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Further Results Related to the Turbulent Boundary Layer
With Slot Injection of Helium

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Data from an experiment involving the slot injection of helium into a turbulent boundary layer in air are analyzed in terms of unconditioned and conditioned Favre-averages. The conditioning is based on two levels of helium concentration so that the contributions to the unconditioned statistics from air, helium and mixture of these two gases can be determined. The distributions of intermittency associated with the two helium levels establish the domains of influence of air, helium and mixture.

INTRODUCTION

LaRue and Libby¹, identified henceforth as A, present the results of hot-wire measurements related to the injection of helium from a slot into a turbulent boundary layer in air. The flow is low-speed, isothermal and essentially two-dimensional on the mean. The ratio of initial helium velocity to free stream velocity U is roughly 0.2 while the ratio of initial boundary layer thickness to slot height s is approximately five. Profile measurements of a variety of statistical quantities are made at several downstream stations indicated by values of the ratio x/s . In A the data are presented in terms of conventional, unconditioned statistics at all downstream stations and of

Favre-averaged, unconditioned quantities at one station. Here we reanalyze these data in terms of unconditioned and conditioned Favre-averaged statistics.

Because of a number of applications involving thermal protection, skin-friction reduction and boundary layer control, there is an extensive literature related to slot injection; appropriate entries to this literature are given in A. However, experimental results involving hot-wire anemometry and thereby providing data on fluctuating quantities are sparse; A provides the first such data involving measurements with foreign gas injected from the slot.

Of considerable interest and importance relative to the development of predictive methods for turbulent slot flow are the data in A showing that intense turbulence exists within the boundary layer in a region roughly six slot heights downstream of the end of the splitter plate. It is in this region that the oscillating surface separating the air and helium and anchored to the end of the splitter plate is close to the wall and results in values of the relative density intensity $(\overline{\rho'^2})^{1/2}/\bar{\rho}$ of over 50%. Downstream of this region molecularly enhanced by turbulent strain destroys this surface, the turbulence becomes less intense and approaches that exhibited by a conventional boundary layer. A predictive method must describe the region of intense turbulence if it is to treat accurately the slot flow.

The details of the experimental arrangement and techniques are given in A and need not be repeated here. It is sufficient to outline briefly the essentials of the experiment. A three-sensor hot-wire probe similar to that used by Stanford and Libby² is employed. Because the analysis of the data given here calls for conditioning and therefore greater accuracy than required in A, we

utilize here only the results from two of the sensors, those yielding the streamwise velocity component u and the helium mass fraction c . Accordingly, we outline the techniques applicable to only these two sensors. The probe is subjected to an absolute calibration scheme so that voltage pairs representing the output from the two sensors can be related to the fluid mechanical quantities, u and c . During data collection the sensor outputs are digitally recorded on tape and subsequently converted to time series in u and c . For the results presented here the time series involve 27,000 entries at three streamwise locations and 136,000 entries at two others ($x/s = 1.94, 5.81$). Under the benign assumption that the mass density ρ is uniquely related to the helium concentration, a fourth time series in ρ can be developed. All four time series and others we shall find useful in connection with conditioning are subjected to the usual techniques of time series analysis in order to provide a variety of statistical information of interest in the characterization of the slot flow.

We use here the same quantities as in A for non-dimensionalization, namely the free stream velocity U , 4.95 m/s; the free stream density ρ_0 , $1.20 \cdot 10^{-3}$ gm/cc; and the slot height s , 1.31 cm (Due to a typographical error the value of s is given incorrectly in A).

Conditioned sampling (cf., e.g., Coles and van Atta³, Kovaszny et al⁴ and van Atta⁵) is widely recognized as useful in exposing in turbulent flows essential physical features obscured by the usual unconditioned averaging. In the slot flow considered here we are interested in the contributions to unconditioned statistics from pure air, from pure helium and from mixture. To determine these contributions calls for two levels of discrimination, i.e., two levels of helium concentration. Thus we supplement the three time series

discussed earlier by two series corresponding to two intermittency functions $I(\underline{x},t)$, each defined by

$$\begin{aligned} I(\underline{x},t) &= 1, \quad c > c_0 \\ &= 0, \quad c < c_0 \end{aligned} \tag{1}$$

where c_0 is a specified level of helium concentration.

Our discrimination strategy warrants some comment; discrimination of a signal related to a scalar quantity usually involves specification of a gate or level, e.g., a value of c_0 in Eq.(1), and a hold time which is introduced to exclude spurious level crossings and can be selected on the basis of one of several criteria; LaRue⁶ selects a hold time such that the crossing frequency becomes relatively insensitive to further increases in that time. When discrimination is carried out on a digital signal as in the present instance, there is implicitly introduced a hold time of at least one half of a digital time step and more extended hold times must be multiples of that step. Here we employ a zero hold time, i.e., we set $I(\underline{x},t)$ to zero or unity in accordance with Eq.(1) at each entry in the time series in c ; the principal justification for this simplistic strategy is ease in computation. However, because our sampling rate per channel is 2780/s and our sample and hold time is 10^{-5} s, the number of spurious crossings is believed to be small and the resulting determination of the intermittency functions to be adequate for our purposes.

Since we want to identify the contributions to various statistics from pure air, pure helium and mixture, we select two values of c_0 ; with $c_0 = 0.002$ we consider all data for $I = 0$ to correspond to pure air; with $c_0 = 0.90$ we similarly consider all data for $I = 1$ to correspond to pure helium. Data

not included in these two subsets corresponds to mixture. As in all discrimination these two levels are somewhat arbitrary but representative. In the discussion which follows we shall drop the adjective pure so that "air" and "helium" are to be understood to denote the pure species.

