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SUMMARY OF RESEARCH  
REPORT

GRANT NAG-1-1920

"PRESTON PROBE CALIBRATIONS AT HIGH REYNOLDS NUMBER "

SUBMITTED TO:

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# PRESTON PROBE CALIBRATIONS AT HIGH REYNOLDS NUMBER

## OBJECTIVE:

The overall goal of the research effort performed under grant NAG-1-1920 is to study the performance of two Preston probes designed by NASA Langley research Center across an unprecedented range of Reynolds number (based on friction velocity and probe diameter), and perform an accurate calibration over the same Reynolds number range.

## MOTIVATION/BACKGROUND

A Preston probe is a device used to measure wall shear stress ( $\tau_w$ ) in a turbulent flow. Simply stated, a Preston probe is a Pitot probe placed in contact with a wall. Preston probes are typically used in turbulent boundary layers where the wall shear stress cannot be easily measured by some other method. If the probe is placed in a region that scales on inner layer variables, then the relationship between the Preston probe pressure and the wall shear stress can be written as

$$\frac{\Delta P}{\rho u_\tau^2} = j_1 \left( \frac{u_\tau D_{pp}}{v} \right) \quad (1)$$

where  $P$  is the dynamic pressure measured by the Preston probe,  $j_1$  represents the functional dependence and  $D_{pp}$  is the diameter of the Preston probe. Equation 1 can be re-written in the form originally used by Preston [1954]. That is

$$\frac{\tau_w D_{pp}^2}{4\rho v^2} = j_2 \left( \frac{\Delta P D_{pp}^2}{4\rho v^2} \right) \quad (2)$$

where  $j_2$  represents the functional dependence. Once  $j_2$  is determined, the wall shear stress can be calculated by measuring the dynamic pressure and by knowing the geometry and fluid properties. The functional relationship  $j_2$  is usually established in a pipe flow because the wall shear stress can be accurately determined from the pressure gradient.

Current calibration curves, particularly that by Patel [1965] cover only a limited range of Reynolds numbers, and in high Reynolds number applications, the Preston probe can only be used with considerable uncertainty. To reduce this uncertainty, and allow the accurate

measurement of skin friction at high Reynolds number, new experiments in the Princeton Superpipe facility are proposed.

The Superpipe apparatus was built to enable very accurate measurements across a wide range of Reynolds numbers, up to very large values. Operating with compressed air as the working fluid considerably reduced costs. The final design incorporates a closed loop system with an aluminum test pipe located inside high pressure piping. A sketch of the facility is shown in **Figure 1**.

The facility measures 34 m long and 1.5 m wide (centerline to centerline), and weighs 28 tons. The primary components include a pumping section, a heat exchanger, a return leg, a flow conditioning section with a 4:1 contraction, and a test leg. The test pipe is located inside the test leg which is constructed of 8 in NPS pipe and has two access ports for measurements. The first access port is located 160 (test pipe inner) diameters downstream of the contraction. The second access port functions as the primary test section, and is located 196 diameters downstream of the contraction and 6 diameters upstream of the end diffuser. The test pipe was divided into sections approximately 4.6 m long which were connected with custom-designed couplings that ensured repeatability of the connections. With consecutive sections connected, the inside diameter of the test pipe was honed to a diameter of  $129.36 \pm 0.08$  mm. Mismatches between pipes (steps) are less than 0.08 mm which was determined to have no effect on the mean flow measurements (see Zagarola, 1996). The pipe was honed and polished in two stages. After the second polishing, the inside of the test pipe was polished to an *rms* surface finish of  $0.15 \pm 0.03$   $\mu\text{m}$  which corresponds to an average roughness height (twice the *rms* value) of  $2.7 \pm 0.5$  viscous lengths at a Reynolds number of  $40 \times 10^6$  (corresponding to the most severe requirement). An average roughness height of less than 5 viscous lengths is a widely accepted criterion for a smooth. For further details on the experimental facility, see Zagarola [1996].

