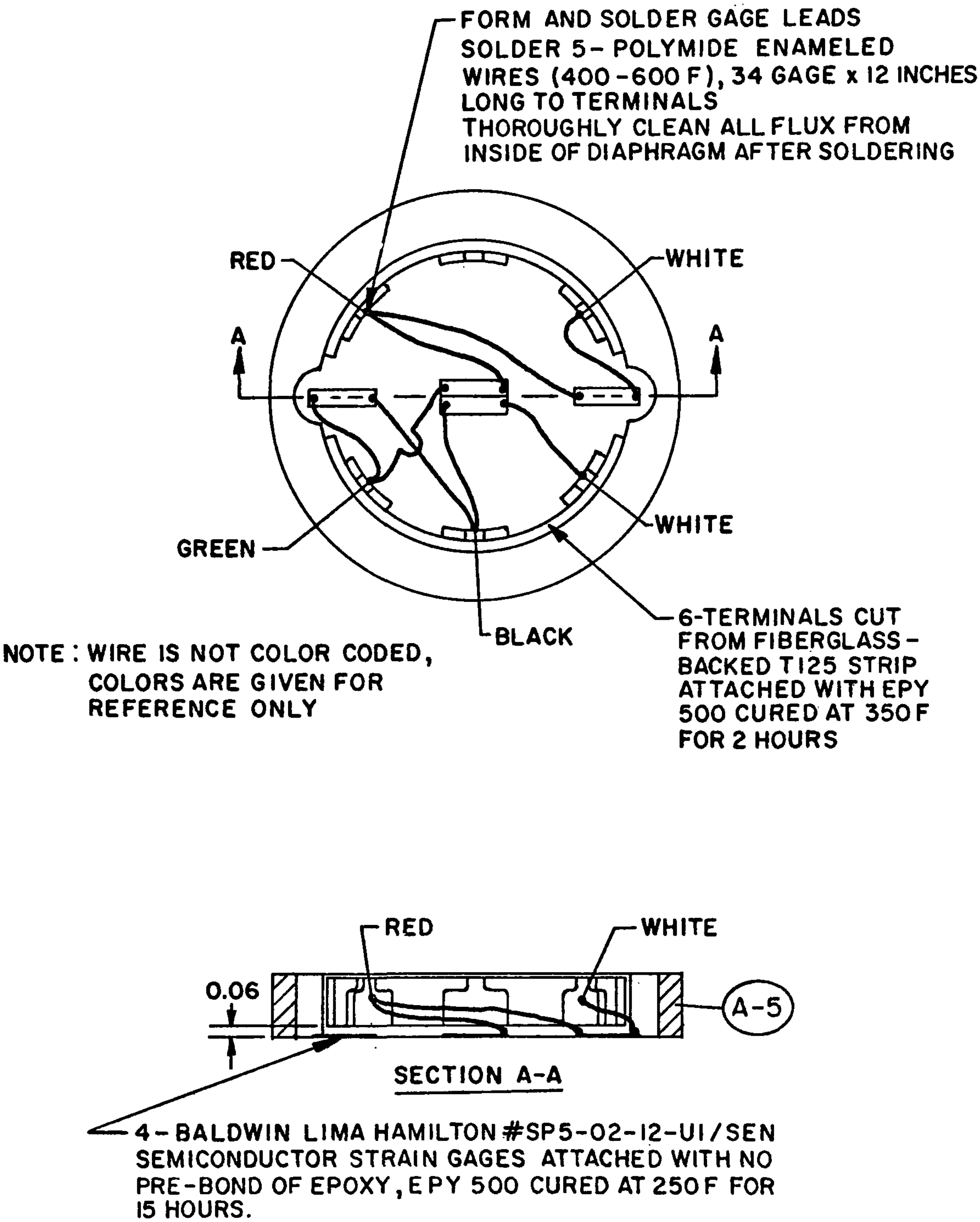
DRAWING AND ASSEMBLY NUMBER A2

NOTE: ORDER OF ASSEMBLY IS INDICATED BY INSTRUCTION NUMBERS



INTERNAL ASSEMBLY

DRAWING AND ASSEMBLY NUMBER A3

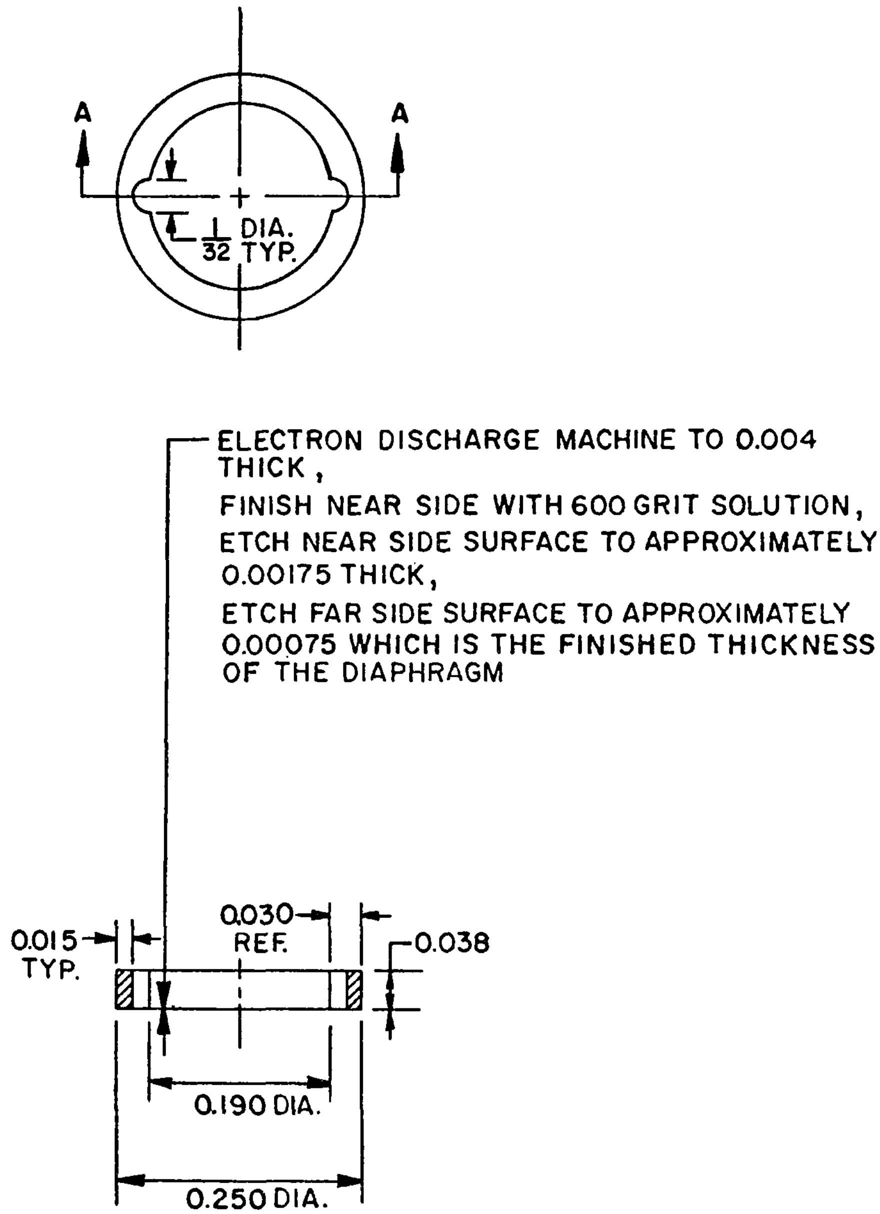


DIAPHRAGM ASSEMBLY

DRAWING AND ASSEMBLY NUMBER A4

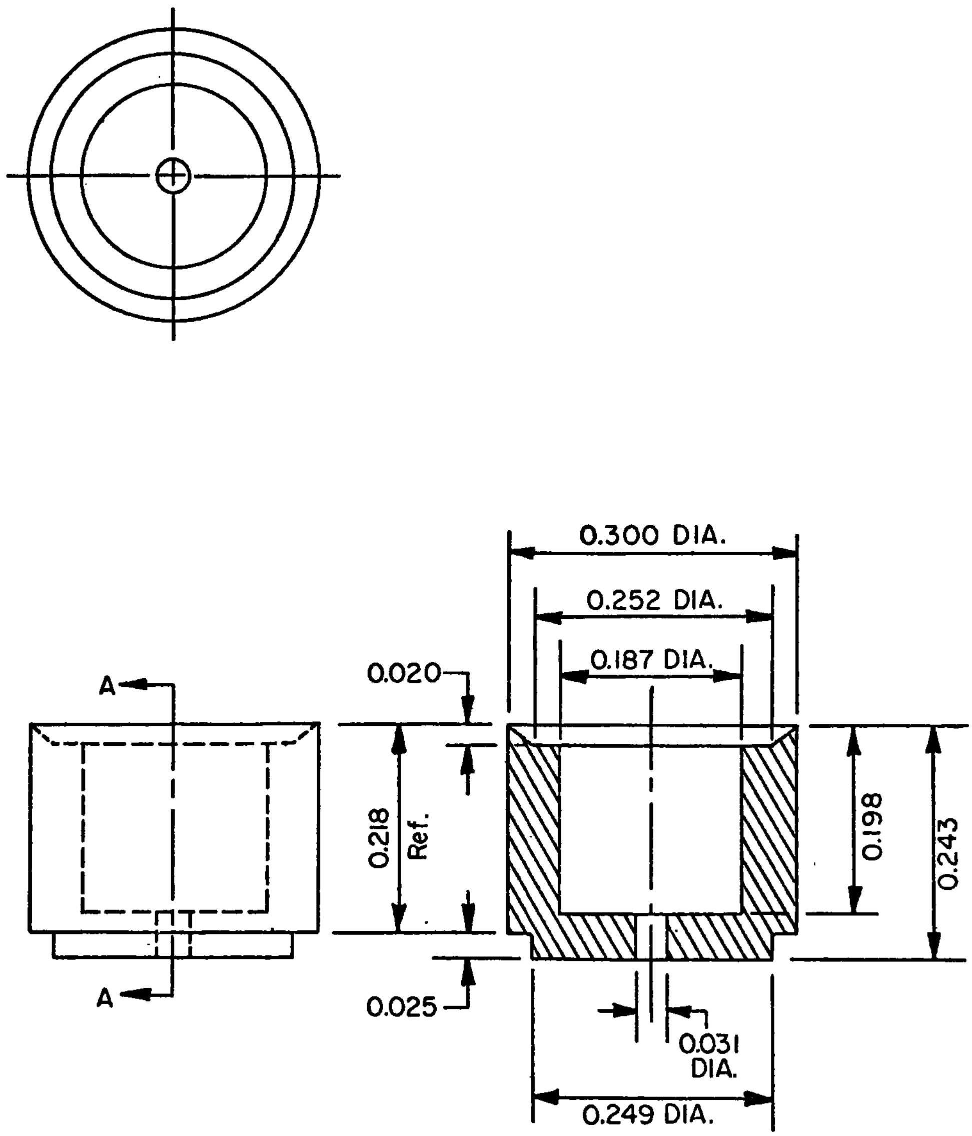