In earlier studies related to the turbulent mixing of helium and air we present results principally in terms of conventional averages with Favre-averaged results provided for purposes of comparison, e.g., to establish the differences between the conventionally averaged streamwise velocity component $\bar{u}(x)$ and its Favre-averaged counterpart $\bar{u}(x)$. In recent years there has been increasing adoption of Favre-averaging for the description of turbulent flows involving significant density variations. Accordingly, we use exclusively Favre-averaging in the present work. We employ the standard notation of () to denote a mean value, e.g., $\bar{u} = \overline{\rho u / \rho}$, and ()' to denote the fluctuation.

The combination of Favre-averaging and conditioning calls for comment, at least to establish notation. Consider the following definitions of representative quantities:

$$\begin{aligned} \bar{\rho}(\bar{u})_1 &= \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T dt \rho u I & (2) \\ \overline{(\rho u'^2)}_1 &= \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T dt \rho (u - \bar{u})^2 I \\ \overline{(\rho u' c')}_1 &= \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T dt \rho (u - \bar{u}) (c - \bar{c}) I \\ (\bar{u})_0 &= \bar{u} - (\bar{u})_1 \\ \overline{(\rho u' c')}_0 &= \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T dt \rho (u - \bar{u}) (c - \bar{c}) (1 - I) \end{aligned}$$

The subscripts 1 and 0 denote averages corresponding to $I = 1, 0$ respectively.

Only fluctuations relative to the appropriate unconditioned, Favre-averaged mean are considered.

The quantities in Eq.(2) with the subscript 1 when divided by \bar{I} give the so-called zone averages of Kovaszny et al⁴ where \bar{I} is the average of the intermittency function and equal to the percent of time at the spatial location in question the intermittency function has the value unity. Similarly the quantities with the subscript 0 when divided by $(1 - \bar{I})$ are the zone averages corresponding to $I = 0$. For the purposes of examining the various contributions to an unconditioned quantity we find the definitions given by Eq.(2) to be more useful than the related zone averages.

RESULTS

To provide a clear display of results we show the data at each downstream station in a sequence from left to right of increasing values of x/s . Unconditioned Favre-averaged quantities are indicated by flagged open symbols. Full shaded symbols denote conditioned results corresponding to air, i.e., to $I = 0$ with $c_0 = 0.002$; open symbols to helium, i.e., to $I = 1$ with $c_0 = 0.90$; and half-shaded symbols to mixture, i.e., to statistics based on data excluded by the two subsets associated with air and helium.

Presenting both conditioned and unconditioned data on the same figure is desirable from the point of view of exposing the various contributions to a particular statistical quantity but leads to a difficulty in those cases in which the unconditioned quantity is due solely to one contributor, i.e., in those cases with $\bar{I} = 1$. For example, suppose at a particular spatial location only concentrations of helium greater than 0.90 occur; then the flagged

open symbols coincide with the open symbols. In these cases we give only unconditioned results with the expectation that the coincidence will be obvious if reference is made to the distributions of the intermittencies (Fig. 2).

Figure 1 shows the evolution of the mean streamwise velocity from a profile characterizing slot injection at $x/s = 0.078$ to a nearly normal profile at the most downstream measuring station where $x/s = 34.9$. Note that the profile at $x/s = 5.81$ which we know from the results of A to be a region of intense turbulence does not reflect that intensity.

To appreciate the conditioned results also shown in Fig. 1 it is useful to consider the distributions of the intermittencies shown in Fig. 2. There the open symbols indicate the percent of time the flow is helium, i.e., has a concentration equal to or greater than 0.90, at the spatial point in question. We see that the initial discontinuous values prevailing at the end of the splitter plate decay with increasing downstream distance until between the two stations, $x/s = 5.81$ and $x/s = 11.6$ the helium is always diluted. The solid symbols indicate the percent of time that air is present, i.e., that c is less than or equal to 0.002. Again the initial, discontinuous distribution diffuses with increasing downstream distance. However, even at the most downstream measuring station, air is seldom present at the wall. The remaining percent of time, i.e., that represented by the difference between the sum of the open and solid symbols in Fig. 2 and unity, corresponds to mixture. The distributions shown in Fig. 2 imply that mixture dominates the boundary layer characteristics at least downstream of $x/s = 5.81$.

If we consider the conditioned streamwise velocities shown in Fig. 1 in the light of Fig. 2, the importance of the contributions from mixture is established. These contributions are seen to increase as might be expected on

physical grounds from a relatively small region centered about $y/s = 1$ at $x/s = 1.94$ to a region representing most of the boundary layer thickness at $x/s = 34.9$. However, at the latter station the amount of helium present at the outer edges of the boundary layer is so small that the contributions of air dominate the mean velocity. On the contrary downstream of a station between $x/s = 5.81$ and 11.6 no helium exists as noted in connection with Fig. 2; thus close to the wall mixture determines the mean velocity distributions and of course the distributions of other quantities.

The results in Figs. 1 and 2 are consistent with the distributions of mean helium concentration and density ratio ($\bar{\rho}/\rho_0$) shown in Figs. 3 and 4. The discontinuous distributions of these variables at the end of the splitter plate diffuse with increasing downstream distance. The maximum mean concentration at the most downstream measuring station is 0.047 but it should be noted that this value still corresponds to a significant mean density difference since $\bar{\rho}/\rho_0 - 1 = 0.230$. Thus even at this small concentration helium cannot be considered a passive scalar. Neither Figs. 3 nor 4 indicate high levels of turbulent intensities in the region about $x/s = 5.81$.

Figure 5 shows the downstream evolution of the intensities of the velocity fluctuations in terms of $\overline{\rho u'^2}/\rho_0 U^2$. We see that the intensities near the wall increase from low values prevailing in the slot flow at the end of the splitter plate until at $x/s = 34.8$ values representative of those in a normal turbulent boundary layer prevail. It is somewhat surprising that high turbulent intensities are not evident in the distributions at $x/s = 5.81$; we discuss the implications of this finding later.

