UNIVERSITY OF MINNESOTA
ST. ANTHONY FALLS HYDRAULIC LABORATORY
LORENZ G. STRAUB, Director

Technical Paper No. 10, Series B

Velocity Measurement of Air-Water Mixtures

Limited Distribution Preprint of Paper Presented Before
Hydraulics Division, ASCE, Annual Convention in New York, October 25, 1951

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LORENZ G. STRAUB, JOHN M. KILLEN,
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ABSTRACT

A troublesome aspect of experimental studies of flow phenomena in air-water mixtures has long been that of making accurate velocity measurements. In the past, bulk-flow measurements have been made variously with surface floats, injected dyes or salt clouds, and relationships between the discharge and depth of flow. Point measurements of velocity have been attempted by measuring stagnation pressures in the air-water mixture. These methods have not been of sufficient accuracy for many purposes.

An instrument for making accurate point velocity measurements throughout a section of an aerated flow stream has been invented and developed at the St. Anthony Falls Hydraulic Laboratory. The transit time, between two fixed electrodes, of minute cloudlets of salt solution injected repetitively into the flowing air-water mixture is measured electronically. A rate of 15 injections per sec permits a direct measure of the mean flow velocity over a short stream filament. In the present form of the instrument, this mean velocity is indicated directly on a meter calibrated in feet per second. Measurements can be made in aerated flows with air concentrations exceeding 70 or 80 per cent and at very high velocities.

Velocity measurements with the new velocity meter in nonaerated flows check within 1 or 2 per cent of those made with a Pitot tube. The integrated water discharge in an aerated flow stream, taking into account both the measured air distribution and the velocity distribution and making reasonable estimates of the water discharge through the boundary areas have also checked the water discharge measured directly with an accuracy of 1.5 per cent.

C O N T E N T S

		Page
Abstract		iii
List of Illustrations		v
I.	INTRODUCTION	1
II.	EARLIER STUDIES AND INSTRUMENTATION	6
III.	SALT VELOCITY METHOD	8
IV.	FACTORS ENTERING SELECTION OF VELOCITY MEASURING METHOD	8
V.	OPERATING PRINCIPLES OF THE SAF VELOCITY METER	10
VI.	TEST VERIFICATIONS OF SAF VELOCITY METER	22
VII.	CURRENT STATUS OF DEVELOPMENT OF THE SAF VELOCITY METER	26

L I S T O F I L L U S T R A T I O N S

Figure		Page
1	Aerated Flow in High-Velocity Channel at 8 Degree Slope . . .	2
2	Profile of Aerated Flow at 12 Degree Channel Slope	3
3	High-Velocity Channel and Control Cabinet	5
4	Probe and Injection System of SAF Velocity Meter	12
5	Photographic Record of Undesirable Type of Cloudlet	14
6	Photographic Record of Desirable Type of Cloudlet	15
7	Simplified Block Diagram of Electrical Circuits for the SAF Velocity Meter	17
8	Indicating and Timing Circuits of the SAF Velocity Meter in Unit Chassis	18
9	Control Panel of Indicating and Timing Circuits.	19
10	Sketch of Indications from Electrodes as They Appear on Cathode Ray Tube	20
11	Motion Picture Record of Successive Indications on Cathode Ray Tube	20
12	SAF Velocity Meter Mounted for Open-Channel Measurements . . .	21
13	Velocity-Measurement Comparisons of SAF Meter to Pitot Tube .	23
14	Air-Concentration and Velocity Traverses of Aerated Flow with SAF Instruments	24
15	SAF Velocity Meter Mounted for Traversing Laboratory Open-Channel Flows	27

VELOCITY MEASUREMENT OF AIR-WATER MIXTURES

I. INTRODUCTION

The search for adequate explanation of the physical phenomena of natural occurrences is invariably held in abeyance by the lack of suitable instruments and standards of measurement. Once accurate and detailed measurements can be made, the analytical treatment of a wide range of conditions is usually possible in the light of basic experimentation. The insufflation of air into high-velocity streams of water in open channels is one of the many fluid mechanics phenomena still held back in its complete analytical explanation by the inadequacy of instrumentation required for experimental observations.

The ability of high-velocity streams of water to entrap and hold large quantities of air is apparent in flows over spillways or down steep chutes. The "white water" produced by this air insufflation of open-channel flows is a heterogeneous mixture, varying in bulk density throughout the depth of flow and exhibiting pulsating density variations at all depths. The definition of air-entrained flow as regards bulking, velocity, depth and slope relationships, is important to the designing engineer; however, he has few conclusive data on which to base quantitative estimates of these factors when considering design for freeboard and energy dissipation in steep gradient structures. Typical patterns of air-water mixtures in high-velocity flows in open channels are shown photographically in Figs. 1 and 2. Figure 1 shows the water surface recorded by high-speed photography and similarly Fig. 2 shows the profile (through a transparent wall) of an air-entrained stream at a steep gradient.

This paper concerns the development of an instrument, for convenience referred to as the SAF velocity meter, particularly designed for the measurement of velocities and hence velocity traverses in air-water mixtures. The development of this instrument is one phase of a comprehensive experimental and analytical investigation of air insufflation and air-entrained flows which was first undertaken at the St. Anthony Falls Hydraulic Laboratory more than ten years ago, initially under the sponsorship of the Engineering Foundation

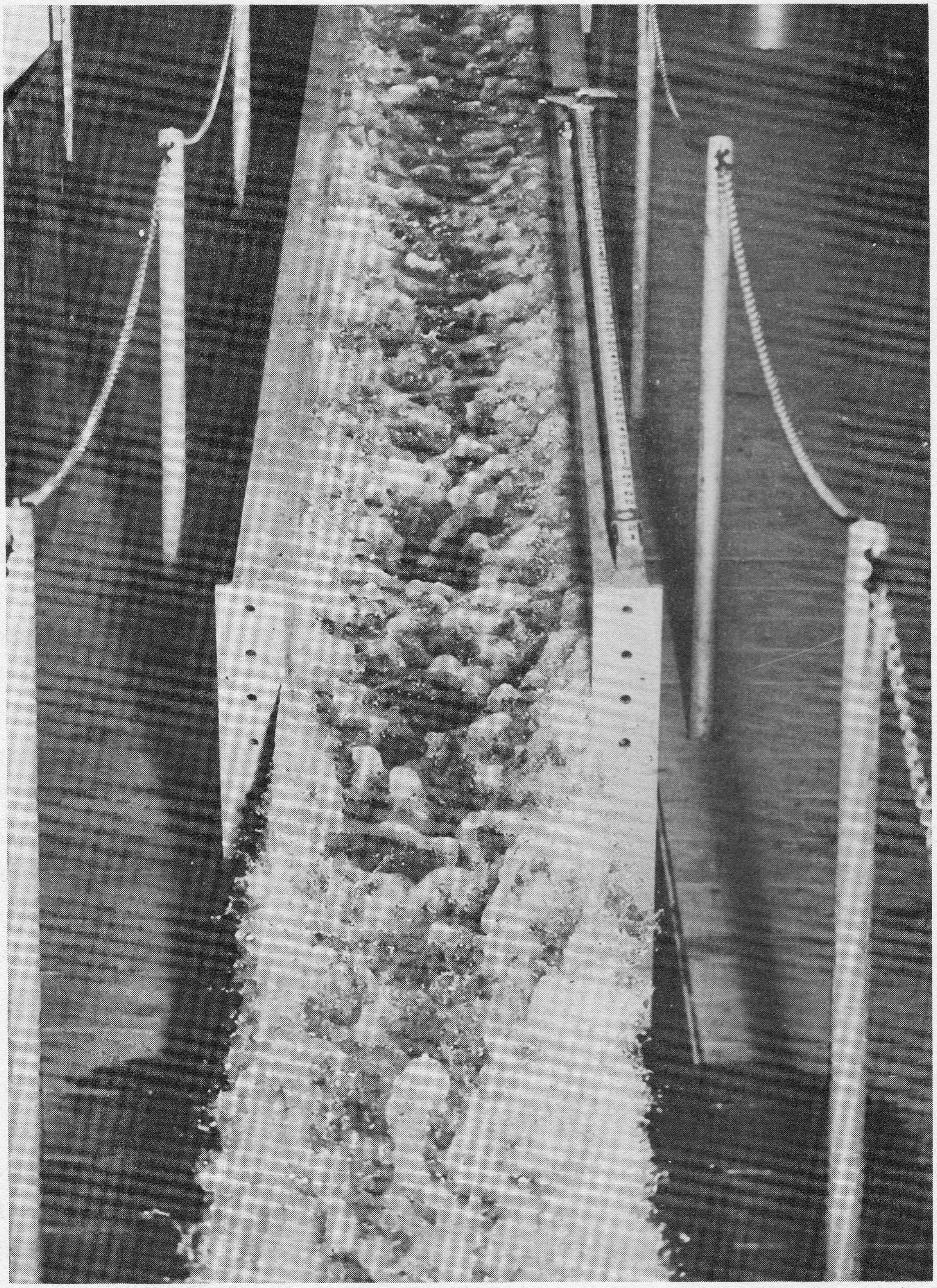

Fig. 1— Aerated Flow in High-Velocity Channel at 8 Degree Slope

The channel is 18 in. wide, 12 in. deep, and 50 ft. long. The photograph was taken at a speed of approximately 1/50,000 sec.