DIAPHRAGM

MATERIAL: BRYLCO ALLOY 25 , FULL HARDENED (38 –40 Rc) AGED AND LAPPED TO 0.038 THICKNESS



SECTION A–A

DRAWING AND PART NUMBER A5

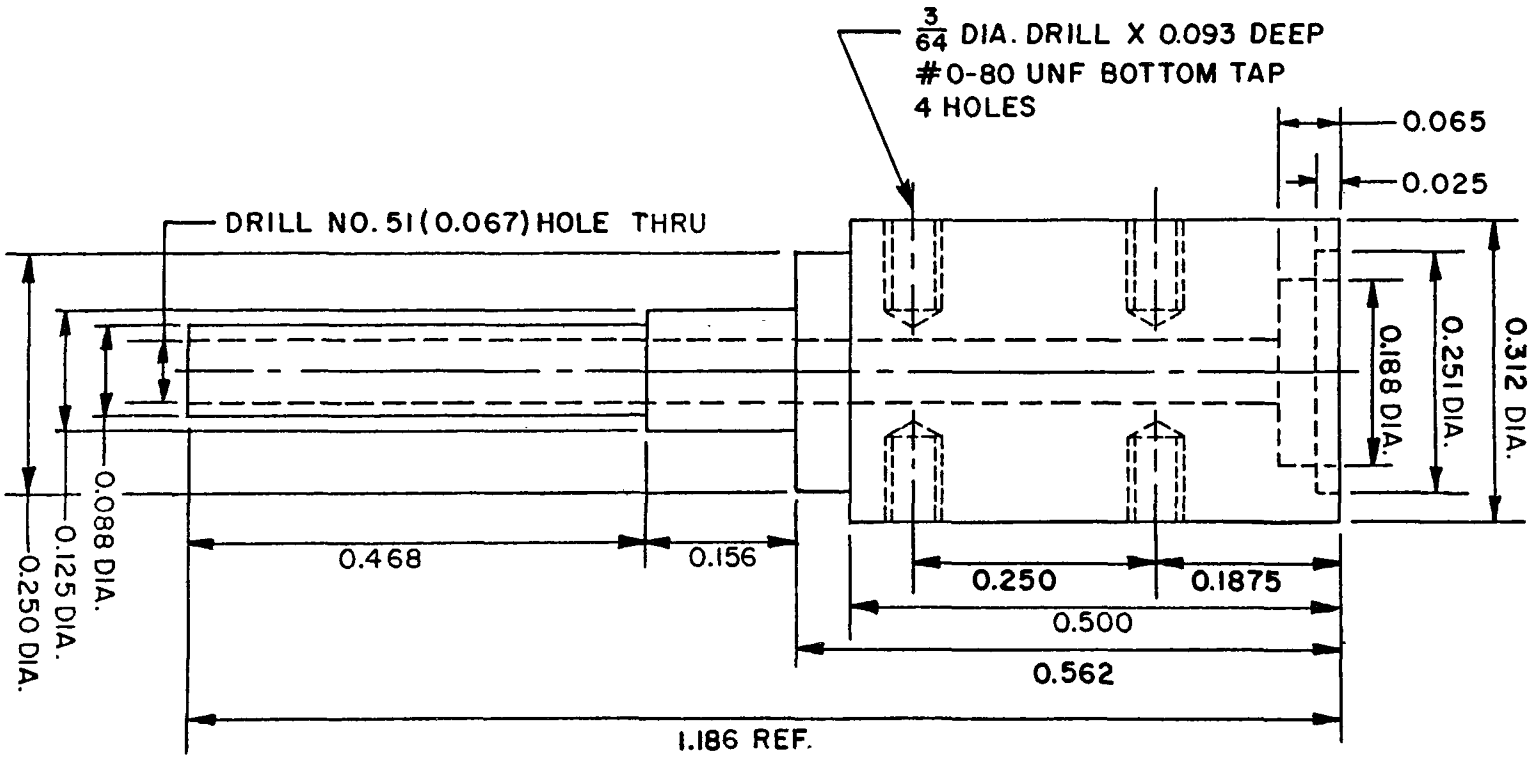


SECTION A-A

MATERIAL : BRYLCO ALLOY 25, FULL HARD

CAP

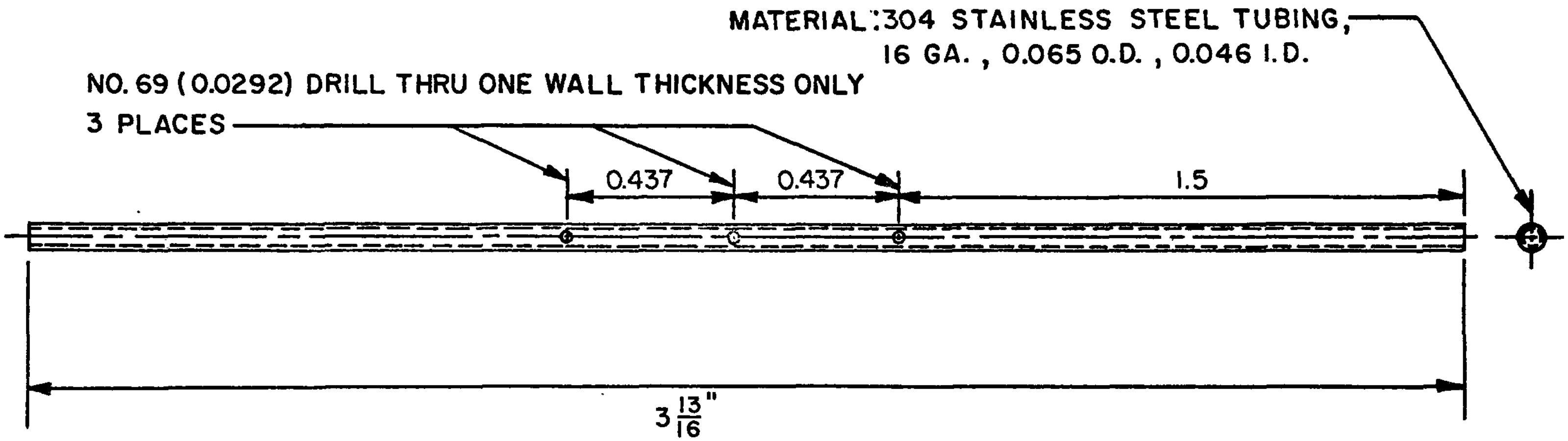
DRAWING AND PART NUMBER A6



