AN EXPERIMENTAL METHOD FOR STUDYING ENTRANCE FLOW IN A CIRCULAR PIPE

Thesis for the Degree of M. S.

MICHIGAN STATE UNIVERSITY

Clarence Gordon Chambers, Jr.

1959

THESIS

This is to certify that the

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AN EXPERIMENTAL METHOD FOR

STUDYING ENTRANCE FLOW IN A CIRCULAR PIPE

presented by

CLARENCE GORDON CHAMBERS, JR.

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AN EXPERIMENTAL METHOD

FOR

STUDYING ENTRANCE FLOW IN A CIRCULAR PIPE

By

Clarence Gordon Chambers, Jr.

A THESIS

Submitted to the College of Engineering
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Experimental Background

The purpose of this experiment was to develop a technique for the study of fluid flow with a hot wire anemometer. The flow in the entrance section of a circular pipe was chosen for the study because the flow development there was well predicted by theory[1] and other investigators.[2,3].

The flow pattern consists of a core of fluid moving through a pipe but unaffected by the pipe. This core gradually decreases in size as the boundary layer builds up. When the core has been absorbed the flow is fully developed. As soon as the flow enters the pipe the fluid adjacent to the surface is affected. This fluid is called the boundary layer. The thickness increases as the flow proceeds down stream.

The tool used to study the flow was the hot wire anemometer. This consists of a probe which supports a small heated wire. The cooling effect of the stream on the wire is then measured. King[4], in England, first effectively used the hot wire to measure fluid velocities.

There are several ways of using the hot wire to measure velocity. Probably the more widely used method is the constant temperature method. In this method the wire is maintained at a given temperature of resistance level by varying the heating current supplied to the wire. The heating current is then related to the velocity of the stream. Another method is to supply a given current and then measure the voltage drop across the wire. In this experiment the constant temperature method was used to measure the average velocity. To measure the turbulence another method must be used since with the anemometer available the current is controlled by hand. In another anemometer[5] an electronic servomechanism is used to control the current, and thus, the constant temperature method can be used for turbulent measurements. In the anemometer used in this experiment the constant current method was used for turbulent measurements.

The hot wire has an inherent thermal lag due to its heat storing properties. To correct for this a compensating network is built into the amplifier. This network will correct for the thermal lag if it is properly adjusted, but it also tends to over correct. Because of this over correction it was not used in this experiment. Since the oscilloscope was used as a null indicator it was also used as a measure of turbulence level. The picture on the oscilloscope is an indication of unbalance and will be an accurate representation of the turbulence if the frequency of the wire is greater than the frequency of the turbulence.

Experimental Set Up and Equipment Used

For this experiment the following equipment was used: a large pipe in which the flow was measured, a fan to produce the flow, a box in which the flow was controlled, and hot wire anemometers to measure the flow.

The plastic pipe's actual diameter was 5.65 inches. This was Republic SRB pipe, made of cellulose acetate butyrate. Originally a clear plastic pipe was ordered, but this was not available, since the manufacturer normally puts a black dye in the material to prevent sun damage in normal outside use. The reasons for picking this particular pipe were the size, large enough to work in, and the material, easy to work since it could be machined with ordinary wood tools. A rather smooth internal surface was expected since the pipe was produced by extrusion. When the pipe was received the inside surface was rough. The experiment was started with this pipe, hoping that this roughness would not give trouble, but it was found that it affected the flow too much. Therefore, before the experiment was run a sanding block was made and the tube was sanded for 32 diameters from the entrance. After sanding with rough and fine sandpaper, the tube was waxed on the inside with a liquid wax and polished, thus producing an extremely smooth surface. The flow in the smoothed tube was satisfactory. The tube was supported in ten wooden support blocks as seen in figure 1. These blocks were set on a large, 3x24 ft. bench which held the entire experimental apparatus. At the entrance of the tube was a laminated fiberglass bell mouth produced by Auto Air Industries of Lansing. The specifications for this bell mouth can be seen in figure 2. The bell mouth was very smooth and sanding it was not necessary. The purpose of the bell mouth was to produce a smooth, even flow entrance into the tube. To limit the entrance angle a large cellotex board was placed at the outside edge of the bell mouth, as shown in figure 3.

The flow was produced by a 2 ft. diameter six-bladed fan, driven by a one-horsepower motor. Due to the flow variations, which might have been motor surging, the fan was switched from 110 volt to a 220 volt power source, hoping to produce a more stable drive. When the motor was connected to 110 volt source its speed could be controlled with a variac, but with 220 volts no control was available. This fan was connected to the control box with a flexible tube. In the plywood control box, 48 x 20 x 15 inches, were 3 filters to filter out any disturbances from the fan and to dampen the flow. In the back part of the con-

SUPPORT BLOCK

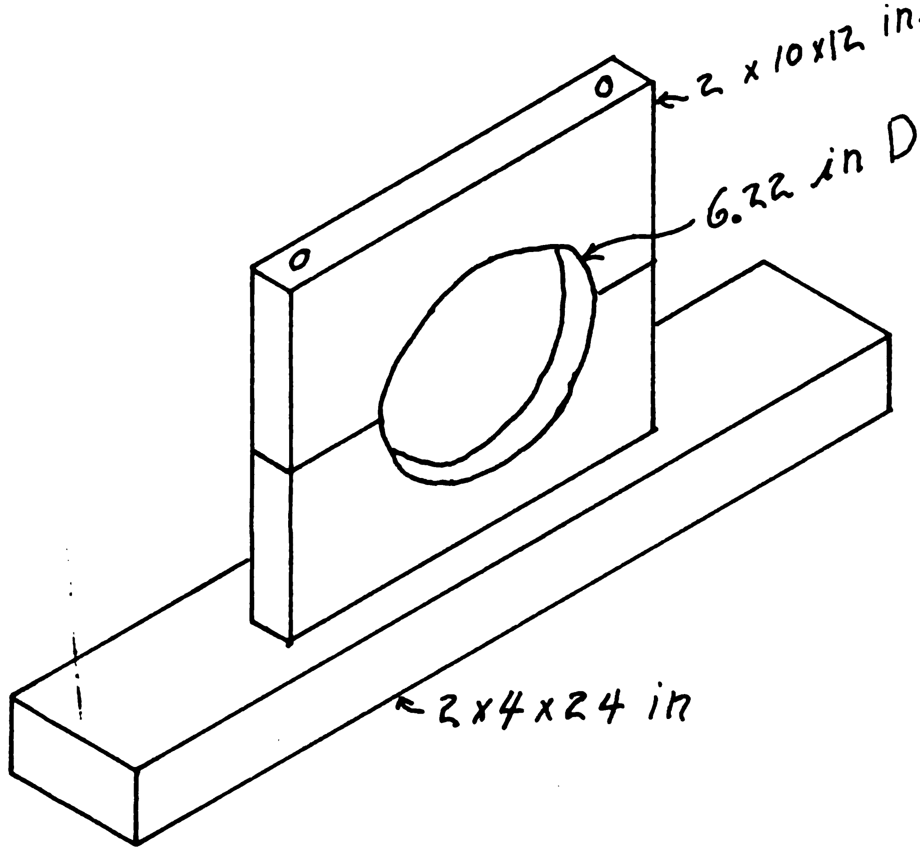


Fig. 1

BELLMOUTH

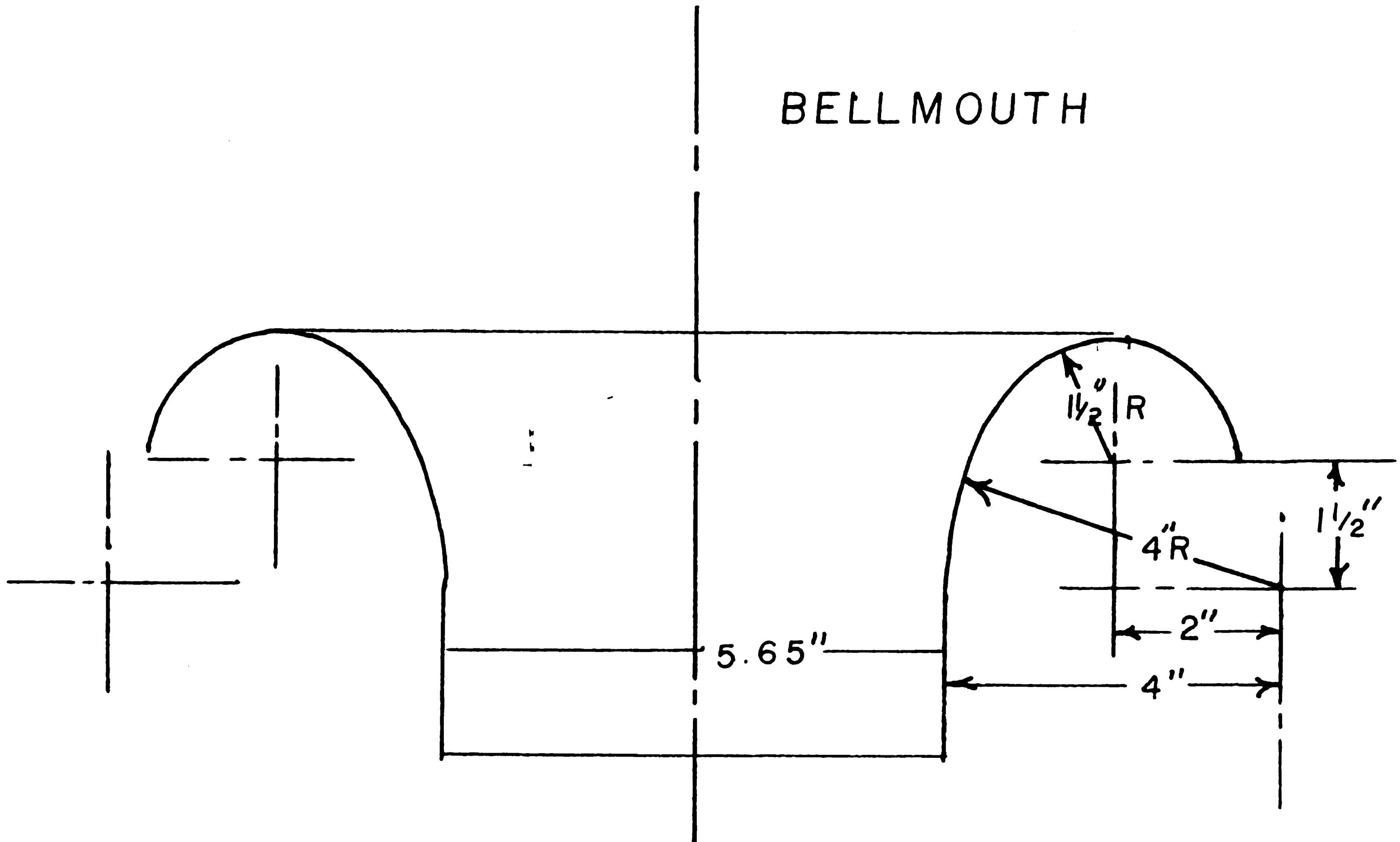


Fig. 2

trol box was a flapper door designed to let in air, and thus effectively control the flow rate in the pipe even though the fan speed could not be varied. The control box and control door can be seen in figures 4 and 5.

This experiment was not only a study of flow patterns, but development of techniques for using the various equipment, as hot wire anemometer, probe positioning devices, and flow controls. The hot wire anemometer probe consists of a very fine wire supported on the end of a probe. This wire was 0.044 inches long and was either 0.00015, 0.00035, or 0.0005 inches in diameter. The probe was supported in the stream and the wire was heated to a constant temperature. In the historical outline several ways in which this can be done have been explained. In this particular experiment the temperature was held constant by holding the resistance ratio at a given value. The measurements consisted of measuring the current necessary to maintain this temperature. In this experiment a model HWB hot wire anemometer (produced by the Flow Corporation of Cambridge, Mass.) was used. This device contains a bridge circuit, appropriate controls for balancing the bridge and measuring the wire current, a square wave generator for turbulence calibration, and an amplifier with a compensation circuit. The compensation circuit is similar to the ones described in the section on Experimental back-

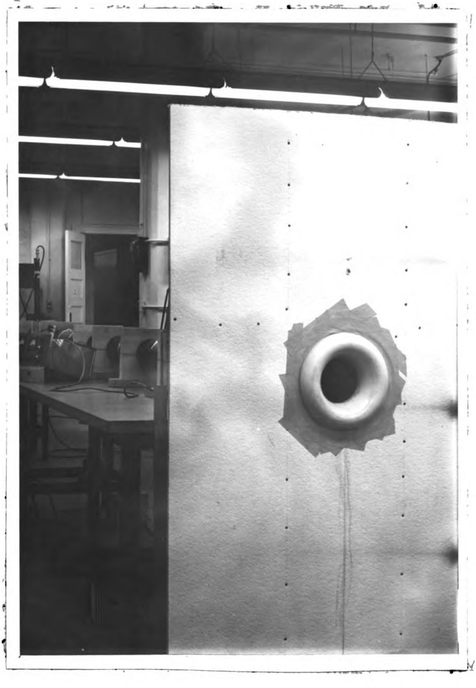


Fig. 3 Bell Mouth backed with cellotex board with test pipe in background.

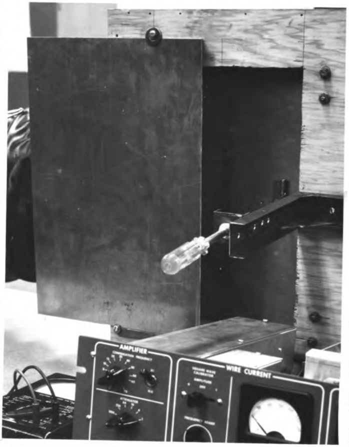


Fig. 4 Control box flapper door

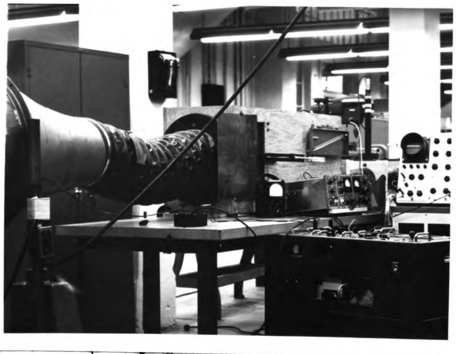


Fig. 5 Fan, flexible tube and control box

ground. In this experiment the amplifier was not used. The provided means of balancing the bridge was a small 3 inch galvanometer mounted on the front panel of the instrument. Since the flow was unstable it was dificult to balance the anemometer using the galvanometer. To make the balancing easier a model 532 Techtronics cathode ray oscilloscope with a D plug-in unit was used. The D plug-in unit is a differential amplifier. The bridge output was connected to the non ground side of each input to completely separate the bridge from the ground. The D unit was set at its most sensitive position, 1 millivolt per centimeter. The oscilloscope was used in two ways: directly on the bridge, and with a large capacitor in parallel with it. The capacitor tended to damp the oscilloscope motion, but not as much as the galvanometer. In using the undamped oscilloscope not only the variations in unbalance could be seen, but also some idea of the turbulence was obtained.

The picture, figure 6, was taken with a square wave output across the bridge to show the effect of the thermal lag of the hot wire. Compare the traces for different connections. The interesting point here is that with the small wires the bridge square wwve output is more nearly

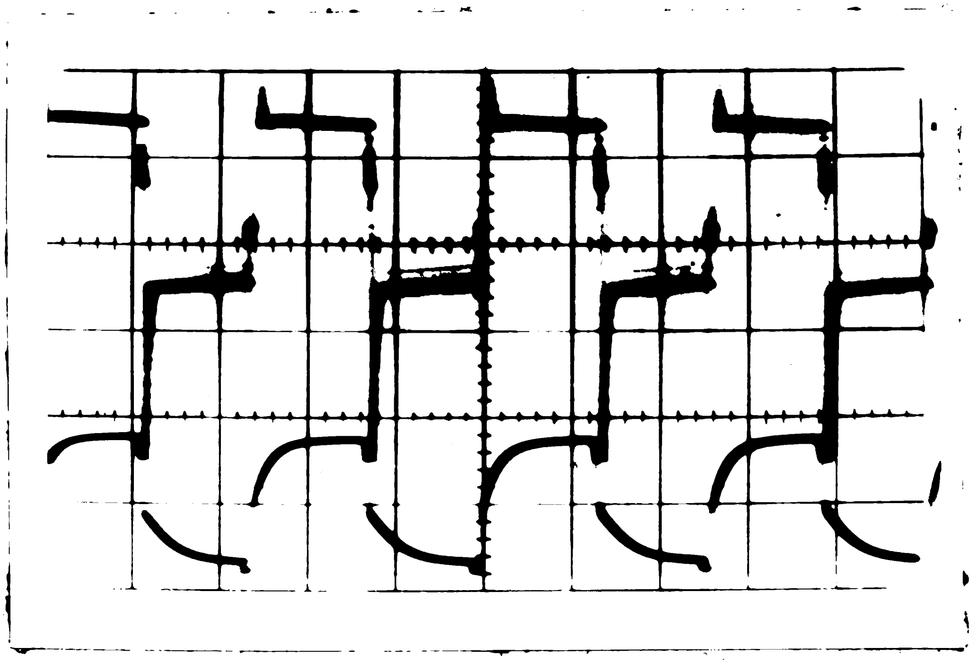


Fig. 6 Top wave output of amplifier and compensation circuit.

Bottom wave output of bridge.

Sweep time 2 milliseconds per centimeter.

true , while the output of the amplifier compensation circuit has a large pip at the beginning of each wave.

For this reason the direct conection was preferred. There was some attempt to calibrate the scope in order to determine what a centimeter of deflection meant in terms of variation of current. This was an incomplete calibration but the calibration curve can be seen in figure 7.

In this experiment the velocity was measured at various points in the tube. The measuring point is determined by 2 dimensions: the length along the tube and the vertical height in the tube. It was assumed throughout the experiment that the flow was symmetrical. The first location, lengthwise, was measured in units of L/D. L was the length from the tube entrance and D was the tube diameter, 5.65 inches. See figure 8 for details of this location. Thirteen stations were used with L/D s of 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26. At L/D = 26 the flow had developed a turbulent boundary layer and thus readings farther down stream were not taken. These stations were the lengthwise locations of the measuring points in the tube, and once the stations were drilled they were maintained.

To measure vertically in the pipe at each station a ½ inch diameter hole was drilled. The hole had to be large enough to accommodate the bottom finder.

EFFECT of UNBALANCE on OSCILLOSCOPE

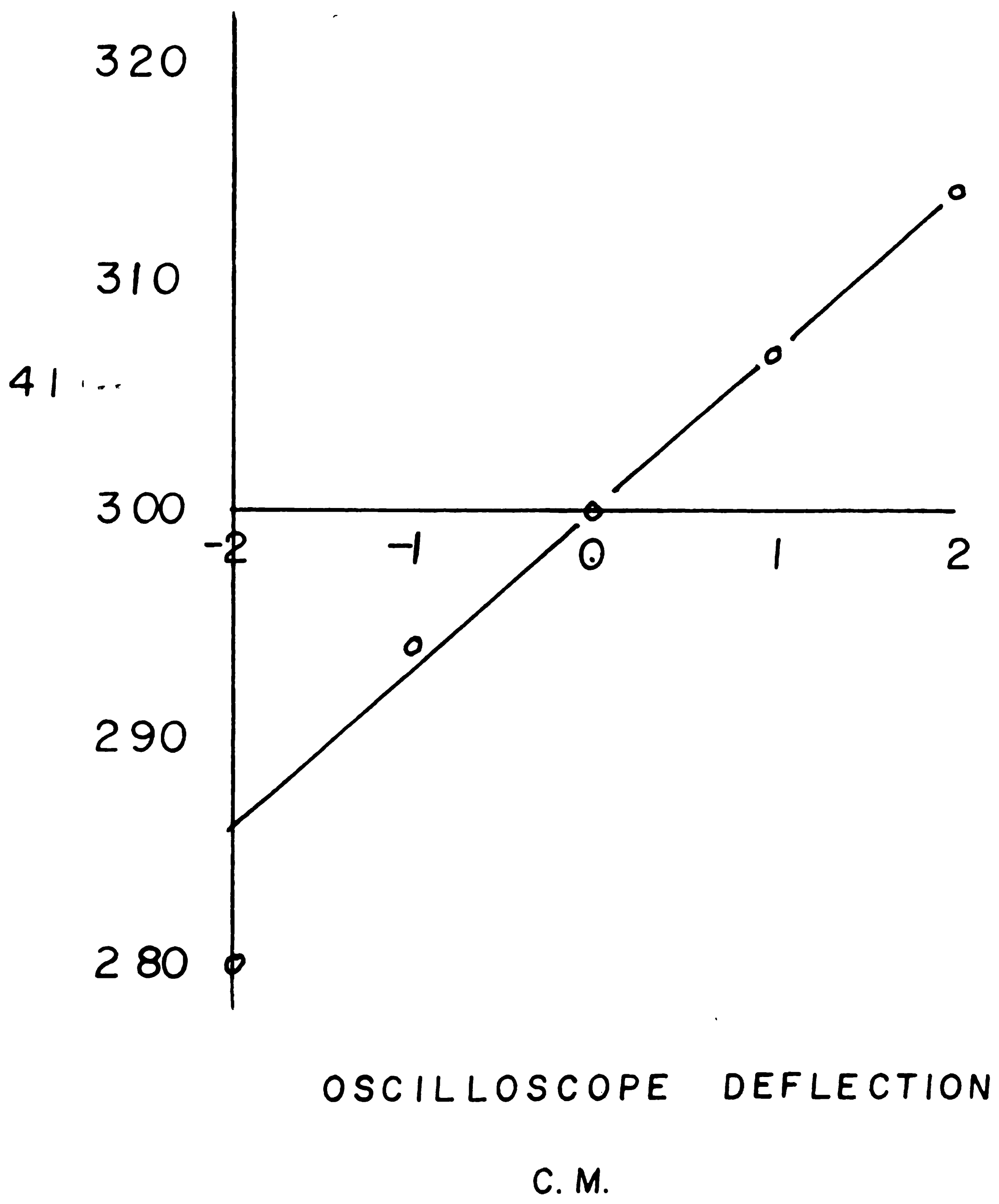


Fig. 7

LOCATION of MEASURING STATIONS

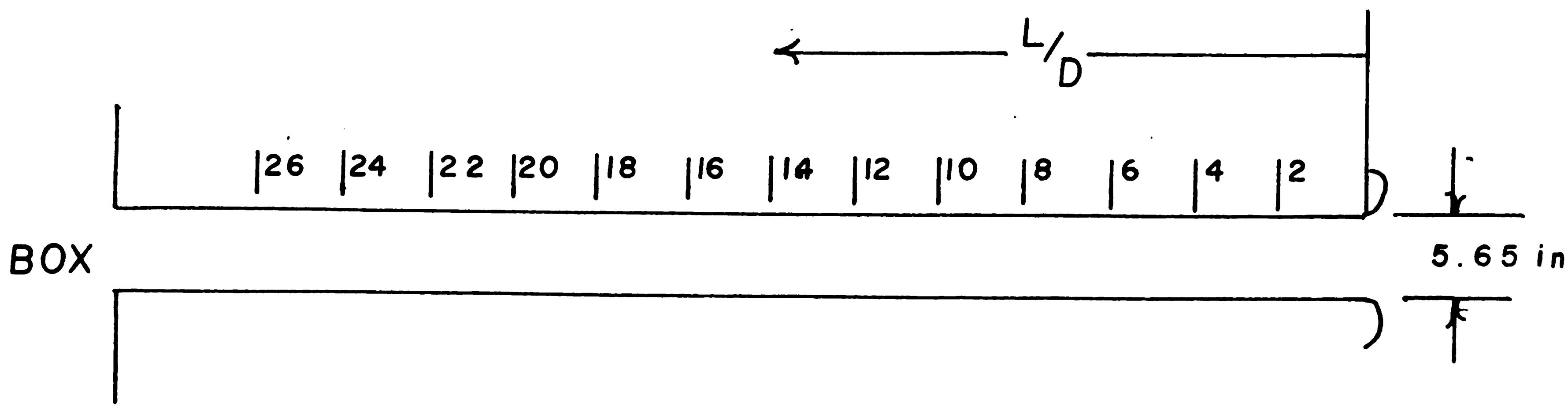


Fig. 8

The plugs were made by cutting out pieces of the original pipe with a hole saw. This hole saw produced a 1/2 inch plug with a small hole in it. The hole was tapped and a supporting washer was screwed to the plug. The hole on the inside was filled with putty and sanded smooth. The hole in the pipe was drilled with a hole saw and reamed by hand to 1/2 inch diameter. The holes not in use were plugged. The hole that was being used was filled with another plug which was tapped with a 1/4-28 tap to accommodate the probe's protective shield. To keep this plug in position, it was glued to the back of a small aluminum plate which was rolled to fit the contour of the tube. The plate was taped to the tube, thus making a tight seal. This plug and the probe's protective shield became part of the probe's support.

Measurements in the vertical direction were done with the probe holding device and the scales mounted on it. See figure 9. There were three ranges of measurement: the top 7/10 of an inch, the center portion of the tube, and the bottom 7/10. Because the important changes in flow were close to the boundary the measurements in the top and bottom sections had to be located accurately, while the measurements in the center were not as critical. The measurements were positioned relative to the bottom with the bottom finder which will be discussed later. Once the bottom was found a dial gage, mounted on the probe

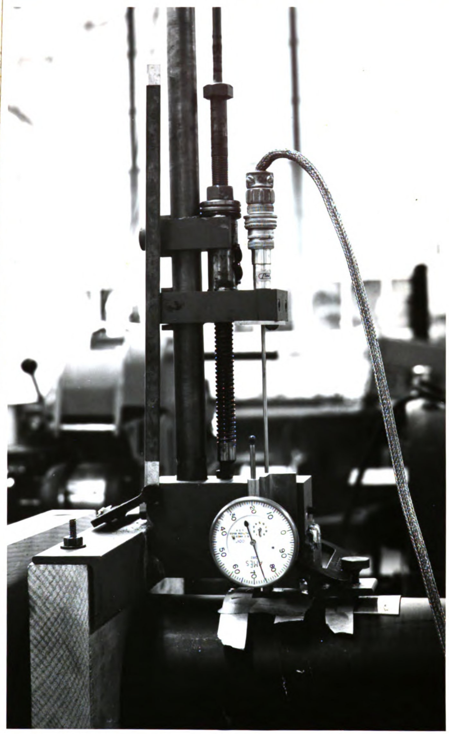


Fig. 9 Probe Holder

holder, was set to its zero point. This dial gage was the basis for all accurate measurements. To measure the bottom section it was read directly.

It is interesting to note the probable accuracy of this location. After run #4 at L/D=22 an attempt was made to see how close to the bottom measurements could be made. A reading was taken at .000 on the dial gage. The flow was turbulent here. The probe was moved to -.001. Here the flow began to smooth out. At -.002 and -.003 the flow was smooth. This indicated that the probe was in the laminar sub layer, which is less than .004 inches thick. From this it can be concluded that the .000 reading was within .005 inches from the bottom. For velocity profiles at the scale plotted here one can not distinguish .01 inches. This dial gage was read directly up to 7/10 of an inch. In the center portion of the tube the probe was located with an ordinary steel scale mounted on a holding device. With the use of a magnifying glass the scale, which is divided into hundredths of an inch, can be read to a hundredth of an inch. Therefore, the locations within the center of the tube were $\pm$ .01 although a change of a 1/4 of an inch would not affect the readings. As the top was approached it was found to be convenient to again use the dial gage. This was done with a 5 inch Pratt and Whitney gage block. This block was clamped in such a way that its top surface rested against the arm which moved the dial gage in the bottom portion of the tube. Now the dial gage read locations at the top of the tube. The probe location was 5 inches plus the dial gage reading.

The probe holder was clamped to the tube with one set of the support blocks, figure 9. Before it was clamped the probe holder was aligned to hold the probe vertically so that it was directly over the hole in the tube. After the holder was clamped in place the bottom finder was attached to the probe and positioned. The probe and bottom finder were moved to the bottom of the tube. When the bottom was found the dial was set at zero. After the bottom finder was removed the run proceeded.