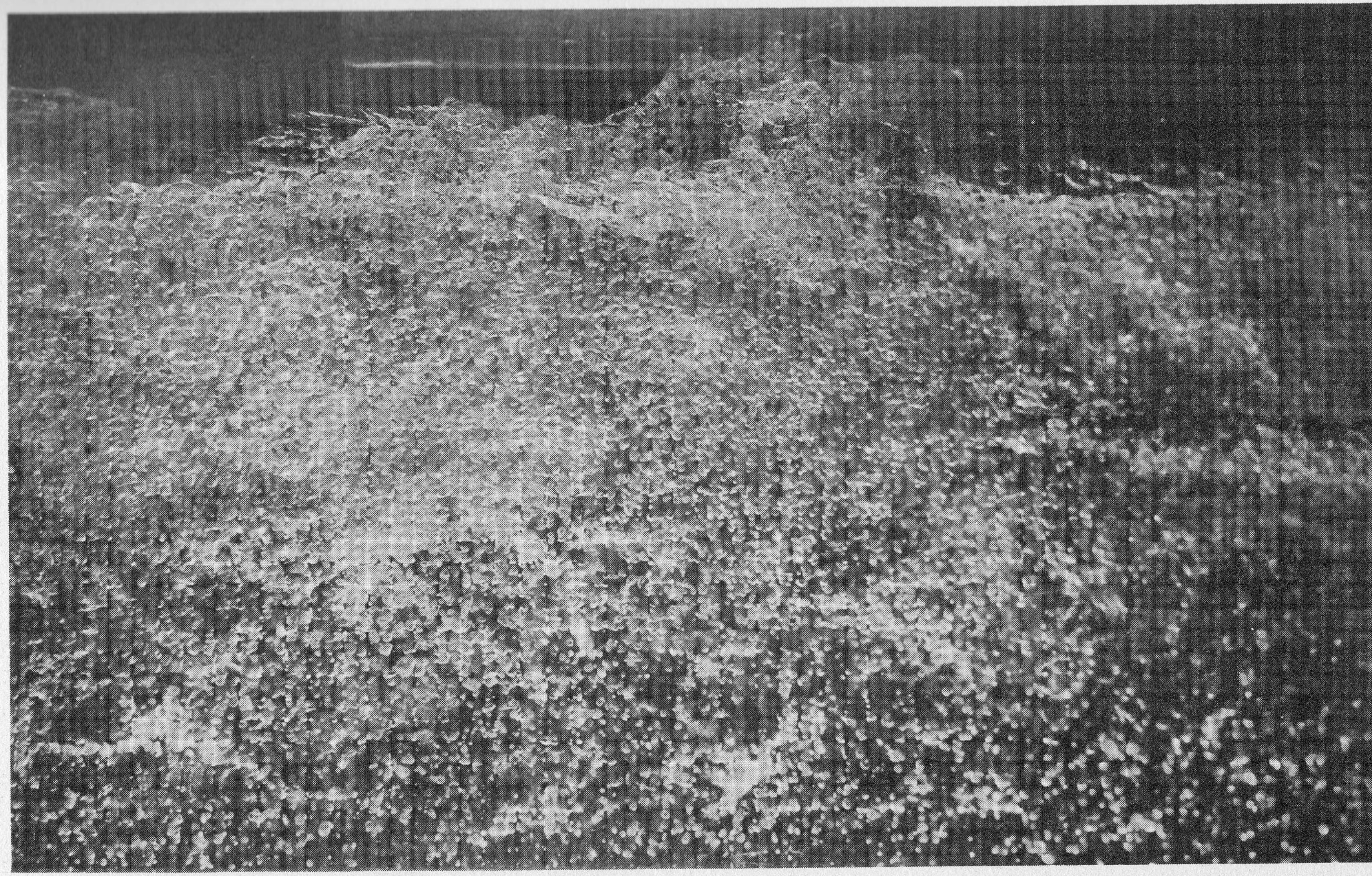

Fig. 2 – Profile of Aerated Flow at 12 Degree Channel Slope

This was photographed through a transparent Lucite side wall of the channel with an exposure time of 1/50,000 sec.

and the ASCE Committee on Hydraulic Research. More recently the studies have been sponsored by the Office of Naval Research.

The St. Anthony Falls Laboratory by nature is uniquely suited for making studies of this character under exceptionally favorable conditions. Large quantities of water are available at the natural 50-ft head of the falls and channels can readily be built to exploit the head and discharge under well-controlled conditions.

The first of these channels was constructed in 1940 in the Laboratory's turbine pit, which is a large vertical shaft inside the Laboratory walls extending from above the normal headwater pool elevation of the falls down to the tailwater pool elevation. Both headwater and tailwater pools extend as canals into the confines of the Laboratory. This first air-entrainment test channel could be set at any slope from horizontal to 45° with the horizontal; the flume section was 1 ft wide, 10 in. deep, and 50 ft long. The research program using this flume did not include detailed velocity measurements; but air-concentration traverses and photographic studies on this experimental setup proved to be invaluable in gaining an understanding of the air-entrainment problem and in developing specialized instruments for a subsequent more comprehensive program.

A larger and more versatile air-entrainment test channel has now been built to replace the earlier setup at the same location in the Laboratory. The flume is 18 in. wide, 12 in. deep, and 50 ft long and can be set at any slope from the horizontal to the vertical, that is, through a slope range of 90°. The design features of this channel are not to be discussed in this paper; suffice it to say, however, that the headbox design presents a region of uniform velocity at the inlet end of the flume which has proved useful for testing the velocity meters through a wide range of velocities. Figure 3 is a photograph of the new test channel and the cabinet which houses the controls for setting of a wide range of slopes, discharges, and related aerated flow conditions.

Instrumentation has been incidental to the entire experimental program of aerated flow so that the sequence of steps leading to the present form of the SAF velocity meter was supplementary to the studies using various test channels. Intermediate models of the instrument found extensive use in the course of the experimental program before the later improvements were made.

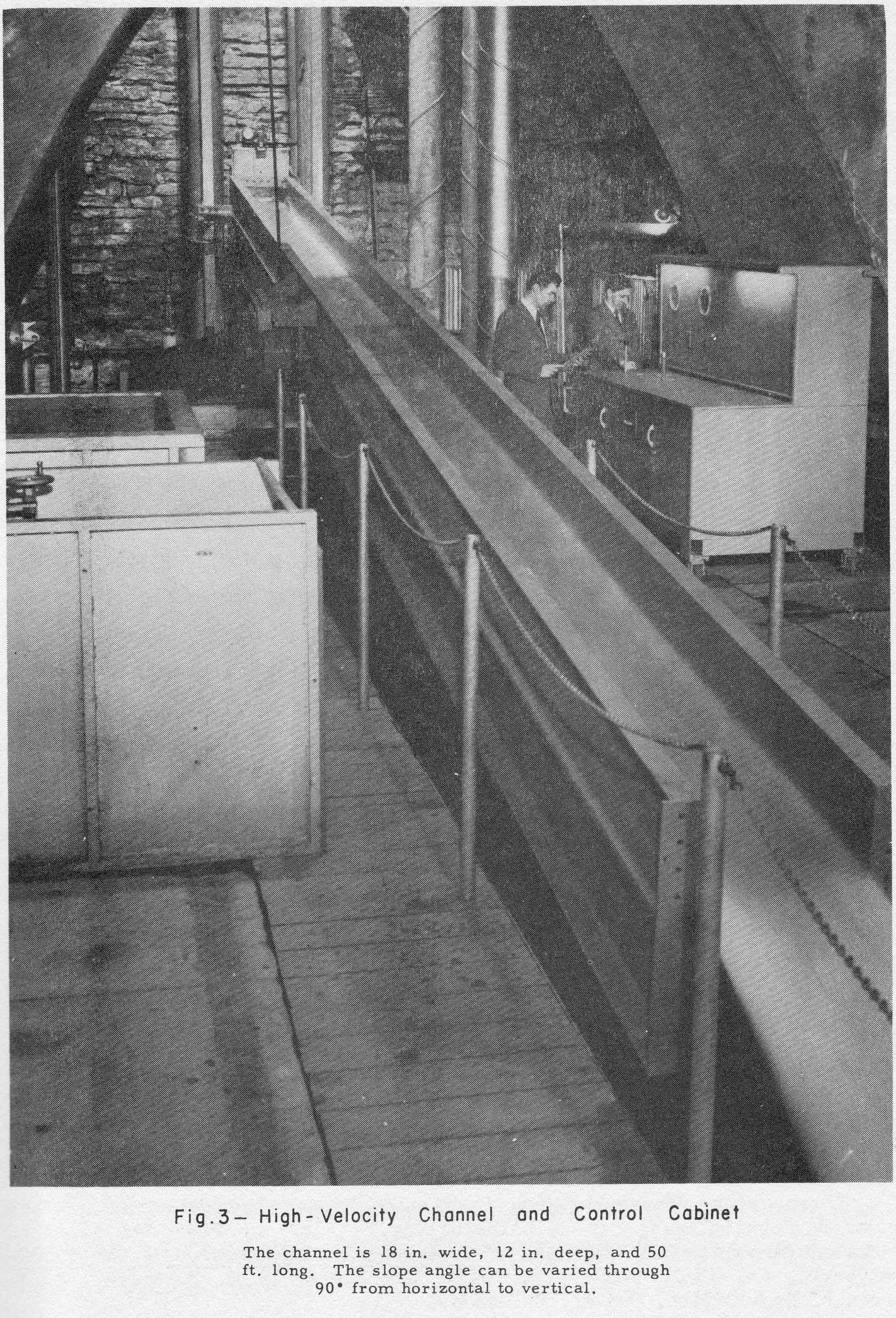

Fig. 3 — High-Velocity Channel and Control Cabinet

The channel is 18 in. wide, 12 in. deep, and 50 ft. long. The slope angle can be varied through 90° from horizontal to vertical.

A report[1] has previously been issued by the St. Anthony Falls Laboratory in which the development of a separate instrument is described for use in measuring air concentration in flowing air-water mixtures. The SAF velocity meter described in the present paper is to be used in conjunction with the previously described air-concentration measuring device to obtain detailed information regarding aerated flows. The functions of the two instruments are complementary in that they are both needed in observations to define air-entrained flows completely, but the two are completely self sufficient so that the accuracies and limitations of either of the instruments are independent of the other.

II. EARLIER STUDIES AND INSTRUMENTATION

A review of the literature relative to air entrainment[2] assembled as an initial phase of the present investigations, reveals that the main experimental effort has been directed toward the determination of air content of flows. When velocity measurements were considered, they were usually employed as a means of obtaining a better estimate of the bulk ratio of air to water in various flows under laboratory or field conditions. There are no precise data on velocity distribution in air-entrained flows which might be used in detailed analyses of shear distribution, energy loss, or other internal flow characteristics.

Ehrenberger[3] of Vienna, Austria, in pioneering studies of air-entrainment phenomena assumed that the velocity distributions in his aerated test channel flows were linear between surface velocities obtained with floats and velocities measured near the flume bottom where there was little entrained

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[1] Owen P. Lamb and John M. Killen, An Electrical Method for Measuring Air Concentration in Flowing Air-Water Mixtures (University of Minnesota, St. Anthony Falls Hydraulic Laboratory Technical Paper No. 2, Series B, 1950).

[2] Owen P. Lamb, Air Entrainment in Flowing Water, A Summary and Bibliography of Literature (University of Minnesota, St. Anthony Falls Hydraulic Laboratory Project Report No. 19, 1949).

[3] Ehrenberger, "Wasserbewegung in steilen Rinnen (Schusstennen) mit besonder Berücksichtigung der Selbstbelüftung," (Flow in Steep Chutes, with Special Reference to Self-Aeration). Osterreichischer Ingenieur - und Architektverein, No. 15/16 and 17/18, 1926. Translated by E. F. Wilsey, U. S. Bureau of Reclamation, Denver, Colorado.

air. With this estimate of the velocity distribution, he used a Pitot tube to obtain air-concentration distribution in vertical traverses, the assumption being that any deficiencies between the stagnation pressure to be expected at the assumed velocity and the stagnation pressure actually obtained were directly caused by the presence of air in the flow at the point of measurement.