The distributions shown in Figs. 6 and 7 correspond to the intensity of the fluctuations of helium concentration $\overline{\rho c''^2}/\rho_0$ and to the mean flux $\overline{\rho u'' c''}/\rho_0 U$. These results clearly indicate the high turbulence intensities in the neighborhood of $x/s = 5.81$; the maximum intensities and mean fluxes are nearly an order of magnitude greater at this station than at stations either upstream or downstream. The results in A relative to the intensities of the fluctuations in the transverse velocity component, $\overline{\rho v''^2}/\rho_0 U^2$ in Favre-averaging, although not sufficiently accurate for quantitative purposes in this interesting region of high turbulence intensity, clearly imply a significant anisotropy of the turbulence there. Whether such anisotropy must be explicitly incorporated into predictive methods is uncertain.

It is interesting to examine the distribution of the various contributions to the mean flux $\overline{\rho u'' c''}$ for our measuring station in this region, i.e., for $x/s = 5.81$. Fig. 8 shows that the negative values of the flux are due principally to mixture; close to the wall helium does contribute significantly and in the outer portions of the boundary layer air does likewise. However, throughout a large portion of the boundary layer mixture contributions dominate. This result indicates that the surface separating the air and helium and attached to the end of the splitter plate is already partially diffused at this downstream station; the total absence of helium somewhat downstream of this station implies that the surface is subsequently fully diffused.

The negative correlations in Fig. 8 are physically explicable from the following point of view; when an element with a concentration of helium greater than the average value at the measuring point in question, it is likely to have been transported from a region of the flow closer to the wall

where the mean velocity is lower. A negative correlation results. The small region in the neighborhood of $y/s = 0.7$ where helium has a positive correlation violates this explanation and may be accounted for by the interaction of a weak favorable pressure gradient and the low density helium. Such an interaction could be cancelled close to the wall by mean shear forces. Whatever the explanation the influence of this positive contribution of the helium results in a dip in an otherwise smooth distribution of the mean flux with increasing distance from the surface.

CONCLUSIONS

The data from an earlier experiment involving the injection through a slot of helium into a turbulent boundary layer in air are reanalyzed in terms of unconditioned and conditioned Favre-averages. Distributions of streamwise velocity and helium concentration with distance from the surface are given at five downstream locations. The conditioning is carried out in terms of two levels of helium concentration in order to determine the contributions to the mean streamwise velocity and to the mean flux $\overline{\rho u''c''}$ from air, helium and mixture. It is found that upstream of a station between 5.81 and 11.6 slot heights helium contributes significantly to the behaviour of the flow close to the wall but is absent elsewhere. Air contributes significantly at all streamwise stations in the outer portions of the boundary layer but is never present at the surface even at the most downstream measuring station, namely at 34.9 slot heights. Thus it is found that mixture plays a dominant role in determining the behaviour of the boundary layer.

The earlier finding of a region of intense turbulence where the surface separating air and helium and attached to the end of the splitter plate oscill-

lates close to the surface is demonstrated in terms of the intensity of the fluctuations in helium concentration and of the mean flux of helium $\overline{\rho u c}$. Of importance is that this intensity is not evident in the mean profiles and in fact does not appear in the distributions of the intensity of the streamwise velocity. In the aforementioned intensity of the fluctuations of helium concentration and mean flux it does become evident. In our earlier study it is manifest in the intensity of the transverse velocity component. The implication from this result is that predictive methods may have to include explicitly the anisotropy of the turbulence, i.e., calculate the separate contributions to the turbulent kinetic energy, in order to describe accurately turbulent slot flow.

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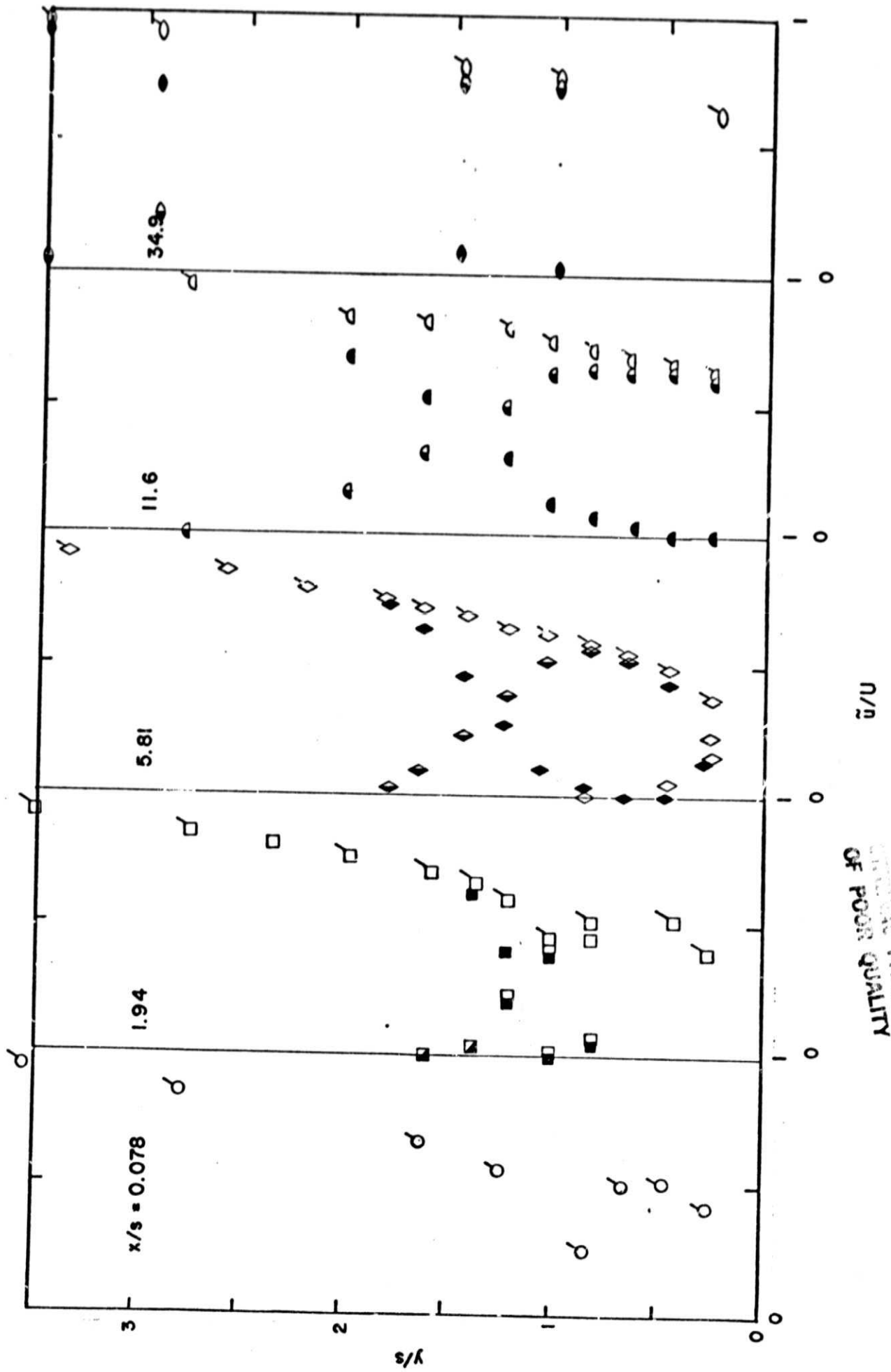
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LIST OF FIGURES