The vertical motion in the probe holder had to be smooth and accurate. To assure this a ballbearing screw was used. On the vertical column there were two blocks: a movable block which held the probe, and a beam which depressed the dial gage. The movable block was connected to the fixed block with the ballbearing screw. In operation, the probe was moved by turning the screw. For large motions the fixed block could be loosened and the two blocks slid together on the vertical support. This provided 2 feet of vertical travel.

After a few trials it was soon evident that an accurate bottom finder was necessary. The first method attempted in finding the bottom was to drop a rod down touching the bottom and setting the dial gage with this. There was difficulty in adjusting the head of the rod to be in exactly the same position as the head of the probe. Hence, this device was given up. The second device, seen in figure 10, consisted of a small piece of 1/2 inch plastic rod about 3 inches long. This rod was drilled just large enough to accommodate the probe. This hole was then polished to produce a transparent tube. The top portion of the tube was drilled and tapped with a 1/4-28 tap to accept the probe shield. The bottom of the finder contained two contact points fastened to lead wires which were connected to a resistance meter. When the bottom finder touched the bottom the contacts were pushed together making an electrical contact. An ordinary Triplet resistance meter was used to indicate this contact. The hot wire was positioned in the bottom finder by aligning the wire with a fine line around the outside of the clear plastic tube. A 3 inch high power magnifying glass was used to increase the accuracy of this alignment. The distance between this line and the end of the bottom finder was carefully measured and found to be $0.730 \begin{smallmatrix} +.005 \\ -.000 \end{smallmatrix}$. With the finder thus positioned the probe and finder were carefully moved down until the bottom was

Fig. 10 Bottom finder

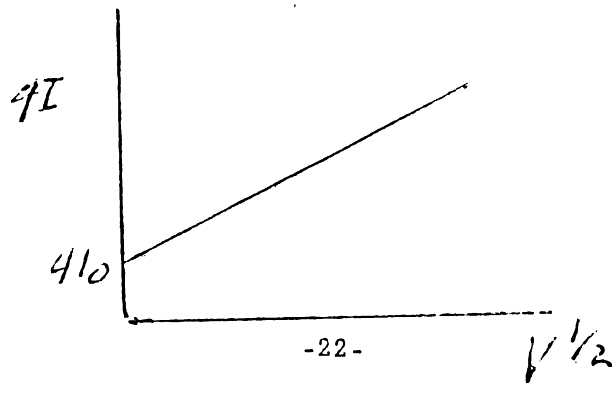
found. Then the dial gage was set to read .730. Using this technique (including positioning of finder on probe) the bottom position was repeatable to $\pm$ .003.

Before using the hot wire probe it was necessary to calibrate it. To do this the probe was placed in a fluid stream near a pitot tube and simultaneous readings were taken. Both the test tube and wind tunnel were used to produce a flow for calibration. Velocities from the pitot tube were determined from table #1 in the pamphlet published by Ellison.[6] The zero velocity reading was called $4I_0$.

Another consideration is the effect of temperature on the measurements. This effect is the same as velocity change. To correct for change in temperature the probe was calibrated by taking readings in zero velocity at various temperatures. This was difficult since the measurements depended upon changes in the ambient temperature. In several days' time sufficient data was obtained to plot temperature versus the $4I_0$ reading. Using this plot corrections for changes in flow temperature were made by changing $4I_0$ in the velocity formula.

Data Taken

Each probe varies in properties and must be calibrated. To calibrate these probes there is a theoretical calibration from known wire dimensions and properties. This method is dificult and not accurate. The best means of calibrating a probe is by actual comparison. For this a pitot tube in the same flow was used. Since the calibration curve is a straight line, it was necessary to take only a few readings. To improve accuracy 8 to 10 readings were taken. These were plotted, the best straight line drawn, and the slope of this line, K, was determined. Rather than using the curve directly to figure velocities, the following formula was derived. As has been stated $V = f(I)$ such that a plot of $V^{1/4}$ versus I^2 is a straight line. This intercepted the I^2 axis at the value of I found in still air. A typical plot looks like this:



The anemometer readings were in terms of 4I and hence, for ease in calculation this value was used. The formula for this straight line is:

$$KV^{1/2} + (4I_0)^2 = (4I)^2$$

After rearranging

$$KV^{1/2} = (4I)^2 - (4I_0)^2$$

Dividing by K and squaring both sides gives

$$V = \left[\frac{(4I)^2 - (4I_0)^2}{K}\right]^2$$

Where

$$K = \frac{(4I)^2}{(V)^{1/2}}$$

and is found from the calibration plot.

The calibration curves for the probes used for this experiment can be found in the appendix.

The effect of wire size is interesting. A small wire will follow fast velocity fluctuations. A larger wire holds more heat and thus will not follow fast velocity flucuations. A small wire does not take as much current as a large wire to maintain a given temperature. Thus, a given variation in velocity will produce a greater change of current in the larger wire. Therefore, a small wire is not as sensitive for average velocity measurements but is better for turbulent measurements. In this experiment three different wire sizes were used, but the wire size used was arbitrary depending on what was available. Only two small probes were available, and because the wires were replaced only at the factory, which took three to six weeks, it was impossible to have a choice of wire size.

Another point affecting the velocity measurements was the resistance ratio at which the wire was operated. This resistance ratio, determined by a setting on the anemometer, could be varied in steps of 1.1, 1.2, 1.3, 1.4, 1.6, etc. The resistance ratio is the ratio of the resistance of the wire hot to the resistance of the wire cold. A ratio of 1.3 was used first, but it was found that it did not give the desired sensitivity. It might be noted that the slope of the calibration curve for a 1.3 ratio is not nearly as great as the slope of a 1.4 ratio. See calibration curve in the appendix for probe M_2. To gain sensitivity in average velocity measurements the resistance ratio was increased to 1.4. It is possible that a higher resistance ratio could have been used but the probability of burning out a wire would have been increased.

The third interesting point is the orientation of the probe. For small angles the probe measures the velocity in the direction normal to the wire. If a velocity is not the actual velocity times the cosine of the angle between them. In setting up the probe it is essential to align it so that the probe will be perpendicular to the direction of the flow. In this experiment the probe was aligned by eye, and not changed during the runs. The actual use of the probe followed the steps outlined in part III in the hot wire anemometer manual[7].

The data taking period began in December 1958. After the tube was set up a few exploratory readings were taken. These readings indicated large velocity flucuations even in the center of the stream. Enough readings were taken to show that the flow was unsatisfactory. To correct this, the tube was sanded, waxed, and polished (as was previously described) until the interior surface was smooth enough to produce a good reflection. After sanding, trial runs indicated that the flow was improved sufficiently to be acceptable. Then the stations were drilled and complete runs made.

During the first run the flow was adjusted to the desired velocity with the control door. Throughout the run the door was not moved. A second hot wire was used at $L/D \simeq 32$ to monitor the center line velocity. The velocity profiles for the first run can be found in the appendix. The following table, figure 11, lists the flow rate at each station. Since the flow rate had too great a variation, it was decided that to monitor the flow was not sufficient

FLOW RATES

L/D	Run 1 BOT	Run 2 TOP	Run 2 BOT	Run 3 TOP	Run 3 BOT
2	5.55	—	—	3.41	4.16
4	5.55	—	—	—	—
6	4.60	—	—	3.64	4.80
8	4.66	—	—	—	—
10	4.56	4.91	3.75	3.70	4.34
12	3.97	3.50	3.86	4.02	4.53
14	4.68	3.57	3.95	3.48	4.33
16	4.27	3.57	4.02	4.04	4.70
18	4.76	4.65	4.61	4.16	4.79
20	4.85	—	—	4.07	4.57
22	4.65	3.71	3.69	3.98	4.55
24	4.63	—	—	4.06	4.43
26	4.89	4.37	4.91	3.25	4.36

Fig. 11

and that the control door would have to be adjusted during all measurements. In the second and third runs this was done, trying to maintain a constant monitoring velocity. The first run was by the author alone. During this run readings were taken at each station from L/D = 2 to L/D = 26. For this run the gage block was not used to take readings near the top. The readings at the top were taken with the scale. Hence, the readings at the top portion of the tube were not accurate for this run. An attempt was made to correlate the velocity flucuations with the voltage irregularities at the power plant but no definite correlation could be made. Because the variation in the center line velocity was so large and because no temperature correction had been made it was decided to run a second time.

In the second run readings were taken at stations L/D = 26, 20, 16, 14, 12, 10, and 8 in that order. For this run two other Tectronic oscilloscopes were used. The second scope was used as a null balance indicator at the monitoring station. The third scope was used at the measuring station with a Tectronics type AB switching unit. This enabled the author to observe the unbalance at both stations simultaneously. The type AB switching unit consists of two vertical amplifiers and an electronic switch to produce a dual trace. In this run the control door was modified so that it could be moved easily. Throughout the second run a second operator continually adjusted the flapper door attempting to maintain a constant monitoring velocity. By using the third scope the author would adjust the measuring probe to within ± 1 centimeter on the scale, being sure that the monitoring probe was within the same limits while making current adjustments.

Some attention should be given the technique of using the monitoring probe. From a temperature correction curve established for a given velocity the appropriate 4I readings were found by the operator at the station. After adjusting the current to this reading the velocity was varied to balance the bridge. This procedure was used throughout the remaining runs.

A small, .00015 inch diameter, wire was used for run #2. The run ended at station L/D $\cong$ 8 when the wire was broken there. The results of run #2 were not as good as was expected. The variation in flow rate was 10%. A variation of 2 or 3% was expected. Due to this large variation it was decided to run a third time.

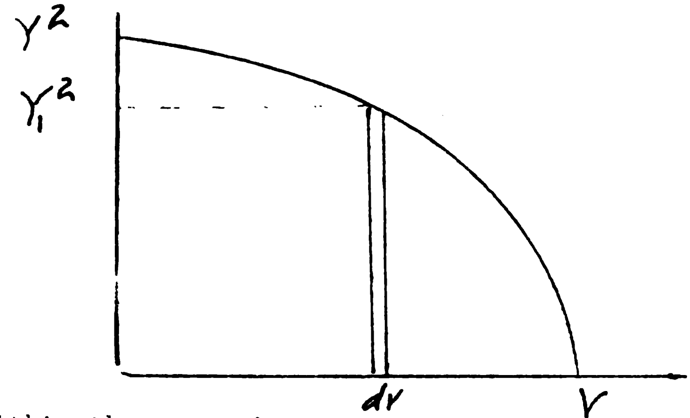
For the third run the limits of allowable variation of unbalance were reduced to 1/4 the value allowed in run #2. A large .0005 inch diameter wire was used. Readings were taken at all stations except L/D $\cong$ 8 and 4. The large wire drew considerably more current than the small ones. In fact, the drain on the supply battery was so great that it gave out before the run was completed. Even with the increased accuracy, and the careful attempts at adjusting the center line velocity the variation in flow rate was 10%. This indicated an unstable flow condition.

Run #4 consisted of 3 sets of readings taken at L/D $\simeq$ 22. The purpose was to check repeatability of readings. The velocity profiles can be found in the appendix.

Data Treatment

The data consisted of a set of 4I readings, one for each y value. The distance from the bottom of the tube was labeled y. The anemometer read the current in 1/4 milliamp units, in other words the anemometer reading was 4 times the wire current in the milliamps. This reading was called 4I. From the 4I readings taken the corresponding velocities were computed using the formula developed on page 23. With these velocities a velocity profile and a flow rate profile were plotted. It is interesting to note the changes in these velocity profiles. The profile in the first case at $L/D \simeq 2$ is flat and extends almost to the boundary. The boundary layer is a few thousandths of an inch thick. Comparing this with the profile at station $L/D \simeq 2$[illegible] the curve portion of the velocity profile extends almost to the center having very little flat portion. By looking at the velocity profiles between $L/D \simeq 2$ and 26 it can be seen that this development continues throughout the length of the stream.

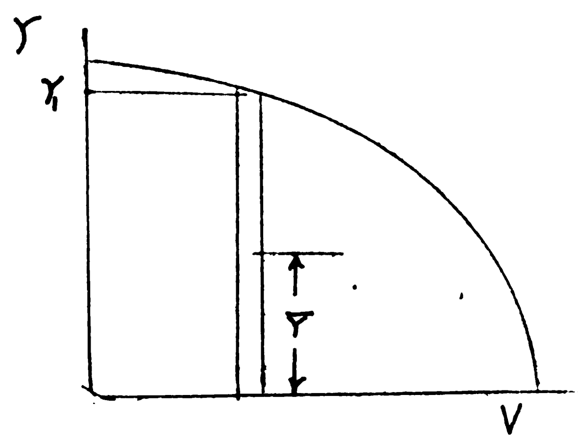
The next use of this data was to calculate the flow rate at each station. To determine the flow rate a plot of r^2 versus v was made. Then the area enclosed by this curve was found, by calculation in the parts which could be divided into rectangles or triangles. The remaining irregular area was measured with a planimeter. The justification for this method can be seen below.



The area within the curve is

$$A = \int_0^r r_1^2 \, dr$$

The flow rate is the volume inside the three dimensional velocity profile which in this case is formed by revolving 1/2 the two dimensional profiles around the center line. Using the theorem of Pappus this volume will be



$$\bar{r} = \frac{r_1}{2}$$

From the diagram above this volume or flow rate, Q, is

$$Q = 2\pi \int_0^V \bar{r}\, r_1 \, dv = \pi \int_0^V r_1^2 \, dv$$

$$= \pi A$$

It might be noted that r^2 was in inches and V was in feet per second. To convert this flow rate which was inches squared feet per second to cubic feet per second it must be divided by 144.

As can be seen from the velocity profiles the boundary layer thickness continually increased as the flow moved down stream. There were several ways in which this thickness could be determined. The plot of boundary layer growth is a plot of the points where $V_t = .9V_c$, where t is the boundary layer thickness, V_t is the velocity at this point and V_c is the center line velocity.

Conclusions

In general, the experimental set up was effective. The flow produced fitted the pattern predicted by theory. It consisted of a core of unaffected fluid surrounded by a boundary layer. The center core was relatively free of turbulence, while the boundary layer was turbulent. At station $L/D = 22$ a laminar sub layer was found. The photographs in figure 12 indicate the relative turbulence at the various vertical locations. It was also found that the boundary layer continually grew in thickness as the flow proceeded.

The plots of boundary layer thickness in the appendix are determined from the velocity of the point compared to the velocity of the center line as has been described. Time did not permit a study of the boundary layer thickness based on the level of turbulence. The author feels that by moving the probe up until the turbulent level dropped off, then reading the y value, a much better measure of boundary layer thickness would be obtained.

From figure 11 the extreme variations in flow rates can be seen. This variation can be caused either by a variation in flow rate or an inaccuracy in measurements.

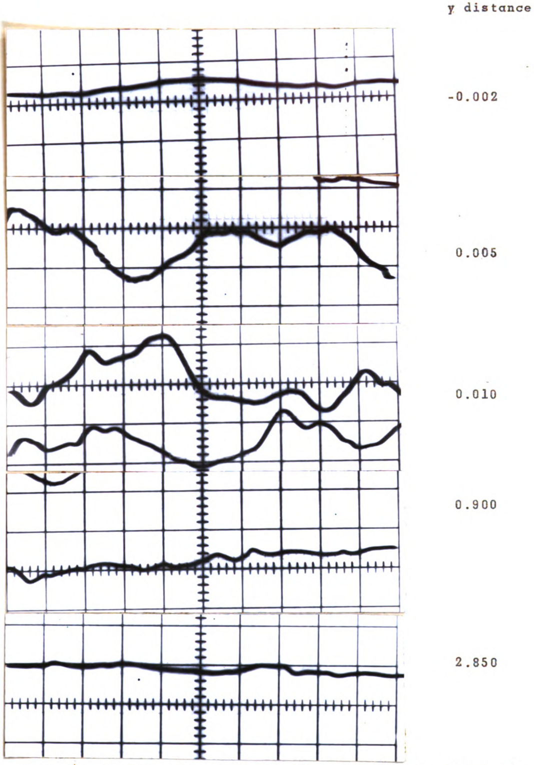


Fig. 12 Turbulence patterns at various y values L/D = 22

The author believes that the measurements are accurate within 5%, thus, a 10% variation in flow rate must be an indication of variations in flow.

The hot wire anemometer is a valuable research instrument, but with the present equipment its value seems to be in turbulent studies rather than accurate measurements of average velocity. These flow rates could be a good measure of the accuracy of the instrument and technique if another more accurate measurement of flow rate were available. Adelberg[8] indicated an accuracy in current measurement of 0.01 milliamps would be needed for good measurement. The anemometer used here had an accuracy of only 0.1 milliamps assuming a perfect balance.

The velocity profiles often have a definite jump at the center line. This occurred too often to be just an accident. There is a possibility that this is the effect of varying flow rates. Another interesting phenomenon found particularly at down stream locations is the variation in turbulence level near the top of the boundary layer. This was observed by watching the oscilloscope. The turbulence pattern would vary from that of the core to that of the boundary layer. By moving the probe down the length of the turbulent phase would increase. This indicated that the boundary layer thickness was continually changing with time. Again this could be caused by or could cause the variation in flow rate.

No effort was made to study the frequency of the turbulent pattern if any existed. The author would like to suggest a tape recorder, wave analyzer and proper accessories for this purpose.

Recommendations and Possible Areas of Future Study

After adjustments were made in experimental apparatus, such as: sanding, waxing and polishing the tube, installing the control door, changing the motor voltage, and limiting the flow access to the bell mouth, the flow pattern was acceptable. If further changes were to be made in this apparatus one might first consider additional sanding and polishing on the inside of the tube. There are yet a few rough spots which might still affect the flow.

Another possible change is replacing the control door, and fan with a constant displacement blower of the Root's or some other type. This blower should be driven with a large variable speed drive. This would give a constant known flow rate which would provide an excellent check on the hot wire measurements. Then if this flucuation in flow still occurred within the tube, it could be attributed definitely to the flow lattern, since the possible variation in the fan would have been removed from consideration.

The velocity measurements again leave question. These measurements were made with a hot wire anemometer. From the calibration formula used in this experiment the error in velocity, due to an error in 4I readings, can be calculated as

$$\frac{\Delta V}{V} = 4\frac{(4I)}{(4I)^2-(4I_0)^2}\left[\Delta(4I)\right]$$

Also due to an error in $4I_0$ is

$$\frac{\Delta V}{V} = 4\frac{(4I_0)}{(4I)^2-(4I_0)^2}\left[\Delta(4I_0)\right]$$

From this it can be seen that an error in 4I of 2 will produce an error in velocity of from 3 to 4%. It is seriously questioned whether an experimenter can adjust the balance of the bridge accurately enough to obtain 4I readings within the limits of $\pm$ 1. The run #4 taken at one station, L/D $\simeq$ 22 gives three consecutive independent sets of readings at one location. The purpose of this was to determine the repeatability of the information gained. By looking at the velocity profiles in the appendix it is easily seen that repeatability is limited. The lack of repeatability definitely limits the areas of investigation available to this set up. Since it is not certain whether the lack of repeatability is due to the measuring device or actual variations in the flow, additional experimenting is needed in this area. The constant displacement blower mentioned previously would limit the possibility of irregular flow. Improvements in the current section of the hot wire anemometer, no doubt, would increase measurement

accuracy. There are three improvements worth considering. First, a finer fine current control, possibly replacing the present potentiometer with a heliopot would be sufficient. Secondly, an increase in the sensitivity of the null balance indicator is needed. This can be accomplished with a higher gain in the oscilloscope. Another method of improving null balance might be with the use of an integrating circuit between the bridge and the null balance indicator to average the unbalance. Hunter Rouse's[9] book gives a formula for the time average of varying velocities in an integral form. Finally, a better current source is needed. During run #3 there was dificulty in obtaining good readings because the battery could not supply sufficient current. This problem can be solved by replacing the present dry battery with storage batteries. Four ordinary 12 volt automobile batteries would be sufficient.

More study of the hot wire anemometer, itself, would seem advisable to the experimenter. Questions such as; probable limits of accuracy, the affect of wire size on sensitivity and turbulent measurements, the possibility of using other anemometers and the possibility of improving the present anemometer, all need to be considered.

Two small sized probes were available to the experimenter. This was not enough since there are three wire sizes which seemed desirable to use for various purposes. Therefore, three probes would be the minimum. But since there is a great possibility of breaking a probe wire, it is desirable to have a spare available. The locating device used in this experiment worked satisfactorily. The ability to come within the sub boundary layer demonstrates the affectiveness of the equipment. The gage block for measuring the too inch of the tube was too heavy for continued use. One could make a new gage block which would solve this problem.

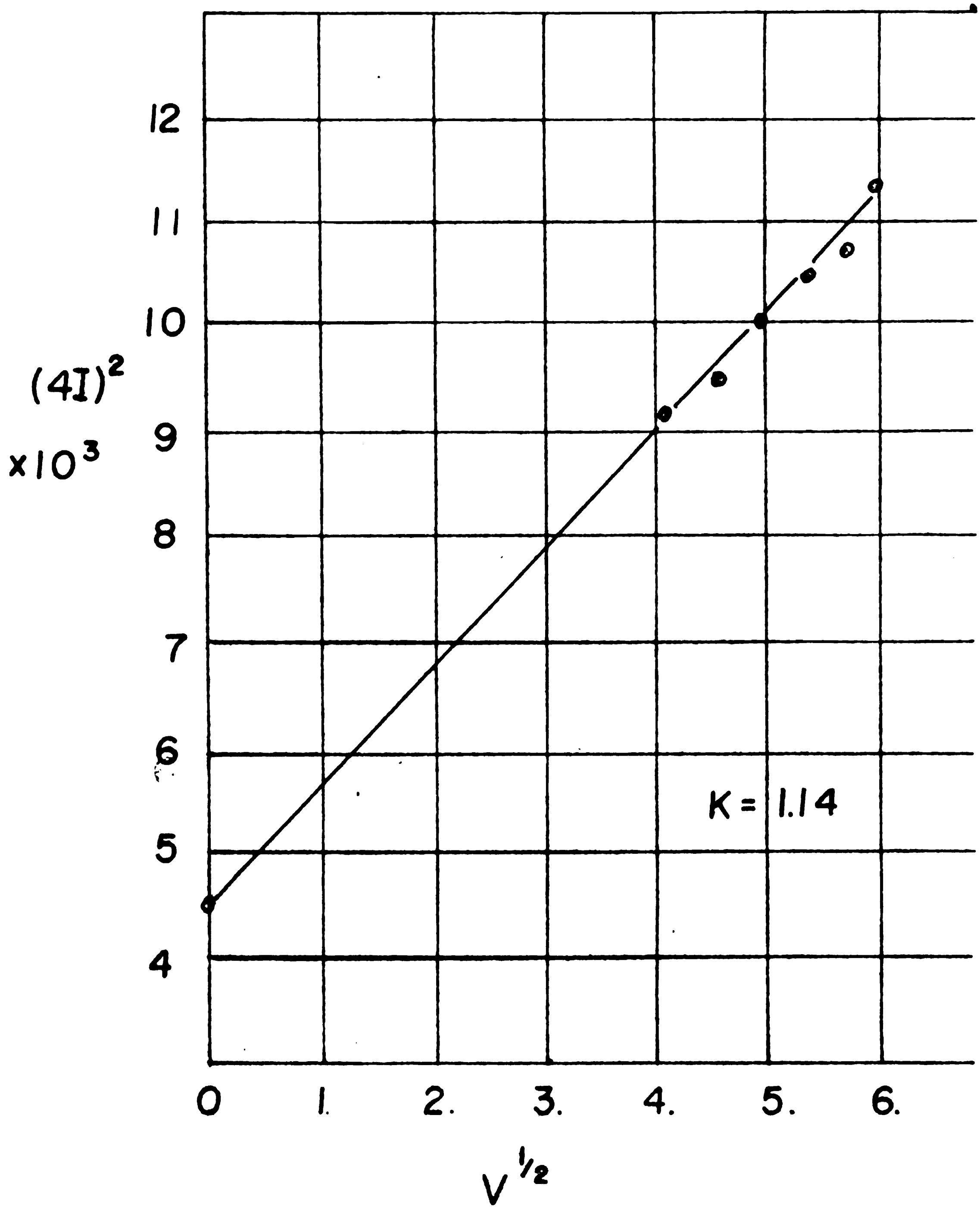
The data taken was sufficient for this phase of the experiment. Both the velocity and flow rate profiles could be affectively plotted. If the variation in flow rate indicates an unstable flow, this flow should be studied rather than an attempt to average the data.

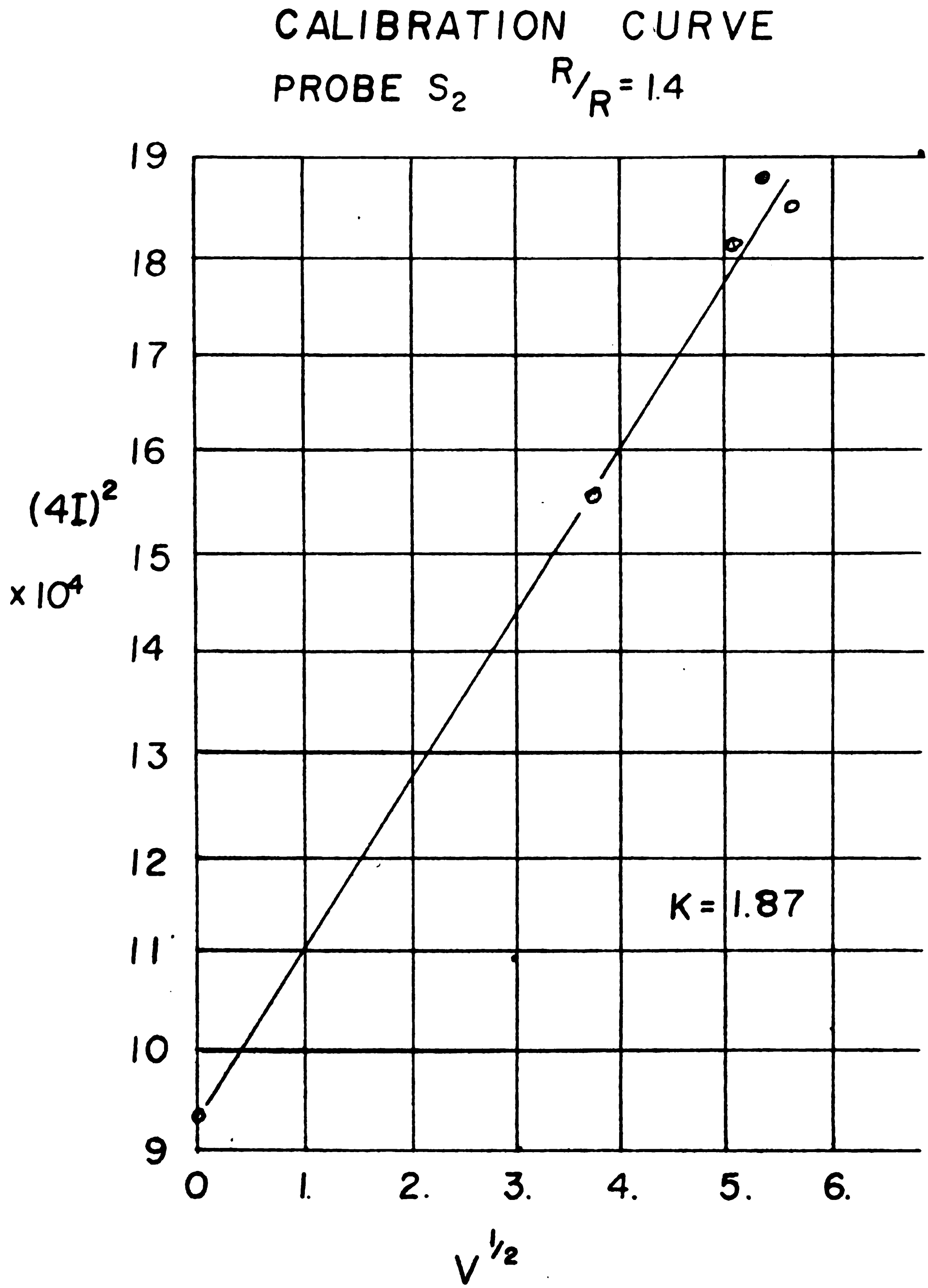
It might be noted that the boundary layer was not of constant thickness with time at any one point. This is evidenced in the fact that the turbulence, as the boundary layer was approached, had times at which it would fluctuate from a smooth pattern to a turbulent pattern, thus indicating the boundary layer was probably growing and then decaying with time. As it has been mentioned earlier, the boundary sub layer was found and pictures were taken of this. The pictures on page 34 are the pattern of turbulence in the stream, the pattern of turbulence in the boundary layer, and also the pattern of turbulence in the boundary sub layer.