Now with newer methods of measuring the air-concentration distribution directly by independent means, the question arises as to the feasibility of using the Pitot tube in conjunction with the data on air content for the purpose of obtaining applicable velocity measurements. If the mixture of air and water were considered to be replaced at every point by a homogeneous fluid of a density the same as the bulk density of the mixture, the Pitot tube could be used to measure the velocity. However, the mechanical function of the Pitot tube involves the concept of a point or region of stagnation in the flow; it is therefore necessary to evaluate the possible difference in behavior between homogeneous and mixed flows in the neighborhood of this stagnation point to weigh applicability of the Pitot tube in measuring the velocity of mixtures. A detailed discussion of the inherent shortcomings of the Pitot tube for measuring the velocity of mixtures will be dispensed with. However, suffice it to say that in the case of points of flow where the amount of air entrained is small, the curvature of the streamlines at the end of the tube will, among other things, cause separation of the air and water as compared to the normal mixture. At higher air-concentration levels, there arises a succession of impingements against the end of the Pitot tube in contrast to a stagnation point and the applicability of the measured values are again questionable. In addition to these and other inherent questionable features of the Pitot tube, the accuracy of the velocity measurements would in any case be limited to the accuracy of the air-concentration measurements instead of being independent of them.

The basic concept of velocity as being distance divided by time provides the most direct means of establishing velocities in open channels. The oldest techniques are based upon this concept. Various float methods have long been used and are still used in river and canal velocity observations, in the form of surface floats, subsurface floats, rod floats, etc. A somewhat later development was to use dye clouds over extended river stretches to determine mean velocities.

III. SALT VELOCITY METHOD

The Allen Salt Velocity Method[4] introduced by C. M. Allen for determining mean velocities and flow quantities by observations over long stretches of channels or conduits marked an advance in measurements of this character. Salt was substituted for previously used coloring material in the injection techniques and then detected by the passage of the salt cloud at some downstream station by recording with an ammeter the increase in conductivity between two electrodes placed in the flow at the downstream station. Various refinements and revised versions of this method were introduced by other investigators. Probably the most practical applications of the Allen Salt Velocity Method were made in closed penstocks, pipelines, and flow through hydraulic machinery for the purpose of establishing efficiencies of hydroelectric plants. The United States Bureau of Reclamation[5] in a study of air-entrained flows, employed the salt velocity methods to obtain mean velocities in extensive reaches of high-velocity open-channel streams in flumes of constant cross section. The velocity measurements were used to gain an estimate of the amount of air entrained in the stream.

IV. FACTORS ENTERING SELECTION OF VELOCITY MEASURING METHOD

The mean velocity of flow through a cross section is readily calculated in homogeneous fluid streams where the discharge and cross section can be directly determined. However, even this latter basic information becomes elusive when air insufflation occurs because then the air discharge and the cross-sectional area are additional points of uncertainty. In fact, the data available to various authors are so inconclusive that contradictory statements have been published as to whether the presence of entrained air results in increasing or decreasing the mean velocity of flow.

In the design of a velocity meter the range of conditions that might confront the instrument are important. Experience shows that insufflation

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[4] C. M. Allen and E. A. Taylor, "The Salt-Velocity Method of Water Measurement," Transactions of the American Society of Mechanical Engineers, Vol. 45, (1923), p. 285.

[5] C. W. Thomas, "Progress Report on Studies of the Flow of Water in Open Channels with High Gradients," (Hydraulic Laboratory Report No. 35, United States Department of the Interior, Bureau of Reclamation.)

might be encountered in streams having a mean velocity as low as possibly 4 fps but usually the velocities are much greater. Thus, the instrument refinements necessary for accuracy at low velocities are unimportant. At higher velocities, where air entrainment is common, the instrument must be rugged, positive in action, and sufficiently versatile to give a reasonable accuracy of velocity measurement throughout a wide aeration-density range.

The customary concept of fluid density applicable to homogeneous fluids is not directly applicable to heterogeneous fluid mixtures of macroscopic proportions. In considering the flow pattern of such a mixture, the filament is made up of random air and water regions. One might for convenience introduce the concept of mean bulk density of the filament, but not without discernment as to the limitations of this concept.

Extensive vertical traverses of air concentration conducted during the earlier studies at the St. Anthony Falls Laboratory indicate that the distribution of air concentration can be approximated by an equation of the logarithmic type when progressing from the flume bottom to the flow surface. Situations might arise where the flow near the bottom of the stream is virtually devoid of entrained air while near the surface nearly 100 per cent air makes up the filament. At lower levels of air concentration where the volume of water exceeds the volume of air, one might expect that the air takes the form of bubbles in the flowing stream of water. At levels where the mean air concentration is very high, it is to be expected that water droplets will be entrained in a moving stream of air. The transition between these two extremes from bottom to top provides a less clearly defined air-water mixture. Observations by means of high-speed photography show other large-scale pulsating phenomena in the air-water flows. At some combinations of slopes and discharges, definite train wave phenomena are superimposed upon the general air-entrainment pattern. Macroscopic air pockets may develop at some flow conditions with the pockets extending far down into the flow. Some conditions are evident in the high-speed photographs shown in Figs. 1 and 2.

The foregoing description of the general character of air-water mixtures in insufflated high-velocity open-channel flow immediately gives rise to the limitations of many customary velocity measuring methods.

V. OPERATING PRINCIPLES OF THE SAF VELOCITY METER

The SAF velocity meter makes use of electronic methods of measuring very short time intervals accurately and easily, as developed extensively during World War II for radar, sonar, and other similar uses. It also makes use of the salt velocity principle which was initially developed to measure mean velocities over long reaches of channel to minimize errors in the observation of time intervals. By use of electronic measurement of time intervals, the distance necessary to observe an accurate velocity can be shortened to such an extent that essentially point velocities can be obtained and therefore velocity traverses over a cross section can be made. In fact even turbulence pulsations can be observed by using very short distance intervals of measurement. The application of an instrument of such basic design to determining velocities in fluid mixtures can be checked against conventional instruments in homogeneous flows.

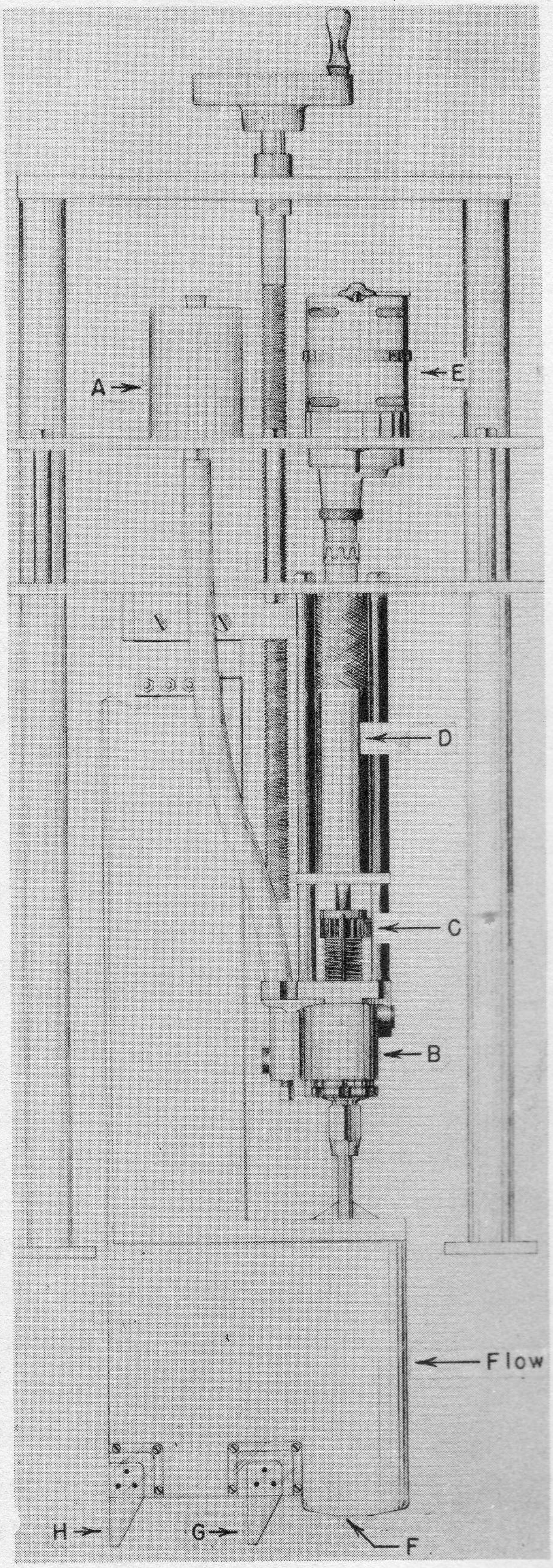
Basically the operating principle of the instrument consists of marking a small element of a flowing mixture and then recording the time interval required for this marked element to traverse a fixed distance. The marking is accomplished by making a diminutive portion of flowing water more highly conductive to electrical current by the injection into the stream of a very small amount of salt solution or similar electric conductor. The passage of this ionized cloudlet is then detected by electrodes in the stream situated at fixed stations in the flow path. The injection must be made sufficiently rapid to label a very small portion of flowing fluid, and the momentum of the injection must be sufficiently low to avoid introducing significant change in velocity of flow from the injection.

Using the foregoing principles, the new instrument combines a mechanical injection system with an electric timing and indicating system for the purpose of measuring velocities in air-water mixtures. In its present design the device can complete the entire velocity measurement from the injection to recording within a distance of 6 in. or less along the flow filament. The marking is done by injecting a miniature slug of 6 per cent saline solution into the flowing stream within a short time interval of less than 1/600 of a second. The volume of each injection is approximately 0.03 cu cm, a quantity sufficiently small to insure no significant momentum effects upon the flowing stream although the velocity of injection is quite high.

The salt solution immediately ionizes the water particles that it contacts so that an ionized cloudlet is placed in the filament of flow of which the velocity is being measured. This cloudlet is then swept past the two electrode stations arranged in tandem along the flow path. Indications are transmitted to the electrical circuit when the front of this ionized cloudlet arrives at each electrode station. By making simple adjustments of the electrical circuit, the time lapse between the instant that the peak indication near the front of the cloudlet arrives at the first electrode station and the instant it arrives at the second station can be accurately measured. In the current design of the SAF instrument, the distance between the electrode stations has been fixed at 3 inches. Only the very tips of the electrodes are left uninsulated and exposed to flow.

In the development of the instrument, much experimental work was done in establishing optimum conditions for injection of the salt solution. The front of the cloudlet is of special importance because it must be sharply defined and vertical to assure sharp and accurate readings. This is accomplished by an abrupt and rapid injection using an injector pump from a Diesel engine as the main component of the system. The injector pump is driven repetitively by a triphammer which in turn is powered by a small electric drill motor. The salt solution to be injected is stored in a small reservoir and fed by gravity into the injector pump. Metering of the quantity injected at each stroke of the plunger is possible because the pump plunger is slotted for variable delivery. It has been found for the open-channel aerated flows now being studied that a rate of 15 injections per sec is most advantageous. At each stroke of the injector pump plunger, the pressure is built up to where it abruptly opens a spring-loaded valve in the outlet port of the injector. This valve closes immediately after the peak of the pressure pulses has passed. The fluid charge then passes through a small injection tube leading from the outward port of the injection pump to the point of injection in the flow stream. At the point of injection the diminutive slug of salt solution in the end of the needle is abruptly forced out into the flow to form the ionized cloudlet whose passage is recorded at the electrode stations.