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Figure 1.

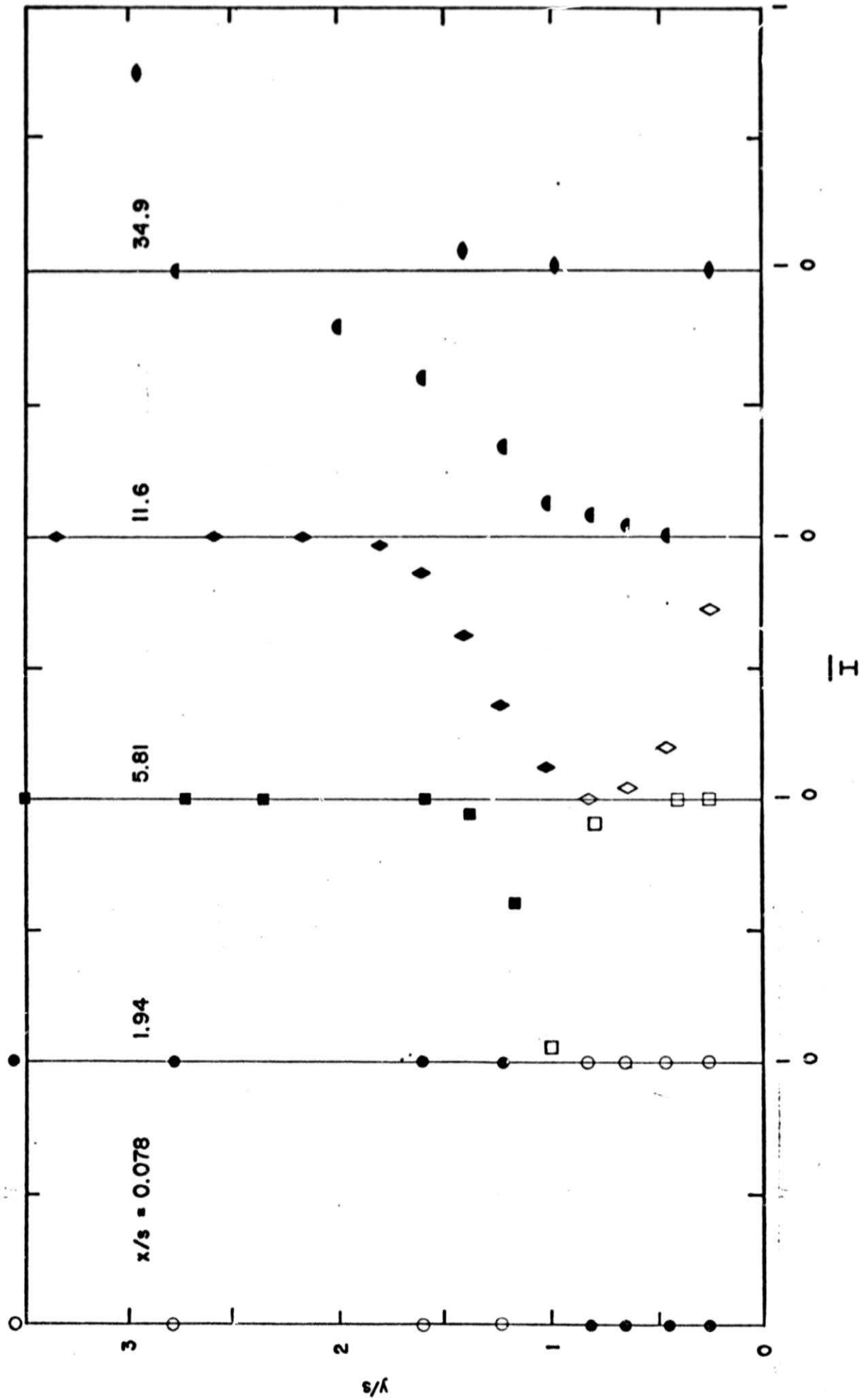


Figure 2.