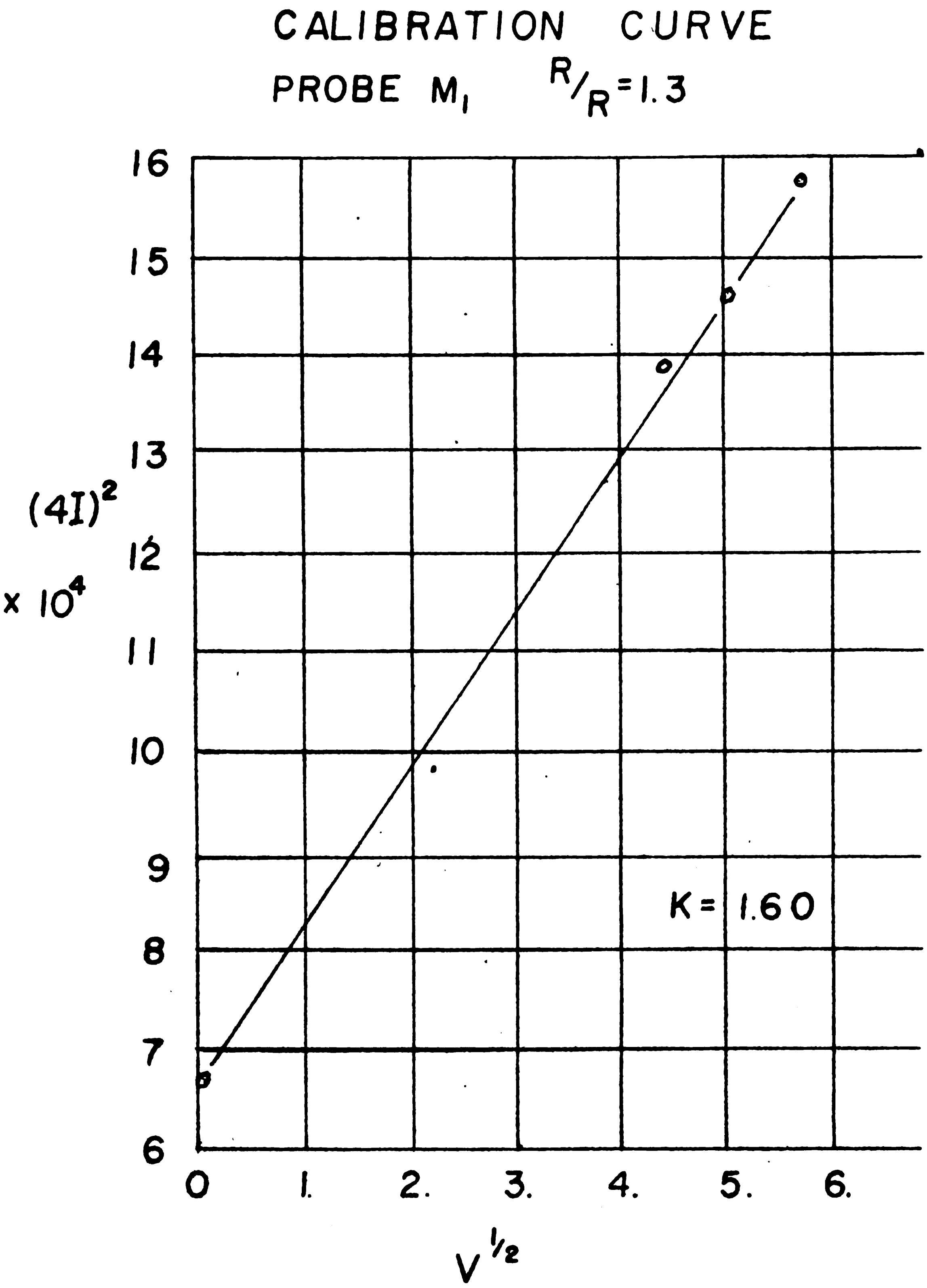
Some of the possible areas of future study are: the hot wire, the hot wire anemometer, and different phases of the flow pattern itself. In this paper the affect of the wire size has been discussed. A further study of this would be helpful. Additional study of the accuracy of the hot wire anemometer would be helpful. Probably the most interesting phase of the flow is the turbulent patterns. The atmospheric conditions have an affect on the turbulent patterns. This was observed in the experiment, but there was not time to study it. The physical surroundings very definitely have an affect on the flow. If some one walked too closely in front of the bell mouth entrance the flow was affected. At times, opening the entrance door to the room would affect the flow. In this experiment these affects were minimized by running nights and Saturdays. The affect of the physical surroundings on the flow should be studied and eliminated as much as possible. This might involve a special room. The study of the affect of a placed phy-ical disturbance in front of the flow might be interesting. This would be the affect of a fan blowing cross ways or blowing into the pick up area. The affect of noise or a sound in front or in back of the tube would be an interesting phase of study. Also the affect of physical disturbances within the tube. There are many possible physical disturbances which could be placed in the tube. Possibly the side of the tube could be made into a speaker, and a sound introduced through the tube boundary into the flow. The author was not able to, but was always interested in placing a strain gage on the tube, and determining whether a measurable strain was produced by the flow. If a measurable strain was produced, then with proper supports and with many strain gages mounted on the tube a research man should be able to measure the actual shearing forces on the tube itself.

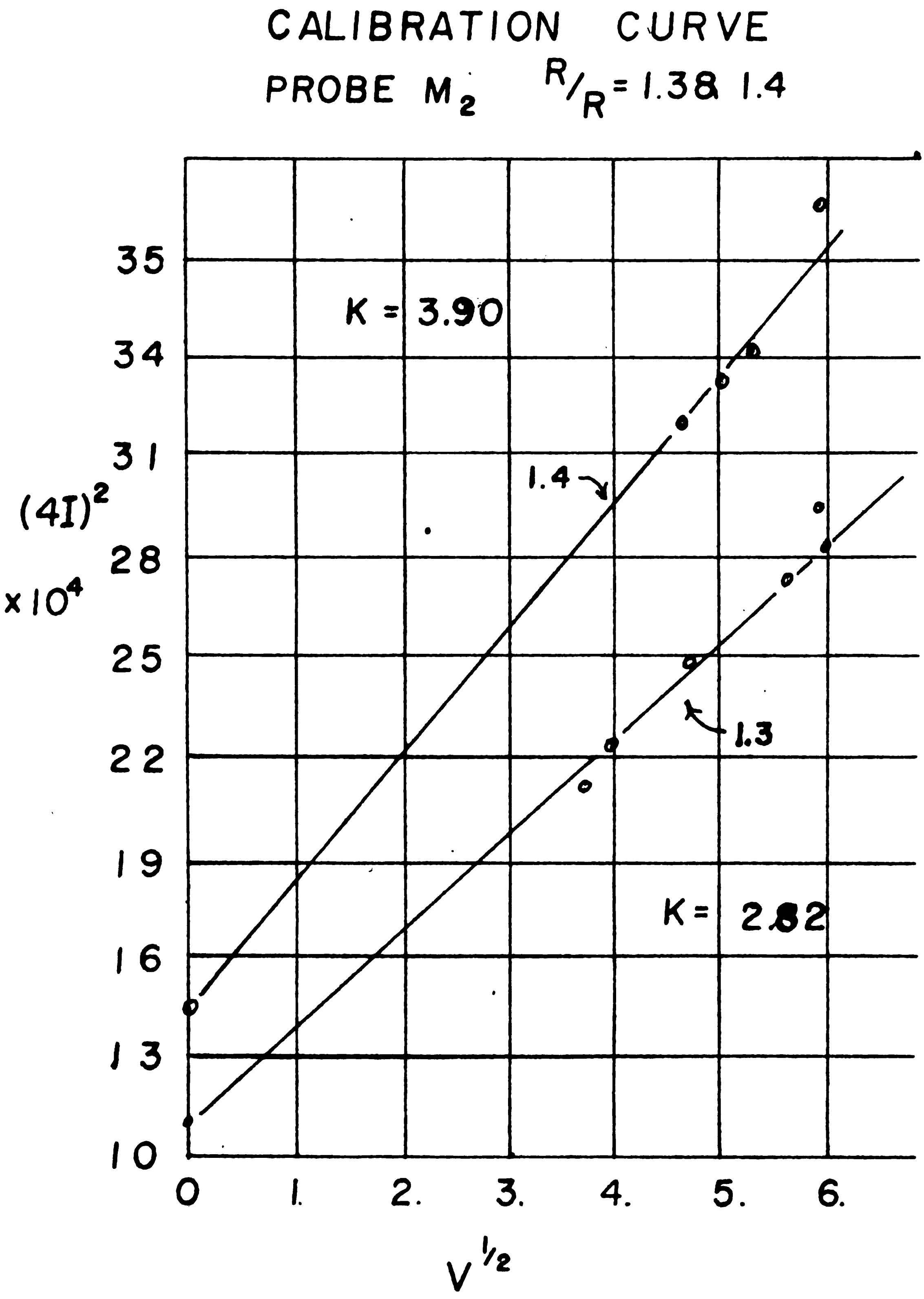
CALIBRATION CURVE

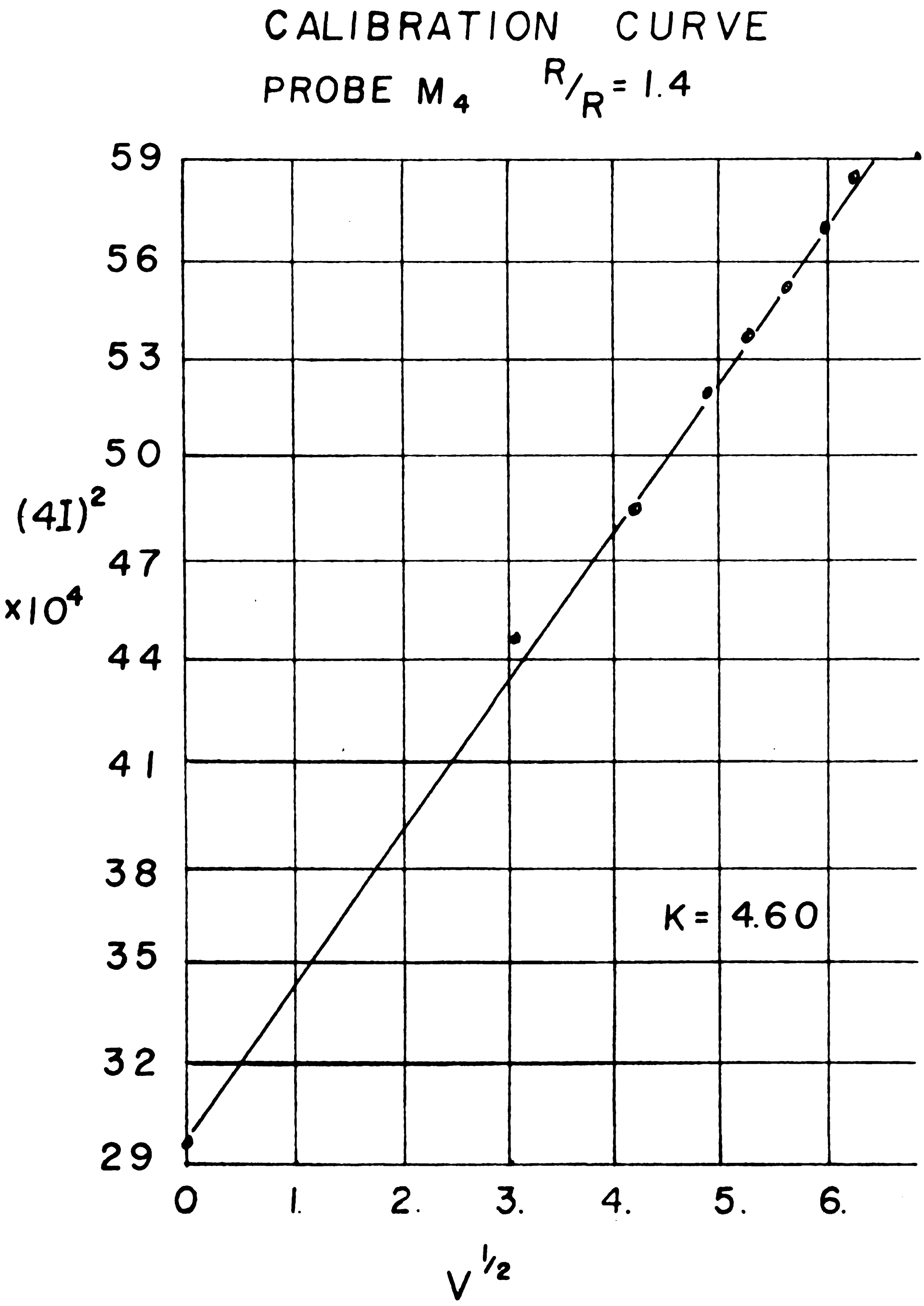
PROBE S_1 $R/R = 1.3$




CALIBRATION CURVE
PROBE S_2 $R/R = 1.4$
$(4I)^2 \times 10^4$
19
18
17
16
15
14
13
12
11
10
9
0
1.
2.
3.
4.
5.
6.
$V^{1/2}$
K = 1.87

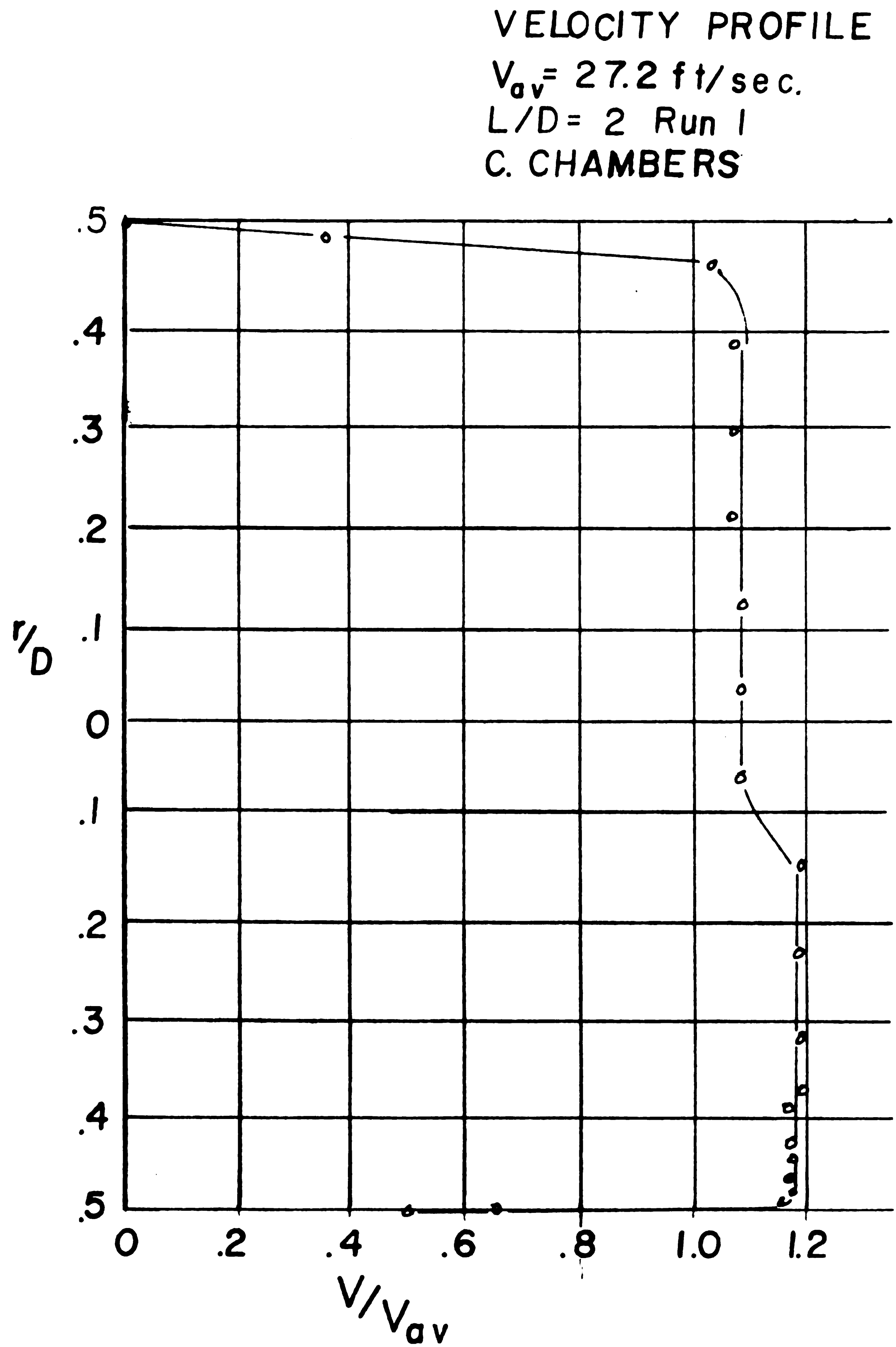

CALIBRATION CURVE
PROBE M1 R/R=1.3
(4I)²
× 10⁴
16
15
14
13
12
11
10
9
8
7
6
0
1.
2.
3.
4.
5.
6.
V^½
K= 1.60

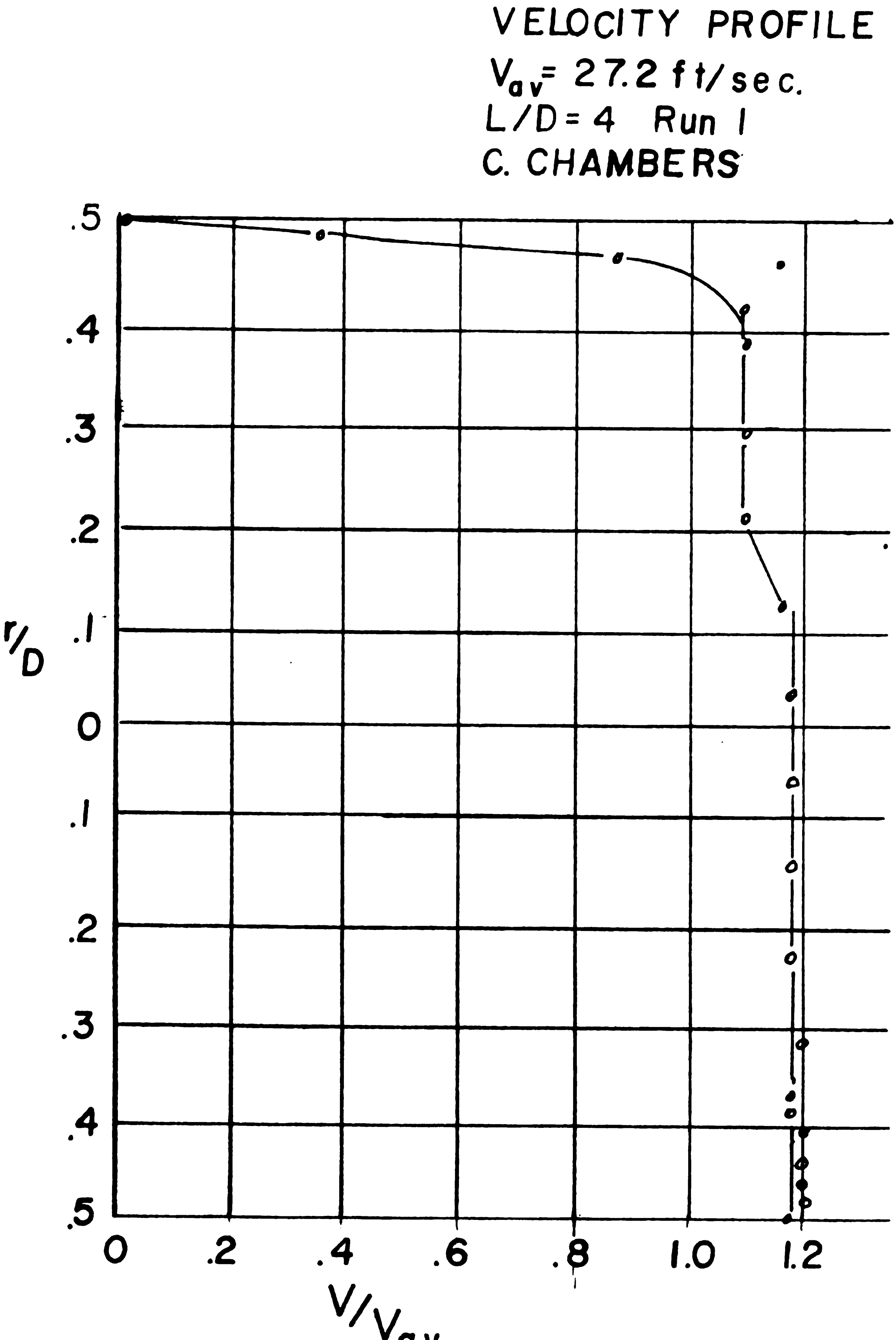

CALIBRATION CURVE
PROBE M_2 $R/R = 1.38$ 1.4
K = 3.90
K = 2.82
1.4
1.3
$(4I)^2$
$\times 10^4$
35
34
31
28
25
22
19
16
13
10
0
1.
2.
3.
4.
5.
6.
$V^{1/2}$


CALIBRATION CURVE
PROBE M4 R/R = 1.4
59
56
53
50
(4I)²
47
x10⁴
44
41
38
35
32
29
K = 4.60
0
1.
2.
3.
4.
5.
6.
V ½

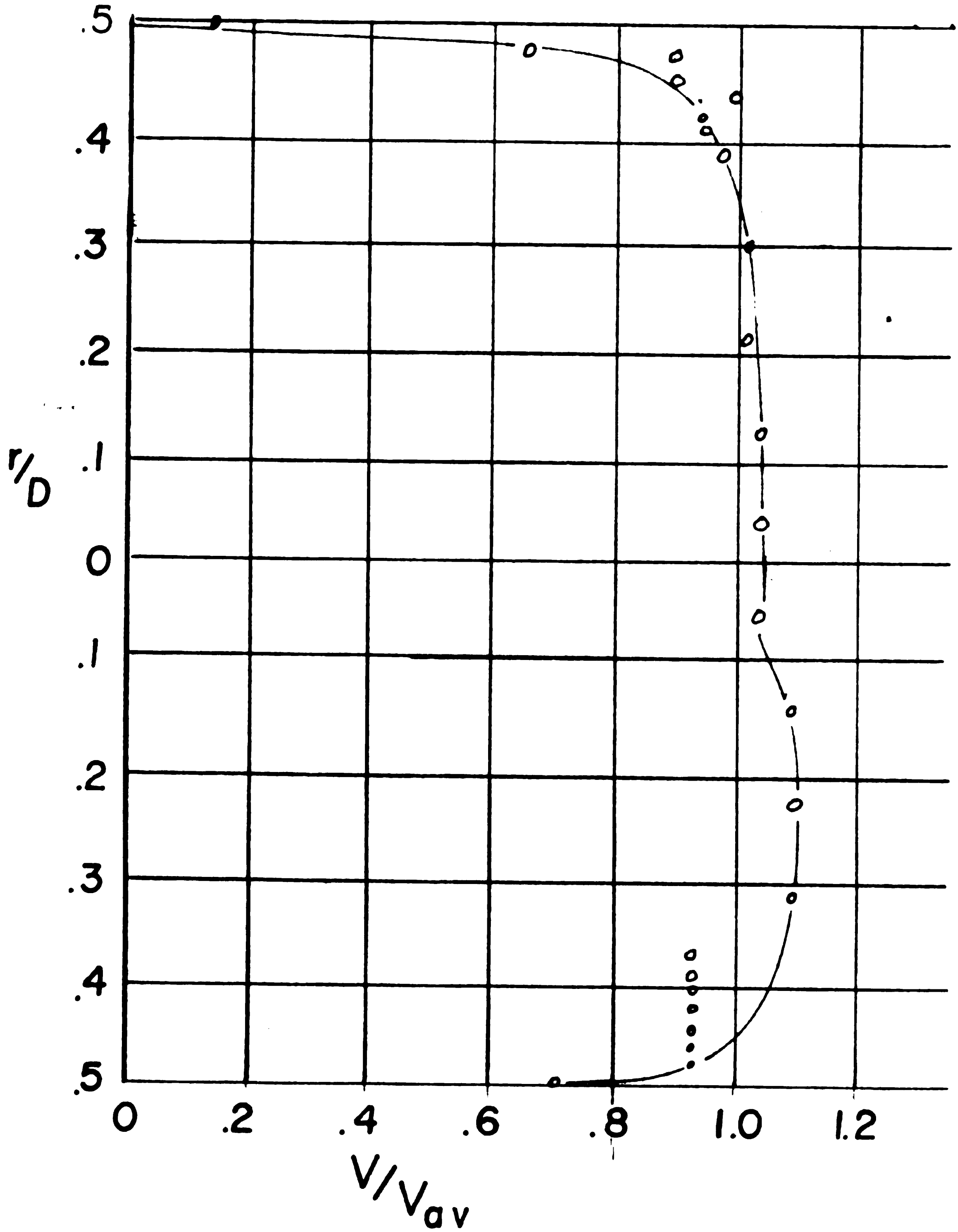
Velocity Profiles

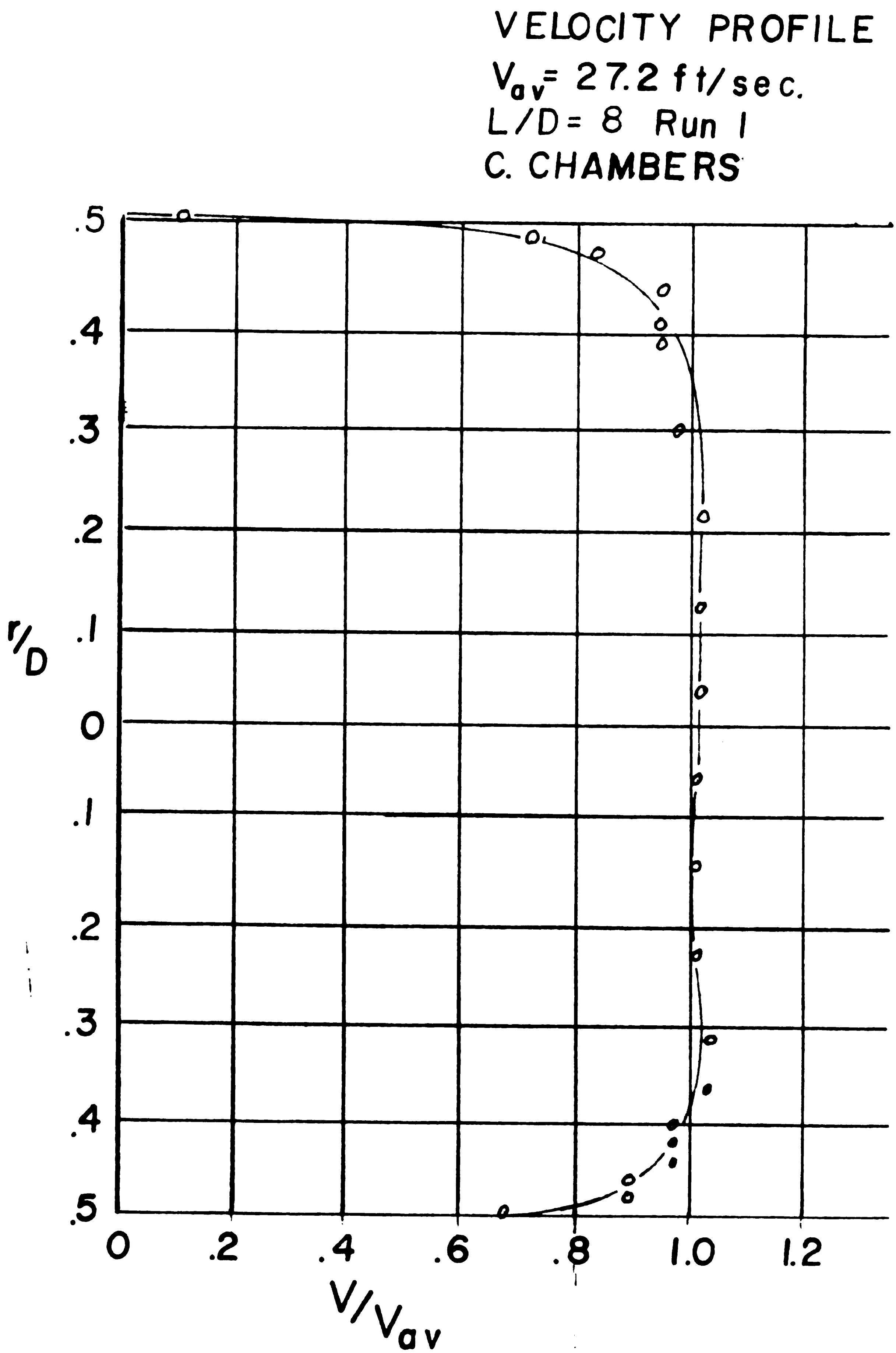
Following are the velocity profiles for each station measured during runs 1, 2, 3, and 4. The ordinate is the ratio $\frac{r}{D}$ where r is the radius of the points plotted and D is the tube diameter, 5.65 inches. The abscissa is the ratio $\frac{V}{V_{av}}$ where V is the velocity measured and V_{av} is the average velocity determined by dividing the average flow rate of all stations by the cross sectional area of the tube, 0.174 ft.^{2}. Note: this gives only one average velocity for each run. The flow rates are listed in figure 11.