Figure 4 is a sketch of the injection system. The salt solution from reservoir A flows down through the tube to the inlet port in the Diesel injector pump B. The pinion C which is attached to the pump plunger can be rotated to set the proper delivery volume. The pump plunger is actuated by



A – Salt Solution Reservoir

E – Electric Motor

D – Trip Hammer

C – Pump Plunger Pinion

B – Injector Pump

H – Downstream Electrode Station

G – Upstream Electrode Station

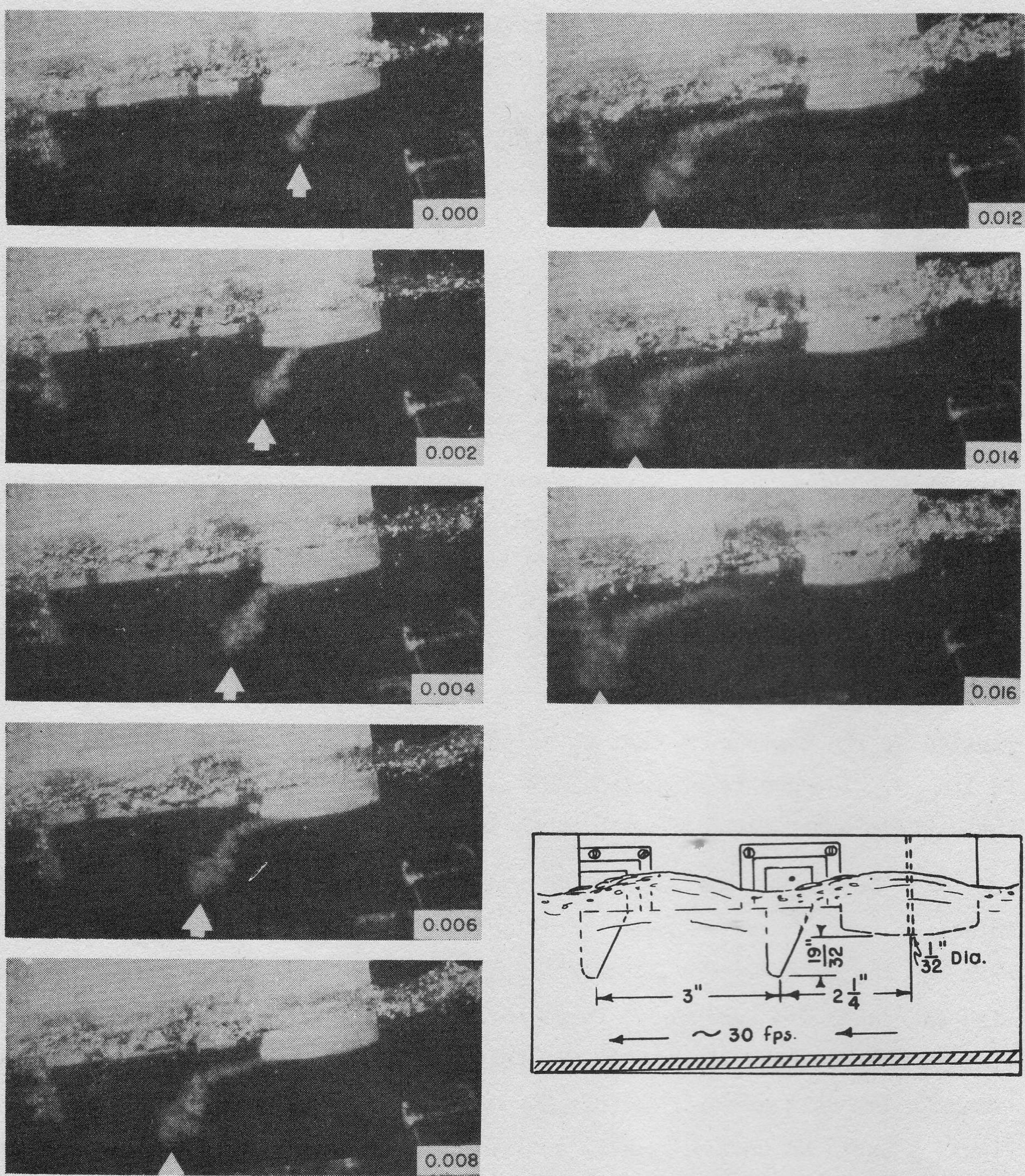
F – Injection-Tube Outlet

Fig. 4 – Probe and Injection System of SAF Velocity Meter

the triphammer D which in turn is driven by the electric motor E. The injection pulse from the pump is carried down through the injection tube to the point of injection at F. If the injected slug encounters any water, its downward movement will be dissipated and the small mass will almost immediately attain stream velocity. The ionized cloudlet in the water will then pass by the tips of the electrodes G and H which are spaced 3 in. apart and a velocity reading will be obtained. If the injected spray does not encounter any water but is rather fired directly into an air pocket, the momentum of the injection will carry the salt solution down past the level of the electrode tips and there will be no indication. The spacings between the two electrode stations, and also between the point of injection and the first electrode station, as well as the difference in level between the point of injection and the electrode tips were all selected so that the salt cloudlets that have attained stream velocity would be the only ones carried past both electrodes, thus forming indications.

The threaded shaft in Fig. 4 is used to position vertically the electrode tips at any desired point in the flow. The lower plate is the only portion of the instrument that is actually inserted in the flow. This plate is 1/8 in. wide and is sharpened at all edges so that it can be inserted into the high-velocity flows without excessive splashing.

Design of the injection system and the nozzle at the end of the injection tube proved extremely critical in obtaining true velocity readings with the instrument. For illustration, two motion picture studies of injection sequences are included. These were made with a 35 mm high-speed motion picture camera operating at 500 frames per sec. Fluorescein dye was substituted for the salt solution so that the shape of the cloudlets would be visible. Figure 5 shows an undesirable injection where the front of the salt cloudlet is inclined with the vertical and has a slight break near the level of the electrode tips. Since the front of the cloudlet is the point at which the beginning of the indication is relayed to the electrical circuit, this injection would tend to promote erroneous readings. Figure 6 illustrates a desirable injection in which the salt cloudlet is compact and the leading edge is vertical. The insulation on the electrodes photographs white. The uninsulated electrode tips are at the very ends of the electrodes and it is this position that marks the point where the velocity is being measured.



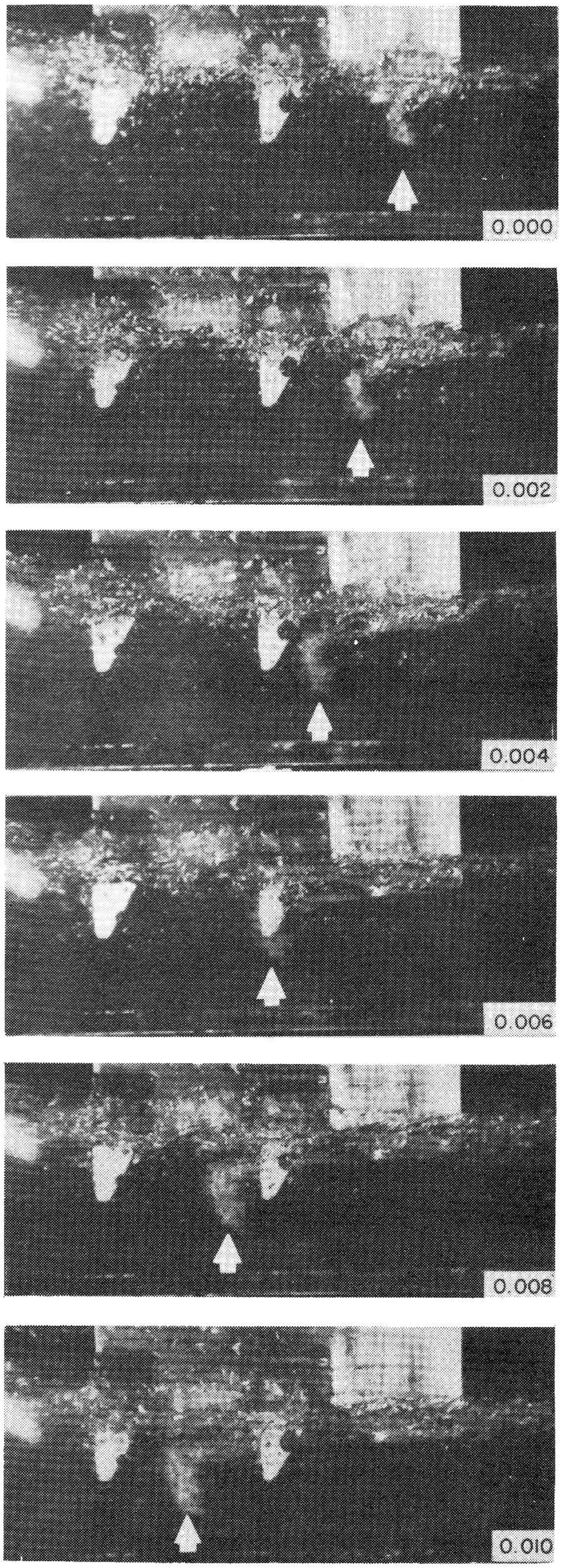
The arrangement shown in this illustration gives a compact cloudlet with its axis tilted to the normal stream flow.

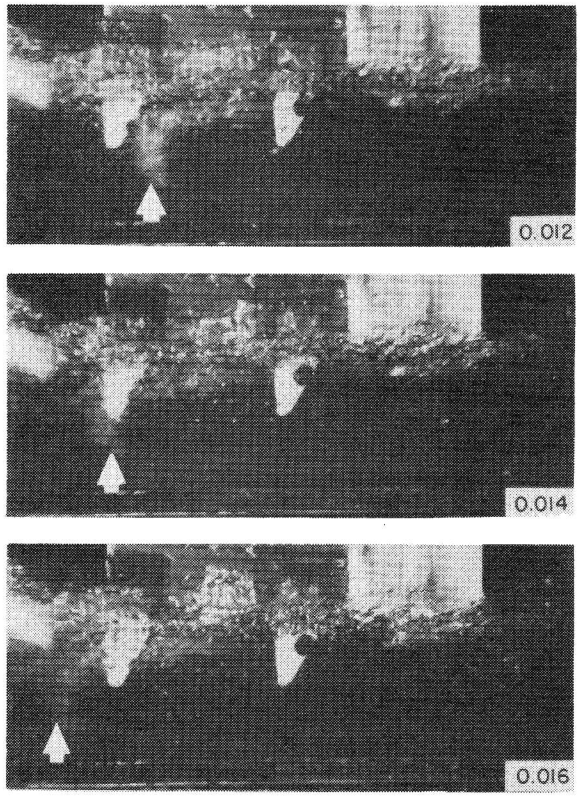
Sketch shows detail of injection-tube outlet and orientation of probe with respect to the flow in which photograph was taken.