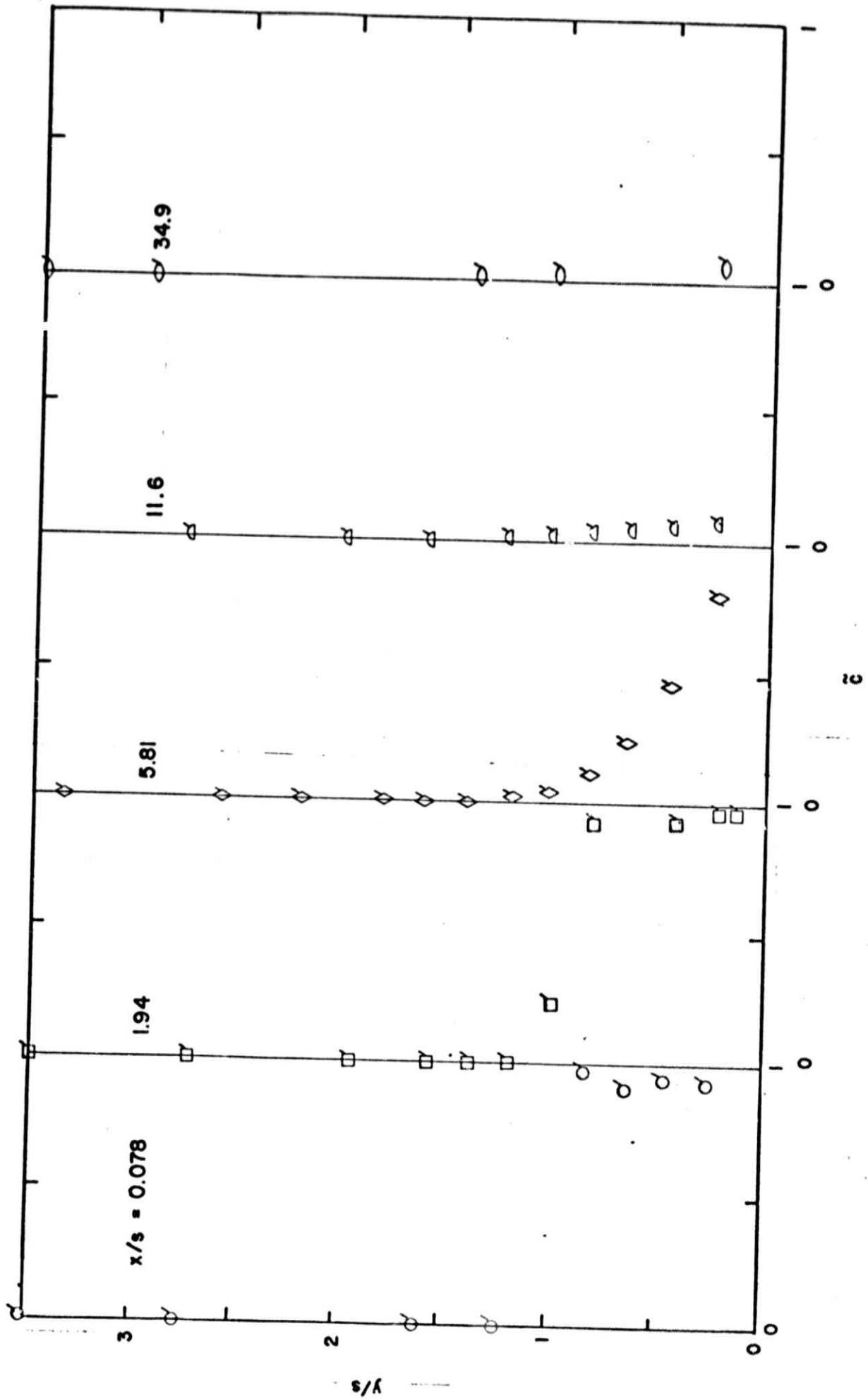
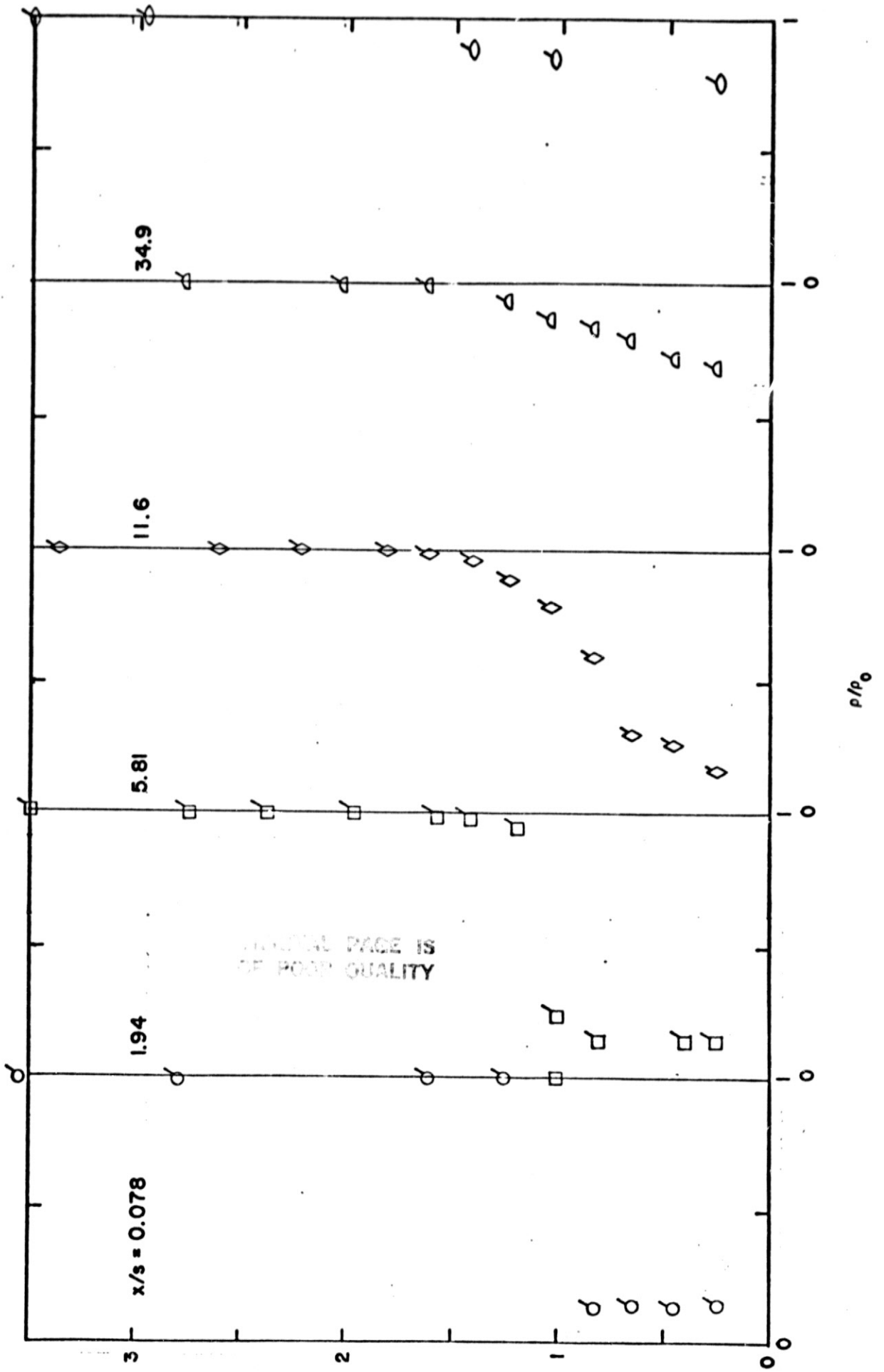


