Greenhouse Gas Emissions A Case Study On The Calibration Of An L-pitot Static Tube

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RATA Tests are often based on "S" Pitot Tubes

Advantages:

- Cheap
- Simple design
- Doesn't plug

Disadvantages:

- Questionable accuracy
- Problems with swirl

3-D Pitot Tubes

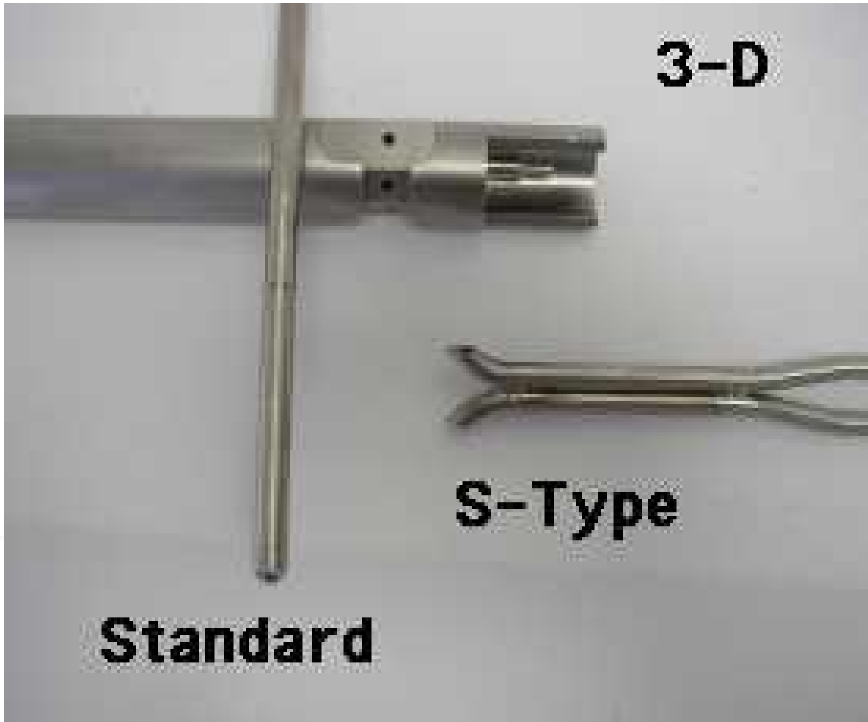
Advantages:

- Can measure swirl vectors (yaw)
- Can measure radial vectors (pitch)

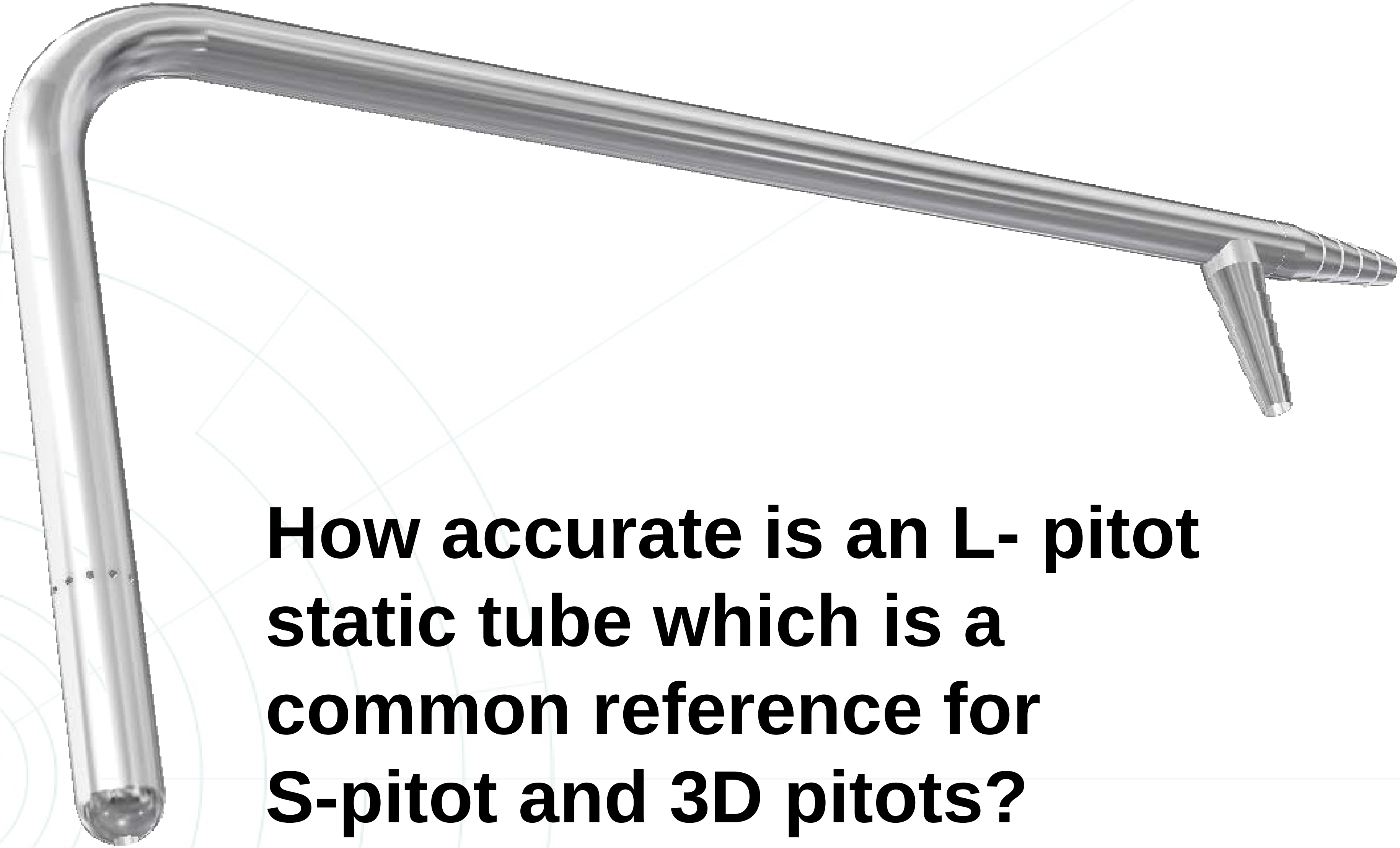
Problems:

- Requires calibration

EPA adds wind tunnel calibration requirements which are often based on L-pitot static tubes



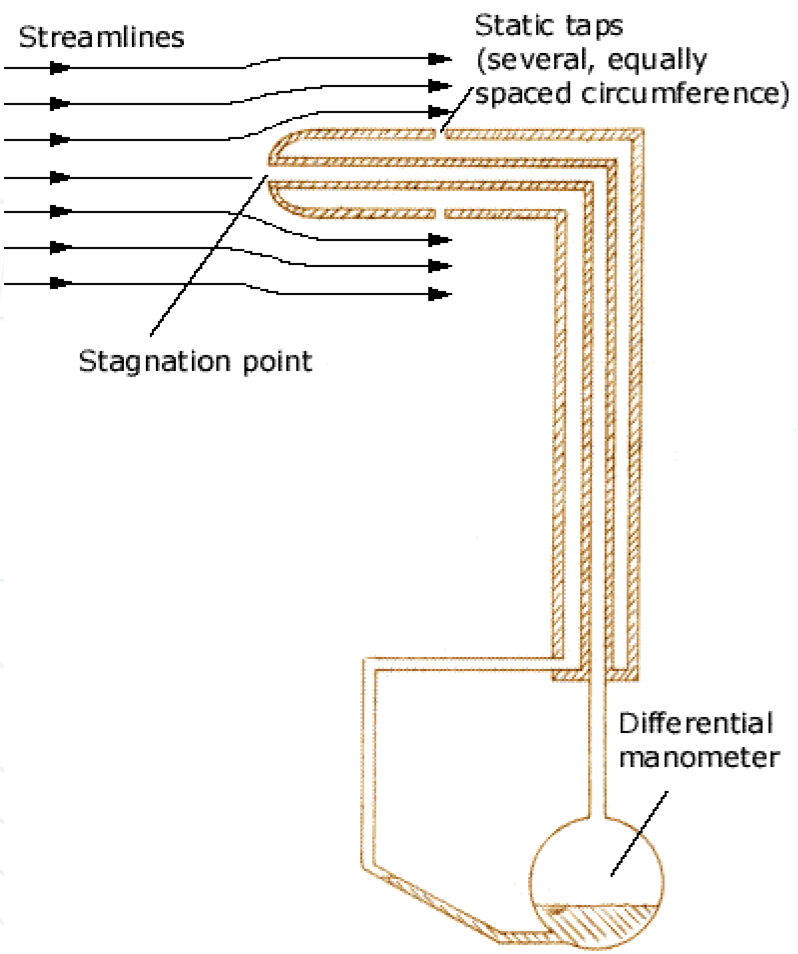
Pitot Static Tubes

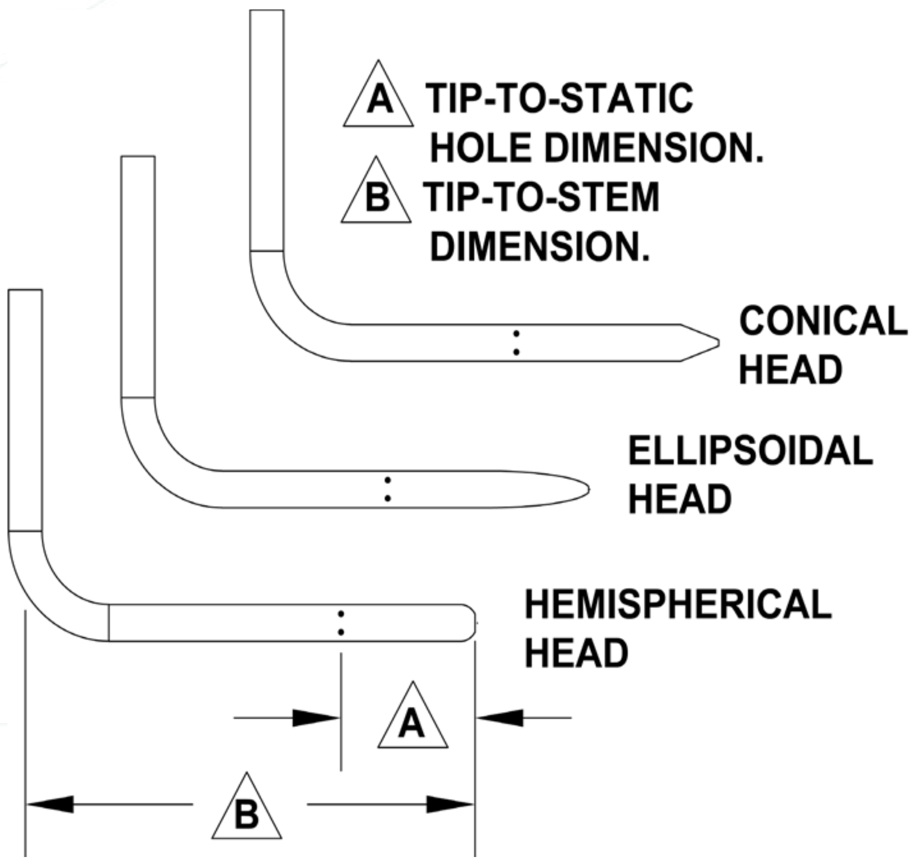