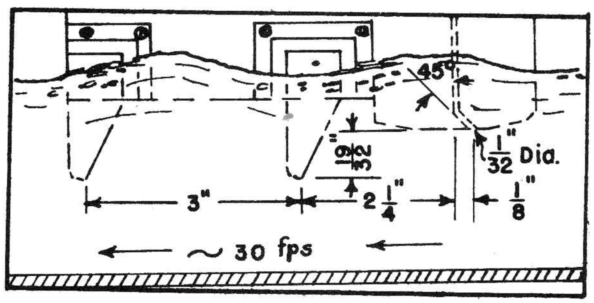
Notations in lower right-hand corners give seconds elapsed from initial picture.

Fig. 5 – Photographic Record of Undesirable Type of Cloudlet

Fluorescein dye was substituted for salt solution in injection to obtain visual record.







The arrangement shown in this illustration gives a compact cloudlet with its major axis nearly vertical.

Sketch shows detail of injection-tube outlet and orientation of probe with respect to the flow in which photograph was taken.

Notations in lower right-hand corners gives seconds elapsed from initial picture.

Fig. 6 – Photographic Record of Desirable Type of Cloudlet

Fluorescein dye was substituted for salt solution in injection to obtain visual record.

The electrical circuits are simply diagrammed in Fig. 7. The leads from each of the electrode stations in the probe are connected to the cathode ray tube through their respective electrical amplifiers. The power supply and sweep generator circuits are necessary for the operation of the cathode ray tube. The circuits are all enclosed in the chassis illustrated in Fig. 8. The electronic timing circuit is similar to a type developed for radar timing during the past war. The electronic timing circuit's function is to place marks on the cathode ray tube screen at the beginning and at the end of each timing interval. Separate knobs on the electrical control panel shown in Fig. 9 as multivibrator and phantastron allow the operator to position the limits of the timing interval at the peaks of the indications from the electrode stations. When these are positioned accurately on the indications from the electrodes, the reading on the phantastron dial can be directly converted into stream velocity. This dial can be set with extreme sensitivity as it has 1000 separate divisions on its ten-turn range. The timing circuit accuracy is on the order of $\pm$ 0.025 milliseconds.

Typical indications that appear on the face of the cathode ray tube are sketched in Fig. 10. The timing marks showing the extremities of the timing interval are properly positioned at the peaks of the indications from the respective electrodes. Repetitive injections result in a succession of such indications on the cathode ray tube screen. They all fall close to each other but there are of course small differences because each indication represents an instantaneous sample of the longitudinal velocity at a point in the flow, and of course the flows in which the measurements are being taken are highly turbulent. At the rate of 15 injections per sec, the visual averaging of the small differences of the indication peak positions and the proper positioning of the timing marks by the operator have been satisfactory.

Figure 11 is a motion picture strip of indications appearing on the cathode ray tube from successive injections. The timing marks were not positioned on the peaks of the indications when these pictures were taken so that the independence of their spacing could be illustrated.

Figure 12 is a photograph of the present design of the SAF velocity meter with the probe elevated above the high-velocity flow beneath. In operation each reading with the instrument takes about 2 min of time. This includes the time necessary for the operator to position the instrument in the flow,

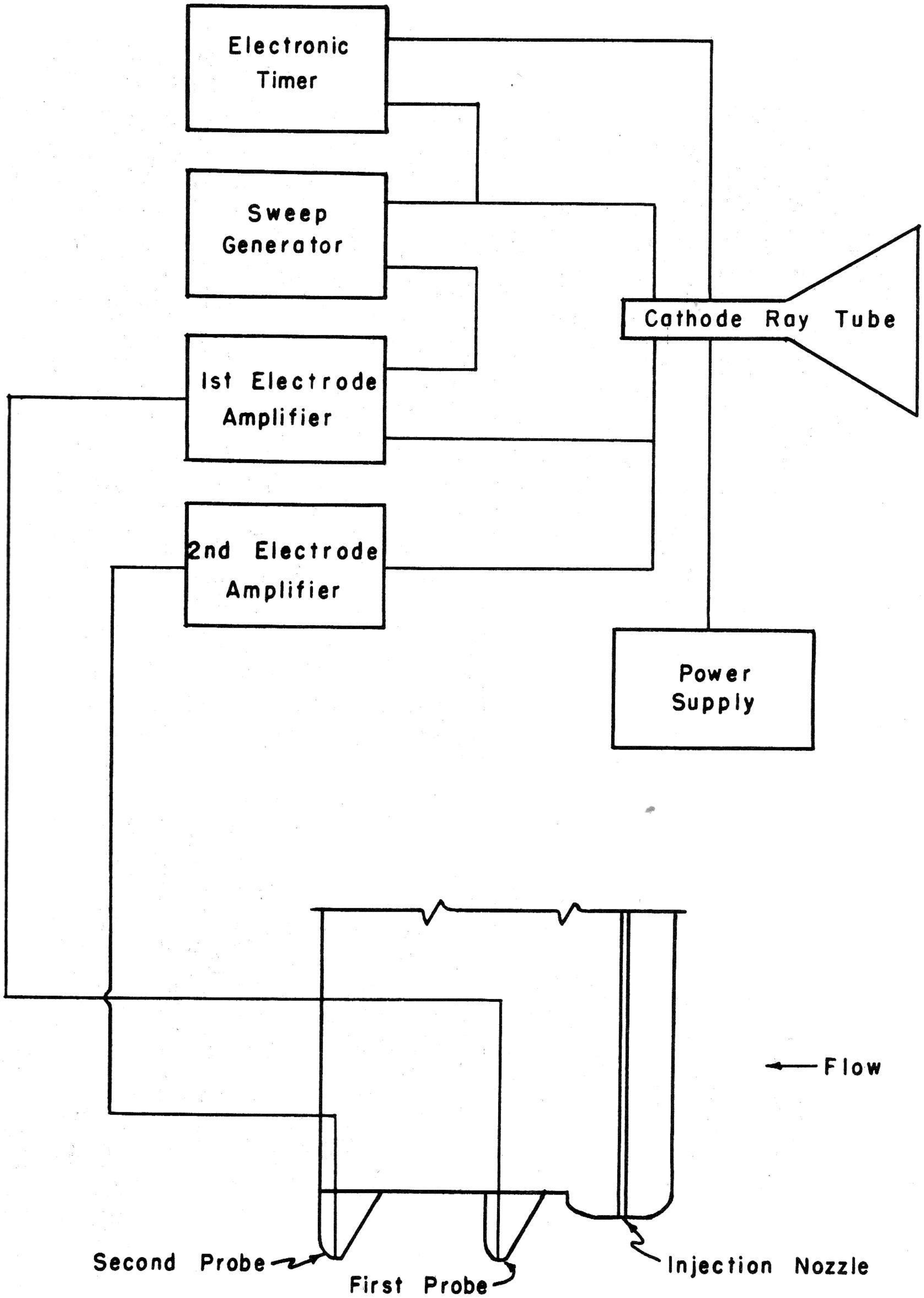


Fig. 7 — Simplified Block Diagram of Electrical Circuit
for the SAF Velocity Meter

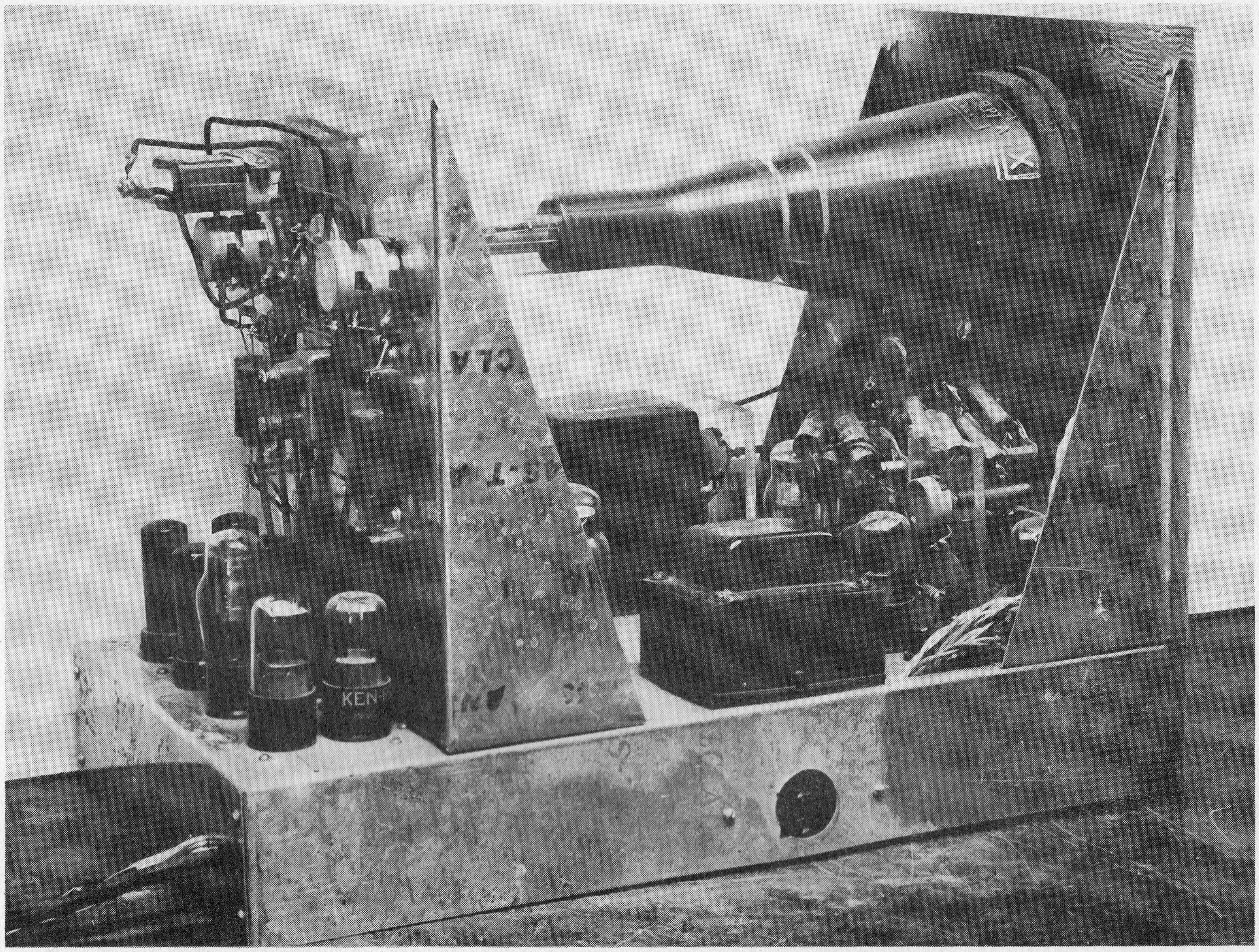


Fig. 8 – Indicating and Timing Circuits of the SAF Velocity Meter in Unit Chassis