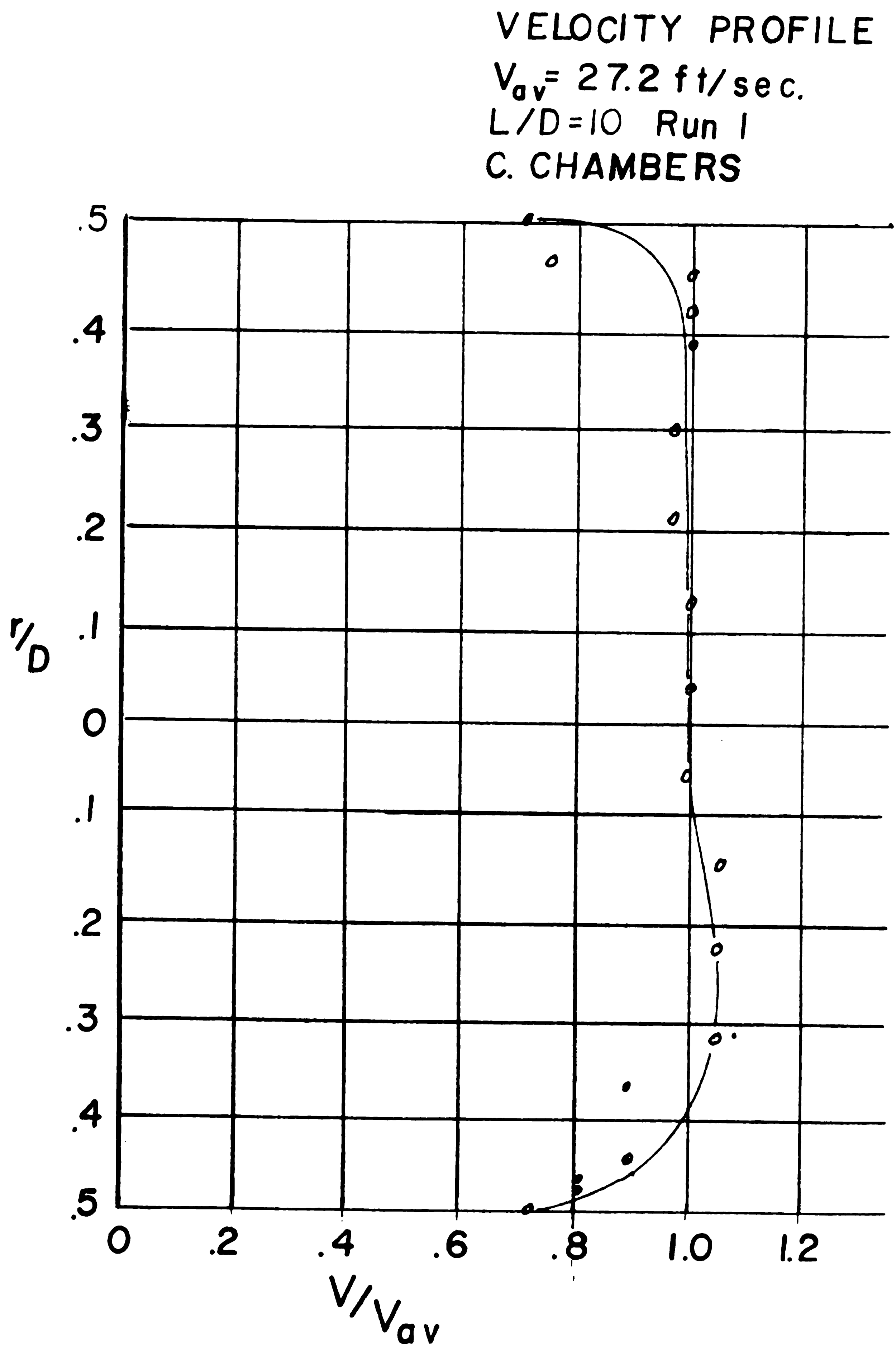

VELOCITY PROFILE
V_{av}= 27.2 ft/sec.
L/D= 2 Run 1
C. CHAMBERS
r/D
.5
.4
.3
.2
.1
0
.1
.2
.3
.4
.5
0
.2
.4
.6
.8
1.0
1.2
V/V_{av}

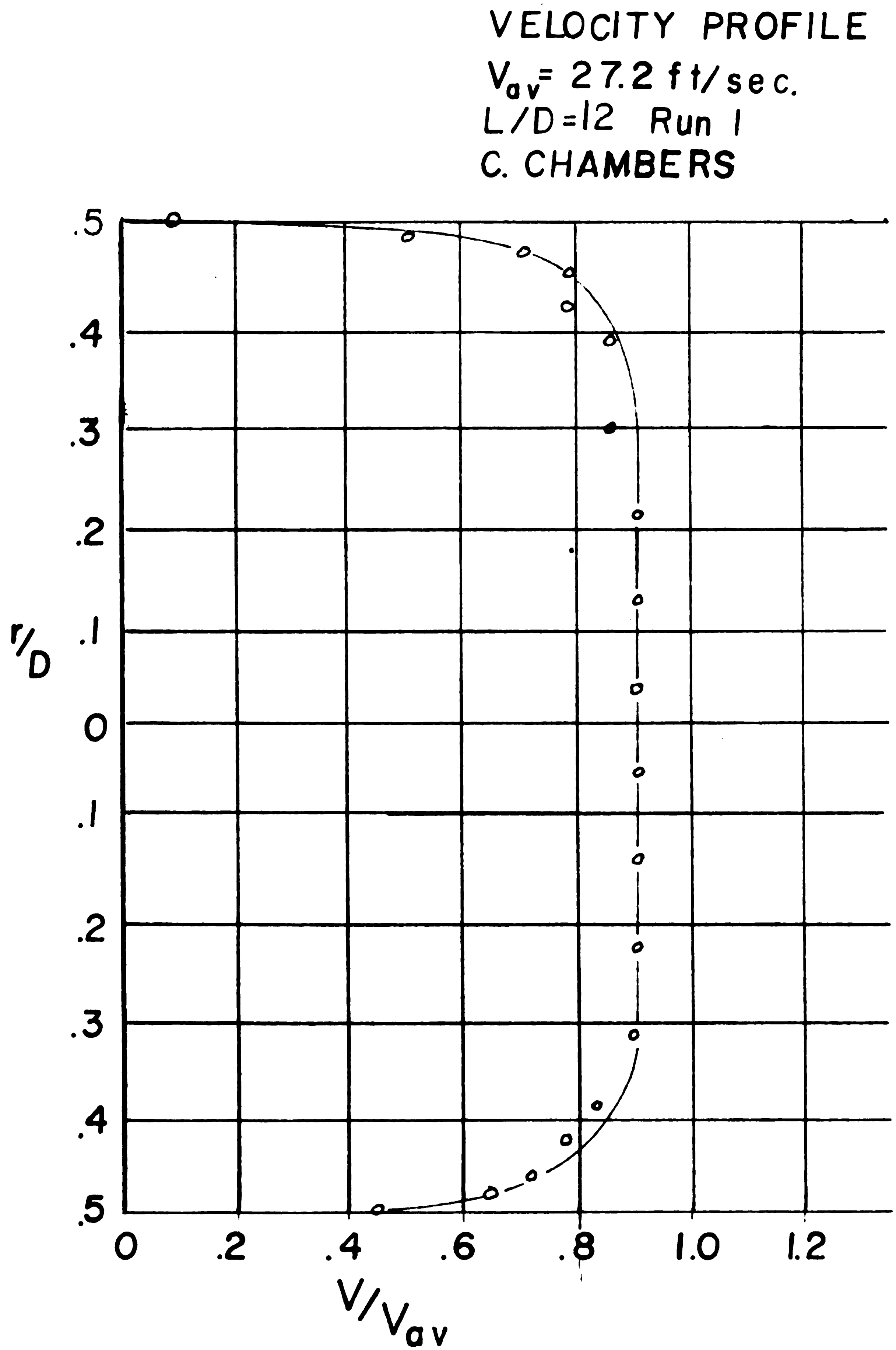

VELOCITY PROFILE
V_{av} = 27.2 ft/sec.
L/D = 4 Run I
C. CHAMBERS
r/D
.5
.4
.3
.2
.1
0
.1
.2
.3
.4
.5
0
.2
.4
.6
.8
1.0
1.2
V/V_av

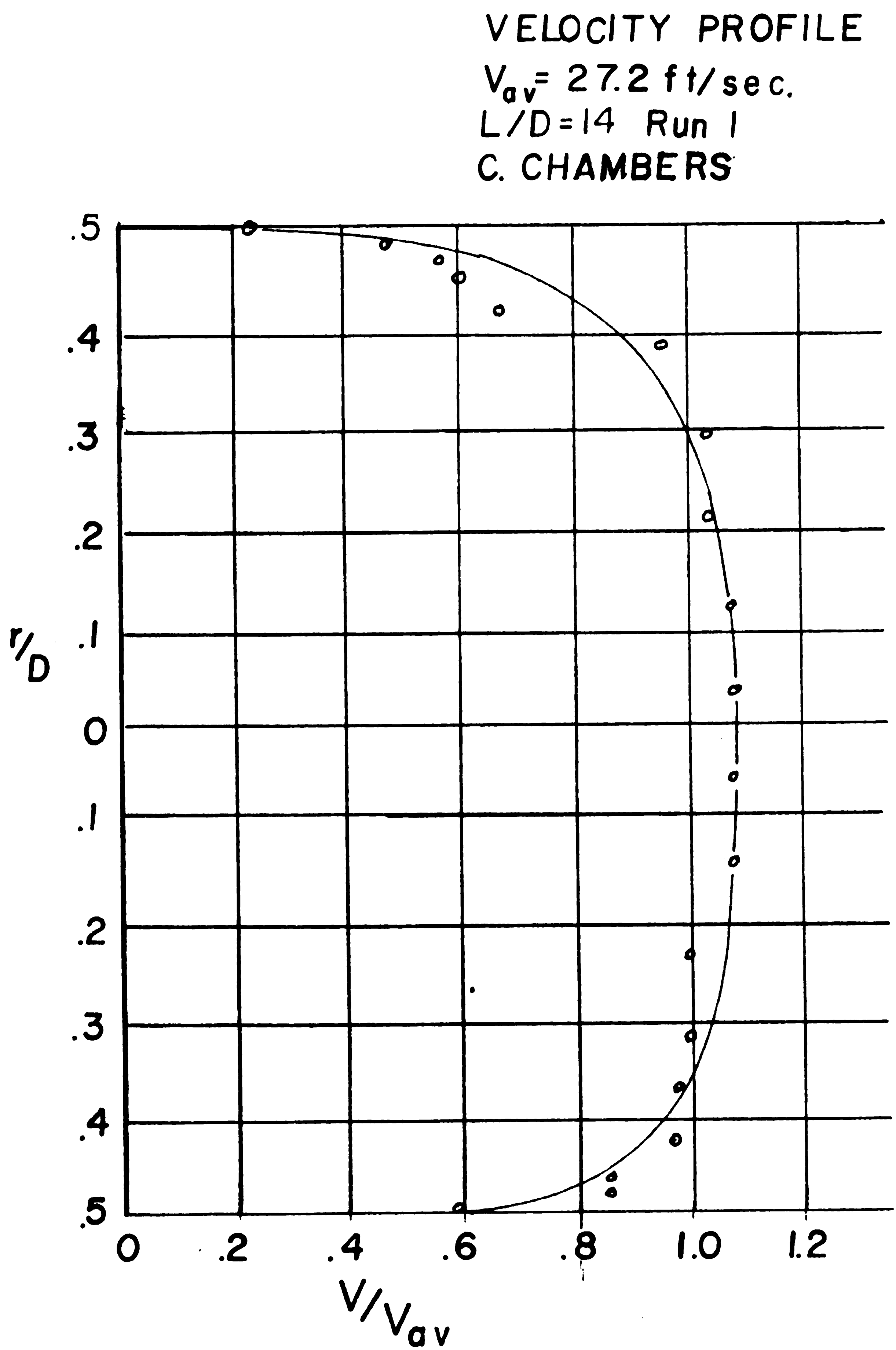
VELOCITY PROFILE
V_{av}= 27.2 ft/sec.
L/D= 6 Run I
C. CHAMBERS

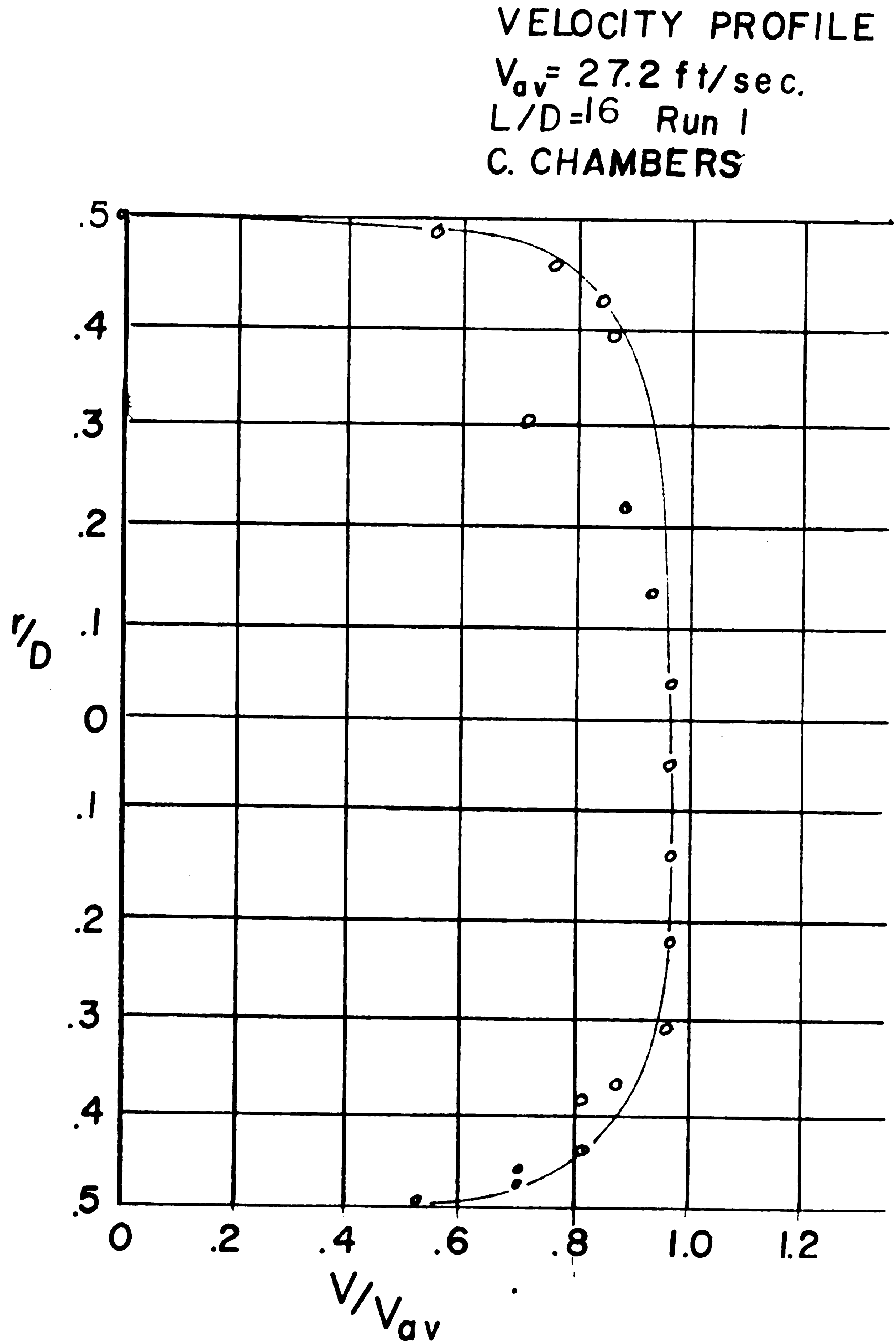



VELOCITY PROFILE
Vav= 27.2 ft/sec.
L/D= 8 Run I
C. CHAMBERS
r/D
.5
.4
.3
.2
.1
0
.1
.2
.3
.4
.5
0
.2
.4
.6
.8
1.0
1.2
V/Vav

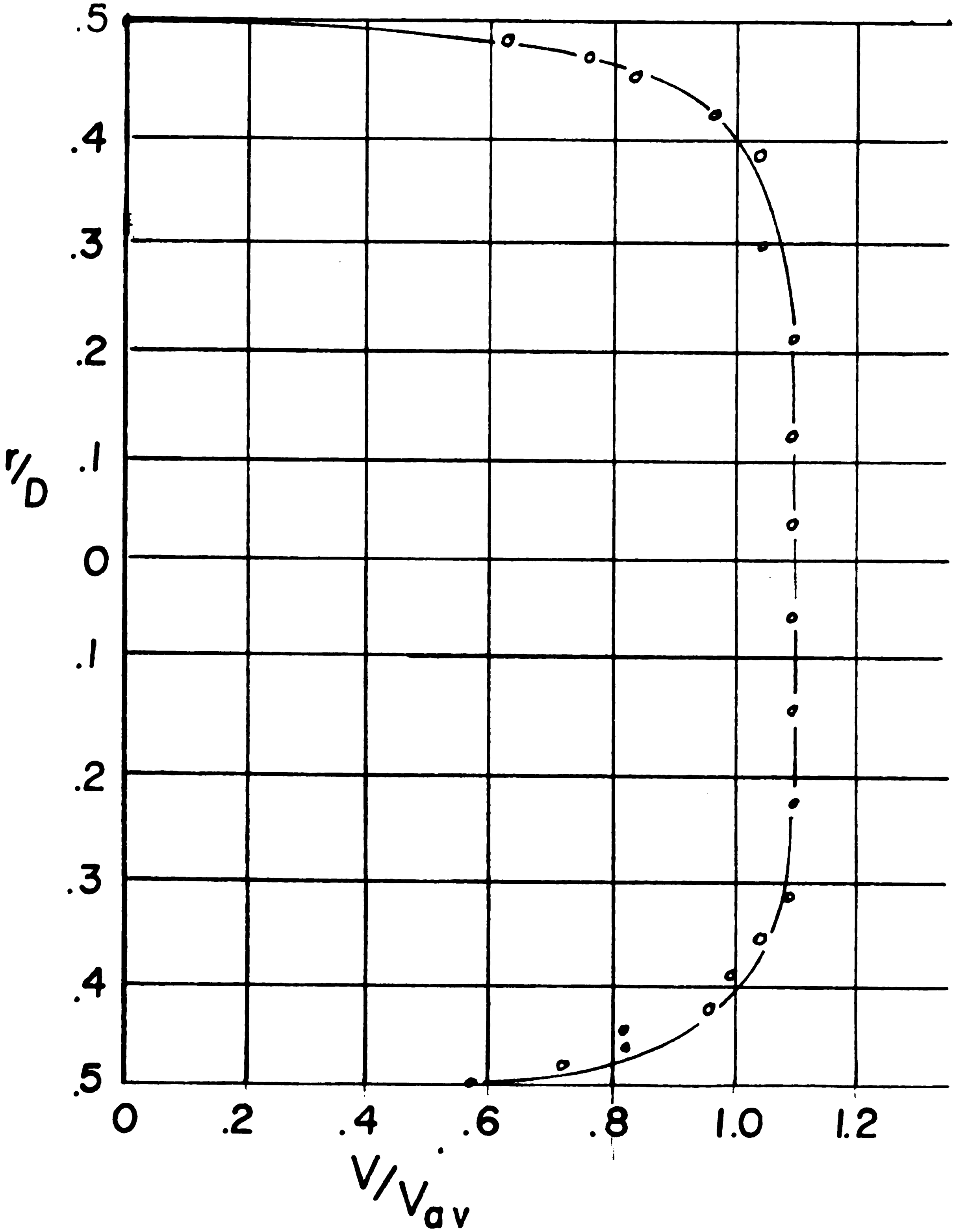

VELOCITY PROFILE
V_{av} = 27.2 ft/sec.
L/D=10 Run 1
C. CHAMBERS
.5
.4
.3
.2
.1
0
.1
.2
.3
.4
.5
r/D
0
.2
.4
.6
.8
1.0
1.2
V/V_{av}


VELOCITY PROFILE
V_av = 27.2 ft/sec.
L/D = 12 Run 1
C. CHAMBERS
r/D
.5
.4
.3
.2
.1
0
.1
.2
.3
.4
.5
0
.2
.4
.6
.8
1.0
1.2
V/V_av

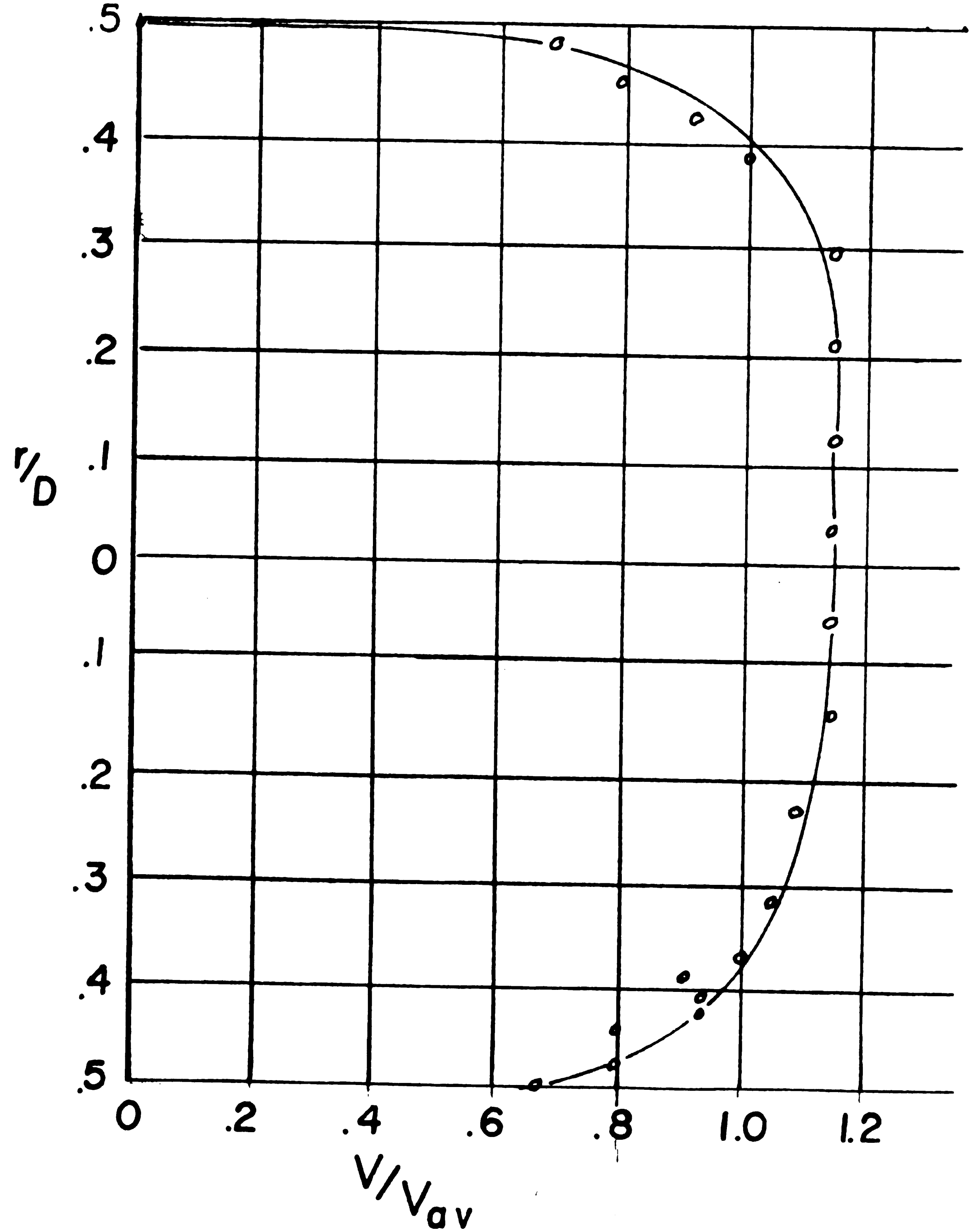

VELOCITY PROFILE
Vav= 27.2 ft/sec.
L/D=14 Run I
C. CHAMBERS
.5
.4
.3
.2
r/D
.1
0
.1
.2
.3
.4
.5
0
.2
.4
.6
.8
1.0
1.2
V/Vav


VELOCITY PROFILE
V_{av}= 27.2 ft/sec.
L/D=16 Run I
C. CHAMBERS
r/D
.5
.4
.3
.2
.1
0
.1
.2
.3
.4
.5
0
.2
.4
.6
.8
1.0
1.2
V/V_{av}