How accurate is an L- pitot static tube which is a common reference for S-pitot and 3D pitots?

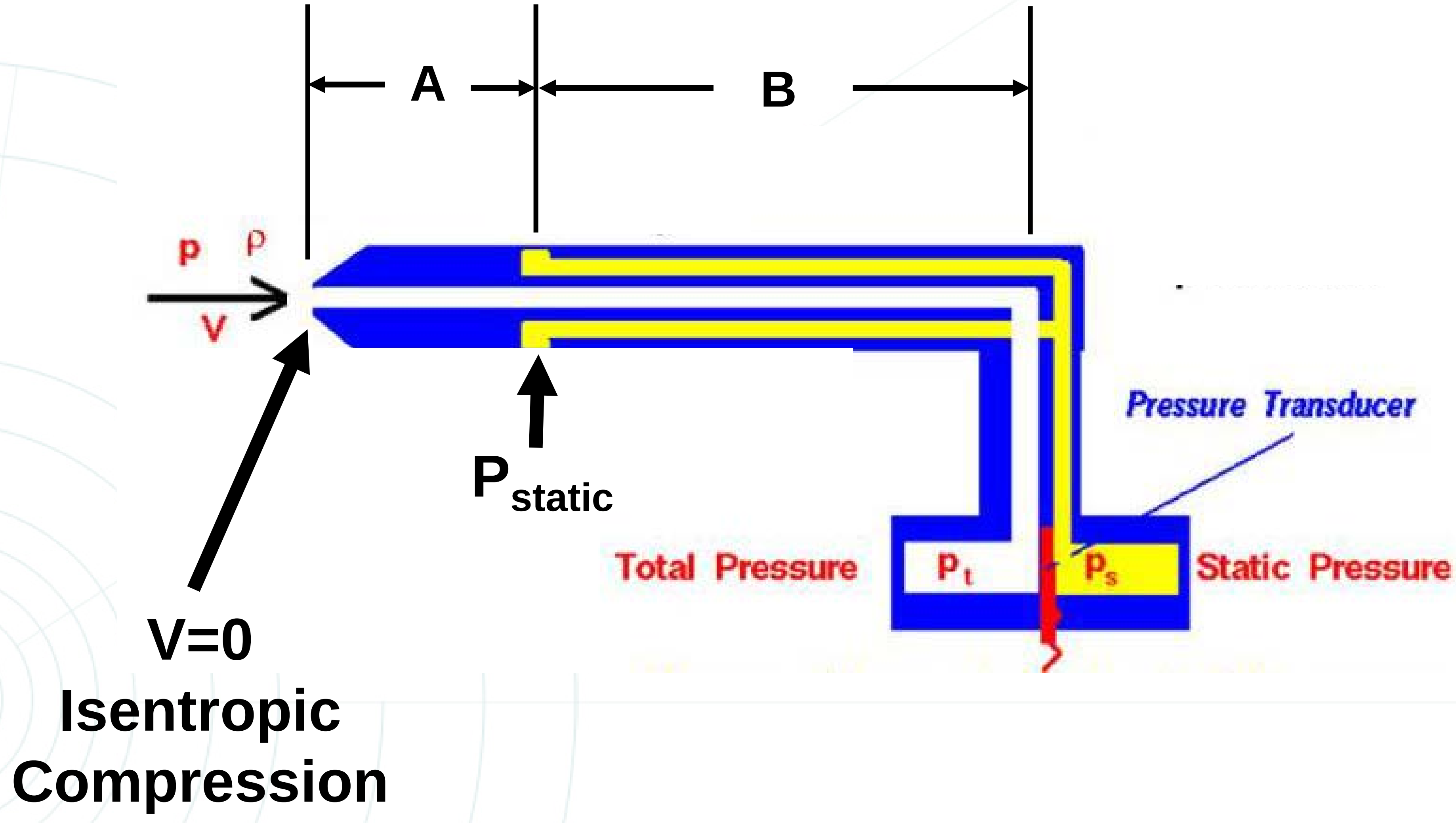
Alternate Calibration Methodology For Point-Velocity Devices (Pitot-Tubes, Anemometers, Hot-Wire Devices) Using NIST Traceable Mass Flow Measurement Standards