MATERIAL: 316 STAINLESS STEEL

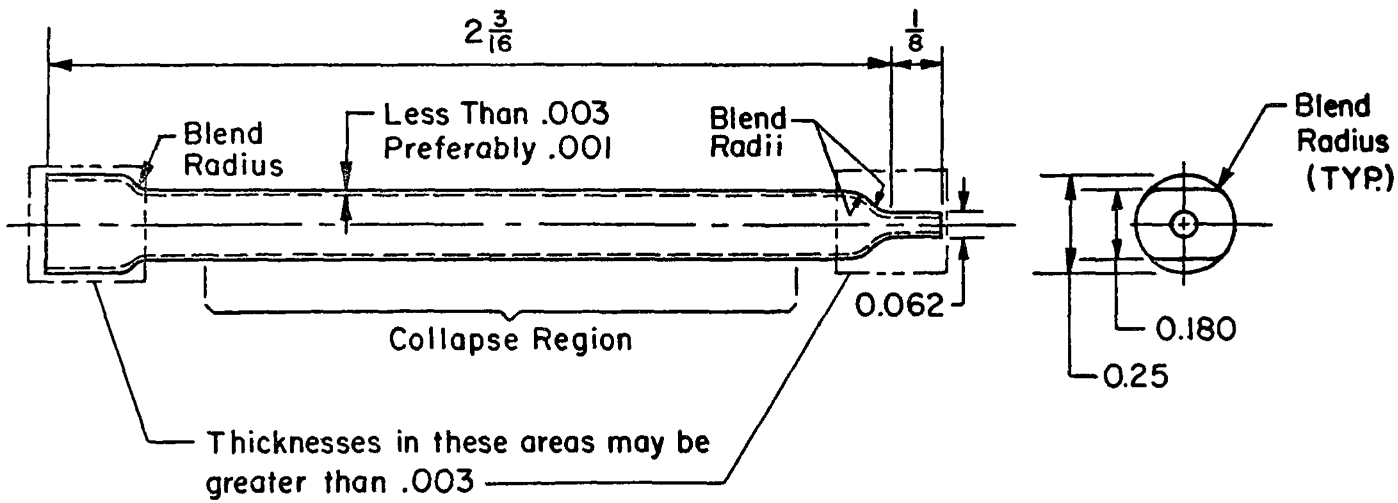
COUPLING

DRAWING AND PART NUMBER A7



CENTER TUBE

DRAWING AND PART NUMBER A8



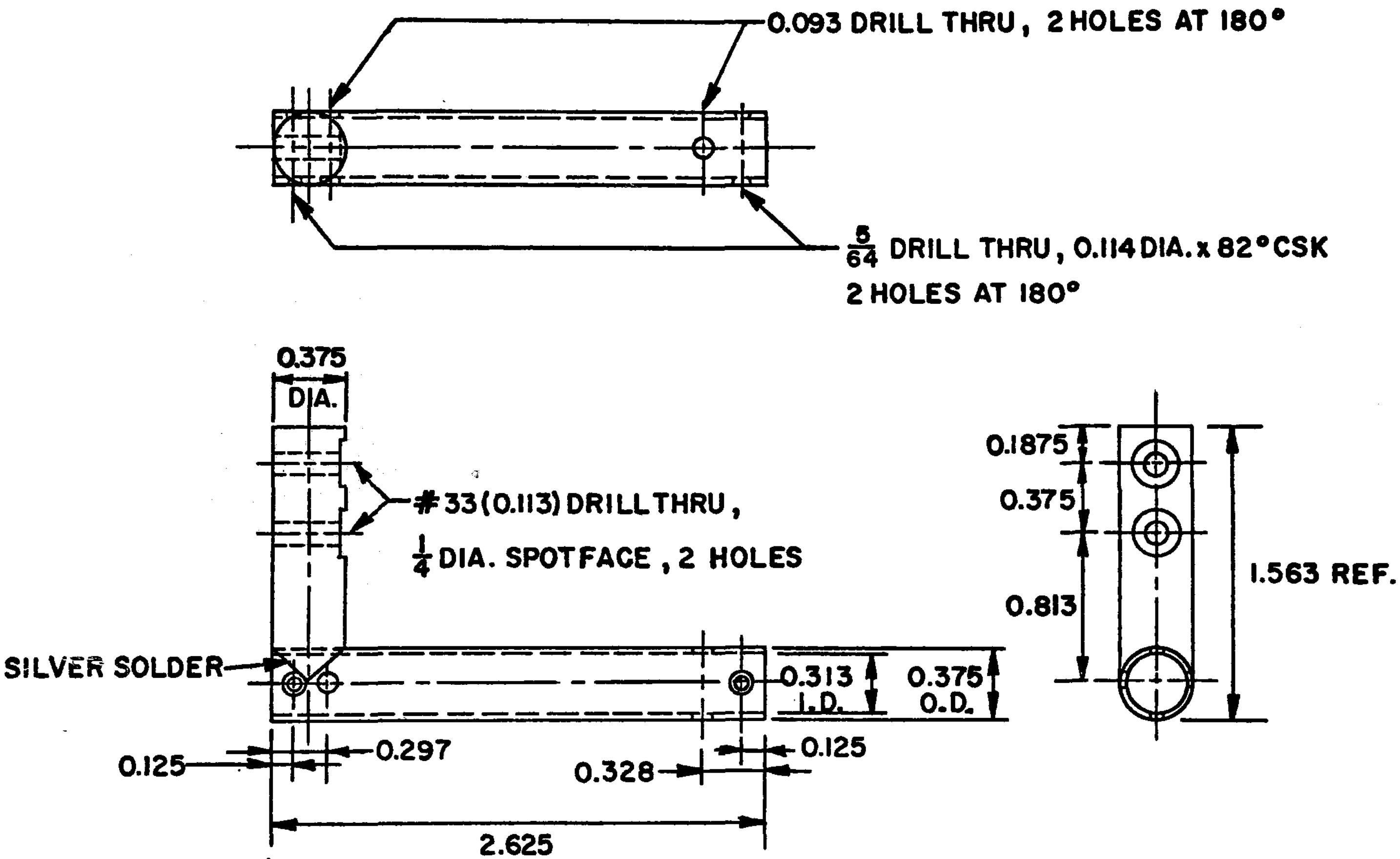
Note: All dimensions are internal

MATERIAL: NEOPRENE RUBBER (mandrel dipped, two dips minimum, must be airtight)