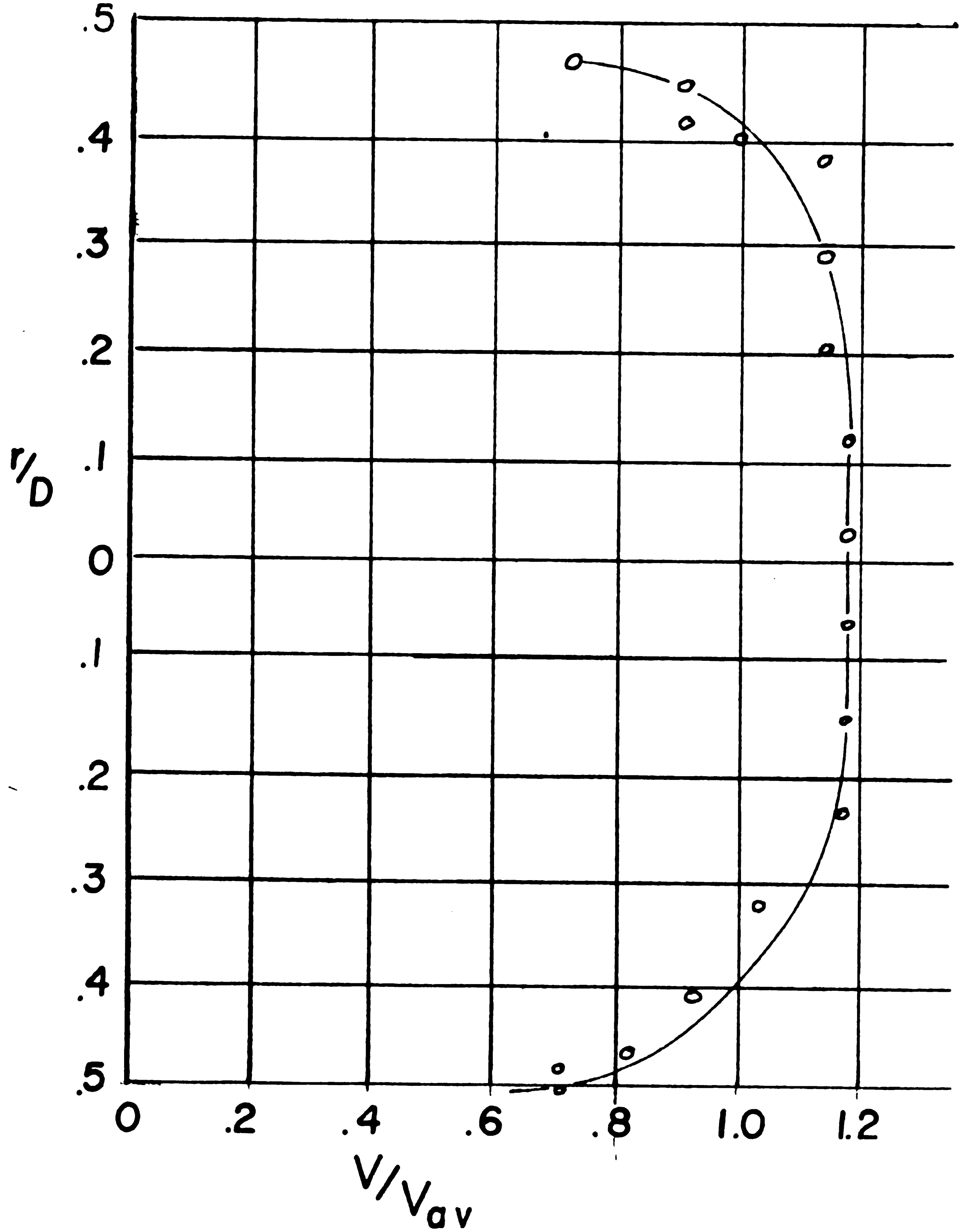
VELOCITY PROFILE
V_{av} = 27.2 ft/sec.
L/D = 18 Run 1
C. CHAMBERS



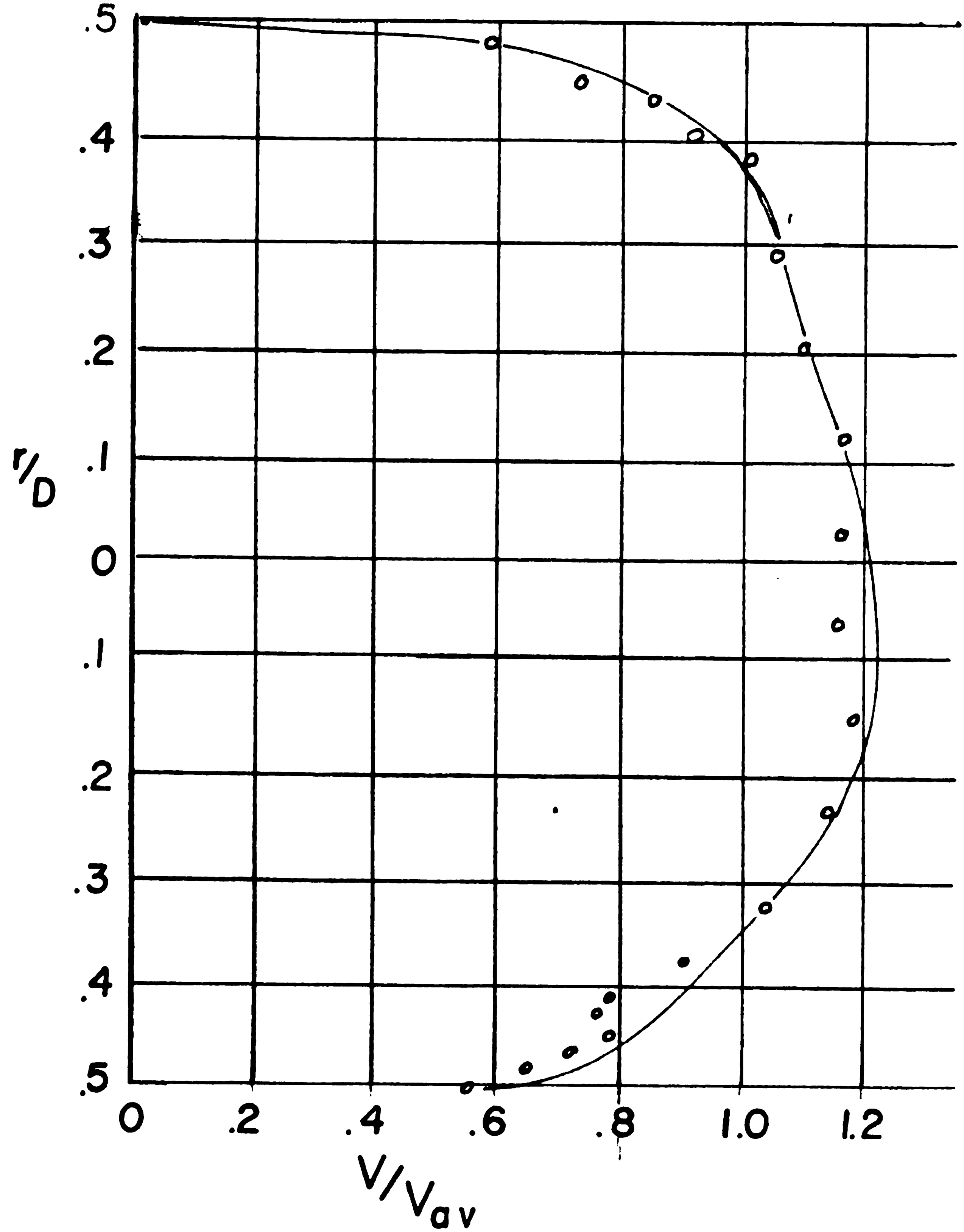
VELOCITY PROFILE
V_{av} = 27.2 ft/sec.
L/D = 20 Run 1
C. CHAMBERS

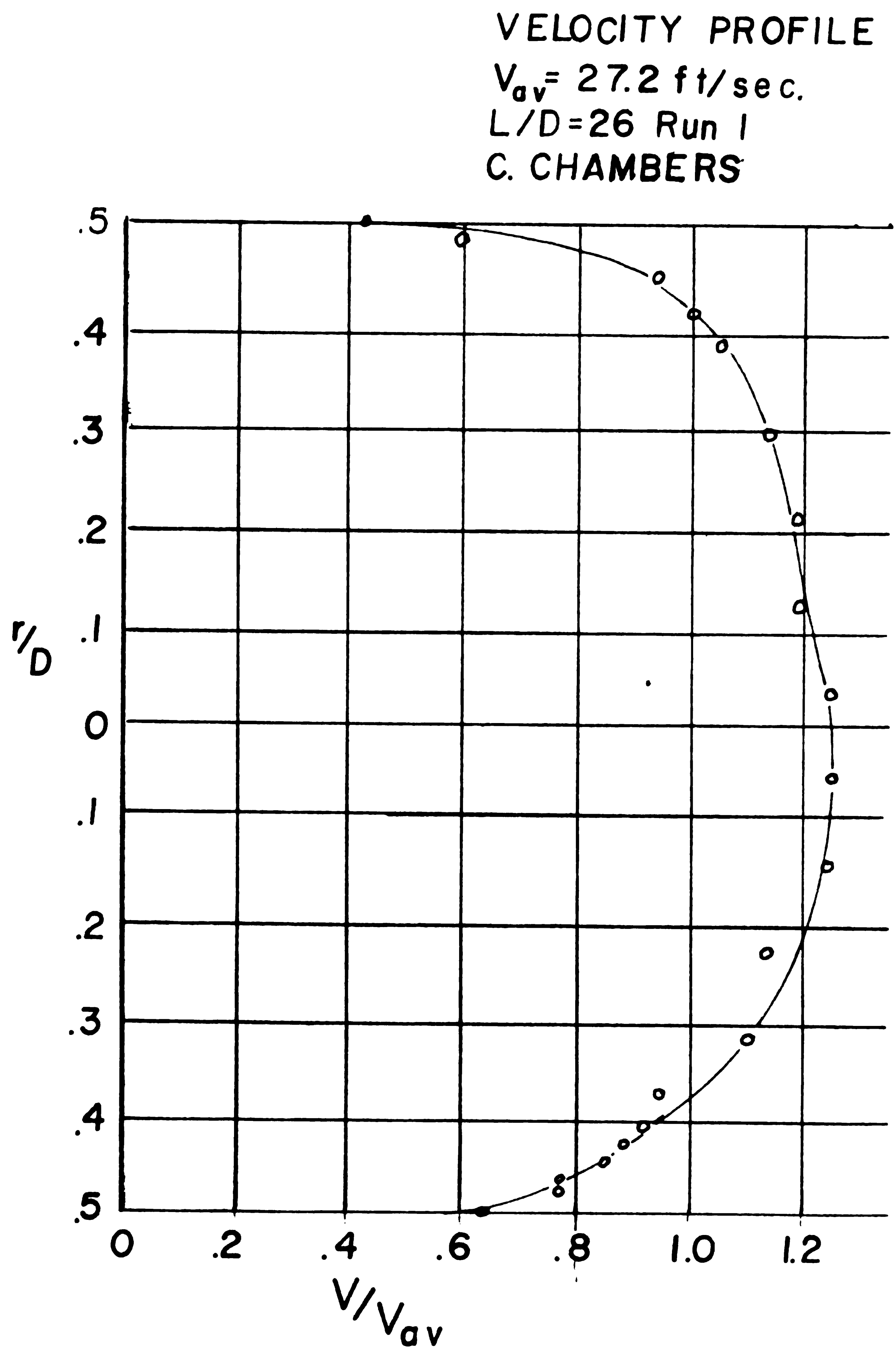


VELOCITY PROFILE
$V_{av} = 27.2$ ft/sec.
L/D = 22 Run 1
C. CHAMBERS

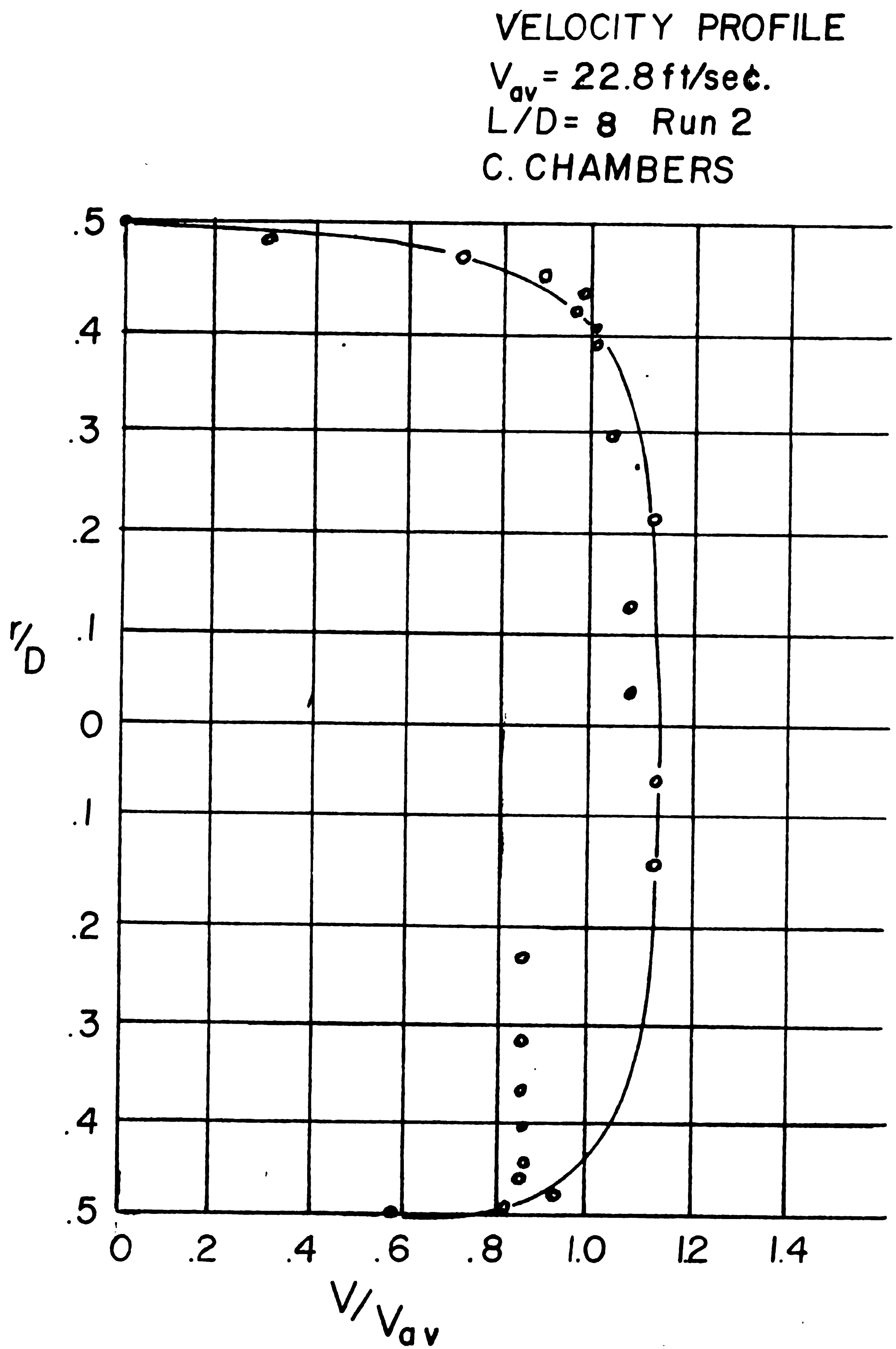


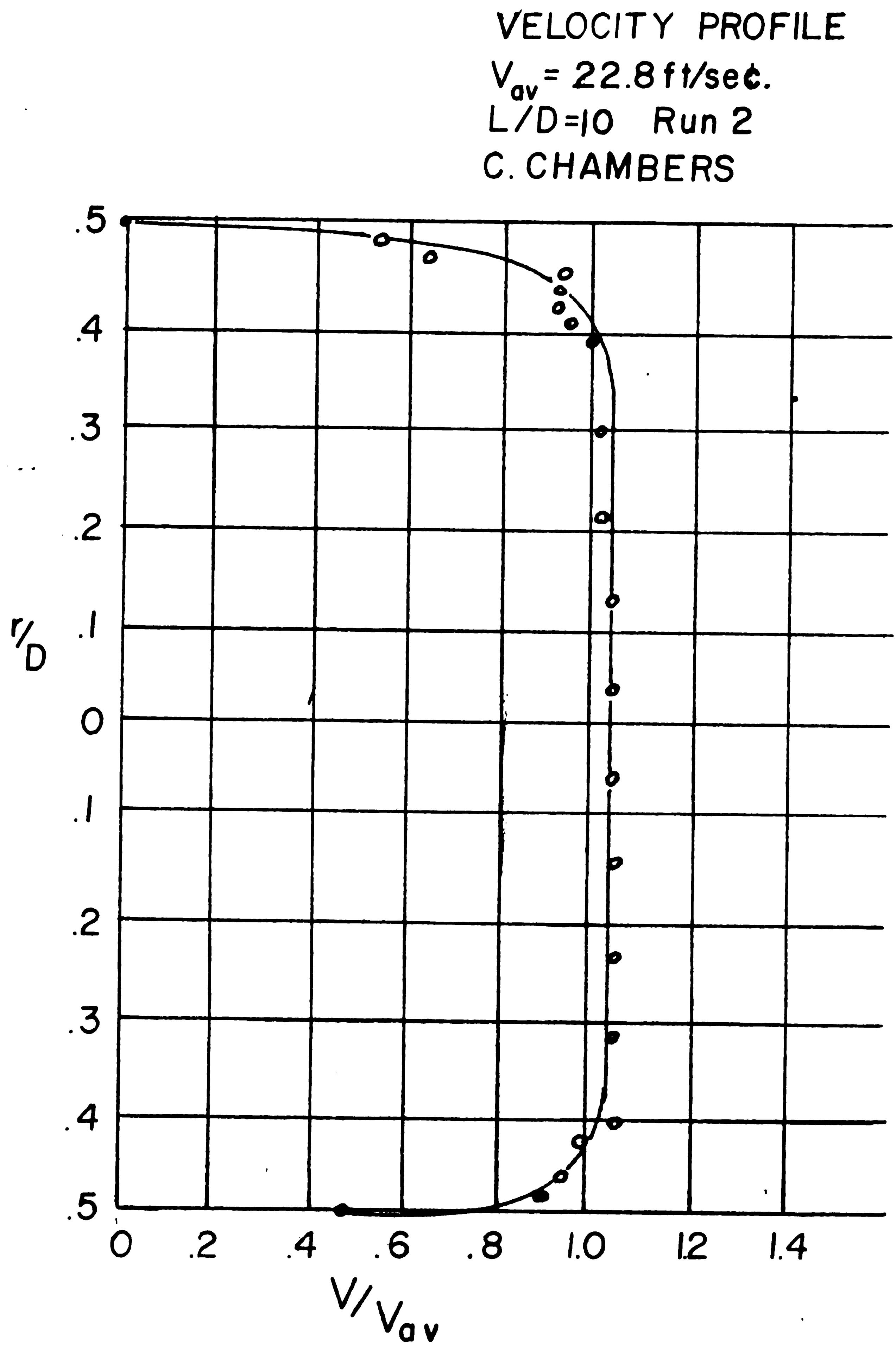
VELOCITY PROFILE
V_{av} = 27.2 ft/sec.
L/D = 24 Run 1
C. CHAMBERS



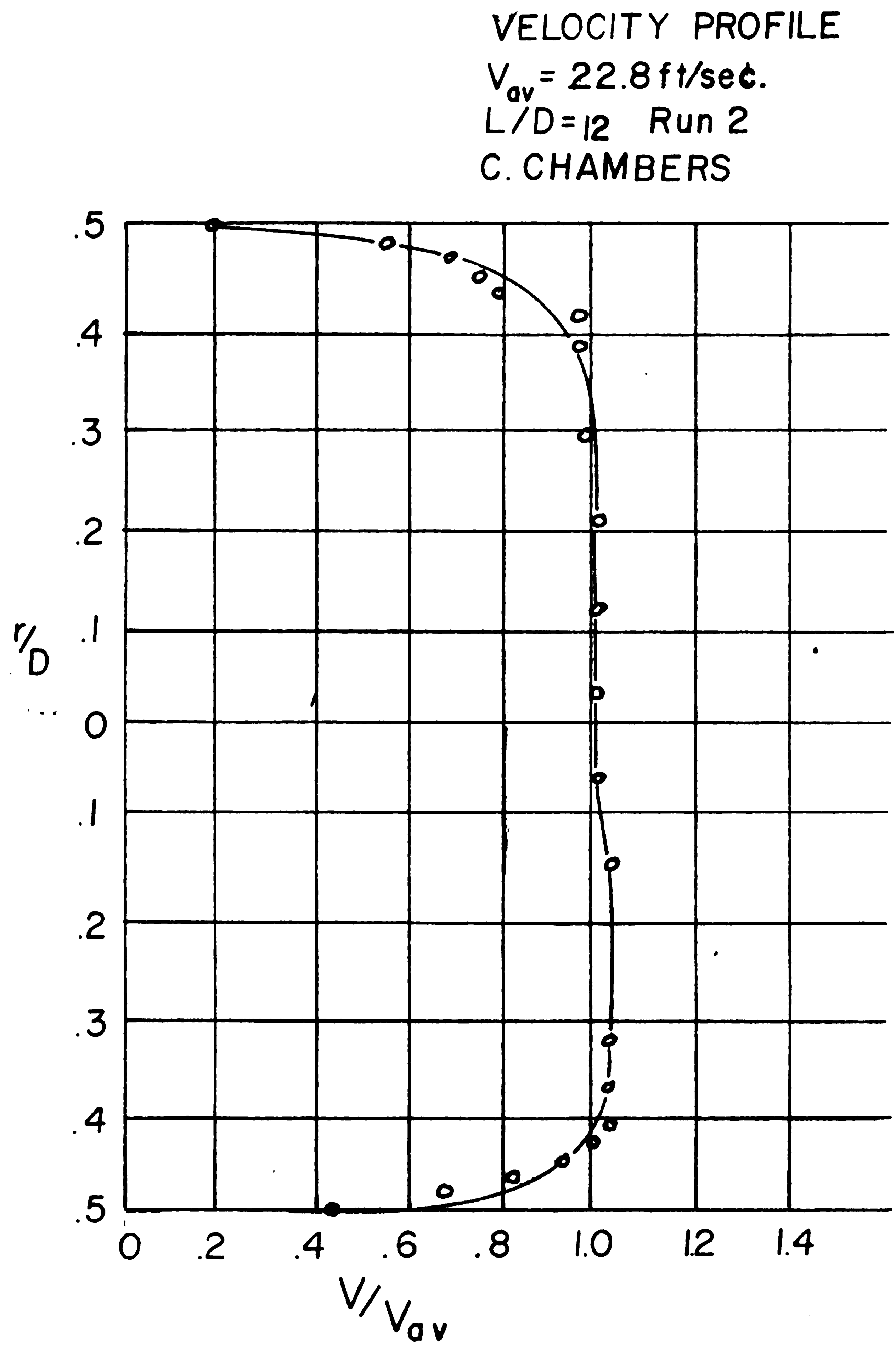


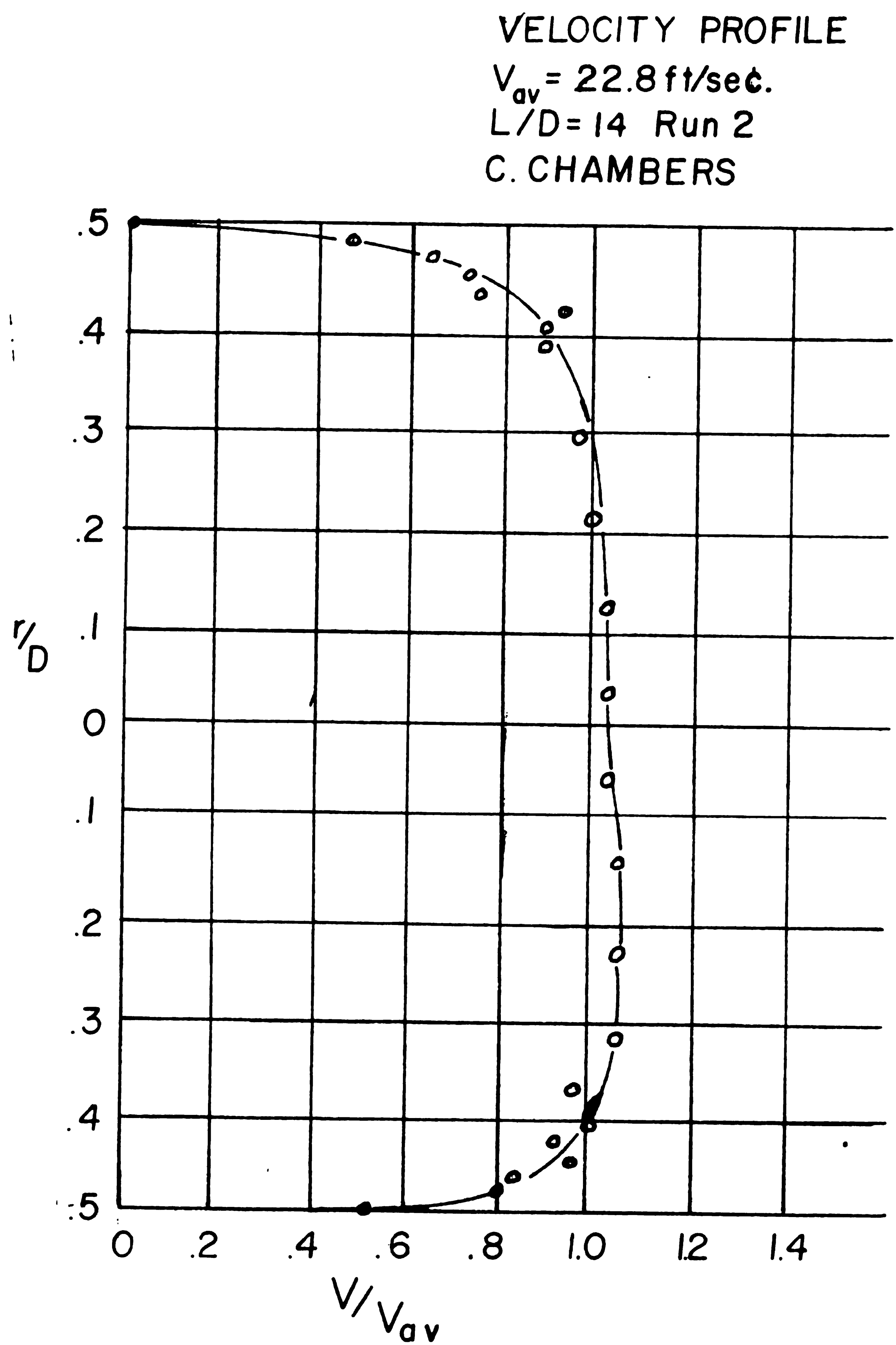
VELOCITY PROFILE
V_{av} = 27.2 ft/sec.
L/D=26 Run 1
C. CHAMBERS
r/D
.5
.4
.3
.2
.1
0
.1
.2
.3
.4
.5
0
.2
.4
.6
.8
1.0
1.2
V/V_{av}

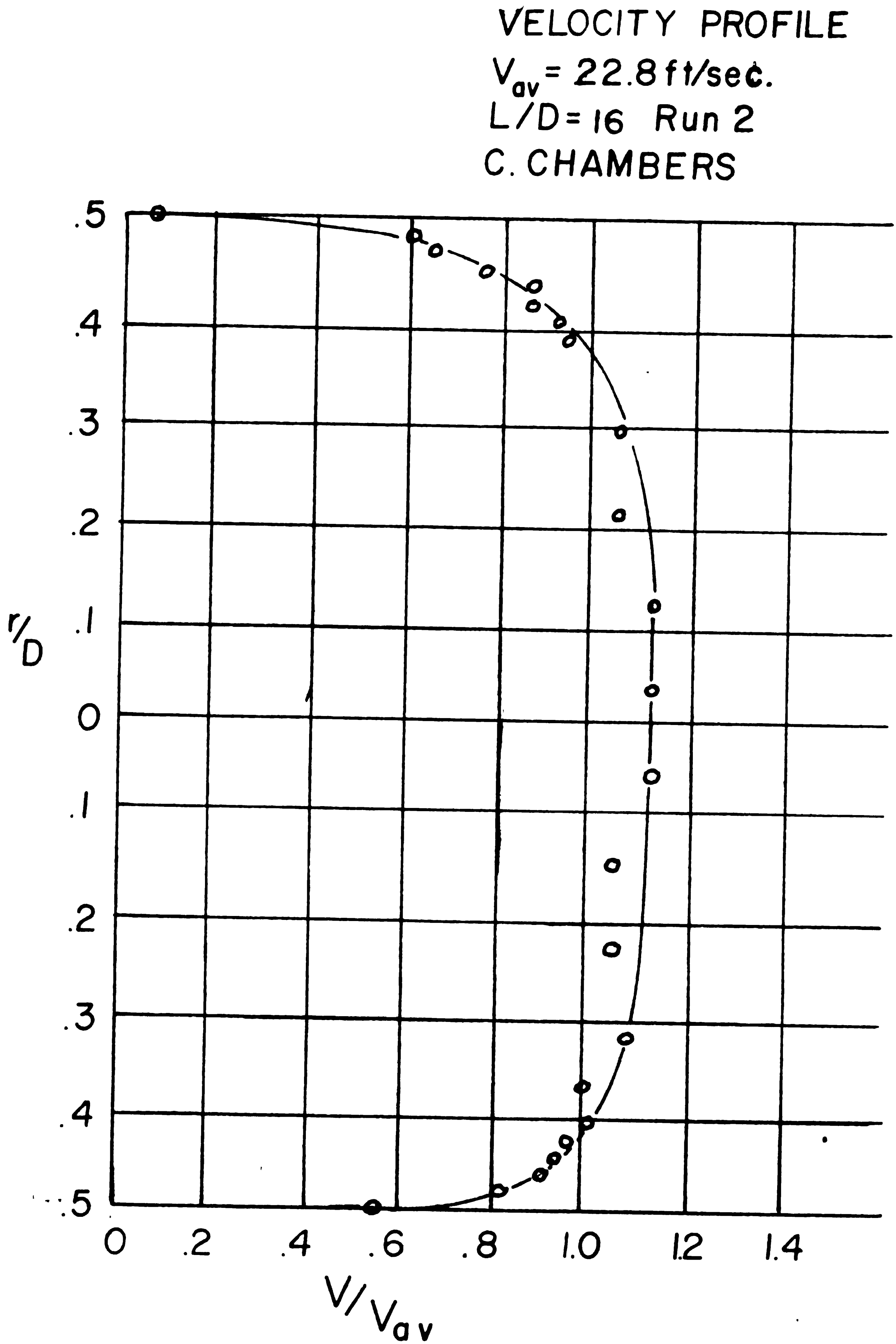

VELOCITY PROFILE
V_av = 22.8 ft/sec.
L/D = 8 Run 2
C. CHAMBERS
.5
.4
.3
.2
.1
0
.1
.2
.3
.4
.5
r/D
0
.2
.4
.6
.8
1.0
1.2
1.4
V/V_av