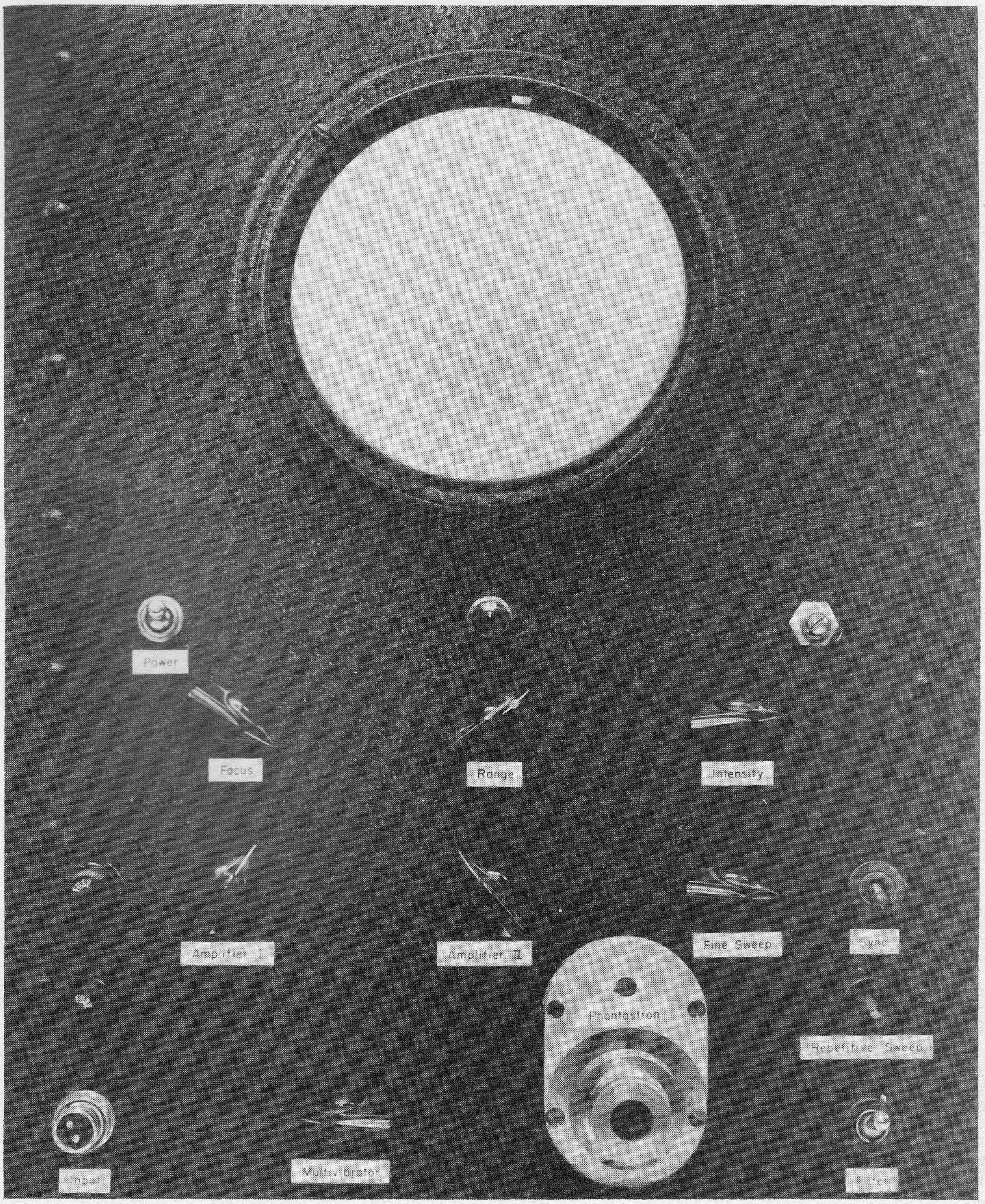


Fig. 9 — Control Panel of Indicating and Timing Circuits

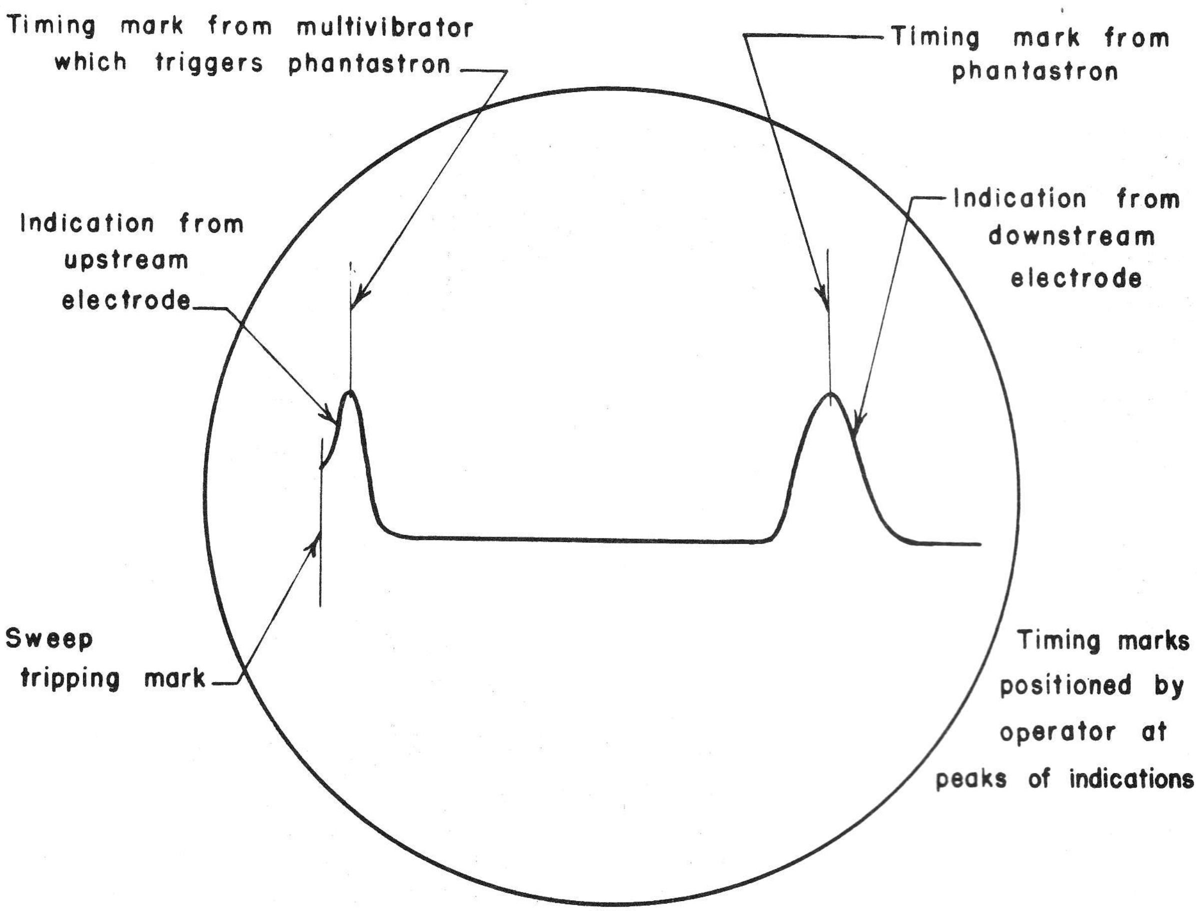


Fig. 10 – Sketch of Indications from Electrodes as They Appear on Cathode Ray Tube

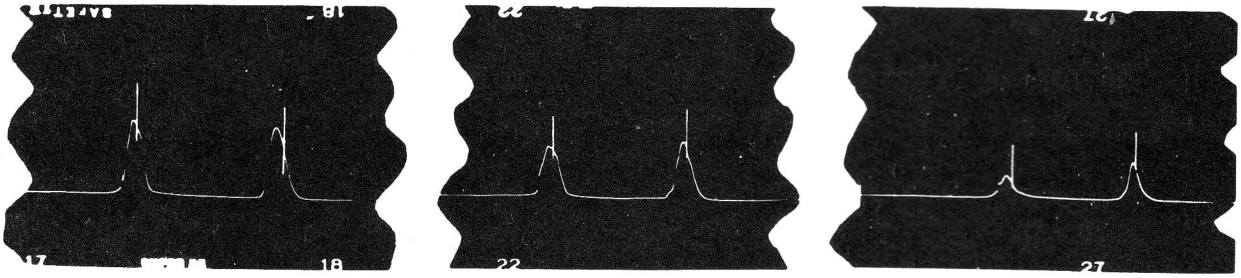


Fig. 11 – Motion Picture Record of Successive Indications on Cathode Ray Tube

The individual frames show the response on the cathode ray tube for the passage of successive cloudlets at 1/15-sec interval.

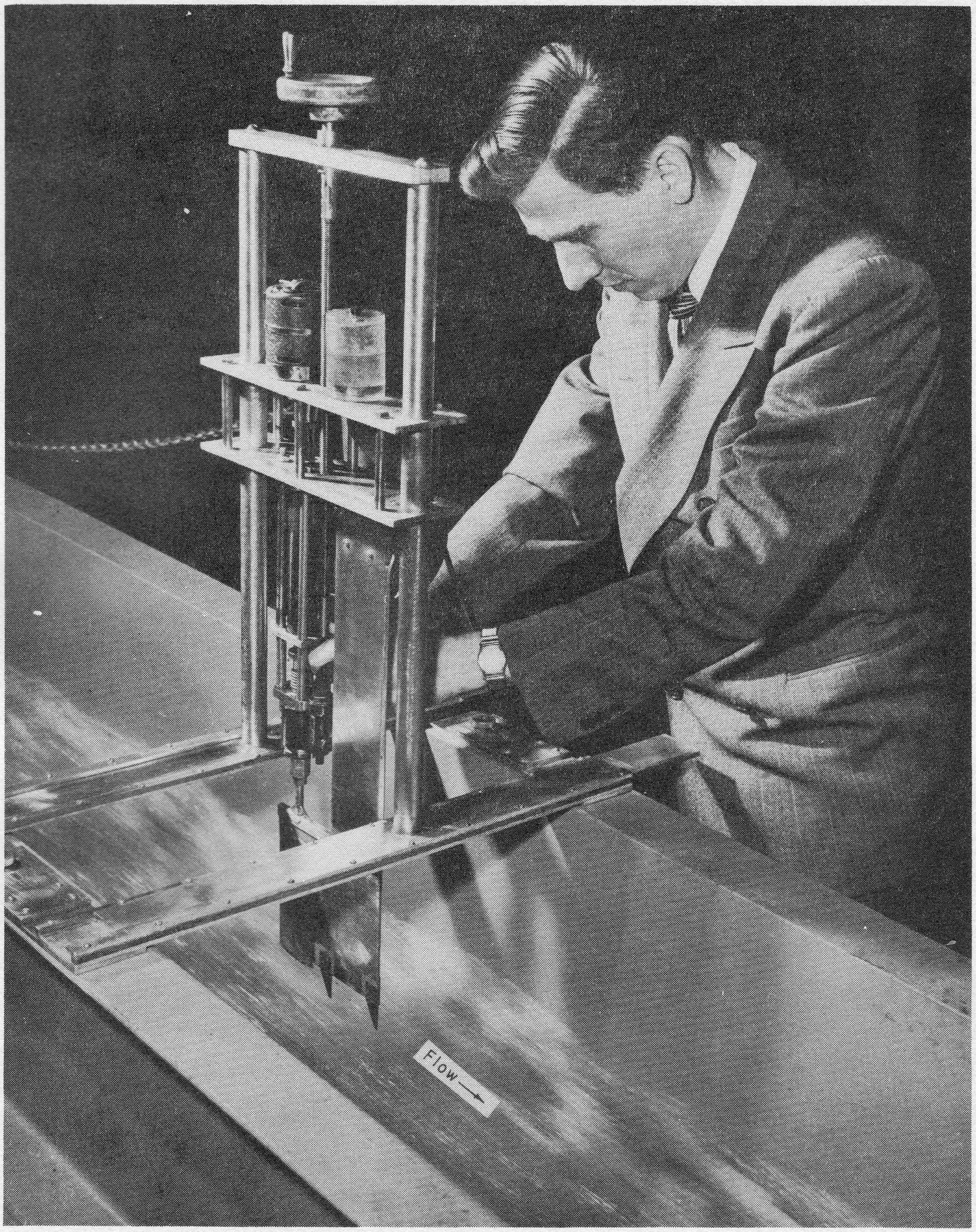


Fig. 12 – SAF Velocity Meter Mounted for Open-Channel Measurements

The electrode stations and injection tube were built into a single 1/8-in. thick brass plate for streamlining in high-velocity flow.

start the injection motor, observe the indications on the cathode ray tube, position the timing marks, and read the velocity on the phantastron dial. The actual procedure can be taught to an observer in a few minutes as the only adjustments necessary for determining the indicated velocity are the two timing marks.