AIR RESERVOIR MEMBRANE

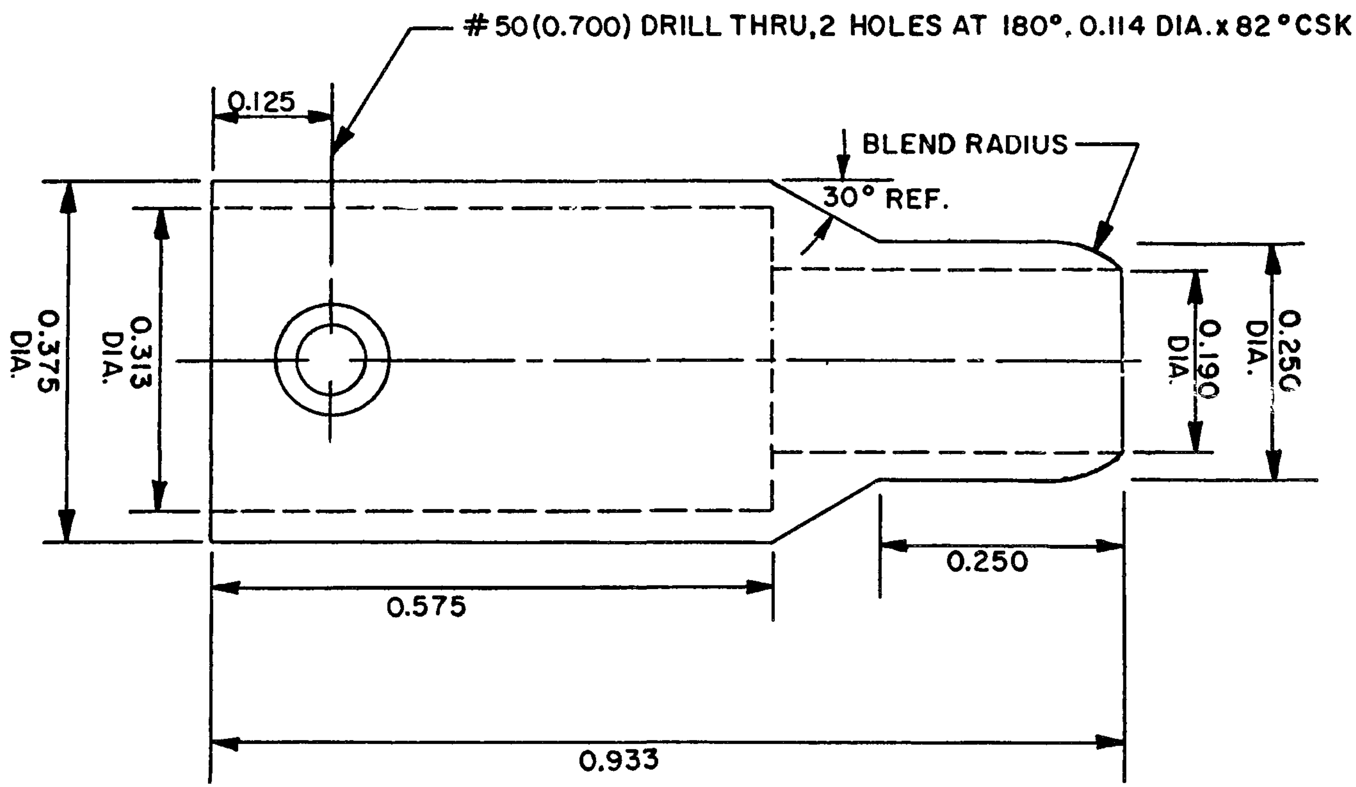
DRAWING AND PART NUMBER A9

MATERIAL: 316 STAINLESS STEEL



HOUSING

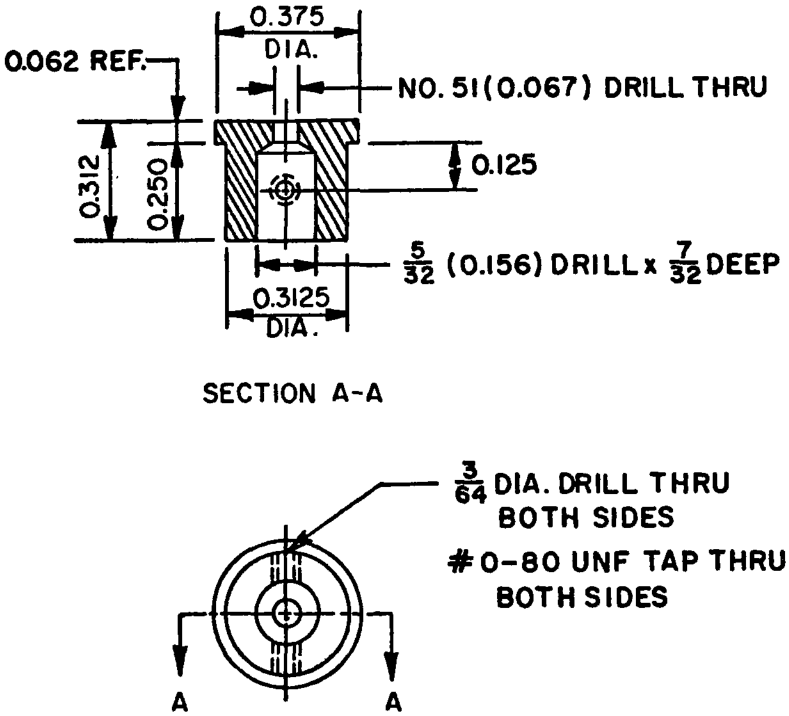
DRAWING AND PART NUMBER A10



MATERIAL: 316 STAINLESS STEEL

SHROUD

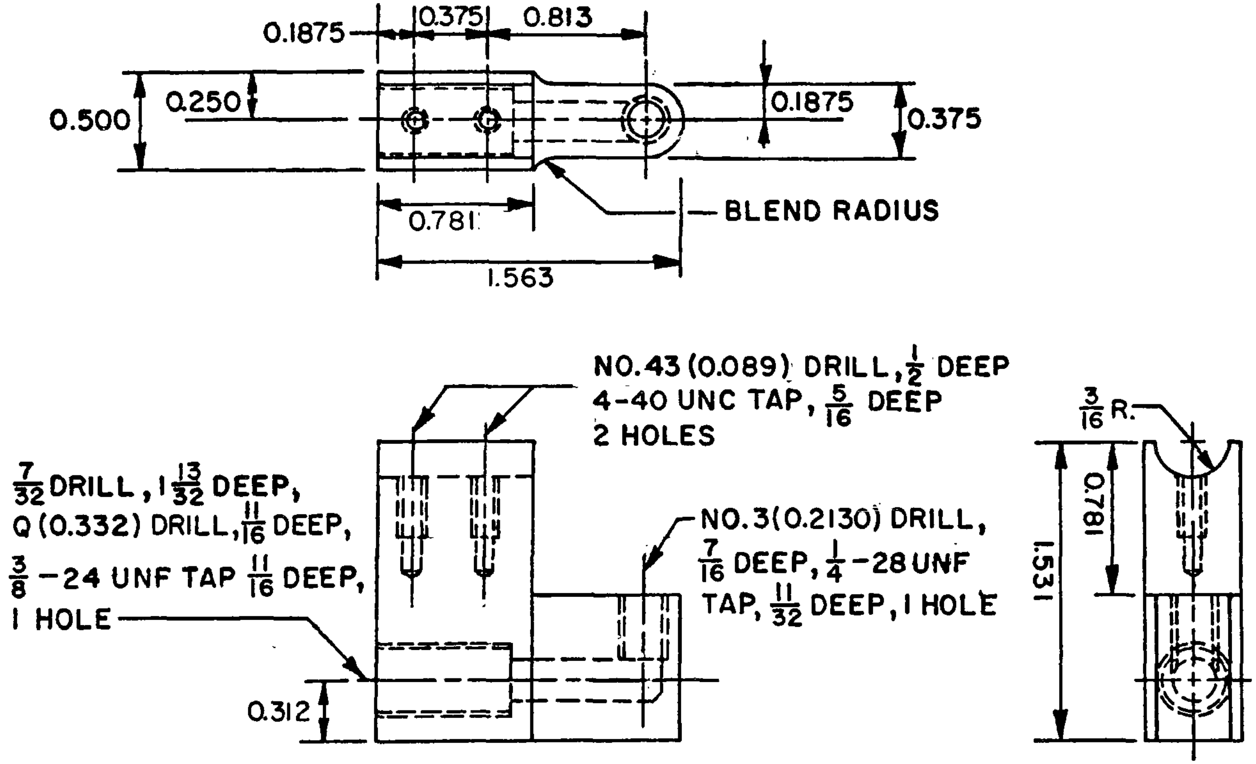
DRAWING AND PART NUMBER A11



MATERIAL: 316 STAINLESS STEEL

END PLUG

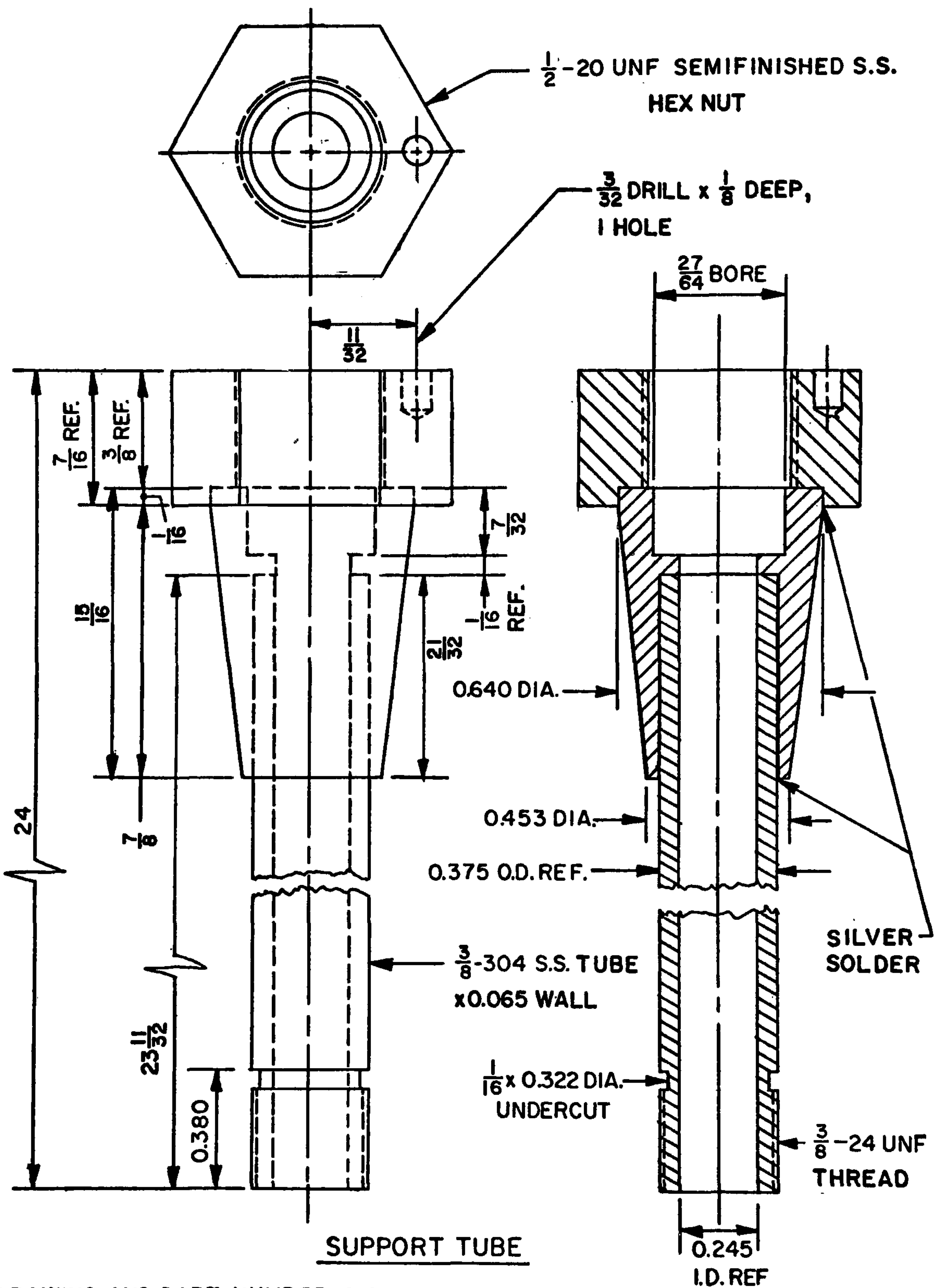
DRAWING AND PART NUMBER A12



MATERIAL: 304 STAINLESS STEEL

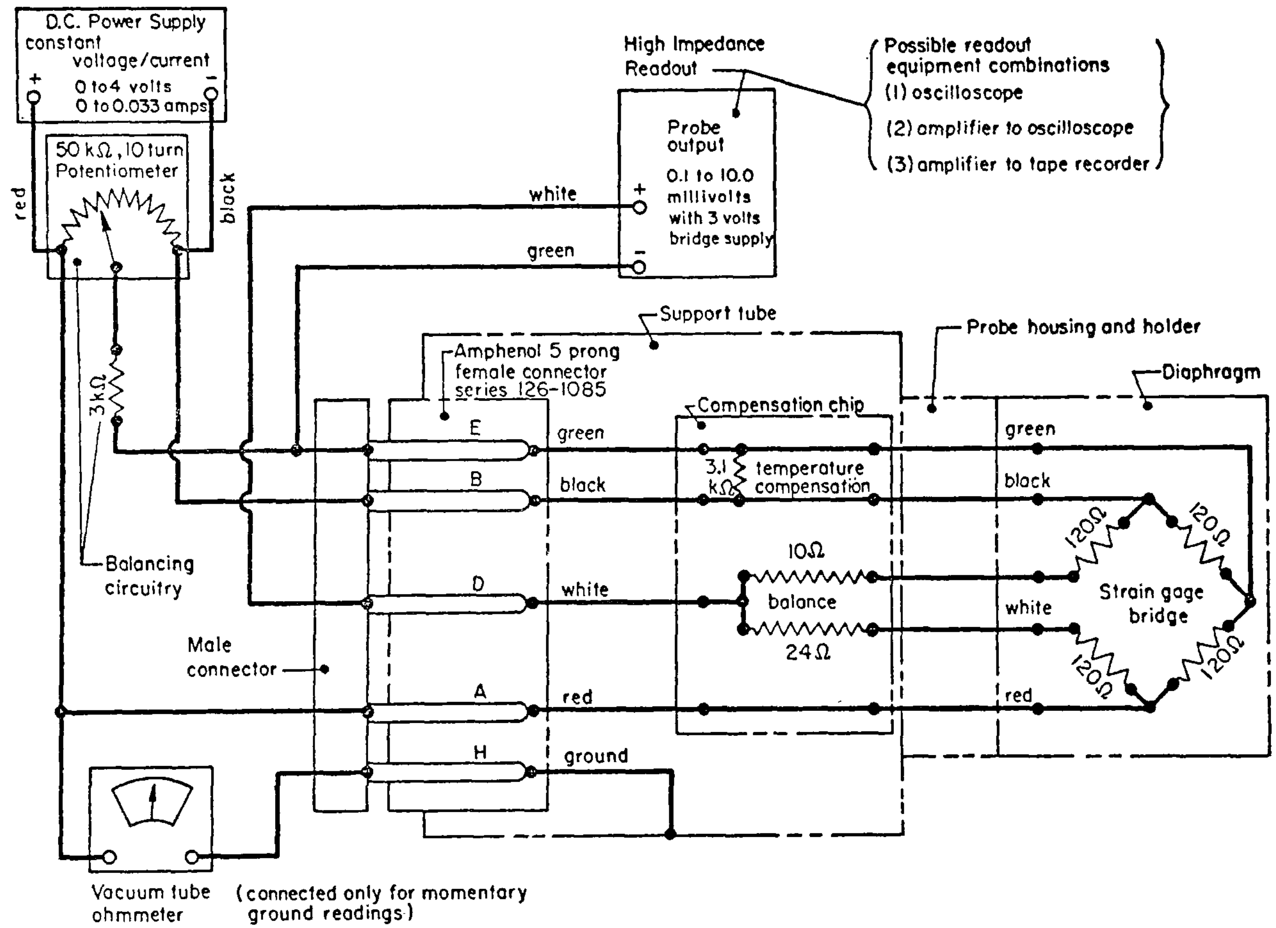
HOLDER

DRAWING AND PART NUMBER A13



SUPPORT TUBE

DRAWING AND PART NUMBER A14



OPERATIONAL CIRCUIT SCHEMATIC

DRAWING NUMBER A15

APPENDIX B

UNIDIRECTIONAL TURBULENCE PROBE OPERATING INSTRUCTIONS

APPENDIX B

UNIDIRECTIONAL TURBULENCE PROBE
OPERATING INSTRUCTIONS

General Notes

All referenced drawings are to be found in Appendix A.

The probe should be handled with care at all times. When it is being moved in air or in water, it should be handled with reasonably slow deliberate motions so as to avoid damage to the strain gages or their compensation circuitry from dropping or jarring.

The unidirectional probe is a complete sealed assembly; any repair or modification other than that described below must be made by Battelle-Columbus technicians or under the close supervision of Battelle-Columbus personnel.

The only field assembly or disassembly that can be performed is the attachment of an extension support tube and wiring to the 2 foot support tube (see drawings A1, A2, and A14) connection and/or removal and replacement of the shroud over the diaphragm (see drawings A11 and A1). If a support tube extension is to be used and its joint with the 2 foot support tube is to be submerged, extreme care should be taken to secure a watertight joint. The entry of water into the two foot support tube will short and cause corrosion in the circuit's compensation and wiring elements.

Nothing but low pressure and low velocity fluids should touch the surface of the diaphragm transducer. DO NOT use compressed air on any part of the probe. A water meniscus over the diaphragm inside the shroud or over the air reservoir membrane inside the probe housing can be removed by air blown from a long-nosed plastic wash bottle.