Pitot-static In A Flow Stream





Pitot-Static Tube Physics



Not All Static Pitot Tubes are the same

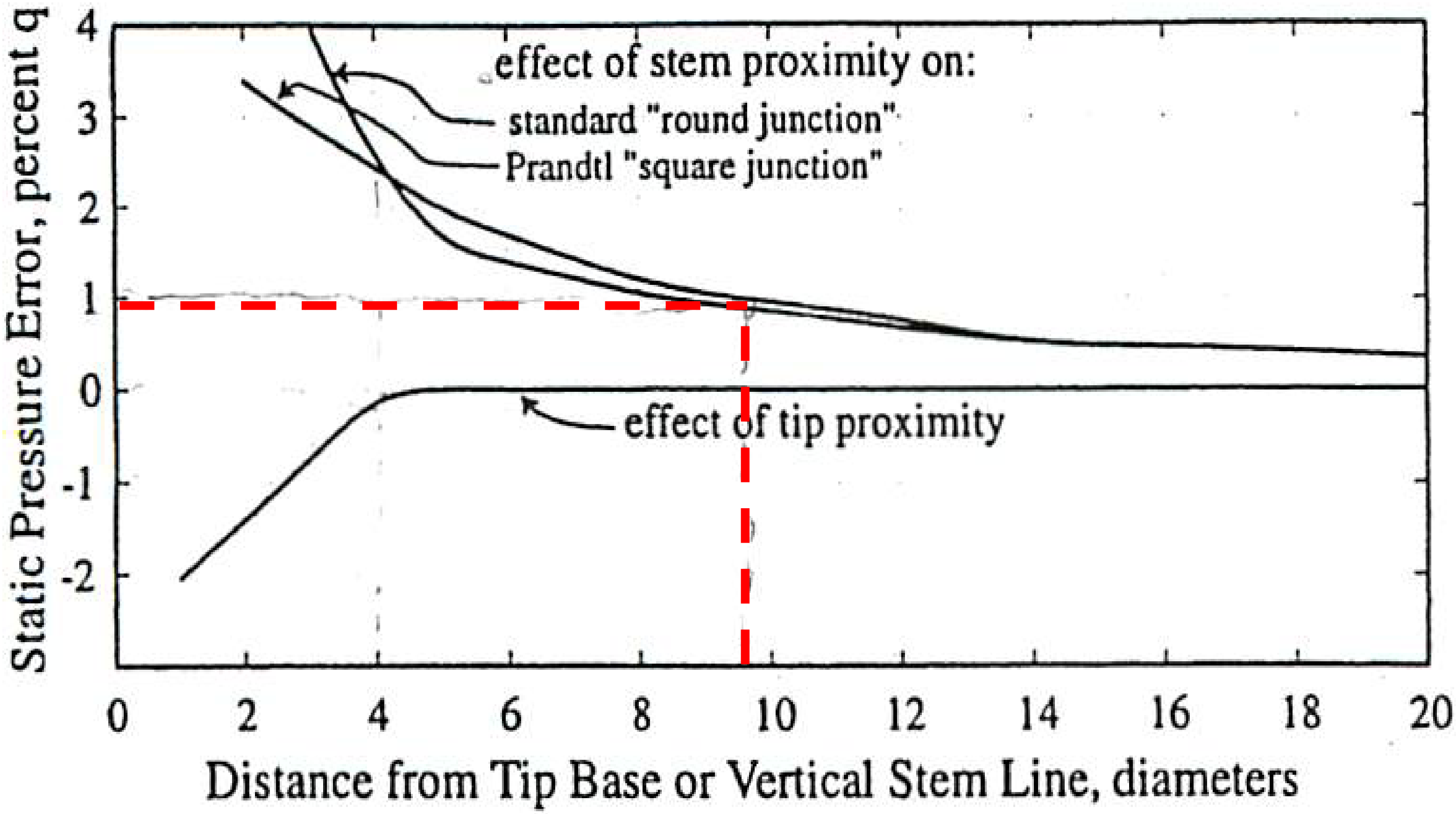
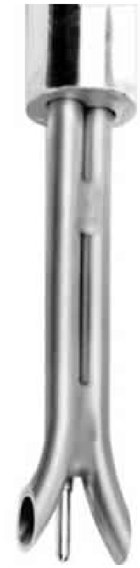


FIGURE 4.9 Effect of static orifice distance from tip or from stem: see Example 4.1.