Each Reynolds number can be achieved by varying either the density or the flow rate. The density is approximately proportional to the absolute pressure since the temperature is always near ambient. The density and viscosity are calculated from the absolute pressure and temperature using real-gas relationships. The absolute pressure is measured by three calibrated pressure gauges with a worst case accuracy of  $\pm 0.3$  % of the reading. The absolute temperature was measured with a calibrated chromel-alumel thermocouple with an accuracy of better than  $\pm 0.05$  % of the absolute temperature for temperatures near ambient. The static

pressure distributions are found using twenty 0.8 mm wall taps equally spaced ( $165.1 \pm 0.1$  mm) over 25 diameters, in the region between the secondary and primary access ports (see **Figure 1**). The pressure gradient and the friction velocity are calculated from the static pressure measurements by a least squares fit. The linear correlation for the pressure gradient calculations are typically greater than 0.9998. The Pitot pressures and static wall pressures are measured with six calibrated differential pressure transducers referenced to a 0.8 mm diameter static wall tap at the same location as the Pitot probe. The worst case accuracy for a differential pressure measurement was better than  $\pm 0.4$  % of the reading. The friction velocity and average velocity have an uncertainty of  $\pm 0.4$  %. The friction factor and Reynolds number have an uncertainty of  $\pm 0.9$  % and  $\pm 0.7$  %, respectively.

## RESULTS

### First Round of Experiments

In the first experiments, 3 Preston probes having outer diameters of 0.058", 0.083" and 0.203" were tested over a large range of pipe Reynolds numbers. Each Preston probe was attached to an access port which was then placed in the primary test section of the pipe flow apparatus. **Figure 2** shows a Preston probe mounted to an access port. The Preston probe was aligned with the flow direction and then glued to the access port to prevent movement. Each Preston probe had a 0.02" static pressure tap located on the upper surface of the probe (see **Figure 2**). A calibration using this static pressure tap is useful when in situations where a static pressure tap can not be place in a wall. The static pressure tap was 5 Preston probe diameters downstream of the tip. The pressures were measured by 4 differential pressure transducers which were connected to the reference pressure tap which is also show in **Figure 2**.

For each Reynolds number, we measured the pressure gradient, static pressure from the Preston probe and the total pressure from the Preston probe. The data were reduced using two methods. For the first method, the static pressure measured on the Preston probe was used to calculate  $P$  (modified Preston probe configuration), and for the second method, the static pressure measured at the reference pressure tap was used to calculate  $P$  (un-modified Preston probe configuration). For both methods, the static pressure was adjusted to correspond with the static pressure at the Preston probe tip using the pressure gradient. The

density and viscosity were calculated using the real-gas relations given in Zagarola [1996] Appendix B.

The results for the un-modified and modified Preston probe configurations are shown in **Figures 3 and 4**, respectively. The results are presented using the ordinate and abscissa preferred by previous investigators. That is

$$x^* = \log_{10} \left( \frac{\Delta P D_{PP}^2}{4\rho v^2} \right) \quad (3)$$

$$y^* = \log_{10} \left( \frac{\tau_w D_{PP}^2}{4\rho v^2} \right) \quad (4)$$

The measurements for the Preston probes with the 0.058" and 0.083" diameter were performed in the test pipe before it was polished a second time. Therefore, the measurements at high pipe Reynolds numbers may have been affected by roughness. The solid symbols indicate measurements performed at pipe Reynolds number where we believe roughness may have affected the measurements (see Zagarola, 1996). These data were eliminated from further analysis. Also shown on the figures is the relation given by Patel [1965] which was established from data in the range  $5.6 < x^* < 7.6$ . Patel relation is given by

$$x^* = y^* + 2 \log_{10}(1.95y^* + 4.10) \quad (5)$$

The results for the modified and un-modified Preston probe are in good agreement with the relation proposed by Patel even for  $x^* = 11.3$ . To obtain better agreement at large values of  $x^*$ , a new relation is proposed which is similar to Patel's but has different constants. For the results using the un-modified probe

$$x^* = y^* + 2 \log_{10}(1.813y^* + 4.743) \quad (6)$$

and for the results using the modified probe

$$x^* = y^* + 2 \log_{10}(1.802y^* + 4.991) \quad (7)$$

The values of  $y^*$  predicted by Equations 6 and 7 are within  $\pm 0.06\%$  of the data for  $6.4 < x^* < 11.3$ . This should permit the determination of the wall shear stress ( $\tau_w$ ) to better than  $\pm 0.8\%$ .