Figure 3.



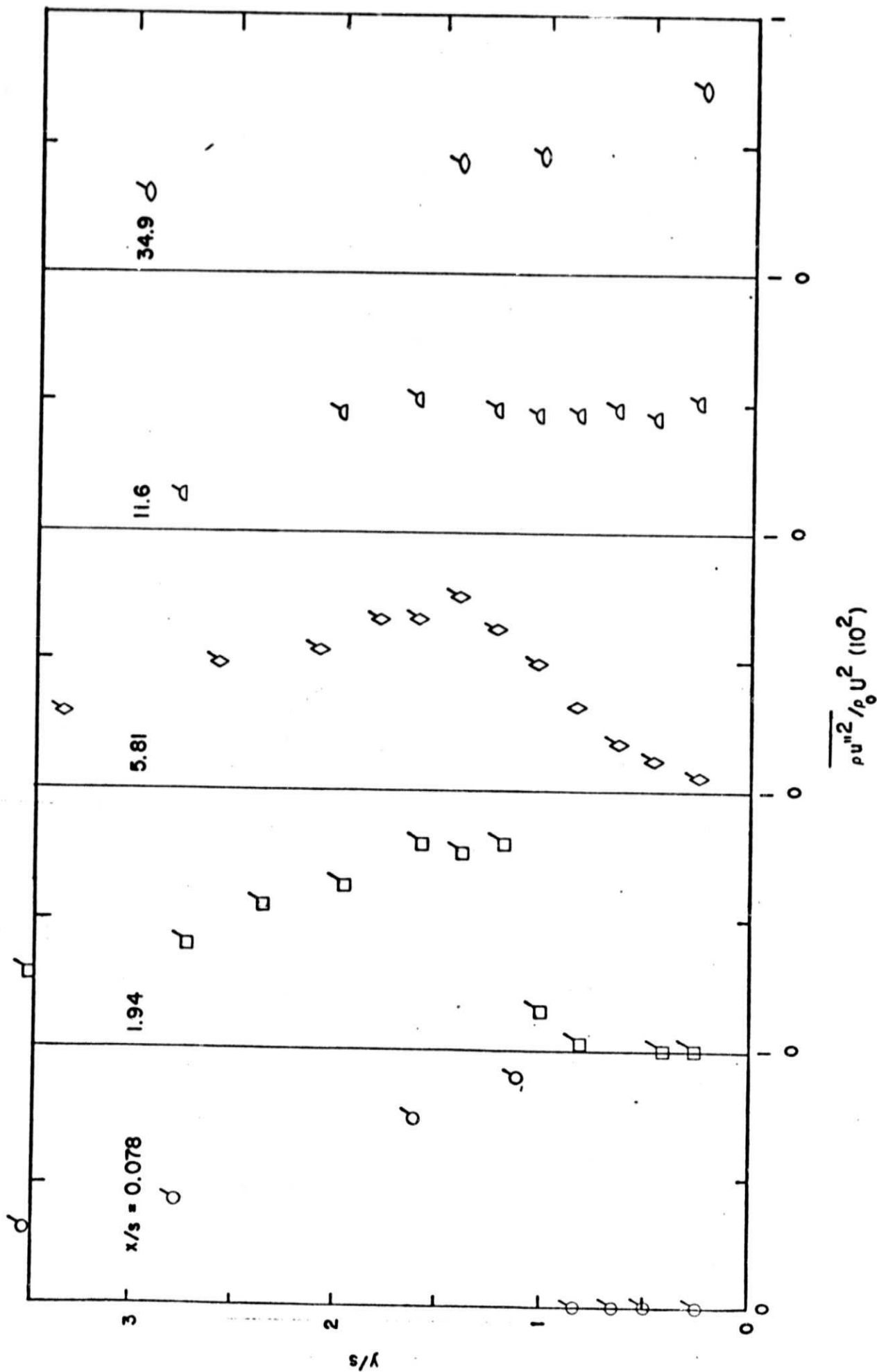