Point-Velocity Calibration

THE ROBINSON ANEMOMETER.

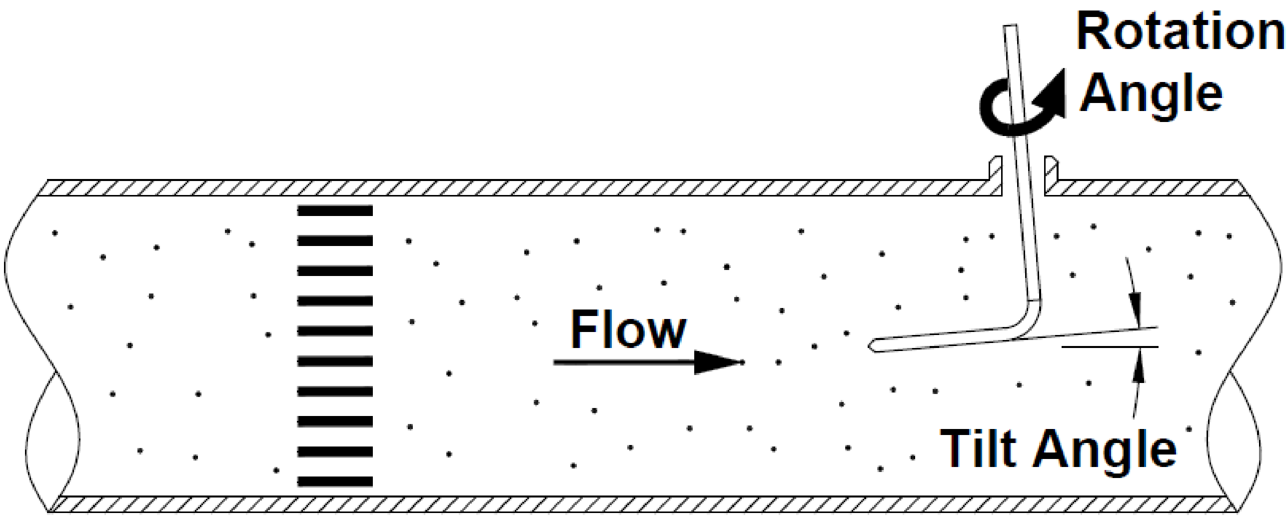


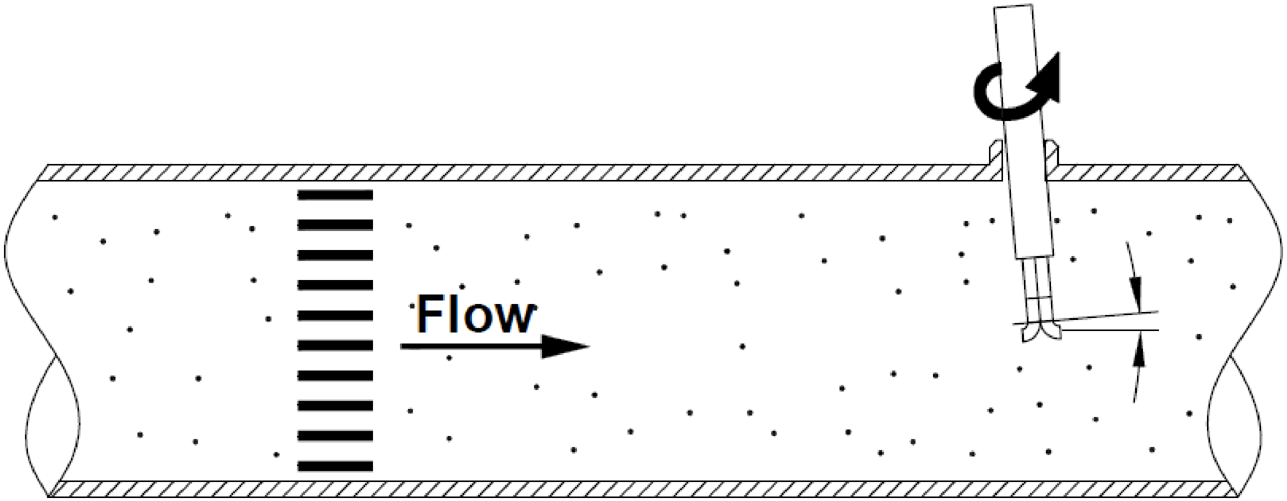
$$V = K_{factor}\,(output)$$

From Lab

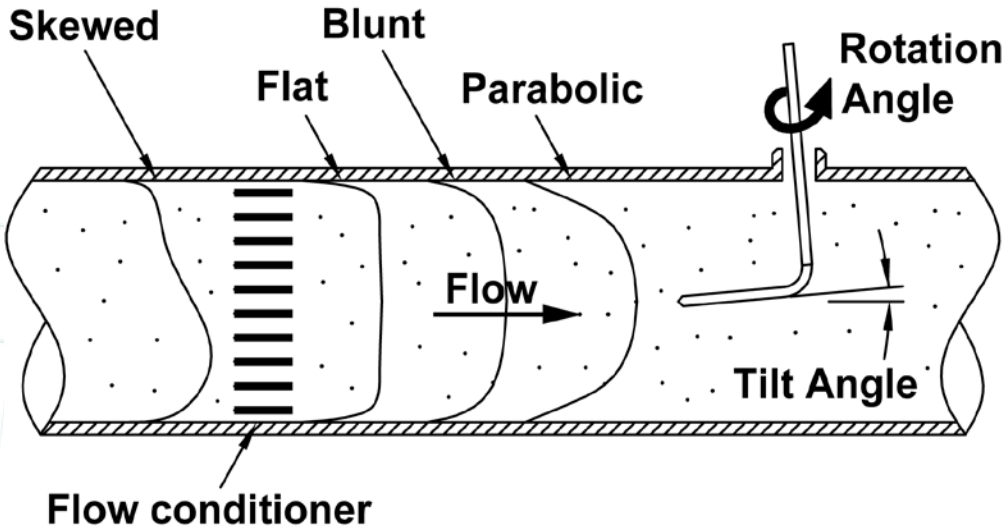
Measured

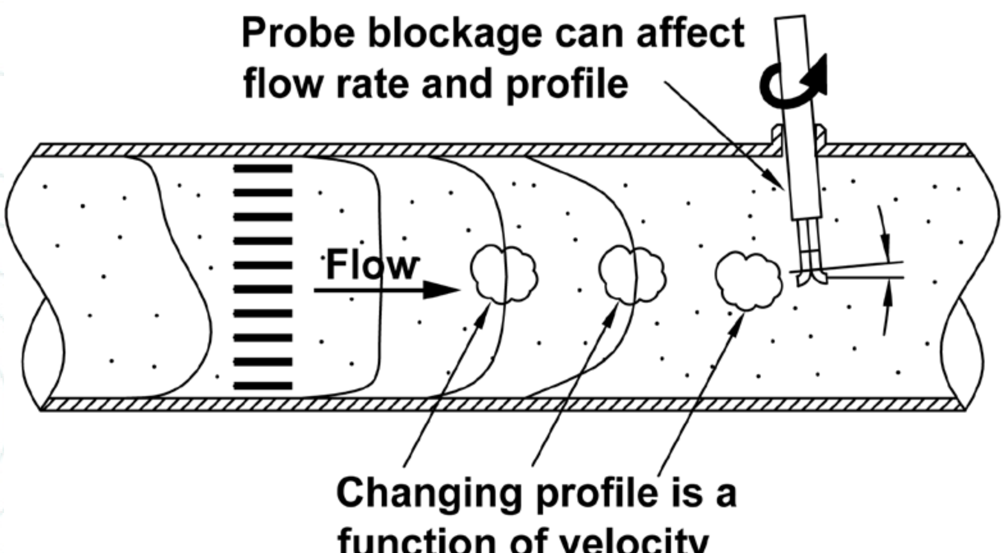
Traditional Method





Traditional Calibration Methodology Pitfalls





STEP 1.

A. Set flow and record velocity with Pitot-Static Tube that has a known Pressure Coefficient (Cp).