## Second Round of Experiments

In the second round of experiments, the 0.058” and 0.083” diameter un-modified probes were tested after the pipe was polished a second time. The surface of the test pipe was carefully prepared to ensure that the surface was smooth and consecutive sections of the test pipe were honed and polished while connected. The pipe was then hand polished along its entire length and inspected. The surface finish at different points along the pipe were measured independently by three different people using a comparator plate. At each point, the estimate from each person was within  $\pm 0.03$  micron of the average value for that point. According to these measurements, the surface finish of the entire test pipe can be conservatively characterized as a  $0.15 \pm 0.03$  micron rms ( $6.0 \pm 1.2 \mu\text{in}$ ) which corresponds to  $k_s^+ = 3.5 \pm 0.7$  at  $\text{Re} = 35 \times 10^6$ , within the generally accepted smooth pipe regime.

The region of interest in the  $x^*$ - $y^*$  plane is described by the  $x^*$  interval  $8 < x^* < 10$ , since this range covers the points taken at high pipe Reynolds number in the first round of experiments which may have been compromised by roughness. The 0.058” and 0.083” diameter probes were both tested in this range, and the results are shown in **Figure 5**. The combined data set can be fit over the range  $7.5 < x^* < 9.9$  by:

$$x^* = y^* + 2\log_{10}(1.854y^* + 4.970)$$

and the agreement among the three curve-fits (each individual probe, and the combined data) over this range is better than 0.3% on the wall shear. However, when compared to equation 6, the new results give consistently 5% lower values of the wall shear.

The new results were extensively checked. Some data points showed greater uncertainty in the determination of the pressure gradient than the original results (this affected 3 points out of 8 for the large tube, and 4 points out of 10 for the small tube), and the curve fit was repeated with these points removed from the data set. The results were virtually identical.

The other two main sources of uncertainty in the data come from the measurement of the Preston tube dynamic pressure (which affects only  $x^*$ ) and the measurement of the average pipe velocity (which affects  $x^*$  and  $y^*$  in the same way). The differences between the first and second set of results are due to a consistent percentage change in both  $x^*$  and  $y^*$ , and therefore

it may be connected with the average velocity determination. In fact, a 0.22% decrease in the  $x^*$  and  $y^*$  values found in the second round of experiments would bring the first and second sets of data to almost perfect agreement. If the average velocity was underestimated by 1.6%, this would produce a 0.22% decrease in both  $x^*$  and  $y^*$ . Given that the average velocity was estimated by assuming that the connection between the centerline velocity and the average velocity was known, and by using a Pitot tube to measure the centerline velocity. A preliminary error estimate suggests that it is possible to introduce a 1% to 2% error in estimating the average velocity using this approach.

Therefore, although the evidence on the errors attending the second data set is somewhat circumstantial, and the measurements have not been repeated using a better approach, it seems probable that the first data set stands uncompromised, and we continue to hold that the correlation given by equation 6 applies to un-modified Preston probes over the range  $6.4 < x^* < 11.3$ .