Velocity Monitoring

The probe should be connected, as shown in drawing A15, to a good quality constant voltage/constant current D.C. power supply for a few hours (if possible) prior to usage. The circuitry input voltage should be 3 volts with a constant voltage setting and the bridge should be reasonably zero balanced (as indicated by its high impedance readout instrumentation) with the 50,000 ohm balance potentiometer (schematically shown in drawing A15). After this warm up period the balance should be set at an exact zero and the power supply should be switched from constant voltage to constant current. The maximum voltage limit should then be adjusted to a higher value of 4.0 volts. Note that the voltage to the bridge should never exceed 4 volts.

During all subsequent handling the readout instrumentation should be adjusted such that a $\pm$ full scale reading will represent $\pm$ 10 millivolts output from the probe. If, during handling, the instrument shows a reading approaching full scale (particularly any rapid change) a potentially dangerous pressure on the diaphragm may be at hand, such as collapse of the air reservoir membrane or excessive water velocity, and corrective action should be taken. Excessive water velocity will be obvious in the stream condition. A collapsed air reservoir membrane will provide a steadily increasing reading to $\pm$ 12 millivolts by the time the probe is immersed in 6 inches of water (see Figure 12 in the main body of this report). A water leak anywhere in the system will change the output drastically and should show as a grounded circuit condition.

The circuitry's resistance to ground should be checked periodically. A vacuum tube ohmmeter has been used for this purpose connected to the powered circuitry in the manner shown on drawing A15. A check on the ground prior to wetting of the probe usually shows a value of over 60 megaohms. Immediately on wetting of the probe this value drops into the 30 megaohm range and with extended immersion it deteriorates. The probe should be removed from the water and dried in air (blow water out of the housing from around the air reservoir membrane) if the ground drops to less than 1 megaohm.

Before immersion the probe should be pointed up or down and filled with water inside the housing around the air reservoir. This is done by applying the snout of a water-filled plastic wash bottle to the bottom most hole in the housing and, while covering the hole on the opposite side of the housing with a finger, squeezing water into housing, thus forcing the air out the top holes. Any air-water meniscus inside the housing will be very tenacious and may affect the depth compensation feature of the probe. The water should then be injected through every hole in turn with two of the other holes covered and one left open for relief. The probe should then be placed in the water to a shallow depth. If any air bubbles stick inside the shroud they can be removed with the wash bottle.

The probe can then be immersed to the desired turbulence monitoring position. Due to the drift of the zero balance point a procedure for rebalancing must be followed just prior to each turbulence monitoring period. This procedure consists of placing a baffle or cover across the opening of the submerged probe in order to induce a zero impinging water velocity on the diaphragm while the circuitry is being balanced to zero. During this period the stability should be checked for assurance that the drift rate has become fairly low (0.20 millivolts/min) and consistent. The rate of drift determines the maximum period or magnitude range over which reasonably accurate velocity readings can be obtained after the zeroing procedure. A conservative velocity monitoring period would not exceed five minutes at low velocities (0.5 to 1.5 ft/sec) before repeating the balancing procedure. After rezeroing, the cover is removed and differential voltages proportional to the water velocities will be obtained.

With the 3000 ohm resistor and 50,000 ohm potentiometer balancing arrangement in the bridge circuitry as shown on drawing A15, the output of the bridge will be 2 to 5 percent less, depending on the amount of balance required, than the proportions presented in Figure 13 in the main body of this report.

Unless some major improvement is effected in the probe's resistance to water entry into the strain gage air volume, as manifested by a lack of wide zero shift or a lack of ground deterioration, the probe should not be left continuously under water for longer than two days. To date the removal of the saturated probe from the water and drying in air for a day has been sufficient to return the zero balance and the circuitry ground to reasonable levels, e.g., less than ± 10 millivolts with no balance circuitry and greater than 60 megaohms to ground.

Refinements in the operating procedures for this probe will undoubtedly turn up with its use. Any questions concerning its initial operation should be directed to the authors listed in Section VIII Acknowledgements.

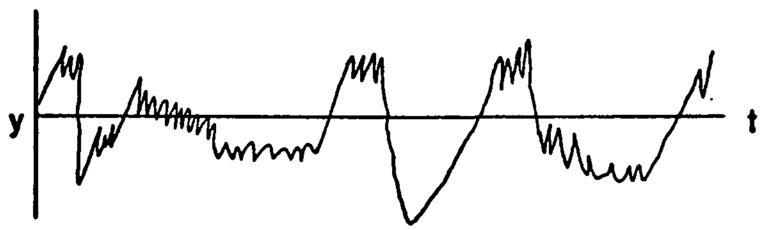
APPENDIX C

CHARACTERIZATION OF RANDOM PHENOMENA

APPENDIX C

Characterization of Random Phenomena

A random signal is one whose amplitude or phase cannot be predicted by a study of previous values of the signal. The signal can represent a voltage, current, stress, pressure, strain, displacement, velocity, acceleration, or almost anything. Such a signal, plotted as a function of time, is represented in the sketch below.



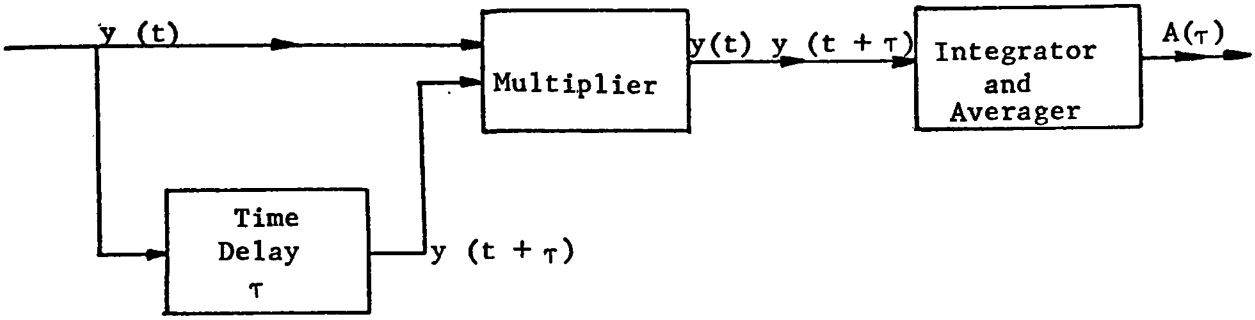
Statistical methods are employed to analyze these random phenomena. The following discussions is restricted to stationary, ergotic random processes. Three important aspects of a random signal are

1. Autocorrelation function
2. Power-spectral density
3. Mean-square value

The autocorrelation function indicates the dependence of the signal upon itself. If y(t) is some random function, the autocorrelation function is

$$A(\tau) = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} y(t)\, y\,(t + \tau)\, dt$$

where τ is a variable time delay. A schematic of an electrical circuit used to obtain the autocorrelation of an electrical signal is shown below.



The autocorrelation function describes, in a sense, the degree of randomness in a signal.