B. Avoid Tilt & Rotation Errors.

STEP 2.

A. Maintain identical flow rate.

B. Remove the Pitot-Static Tube.

C. Position the Point Velocity Device in the exact same location.

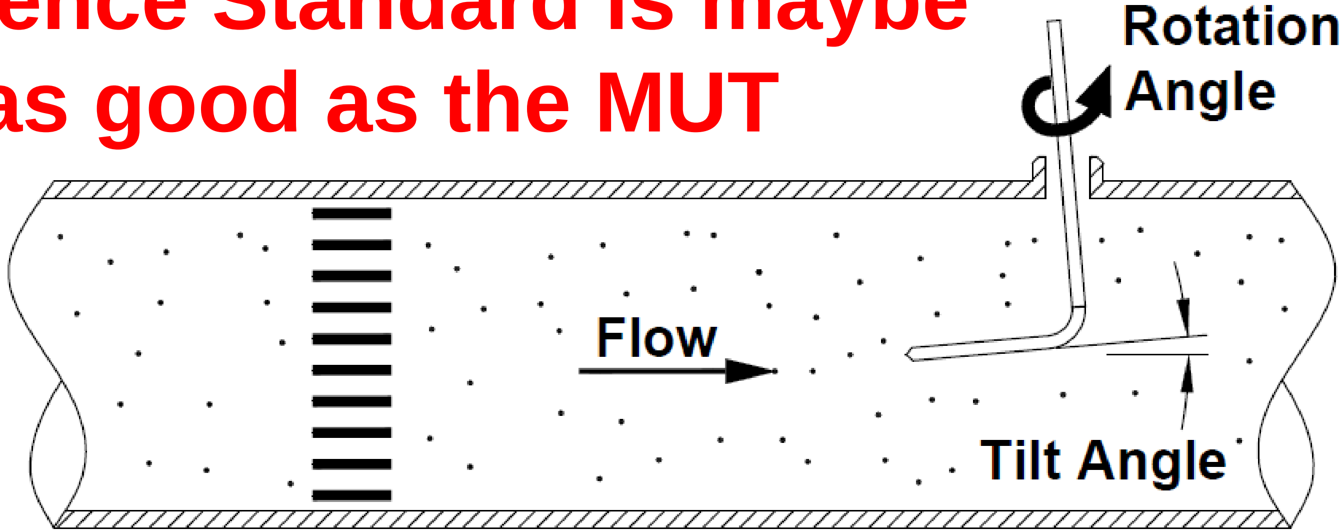
D. Make sure the blockage of Point Velocity Device does not alter the fluid velocity by reducing the flow area or increasing the pressure drop causing a lower fan output.