## REFERENCES

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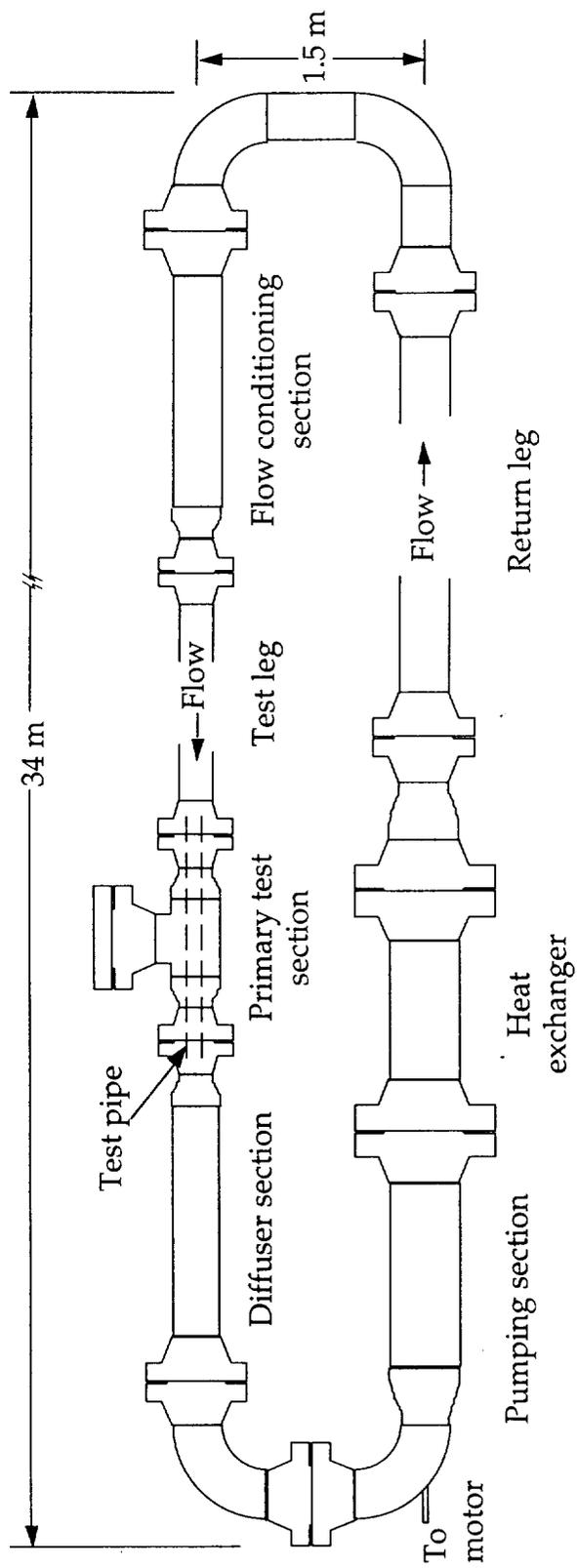
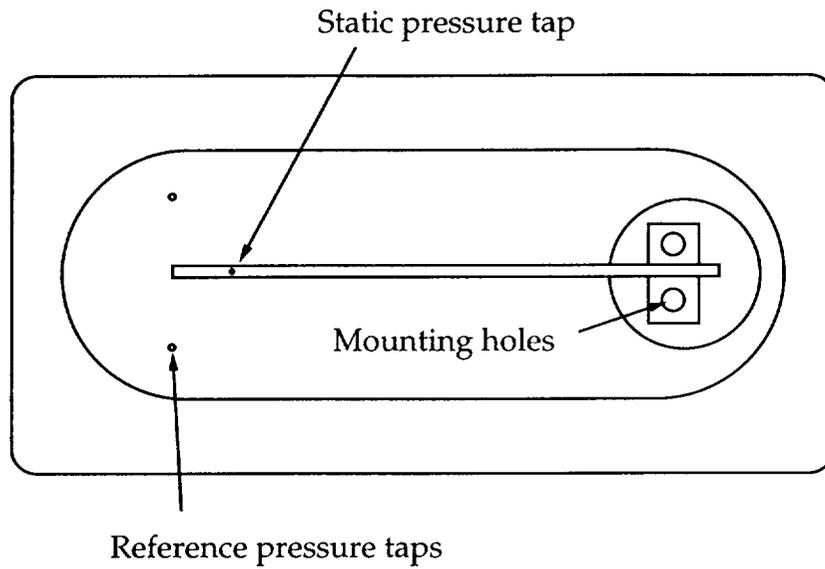
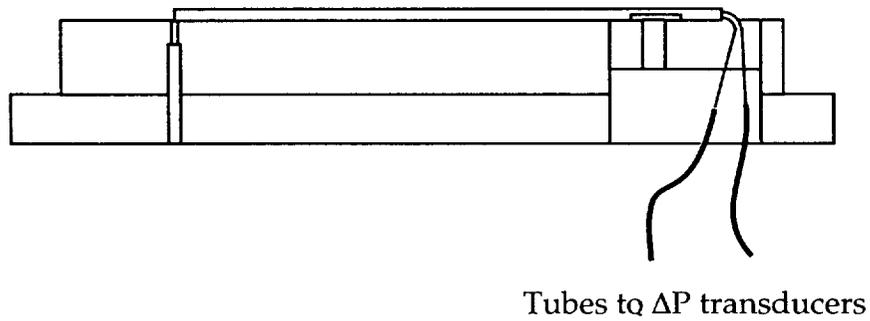