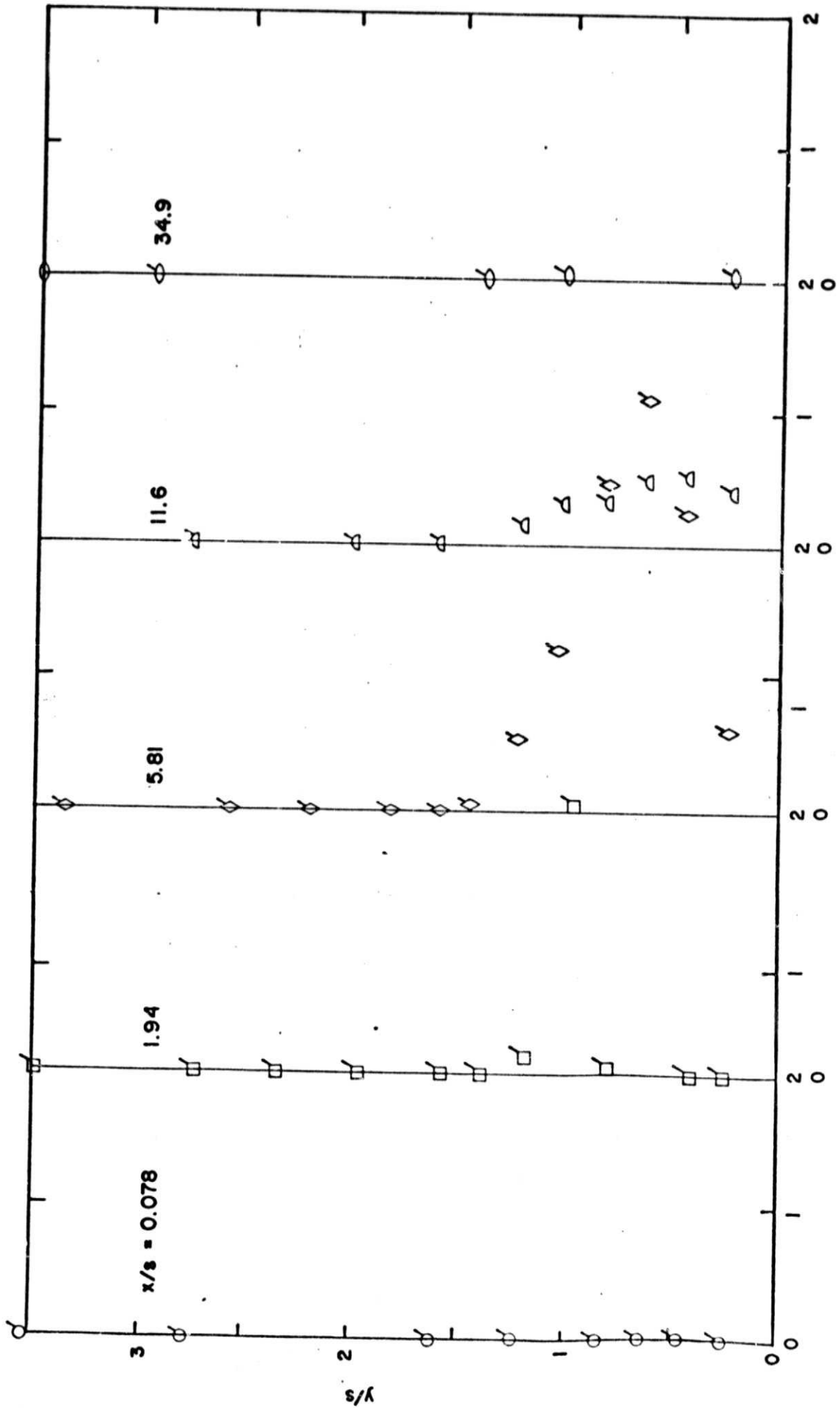
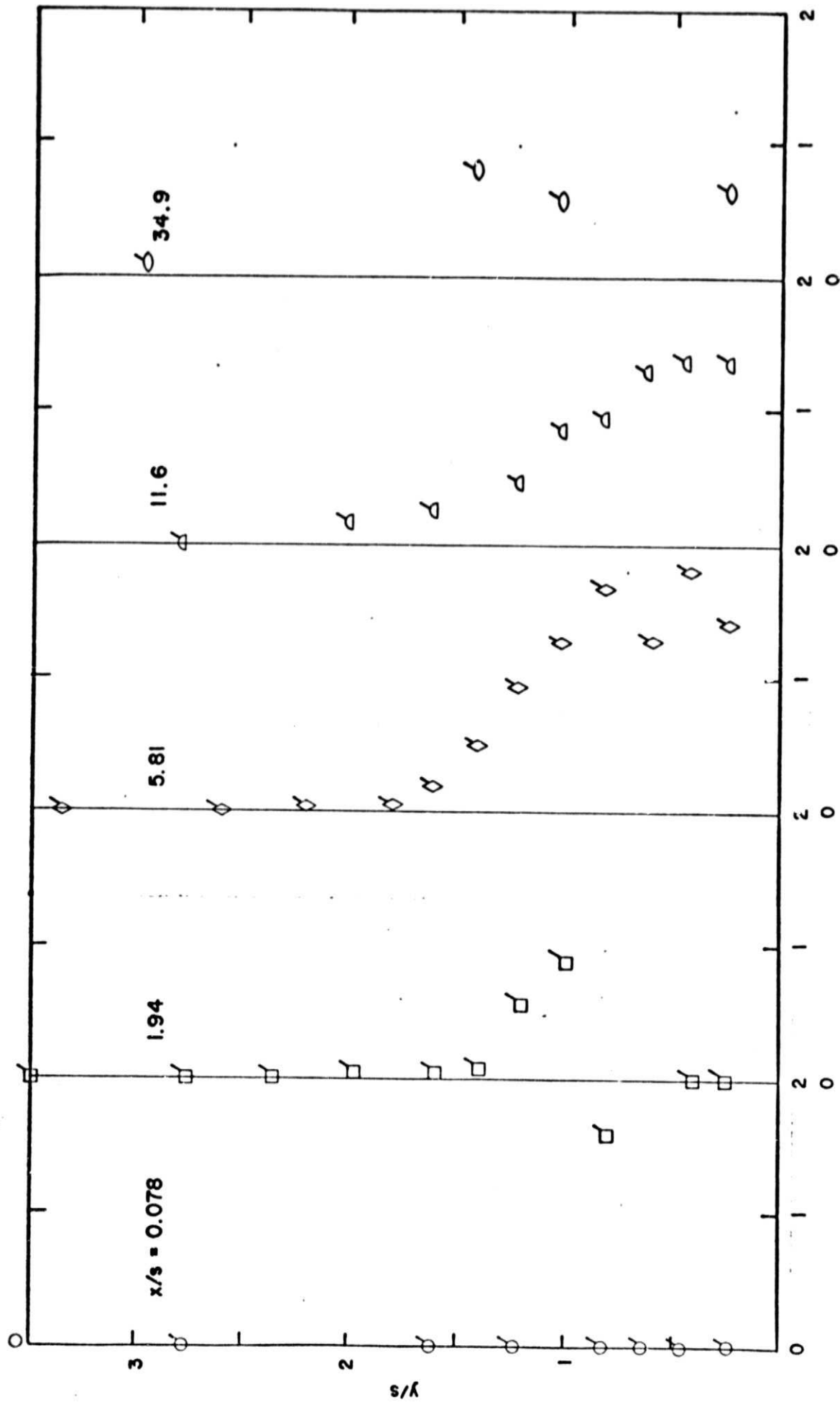