E. Make sure velocity range does not cause an adverse localized velocity gradient.

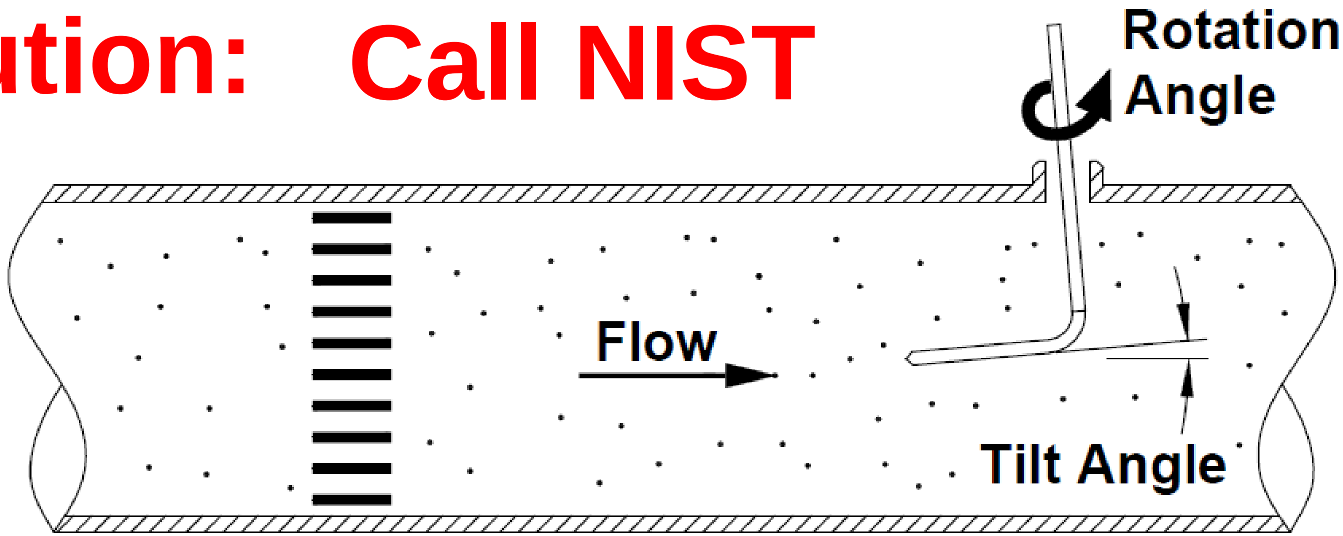
F. Avoid Tilt & Rotation Errors.