The present instrument has some limitations as regards making accurate measurements very close to the wall. The mounting permits it to be used up to 3/8 in. from the side walls and it is doubtful that accurate readings could be obtained closer than this distance from the wall because of electrode interference set up by the steel wall boundaries. When the point of measurement is closer than 3/8 in. to the bottom of the channel, it is probable that there will be excessive interference with the injection cloudlets which would promote erroneous measurements.

VI. TEST VERIFICATIONS OF SAF VELOCITY METER

Various experiments have been made to test the practicality of operation, the effectiveness, and accuracy of the SAF velocity meter in its present form. The most direct check that can be made is probably a comparison with a Pitot tube in a nonaerated stream. Figure 13 is a typical check comparison between the Pitot tube and the SAF velocity meter in a stream of water in a channel. Independent observations were made by two observers. The velocities indicated by the SAF meter are seen to be slightly lower than those obtained by the Pitot tube at the same point and flow condition, that is, nearly all points fall slightly below the 45° line of perfect correlation. The apparent tendency of the SAF meter is to indicate velocities 1 or 2 per cent lower than the velocities obtained by the Pitot tube. This might be attributable to the velocity deficiency caused by the drag of the first electrode, since the tips of the electrodes are the only obstructions in the flow at the level of the filament being measured.

Experience with the instrument used in aerated flows indicates that it will give a velocity reading when the injection slug comes into contact with a volume in the flow filament that has an appreciable percentage of water. There will be a sufficient number of indications as a result of repetitive injections to obtain mean velocity determinations by the instrument at air-concentration levels up to about 70 or 80 per cent. Above the 80 per cent level of air concentration, there are insufficient numbers of indications on

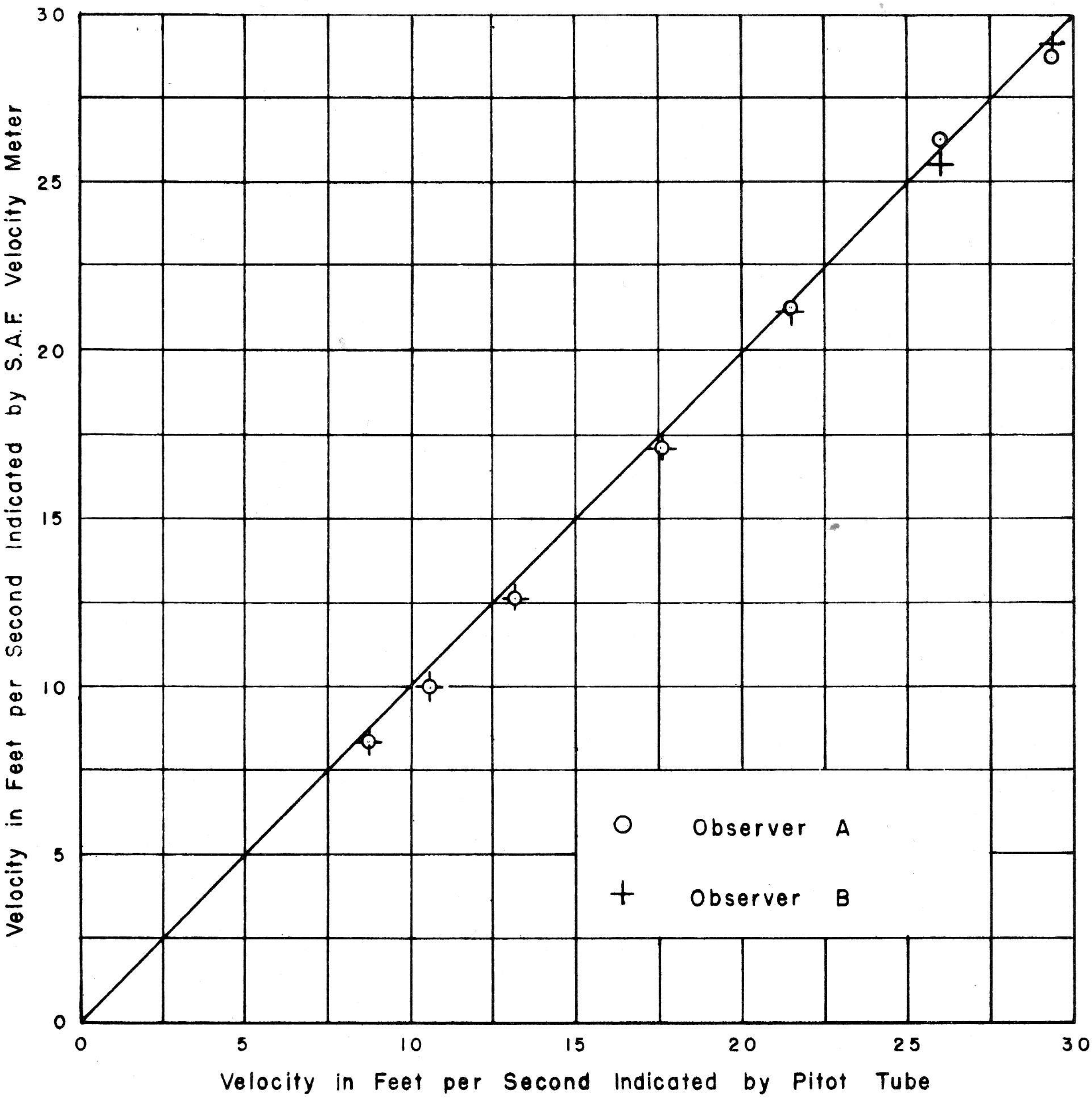
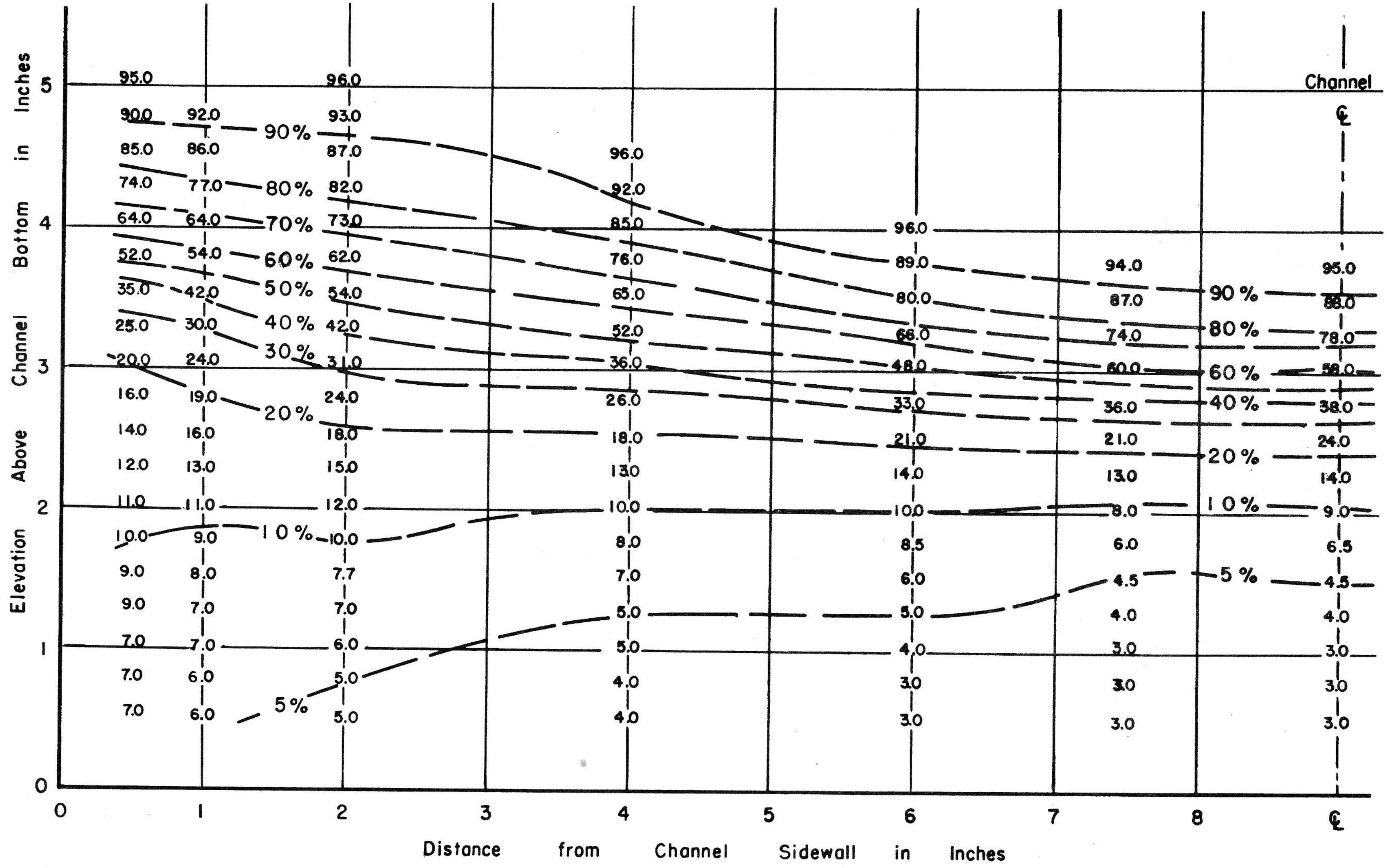
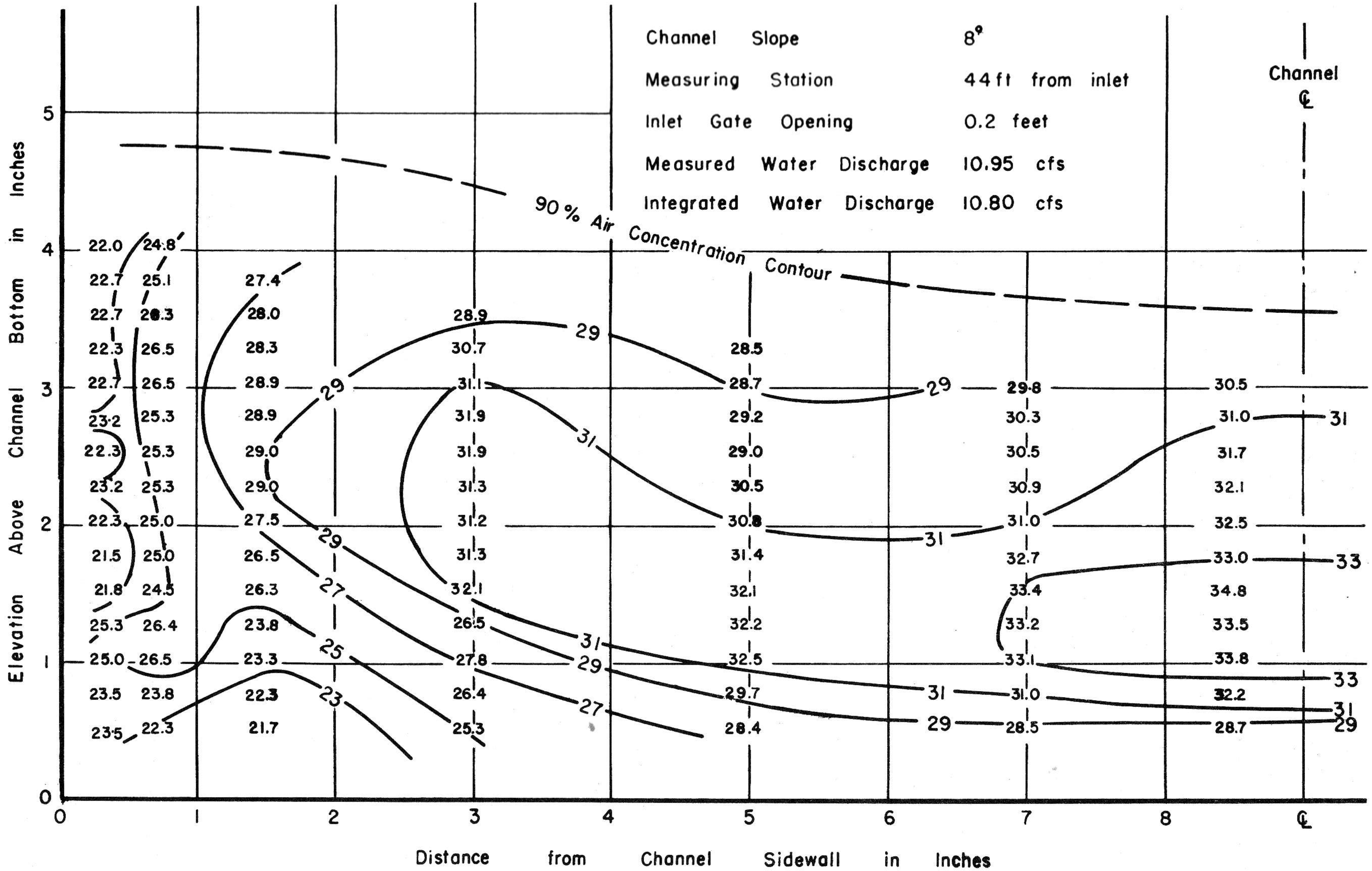