Figure 2.1: Diagram of the experimental facility.

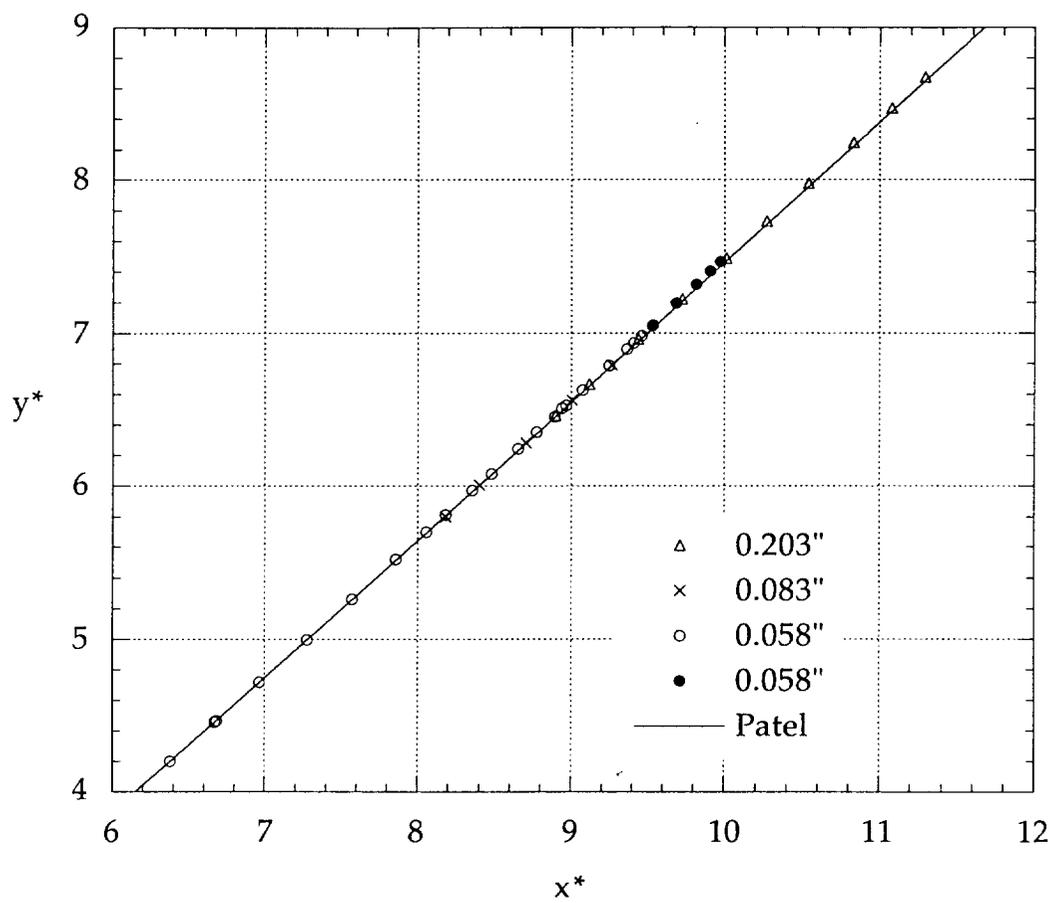
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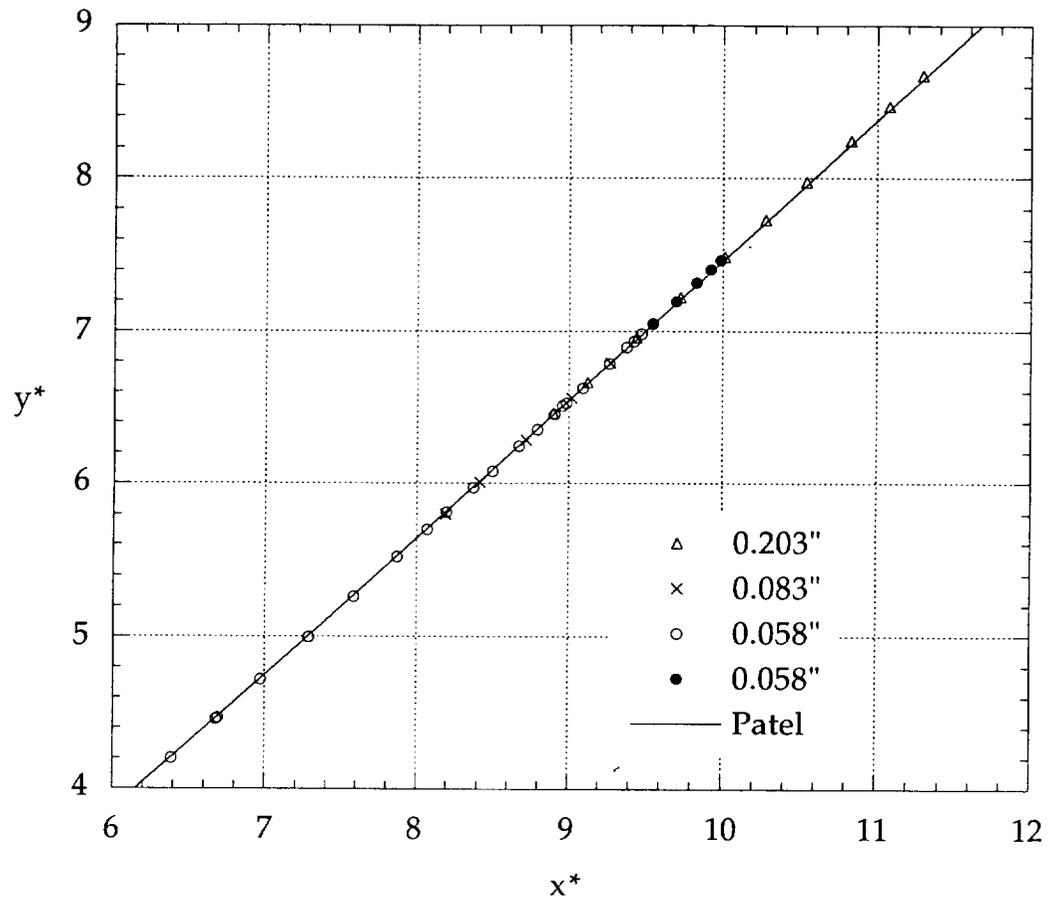