Figure 5.



$\overline{\rho C^{*2}} / \rho_0 (10^2)$



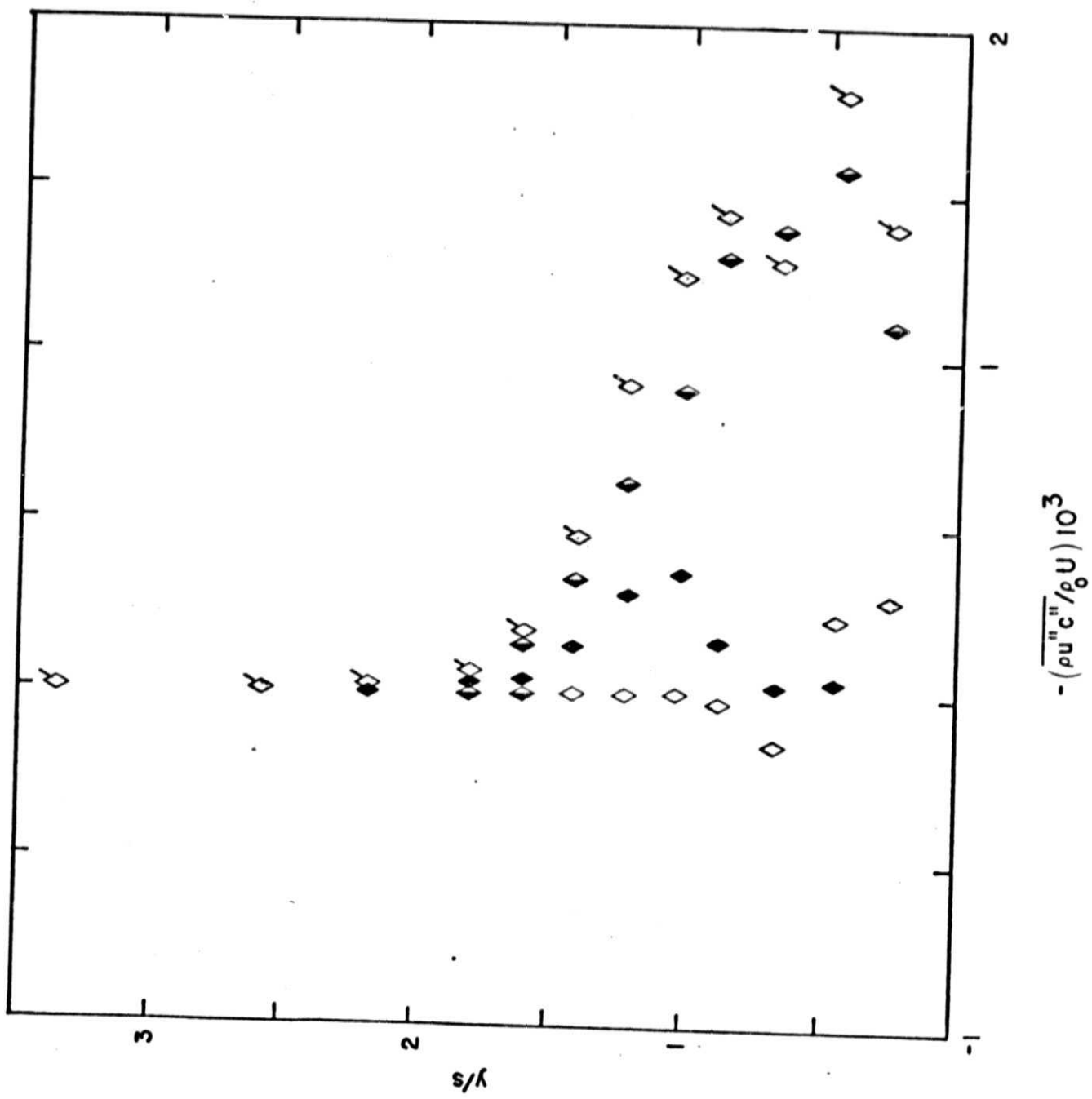


Figure 8.