Fig. 13 — Velocity - Measurement Comparisons of SAF Meter to Pitot Tube
Observations were made in flows in an open channel.



a) Air-Concentration Distribution Drawn from Point Observations

Fig.14 – Air-Concentration and Velocity Traverses of Aerated Flow with SAF Instruments



b) Velocity Distribution Drawn from Point Observations

Fig.14– Air-Concentration and Velocity Traverses of Aerated Flow with SAF Instruments

the circuits to measure mean velocity because the water is mainly in the form of isolated droplets in the air flow. In the highly aerated regions of flow, no direct method of checking the velocity recording of the instrument is available; reliance has been placed upon the consistency of results and the reasonableness of the velocity pattern in a vertical of the stream cross section measuring from points of low air concentration near the stream bottom and high air concentration near the top of the stream.

A plot of the air-concentration distribution and the velocity distribution in an air-entrained stream is shown in Fig. 14. The experimental observations of the air-concentration distribution were obtained with the electric air-concentration measuring instrument previously developed at the St. Anthony Falls Hydraulic Laboratory[6] and the velocity observations were obtained with the SAF velocity meter. Taken together the two distribution plots define the air entrainment and velocity patterns in the flow cross section.

The measured amount of water flowing through the channel was 10.95 cfs, while an integration of the water flow in the cross section, by taking into account both the air-entrainment observations and the velocity observations, gives a bulk discharge of water of 10.8 cfs. There was thus a check of the bulk flow with the integrated discharge within 1-1/2 per cent. This very close check, however, must be considered fortuitous, because the several uncertainties concerning velocities close to the solid boundaries and near the indefinite free surface of flow would appear not to warrant normal accuracies of the order of 1 per cent. Reasonable assumptions concerning the water discharge in the boundary areas had to be made to complete the integration. In any case, the fact that the experimental observations can be correlated so closely illustrates applicability of the instrument to the types of flow for which it was designed.

VII. CURRENT STATUS OF DEVELOPMENT OF THE SAF VELOCITY METER

The SAF meter has recently been mounted in a manner that will facilitate velocity traverses in the aerated open-channel flows being studied at the St. Anthony Falls Laboratory. The new mounting is shown in Fig. 15.

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[6] _Loc. cit._ Note 1.

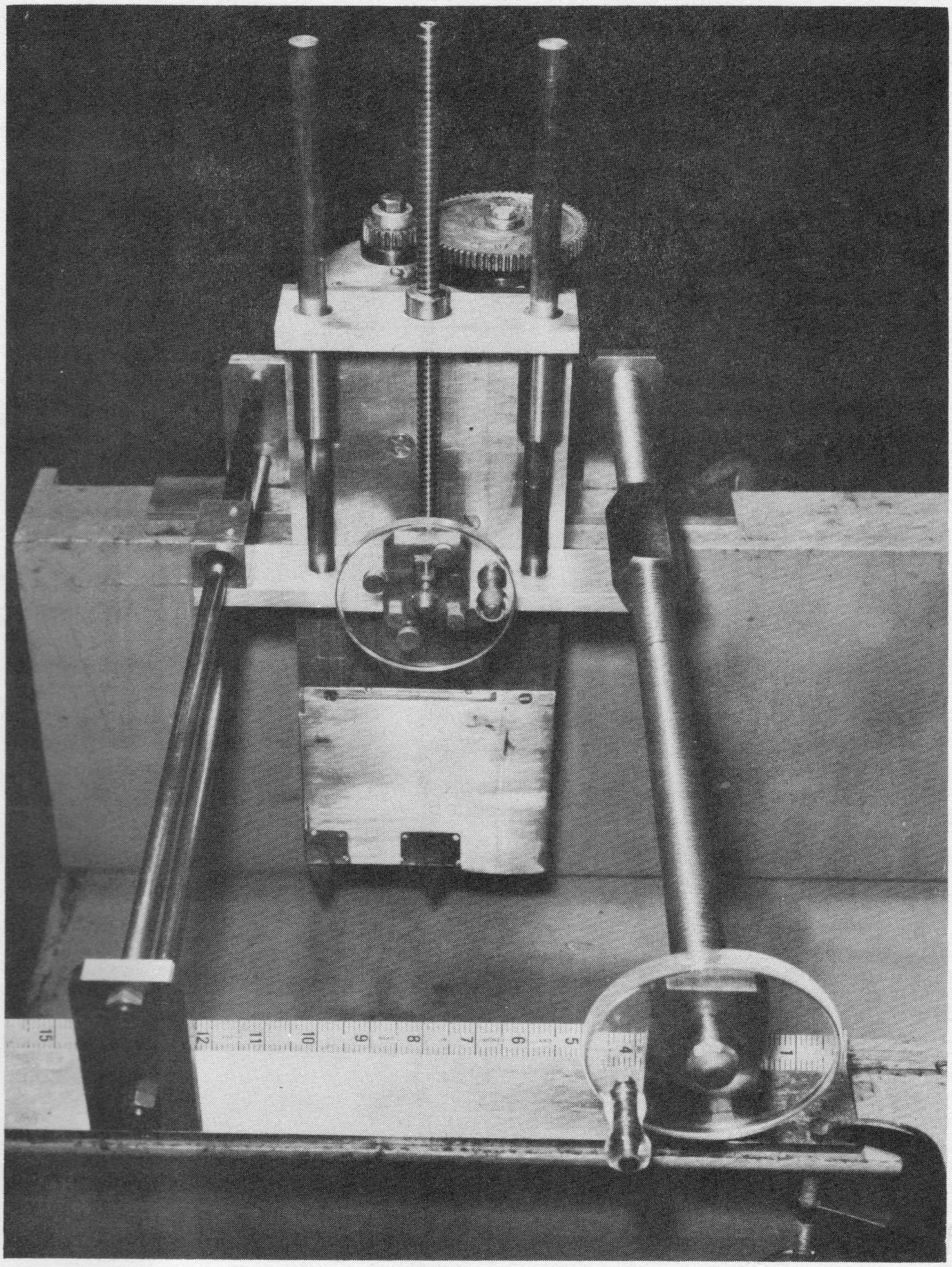

Fig. 15 — SAF Velocity Meter Mounted for Traversing Laboratory Open-Channel Flows

The electrical circuits have been further developed during the past few weeks so that the placing of the limits of the timing sequence on the paths of the velocity indications is done automatically. The averaging of these indicated times is also accomplished positively by the electrical circuit so that the small opportunity for operator bias in placing the timing marks is eliminated. This circuit dispenses with the need for the cathode ray tube which was so essential to the developmental phases of the instrument, thus allowing the entire electrical circuit to be packaged more conveniently. The mean velocity is read directly on the meter, making the instrument entirely objective and simple to use in an experimental study.

The incorporation of the injection tube and the electrode stations into a single plate is a most satisfactory arrangement for a device that must be inserted into high-velocity streams. There should be little difficulty in constructing a similar probe to a larger scale for investigation of aerated flows in large-scale field structures. The compact portable electrical system where the velocities can be read directly on an electrical meter is particularly adaptable to field conditions.

The SAF velocity meter as now being used with the cathode ray tube is quite satisfactory for laboratory observations and the indications are that it delivers an individual reading accurately on the order of 2 per cent of the actual velocity. It is quite sensitive to velocity changes and permits detailed study of aerated flows that was not possible with measuring instruments previously available. Exploratory studies that have thus far been made also indicate that the instrument might be exploited for turbulence measurements in water. Its use for measuring velocities in other fluid mixtures is also possible under proper conditions.