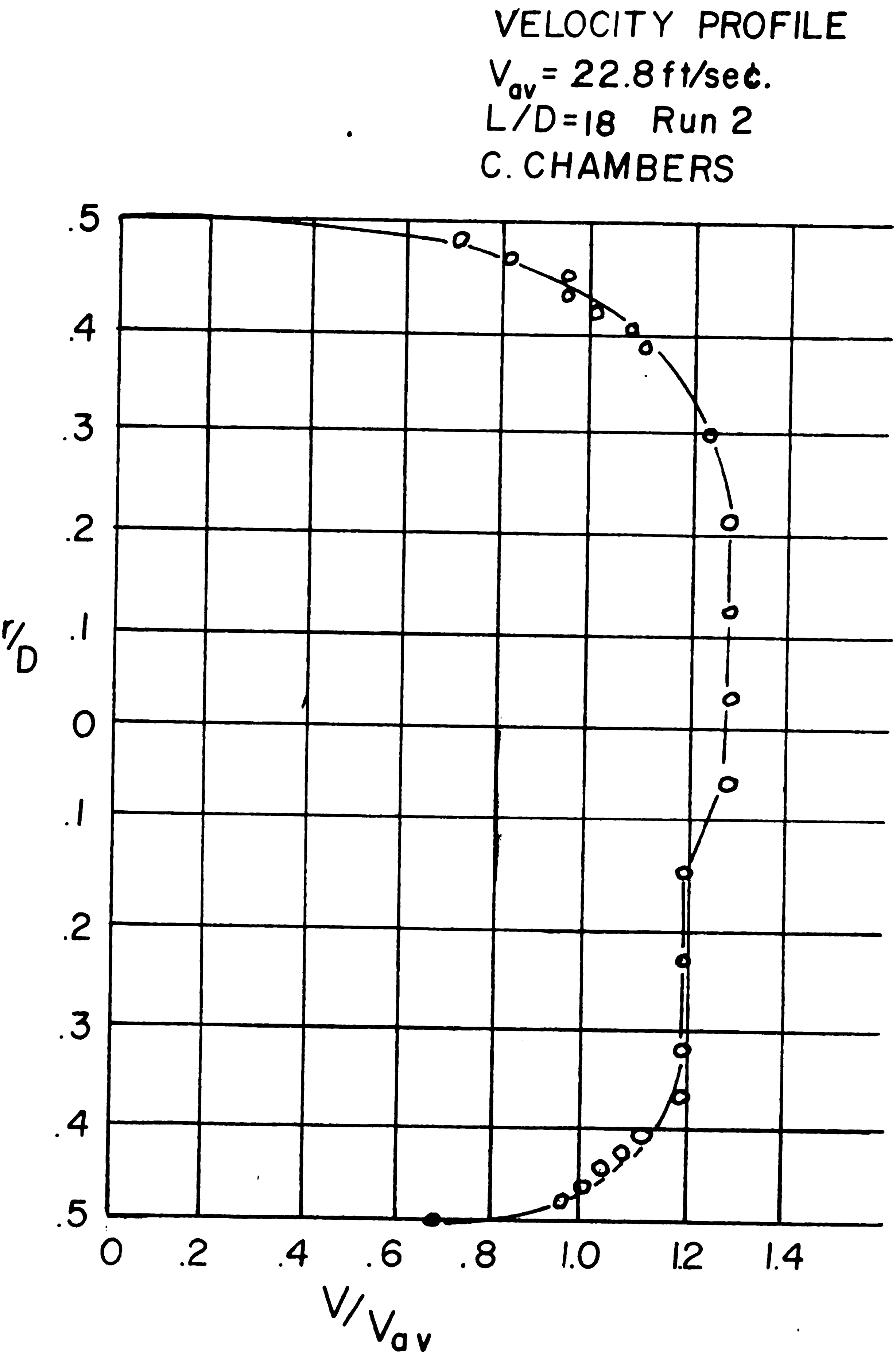
VELOCITY PROFILE
V_{av} = 22.8 ft/sec.
L/D=10 Run 2
C. CHAMBERS
r/D
.5
.4
.3
.2
.1
0
.1
.2
.3
.4
.5
0 .2 .4 .6 .8 1.0 1.2 1.4
V/V_{av}


VELOCITY PROFILE
V_{av} = 22.8 ft/sec.
L/D = 12 Run 2
C. CHAMBERS
r/D
.5
.4
.3
.2
.1
0
.1
.2
.3
.4
.5
0
.2
.4
.6
.8
1.0
1.2
1.4
V/V_{av}

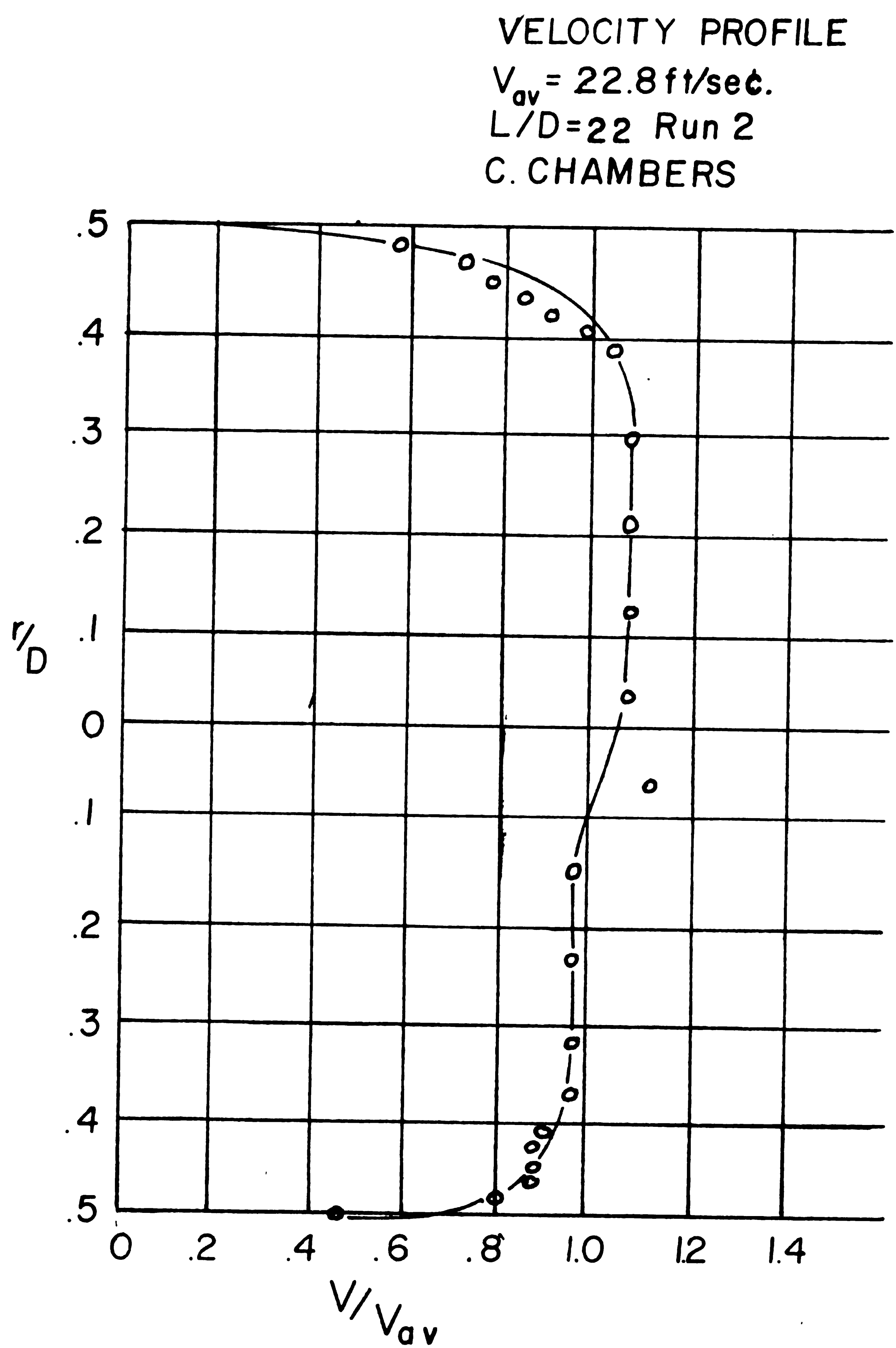

VELOCITY PROFILE
V_{av} = 22.8 ft/sec.
L/D = 14 Run 2
C. CHAMBERS
r/D
.5
.4
.3
.2
.1
0
.1
.2
.3
.4
.5
0
.2
.4
.6
.8
1.0
1.2
1.4
V/V_{av}


VELOCITY PROFILE
V_{av} = 22.8 ft/sec.
L/D = 16 Run 2
C. CHAMBERS
r/D
.5
.4
.3
.2
.1
0
.1
.2
.3
.4
.5
0
.2
.4
.6
.8
1.0
1.2
1.4
V/V_{av}

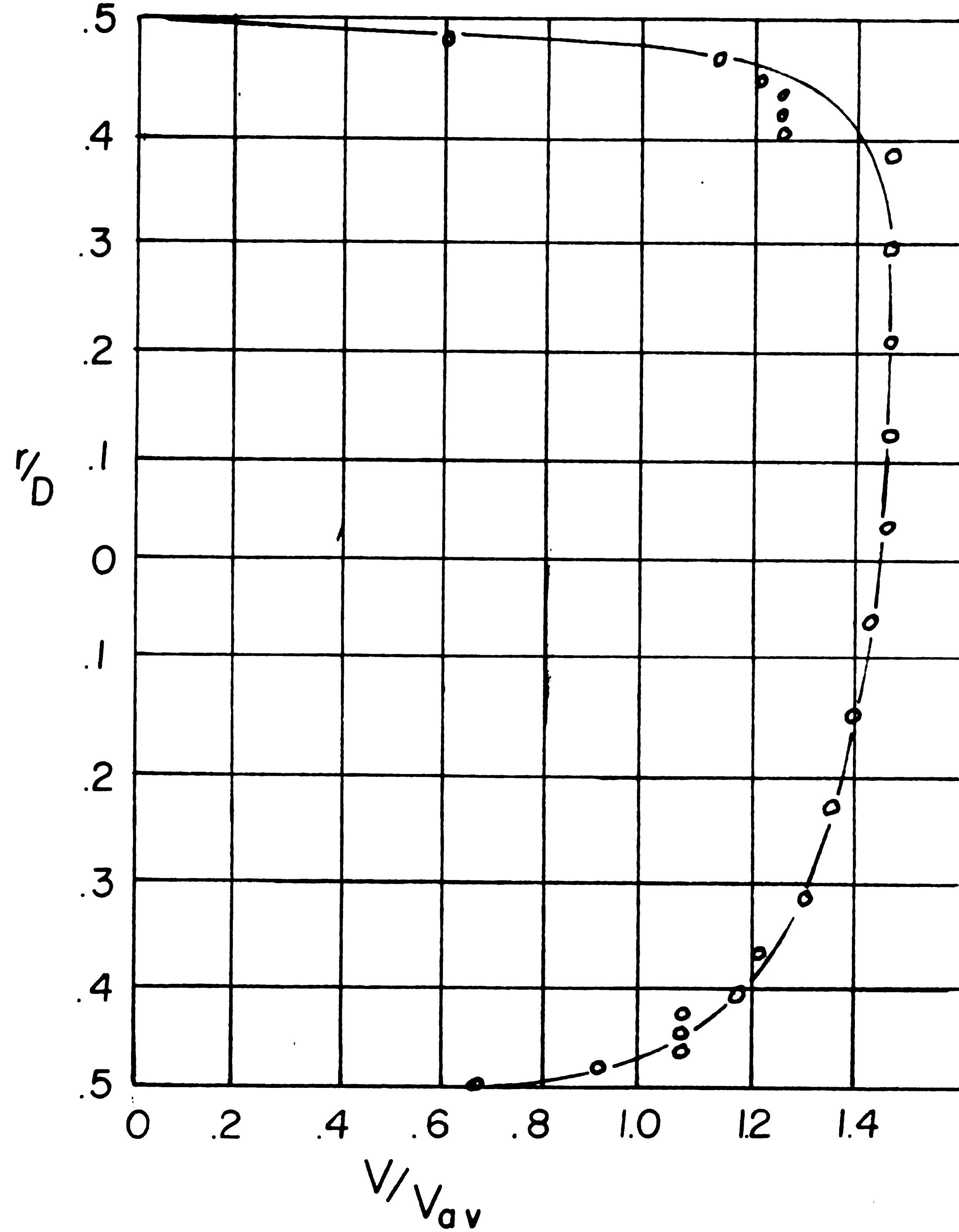
2



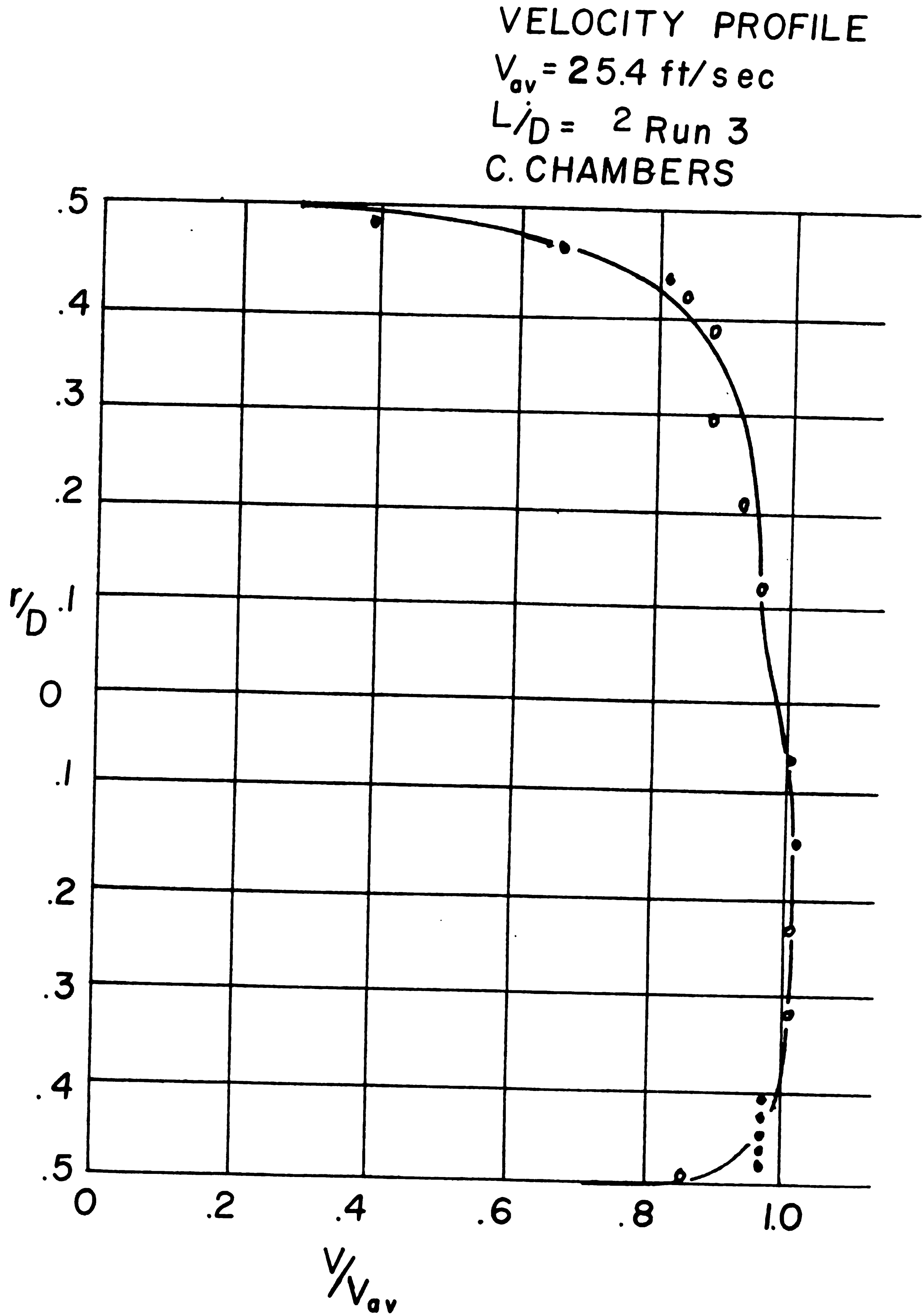
VELOCITY PROFILE
V_{av} = 22.8 ft/sec.
L/D=18 Run 2
C. CHAMBERS
.5
.4
.3
.2
r/D
.1
0
.1
.2
.3
.4
.5
0
.2
.4
.6
.8
1.0
1.2
1.4
V/V_{av}


VELOCITY PROFILE
V_{av} = 22.8 ft/sec.
L/D=22 Run 2
C. CHAMBERS
.5
.4
.3
.2
.1
0
.1
.2
.3
.4
.5
r/D
0
.2
.4
.6
.8
1.0
1.2
1.4
V/V_{av}

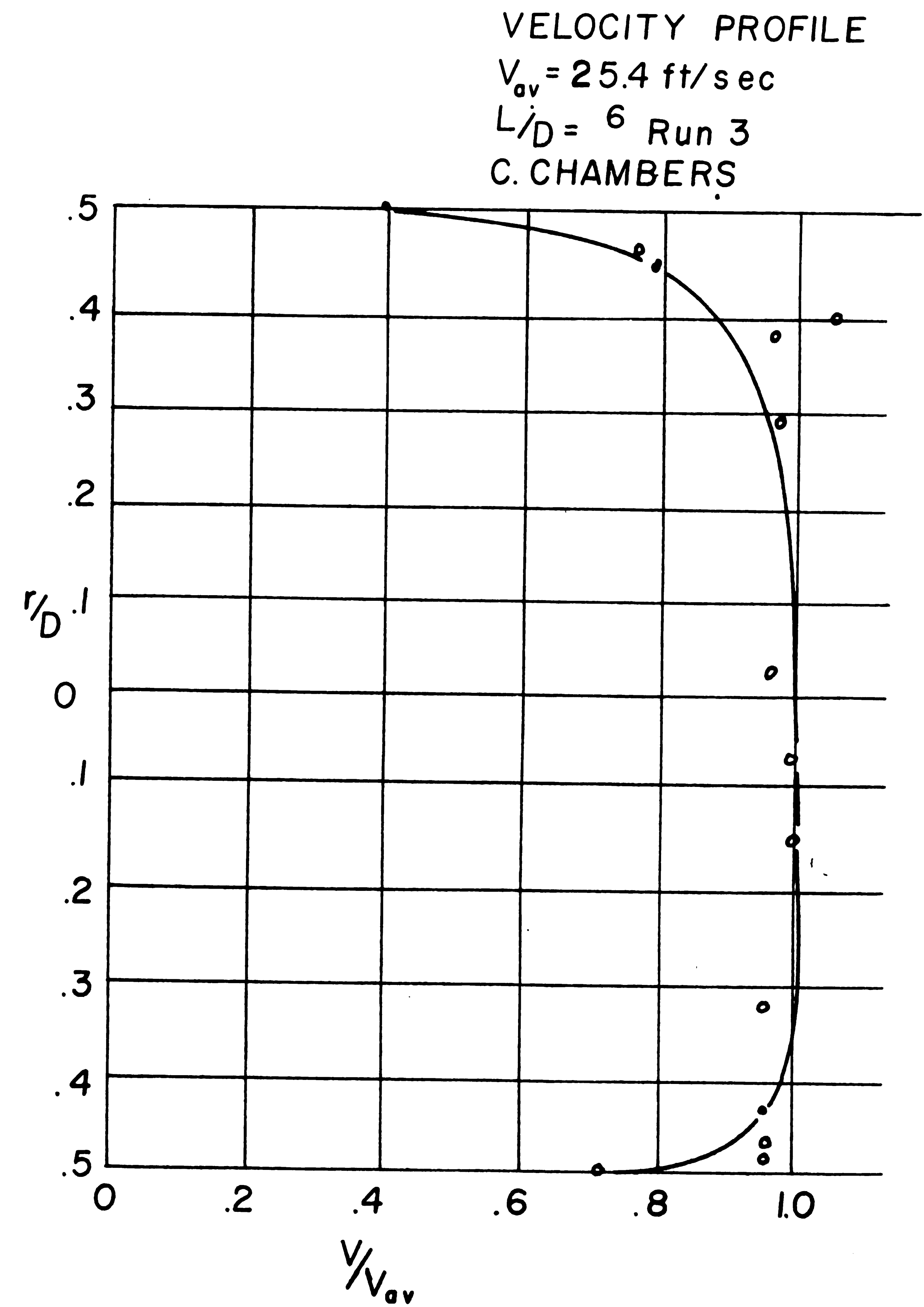
VELOCITY PROFILE
$V_{av} = 22.8$ ft/sec.
L/D = 26 Run 2
C. CHAMBERS