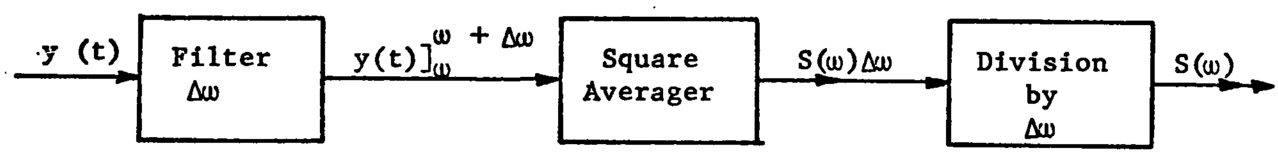
The power spectal density is the Fourier transform of the autocorrelation function, and can be represented by the equation

$$S(\omega) = \frac{2}{\pi} \int_0^{\infty} A(\tau) \cos \omega\tau \, d\tau$$

The power spectral density indicates the mean-square contribution in each frequency interval, $\Delta\omega$, and can also be represented by the equation

$$S(\omega) = \lim_{\Delta w \to 0} \overline{\frac{\Delta (y^2)}{\Delta\omega}}$$

A schematic of a power spectral density analyzer is shown below.



The mean square value of a random signal is

$$\overline{y^2} = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} y^2 (t)\, dt$$

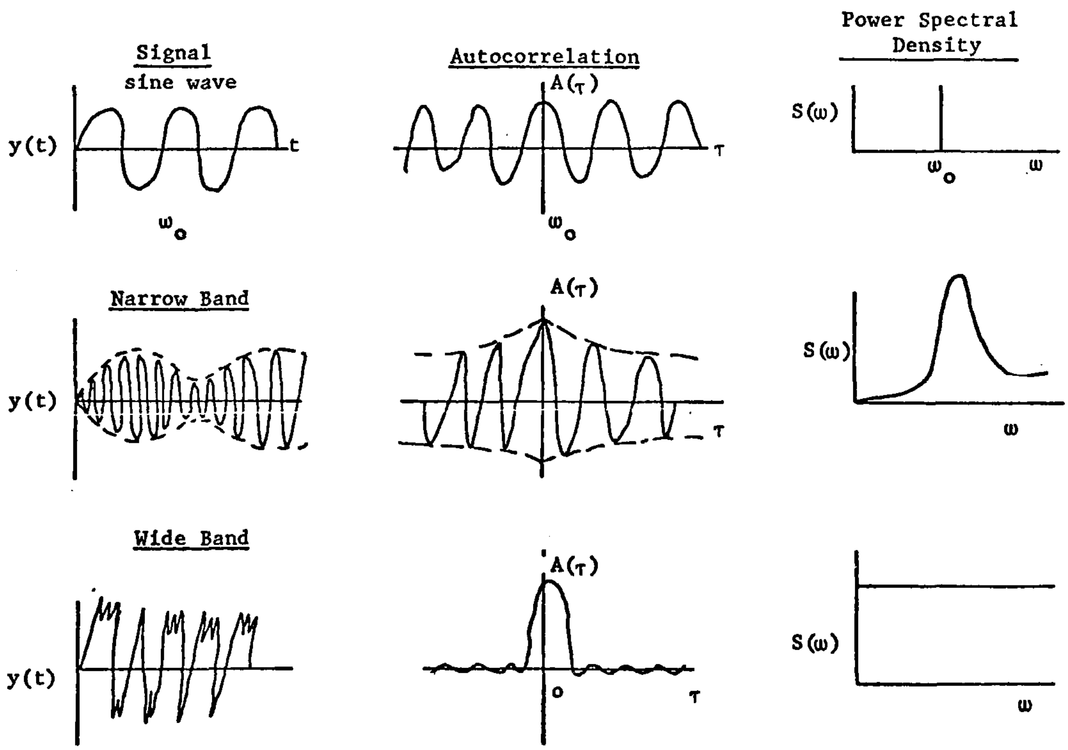
Since a power spectral density plot of a random signal indicates the mean square contribution in each frequency interval, the total area under the curve is also the mean square value of the signal.

$$\overline{y^2} = \int_0^{\infty} S(\omega)\, d\omega$$

The root mean-square value is the square root f the area under the power spectral density curve.

$$y_{RMS} = \sqrt{\overline{y}^2}$$

Typical autocorrelation and power spectral density plots for three types of signals are shown below.



It is proposed to use these methods in characterizing turbulence in a flowing stream. The turbulence detection whose output is proportional to pressure, would be placed at a desired location in a stream. The output would be recorded as a function of time. If the dynamic signals are predominately in the low-frequency spectrum (5 cps or less) the output would be recorded using some type of pen recorder. The analysis of the data could be performed using digital techniques. If the dynamic signals are in the higher frequency range (greater than 5 cps) magnetic tape could be used and the analysis performed using analog techniques.

It is anticipated that static signals (zero frequency) with essentially constant magnitudes are characteristic of smoothly flowing streams, while signals with widely varying magnitudes and frequencies are characteristic of turbulent streams. These extremes and environments between these limits should be clearly indicated by the spectral density and root mean-square value of the pressure history.

1 Accession Number	2 Subject Field & Group	
	Ø2E	**SELECTED WATER RESOURCES ABSTRACTS** INPUT TRANSACTION FORM

5 Organization

Battelle Columbus Laboratories Columbus, Ohio

Applied Solid Mechanics Division

6 Title

MULTIDIRECTIONAL TURBULENCE PROBE DEVELOPMENT
Phase I - UNIDIRECTIONAL TURBULENCE SENSOR DEVELOPMENT

10 Author(s)

Atterbury, Thomas
Sorenson, James E.
Groom, Jack J.

16 Project Designation

EPA, Project 16050 DØW

21 Note

22 Citation

23 Descriptors (Starred First)

*Turbulence, *Turbulent Flow, Non-Uniform Flow, Eddies, *Streamflow, Channel Flow, Flow Profiles, Monitoring-Data collections, *Measuring Instrument Strain Gages

25 Identifiers (Starred First)

*Turbulence Sensing Devices, Measurement of large eddies

27 Abstract

Development of a unidirectional-turbulence probe was undertaken to investigate the feasibility of a small-diameter strain-gaged diaphragm-type pressure transducer and a self-adjusting depth compensation air reservoir for use in the follow-on development of a small (1/2-inch diameter) multidirectional-turbulence probe. A unidirectional probe has been developed which is capable of monitoring water velocities over a range of 0.5 to 5 ft/sec in turbulence frequencies of 0 to over 100 Hertz and which will automatically operate in water up to 10-feet deep.

Sealing inadequacies in both the air reservoir membrane and the pressure diaphragm permit moisture entry into the air volume covering the strain gages. This has given rise to balance drift and circuitry ground problems that have resulted in the placing of limitations on the water exposure and turbulence monitoring times for the unidirectional probe. These problems also suggested that the concepts cannot be immediately incorporated into a multidirectional probe design.

The unidirectional turbulence probe was released to the Environmental Protection Agency for use and further evaluation with recommendations for analysis of data obtained with the probe.

Abstractor	Institution
Jack J. Groom	Battelle Columbus Laboratories

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