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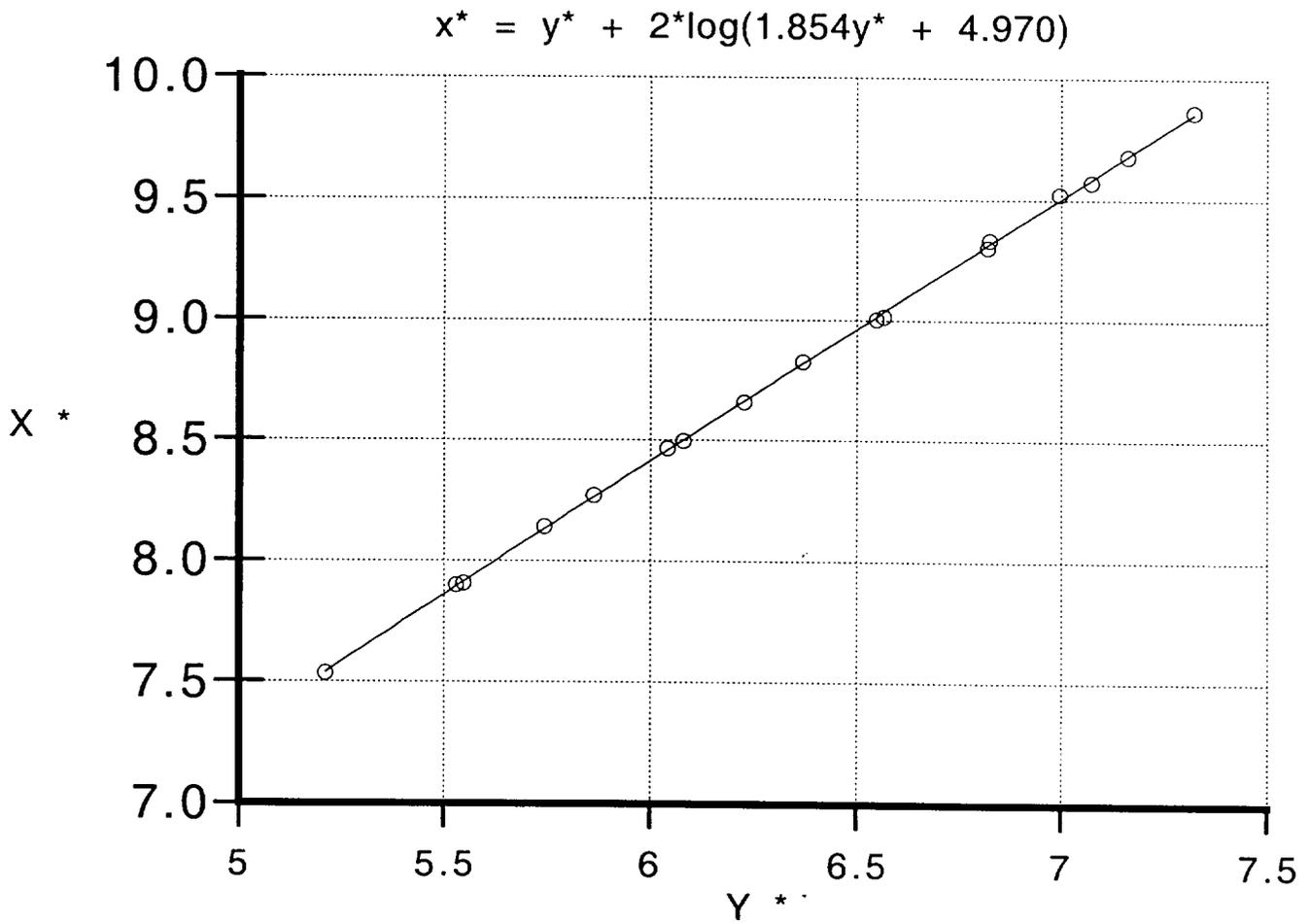
**Figure 2:** Diagram of Preston probe mounted on access port.



**Figure 3:** Preston probe calibration for un-modified probe.



**Figure 4:** Preston probe calibration for modified probe.



**Figure 5:** Preston probe calibration for unmodified probe. Second round of experiments, combined data for 0.58" and 0.83" probes.