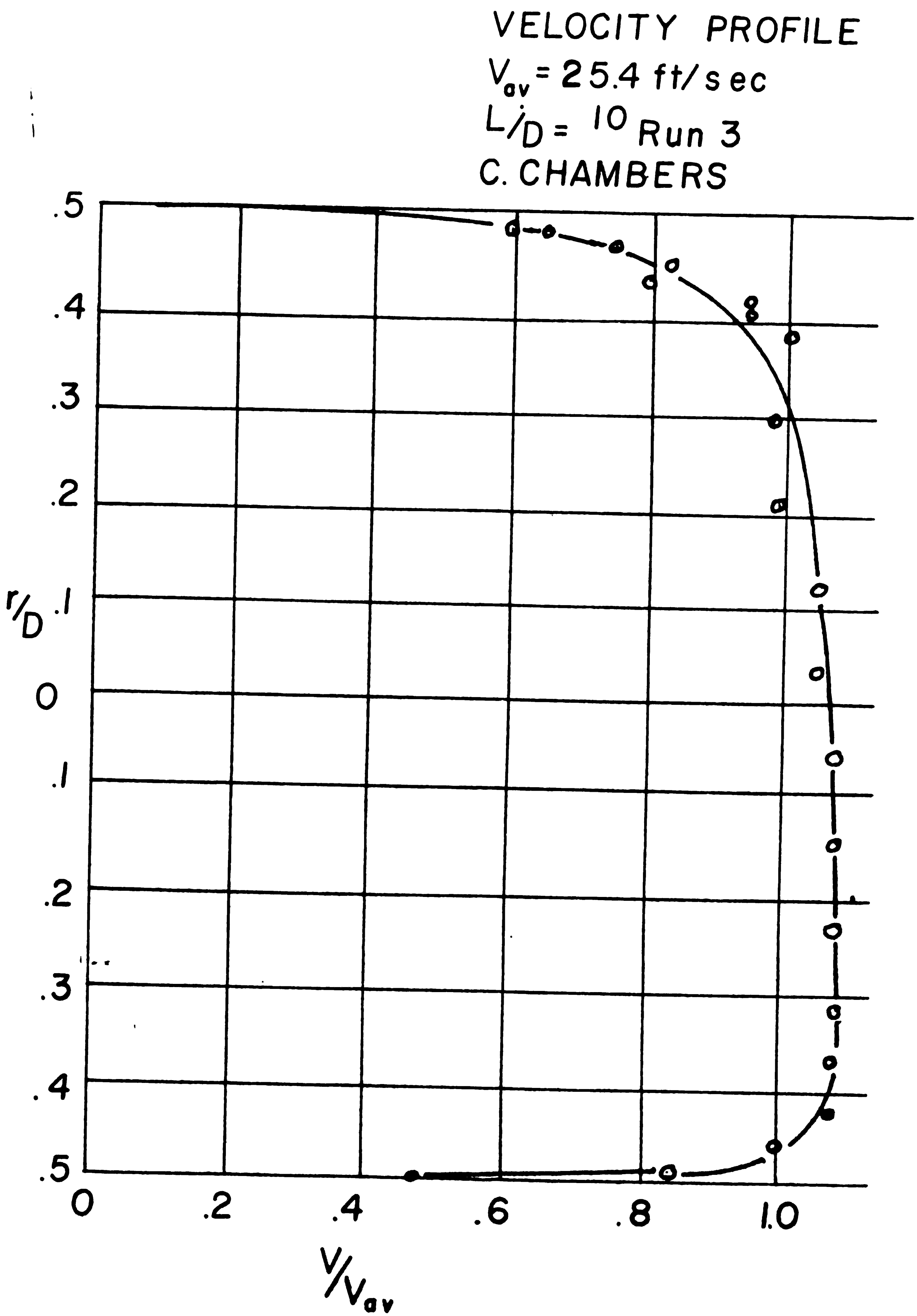
ν

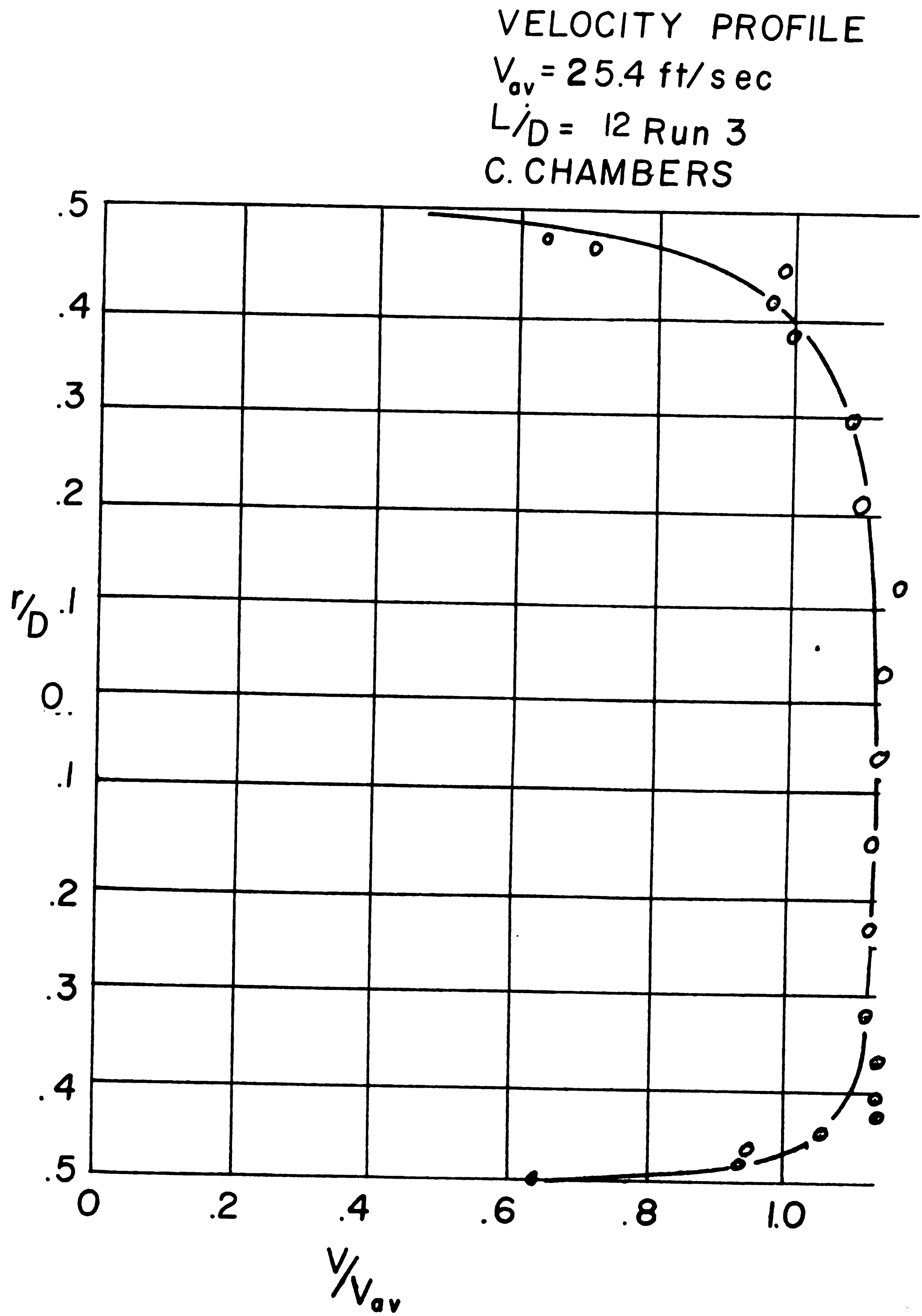


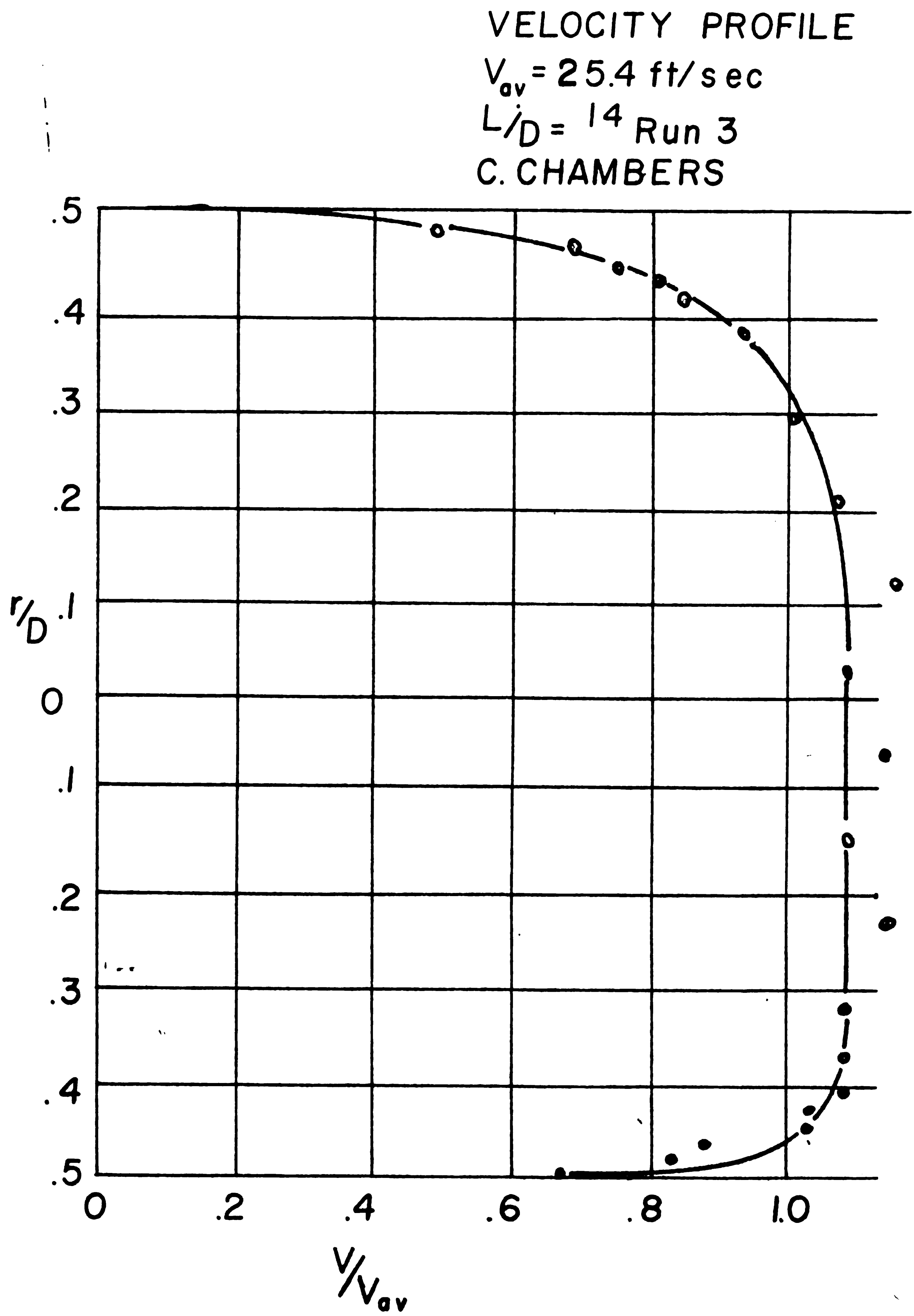
VELOCITY PROFILE
V_{av} = 25.4 ft/sec
L/D = 2 Run 3
C. CHAMBERS
.5
.4
.3
.2
r/D .1
0
.1
.2
.3
.4
.5
0
.2
.4
.6
.8
1.0
V/V_{av}



VELOCITY PROFILE
V_{av} = 25.4 ft/sec
L/D = 6 Run 3
C. CHAMBERS
r/D
.5
.4
.3
.2
.1
0
.1
.2
.3
.4
.5
0
.2
.4
.6
.8
1.0
V/V_{av}


VELOCITY PROFILE
V_{av} = 25.4 ft/sec
L/D = 10 Run 3
C. CHAMBERS
r/D
.5
.4
.3
.2
.1
0
.1
.2
.3
.4
.5
0
.2
.4
.6
.8
1.0
V/V_{av}


VELOCITY PROFILE
V_{av} = 25.4 ft/sec
L/D = 12 Run 3
C. CHAMBERS
r/D
.5
.4
.3
.2
.1
0
.1
.2
.3
.4
.5
0
.2
.4
.6
.8
1.0
V/Vav

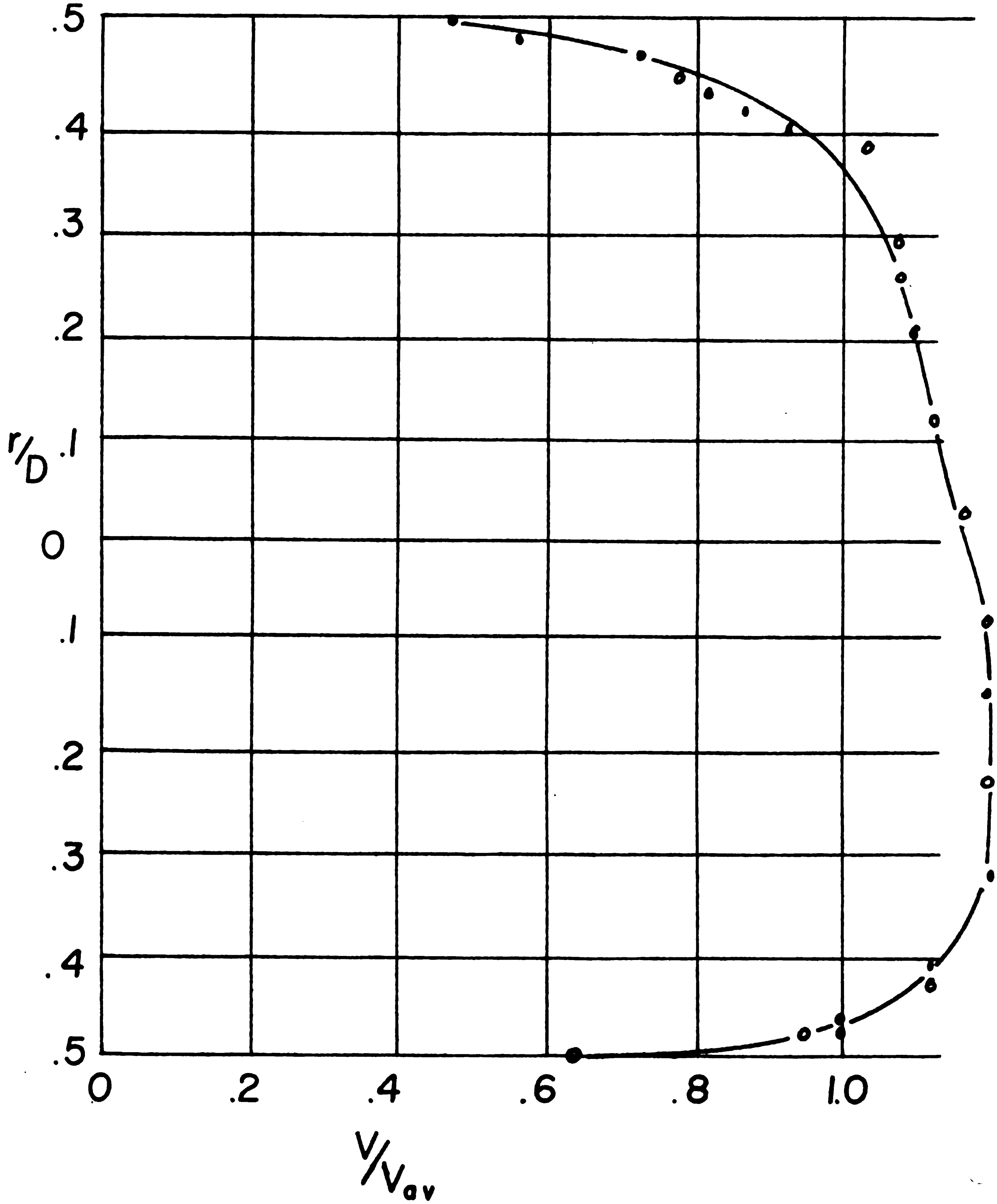

VELOCITY PROFILE
V_{av} = 25.4 ft/sec
L/D = 14 Run 3
C. CHAMBERS
.5
.4
.3
.2
r/D .1
0
.1
.2
.3
.4
.5
0
.2
.4
.6
.8
1.0
V/V_{av}

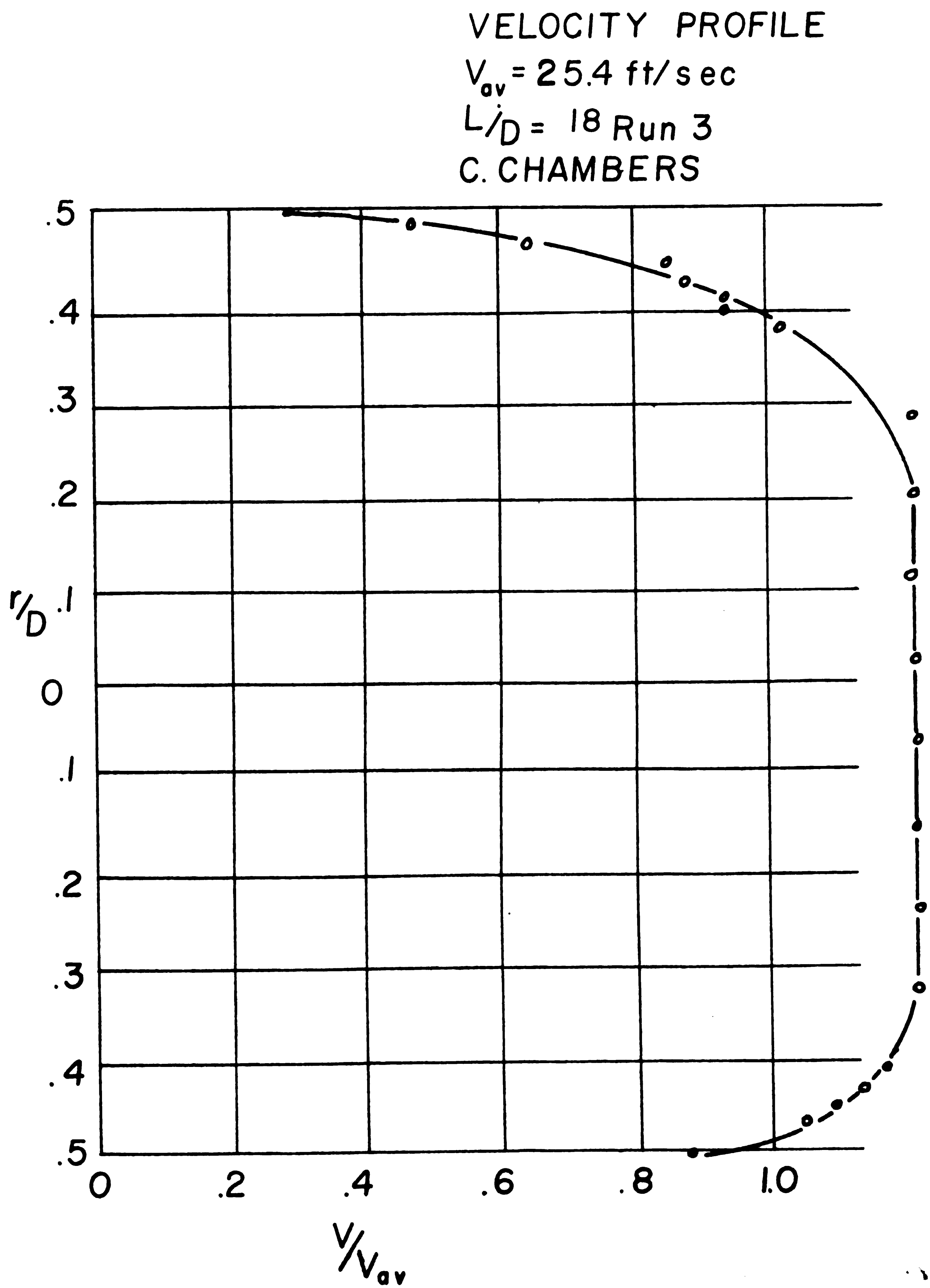
VELOCITY PROFILE

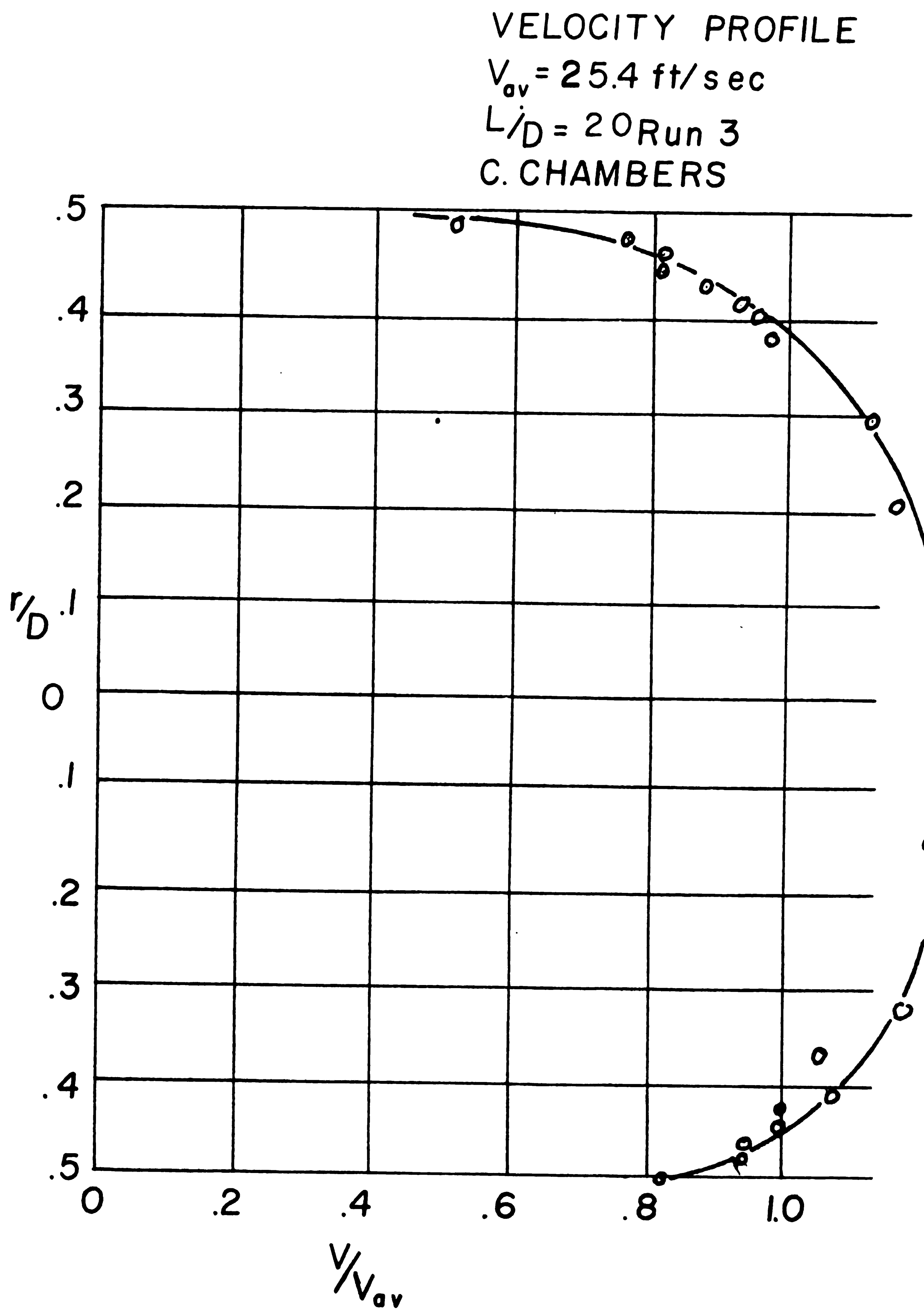
$V_{av} = 25.4$ ft/sec

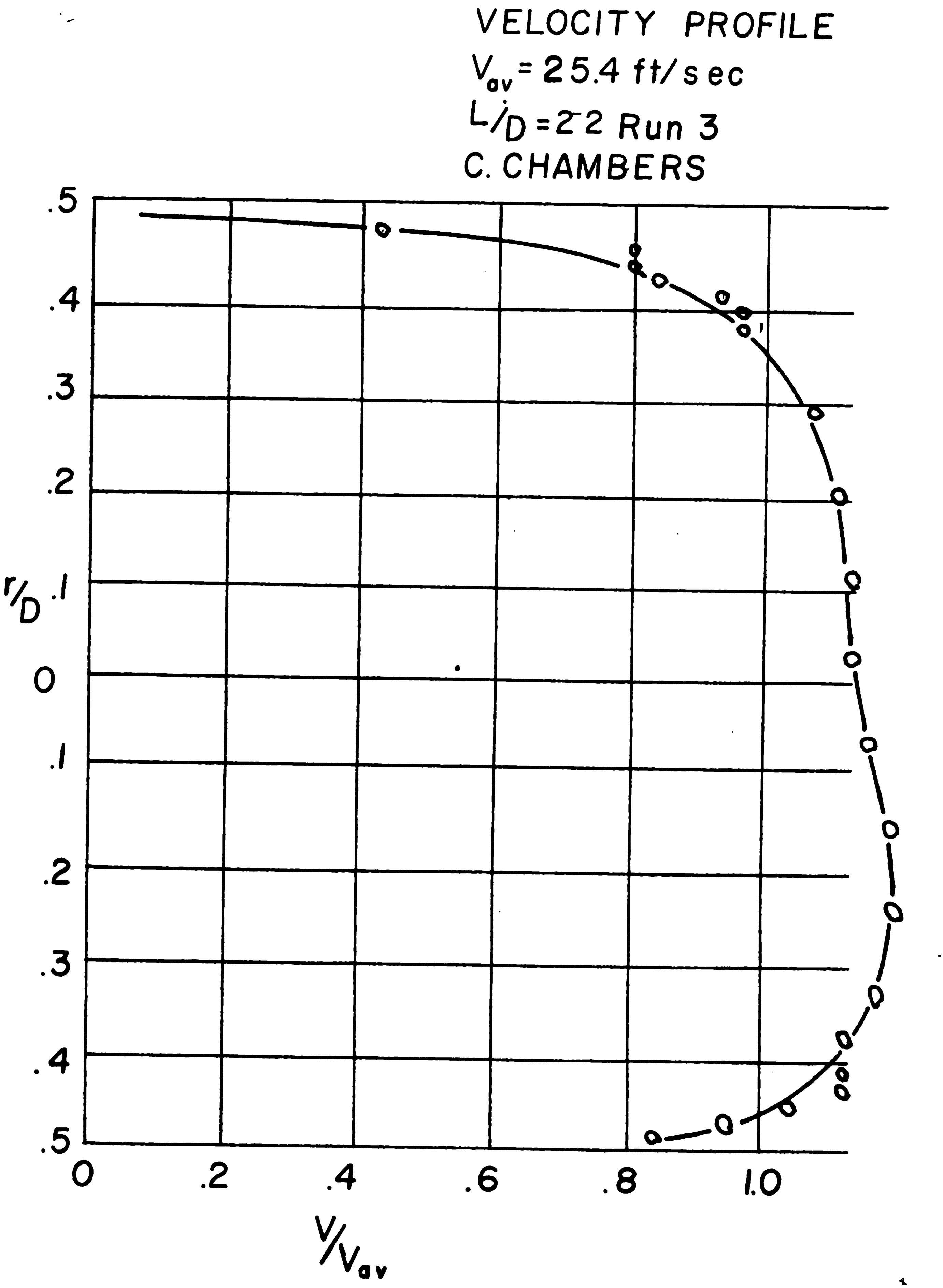
$L/D = 16$ Run 3

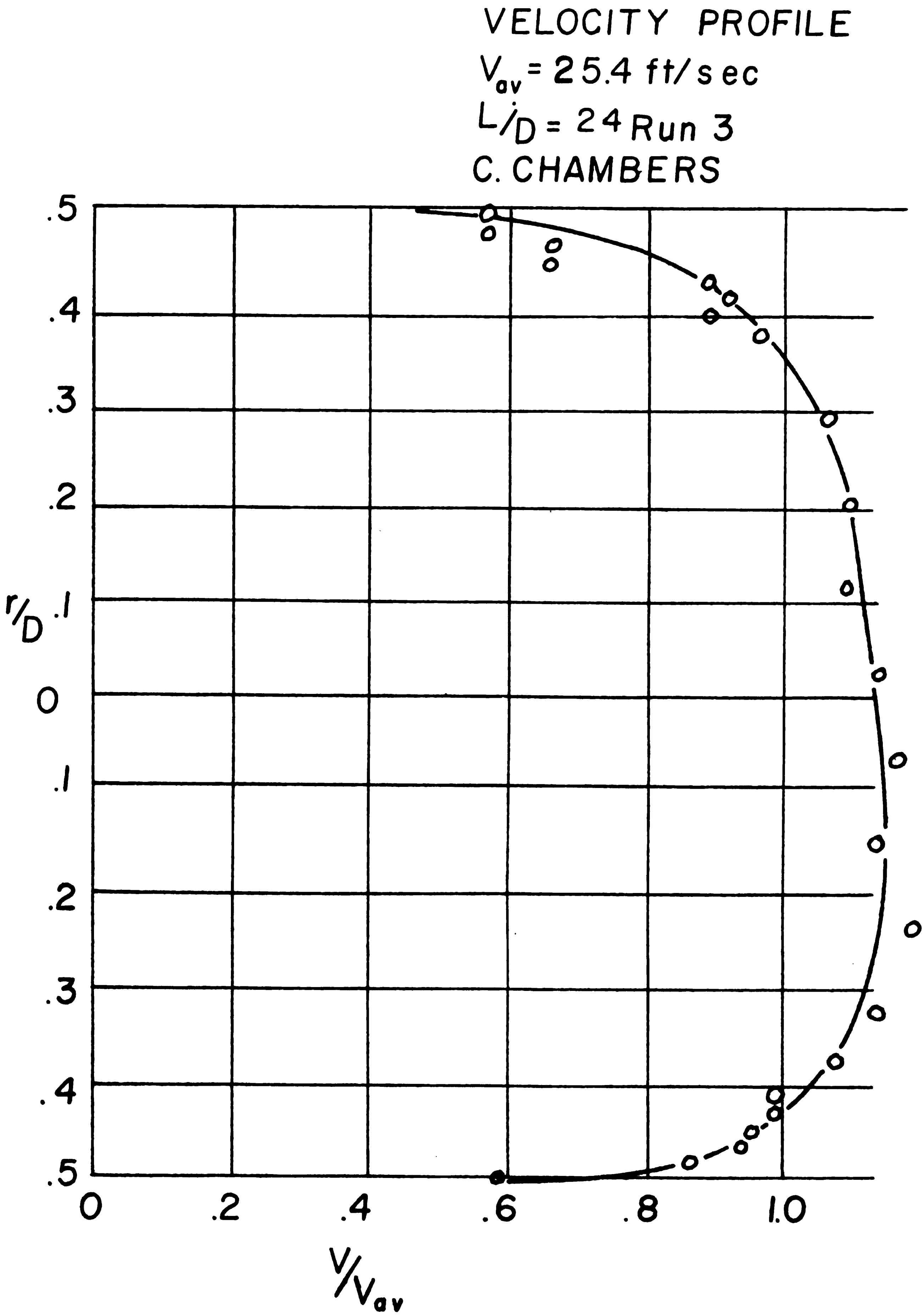
C. CHAMBERS




VELOCITY PROFILE
V_av = 25.4 ft/sec
L/D = 18 Run 3
C. CHAMBERS
.5
.4
.3
.2
r/D .1
0
.1
.2
.3
.4
.5
0
.2
.4
.6
.8
1.0
V/V_av

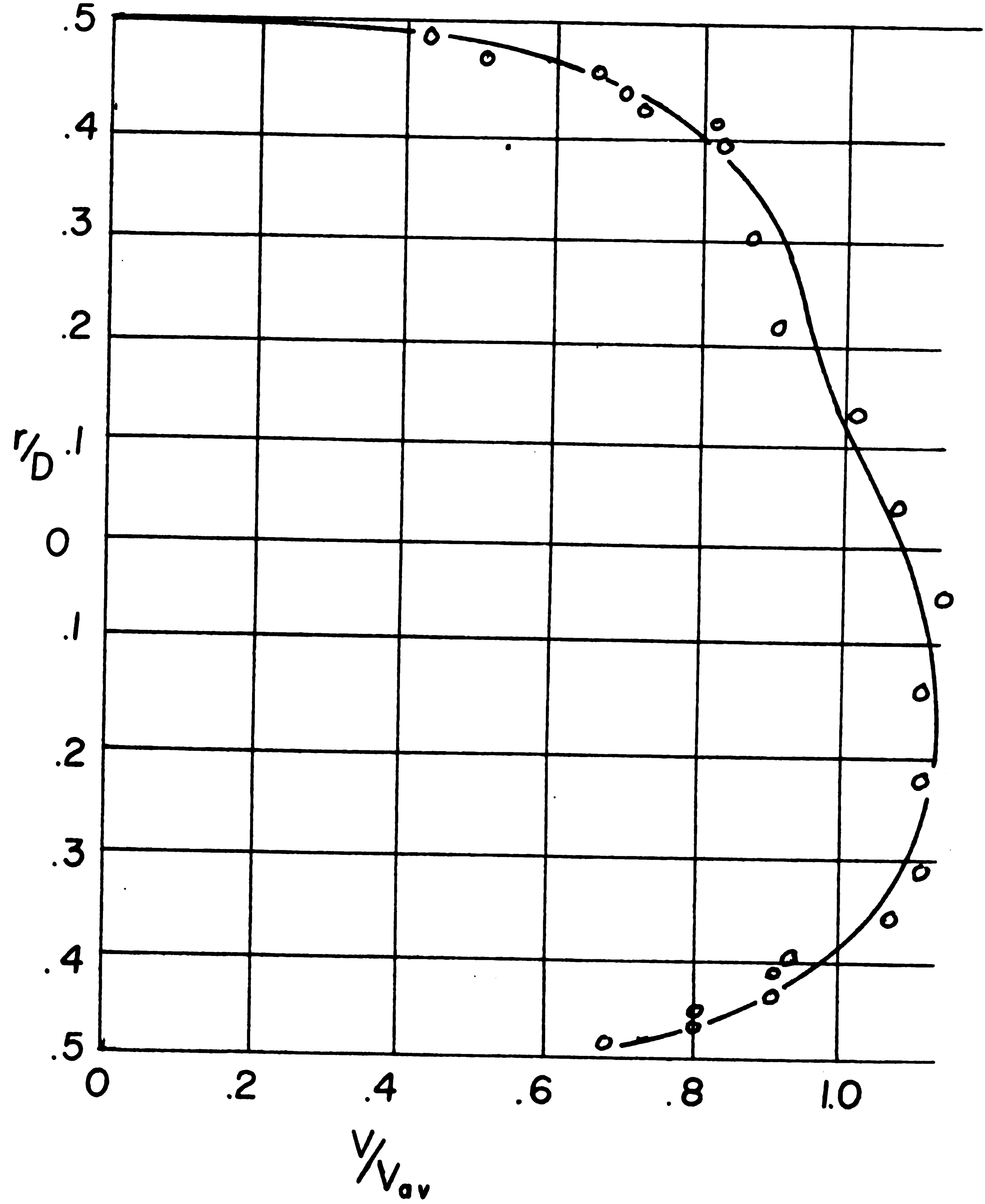

VELOCITY PROFILE
V_{av} = 25.4 ft/sec
L/D = 20 Run 3
C. CHAMBERS
r/D
.5
.4
.3
.2
.1
0
.1
.2
.3
.4
.5
0
.2
.4
.6
.8
1.0
V/V_{av}


VELOCITY PROFILE
V_{av} = 25.4 ft/sec
L/D = 22 Run 3
C. CHAMBERS
.5
.4
.3
.2
r/D .1
0
.1
.2
.3
.4
.5
0
.2
.4
.6
.8
1.0
V/V_{av}


VELOCITY PROFILE
V_{av} = 25.4 ft/sec
L/D = 24 Run 3
C. CHAMBERS
r/D
.5
.4
.3
.2
.1
0
.1
.2
.3
.4
.5
0
.2
.4
.6
.8
1.0
V/Vav

26

VELOCITY PROFILE
V_{av} = 25.4 ft/sec
L/D = 2 6 Run 3
C. CHAMBERS

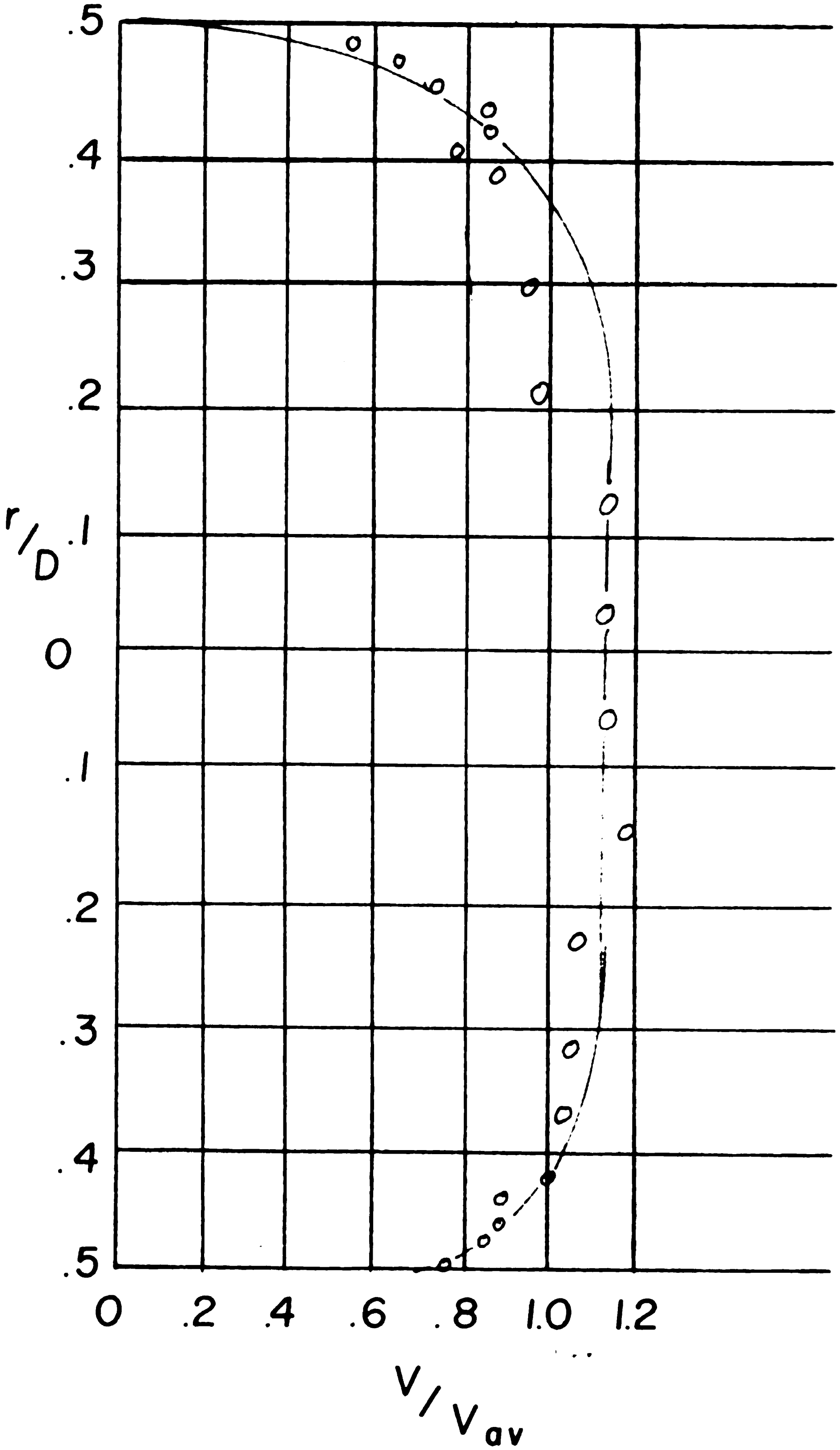


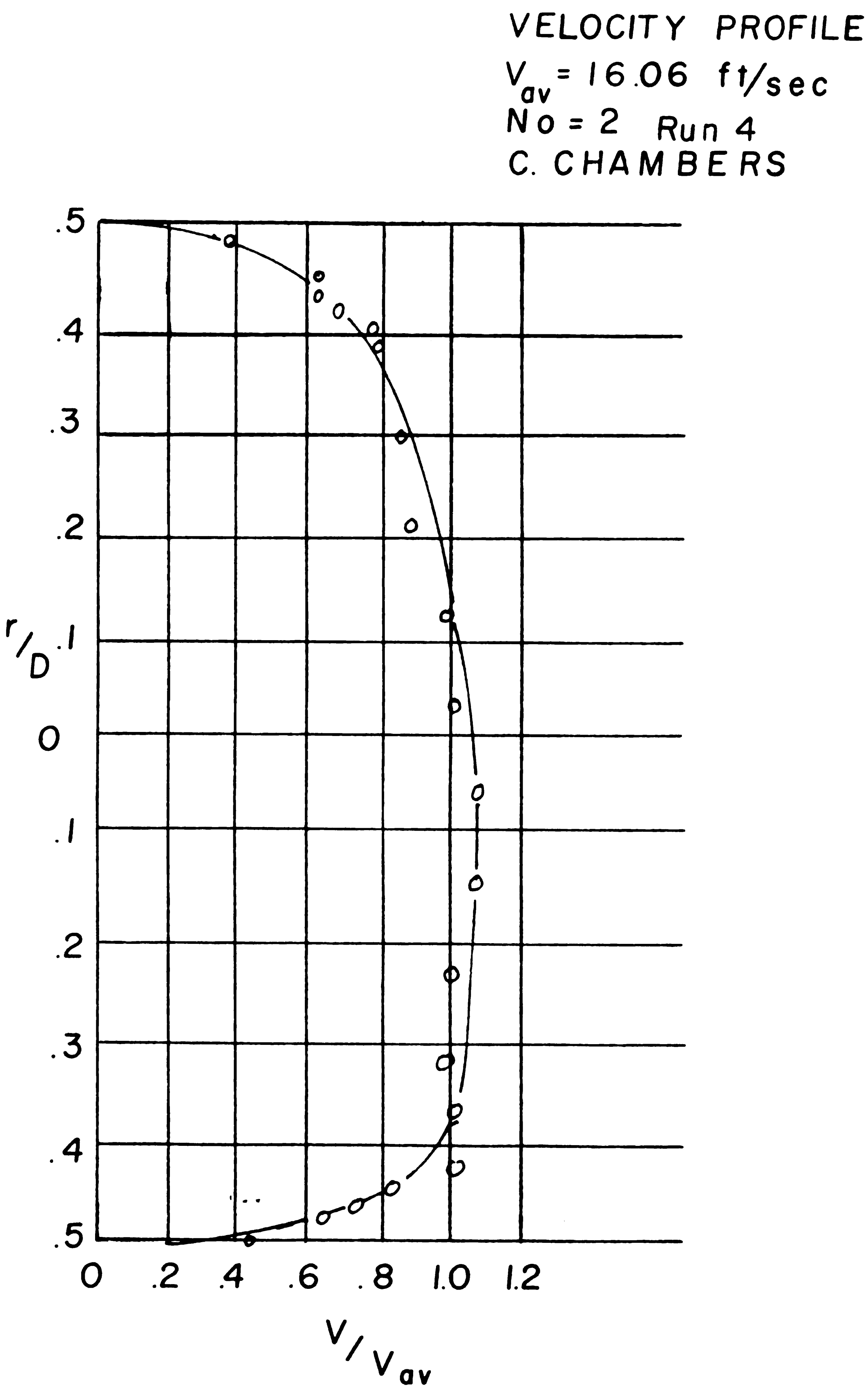
VELOCITY PROFILE

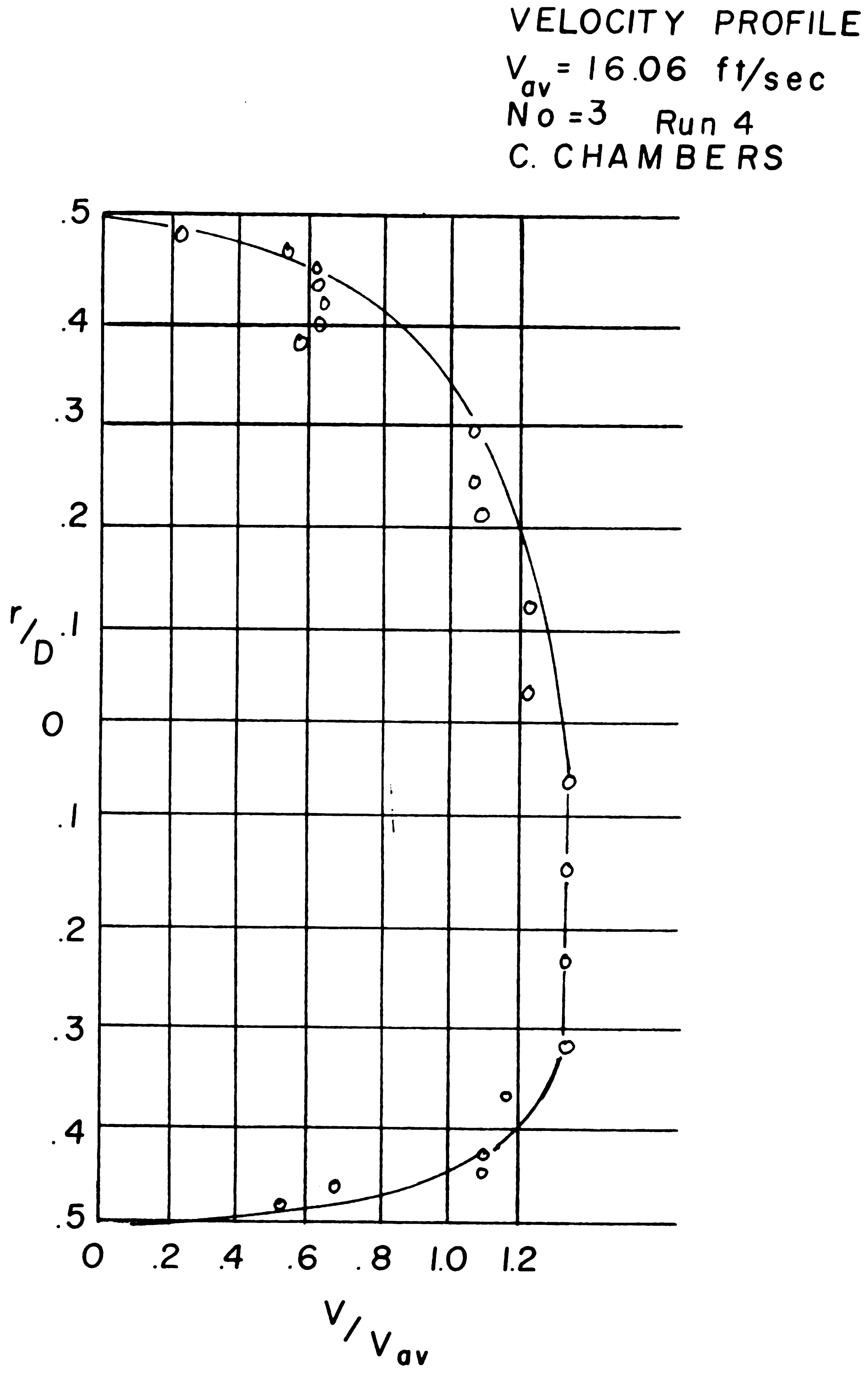
V_{av} = 16.06 ft/sec

No =1 Run 4

C. CHAMBERS



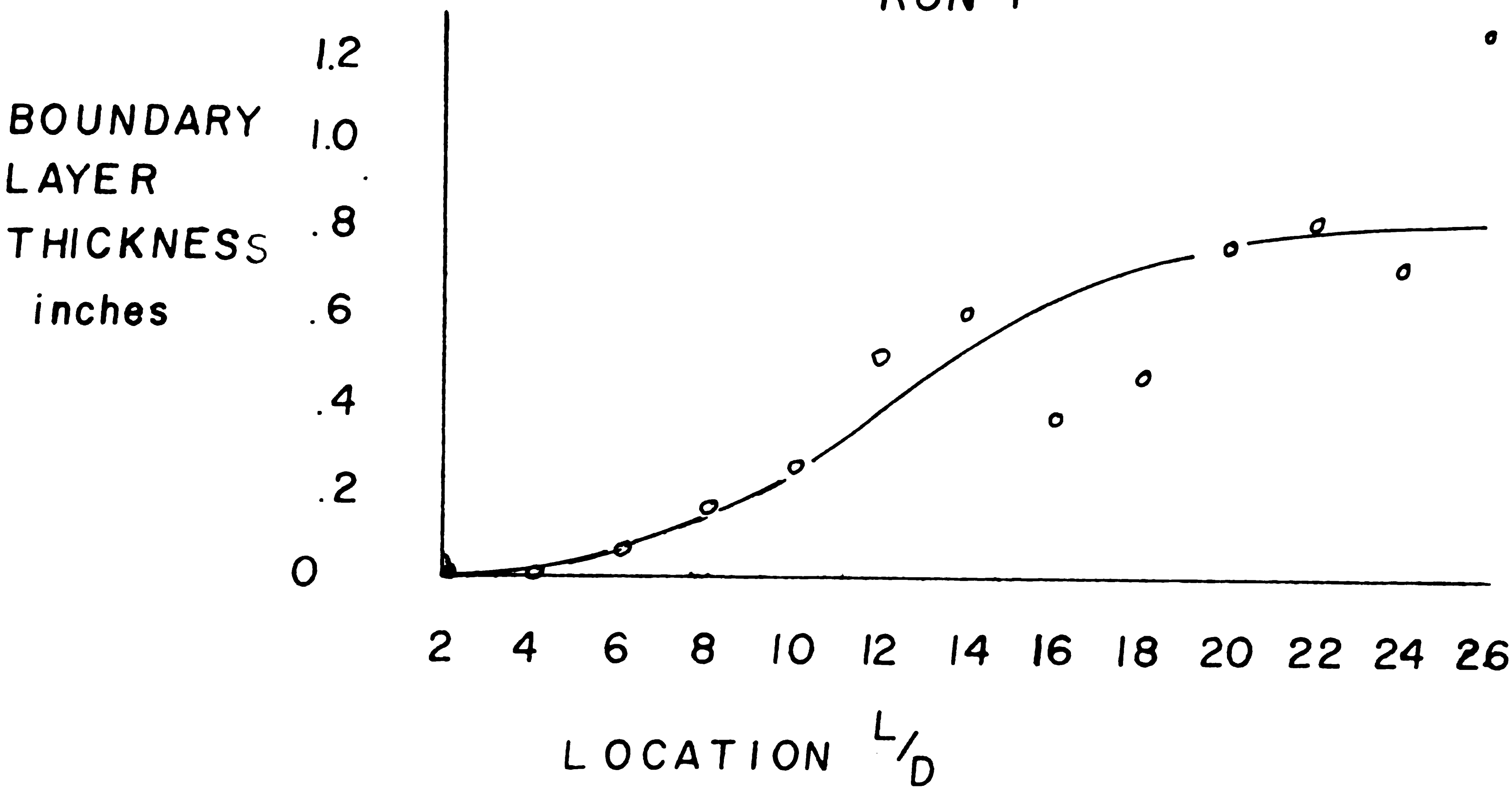

VELOCITY PROFILE
V_{av} = 16.06 ft/sec
No = 2 Run 4
C. CHAMBERS
.5
.4
.3
.2
r/D .1
0
.1
.2
.3
.4
.5
0
.2
.4
.6
.8
1.0
1.2
V/V_{av}



VELOCITY PROFILE
Vav = 16.06 ft/sec
No =3 Run 4
C. CHAMBERS
.5
.4
.3
.2
r/D .1
0
.1
.2
.3
.4
.5
0 .2 .4 .6 .8 1.0 1.2
V/Vav

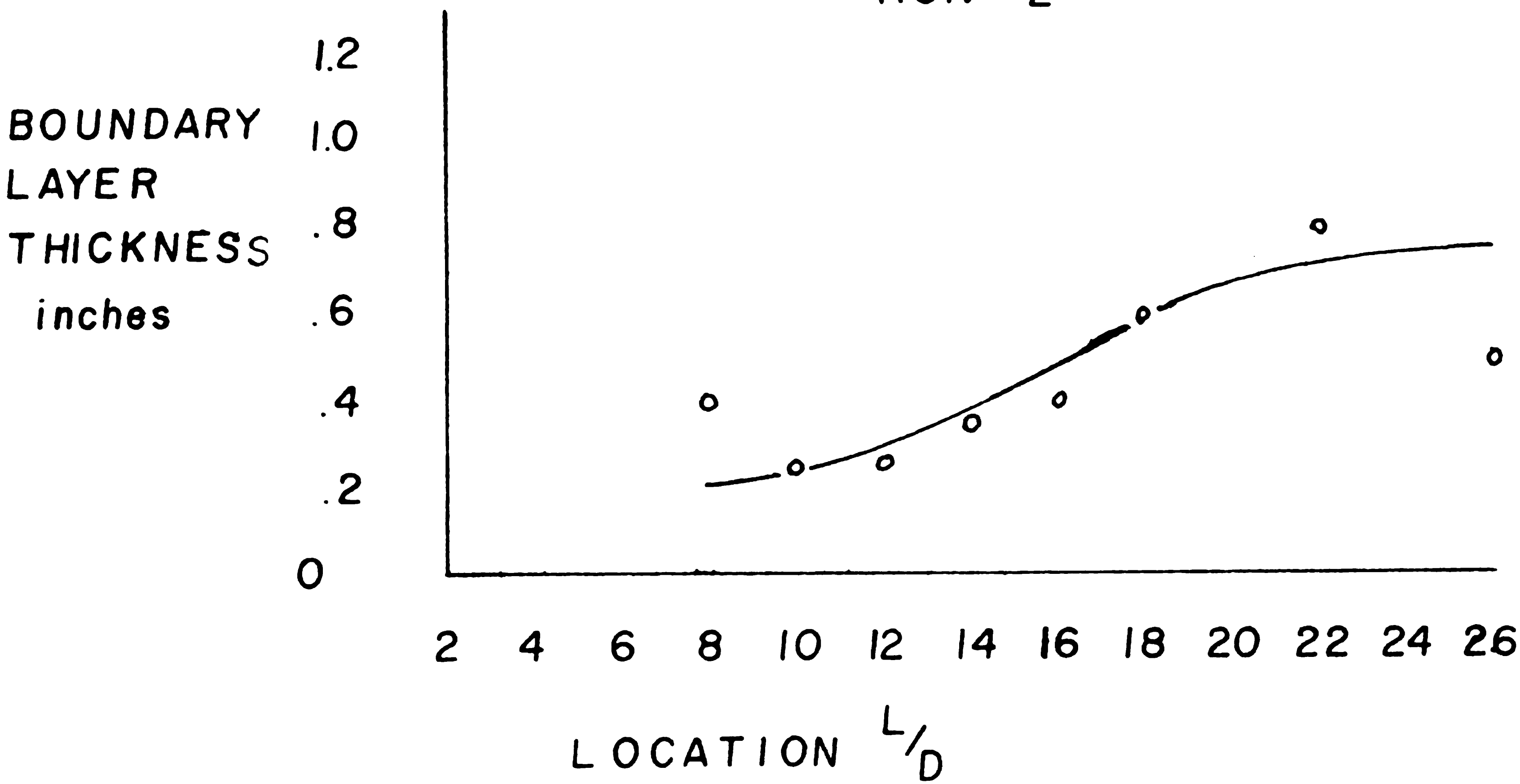
BOUNDARY LAYER GROWTH

RUN I



BOUNDARY LAYER GROWTH

RUN 2



Resistance Bridge

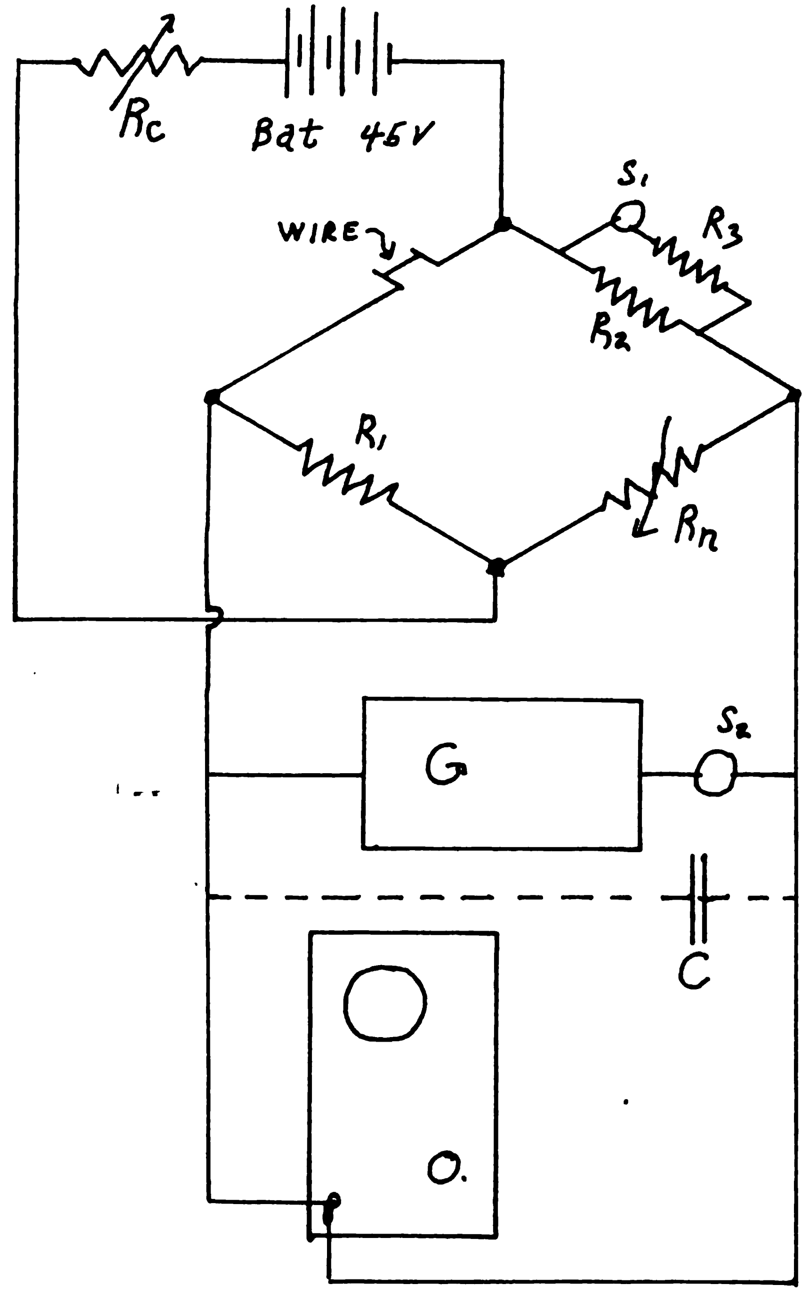
Following is a schematic diagram of a resistance bridge used in this experiment. The wire current was supplied by a large 45 volt battery through the variable resistor R_c. By varying this resistor the wire current could be controlled. With R_c at a very high value enough current to balance the bridge but not enough to heat the wire will flow. This is called cold balance. The variable resistor R_n is used to balance the bridge in the cold position. The switch, S_2, is closed to place the galvanometer G in the circuit to indicate null balance. R_1 is a fixed resistance. The switch, S_1, is closed placing R_3 in parallel with R_2 giving an effective resistance R_f.

$$R_f = \frac{R_2 \quad R_3}{R_2 + R_3} \qquad\qquad R_f < R_2$$

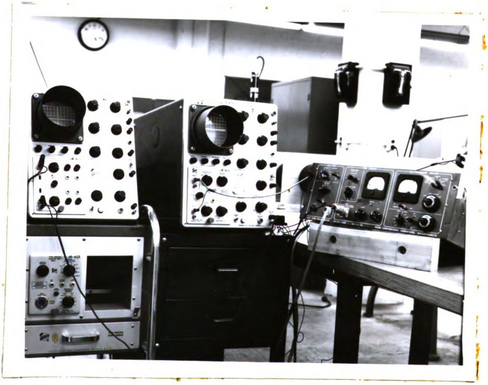
The values of R_1 and R_3 are chosen so that the ratio $\frac{R_2}{R_f}$ is the resistance ratio 1.3, 1.4, etc.

After the bridge is balance cold and switch S_1 closed the resistance R_c is reduced causing an increase in wire current. As the wire current increases the wire heats and its resistance decreases. Thus, by increasing the current the bridge can again be balanced with the ratio of the wire resistance cold to the wire resistance hot equal to the resistance ratio. Balancing can be accomplished either with the galvanometer or the oscilloscope, C. The capacitor, C, was sometimes used to dampen the oscilloscope motion.

RESISTANCE BRIDGE



Experimental set up from down stream end



Equipment at measuring station

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