One Slight Problem

Reference Standard is maybe only as good as the MUT

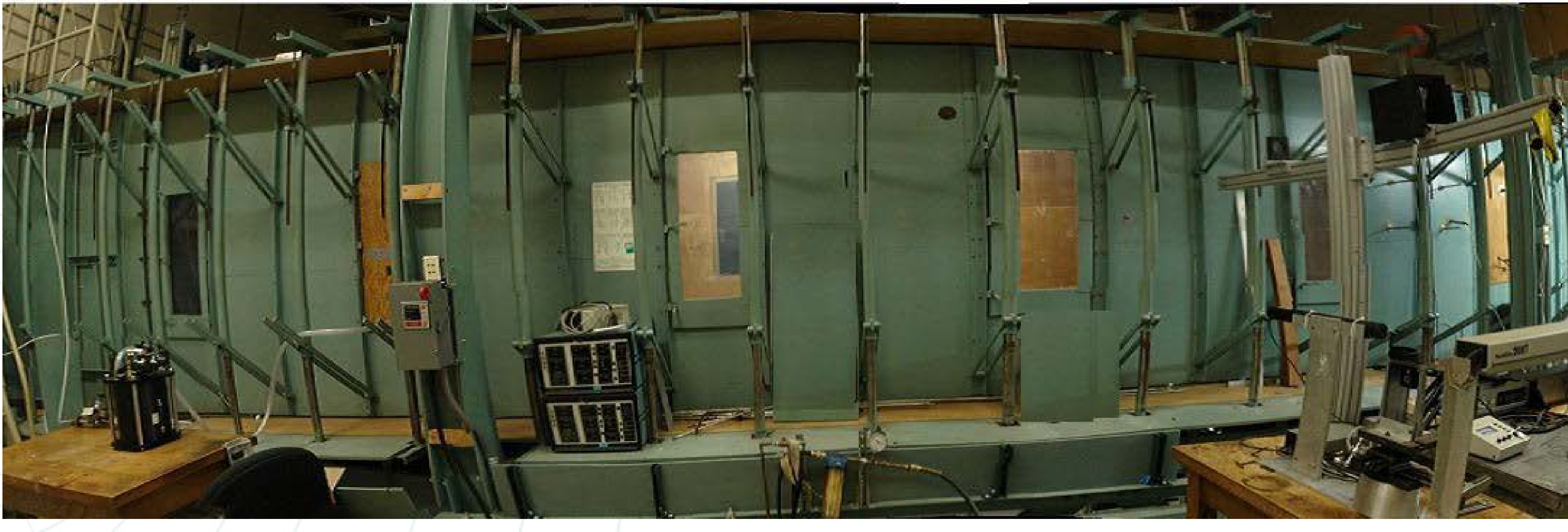


Solution: Call NIST

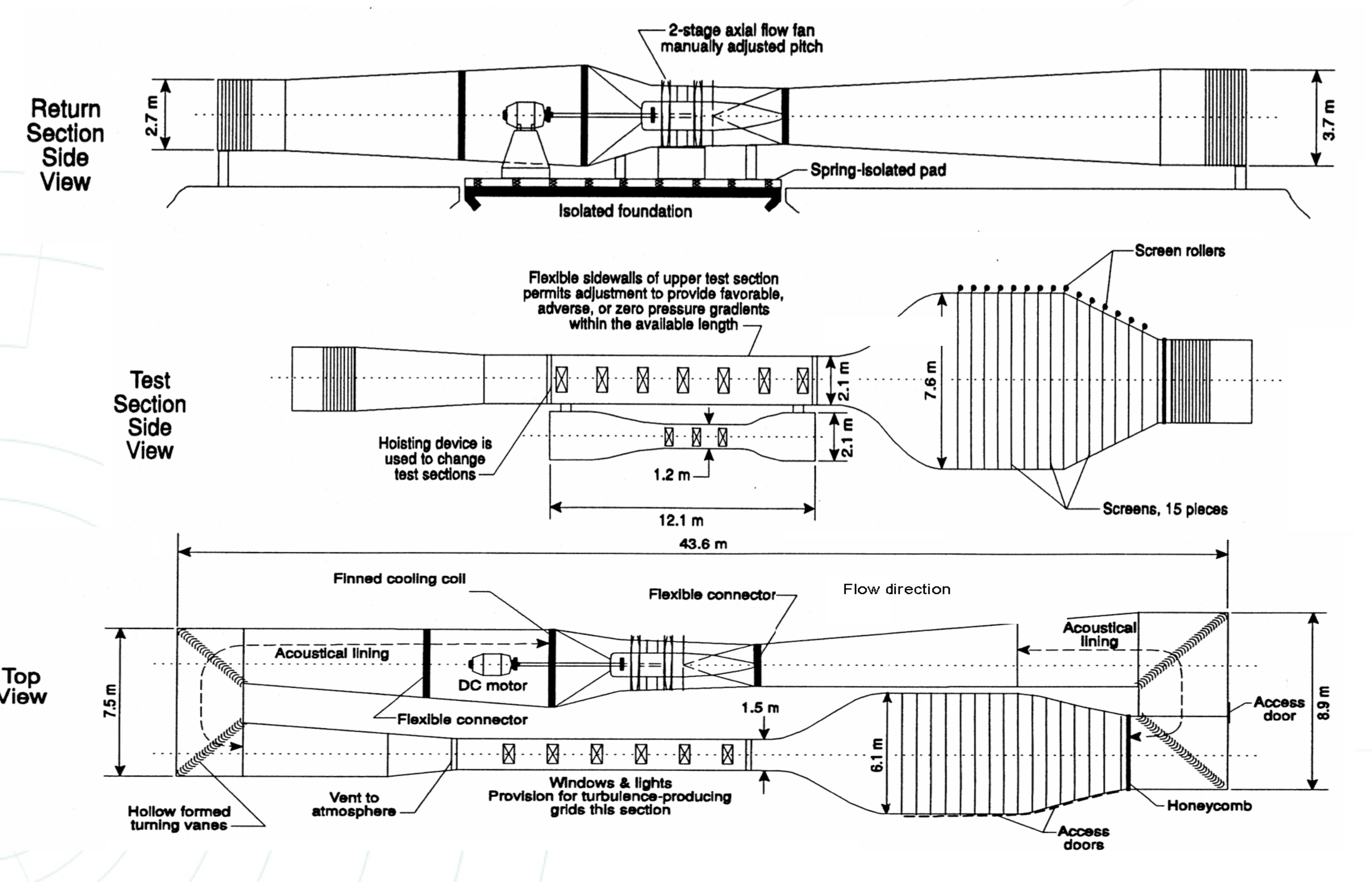


NIST Fluid Metrology Group

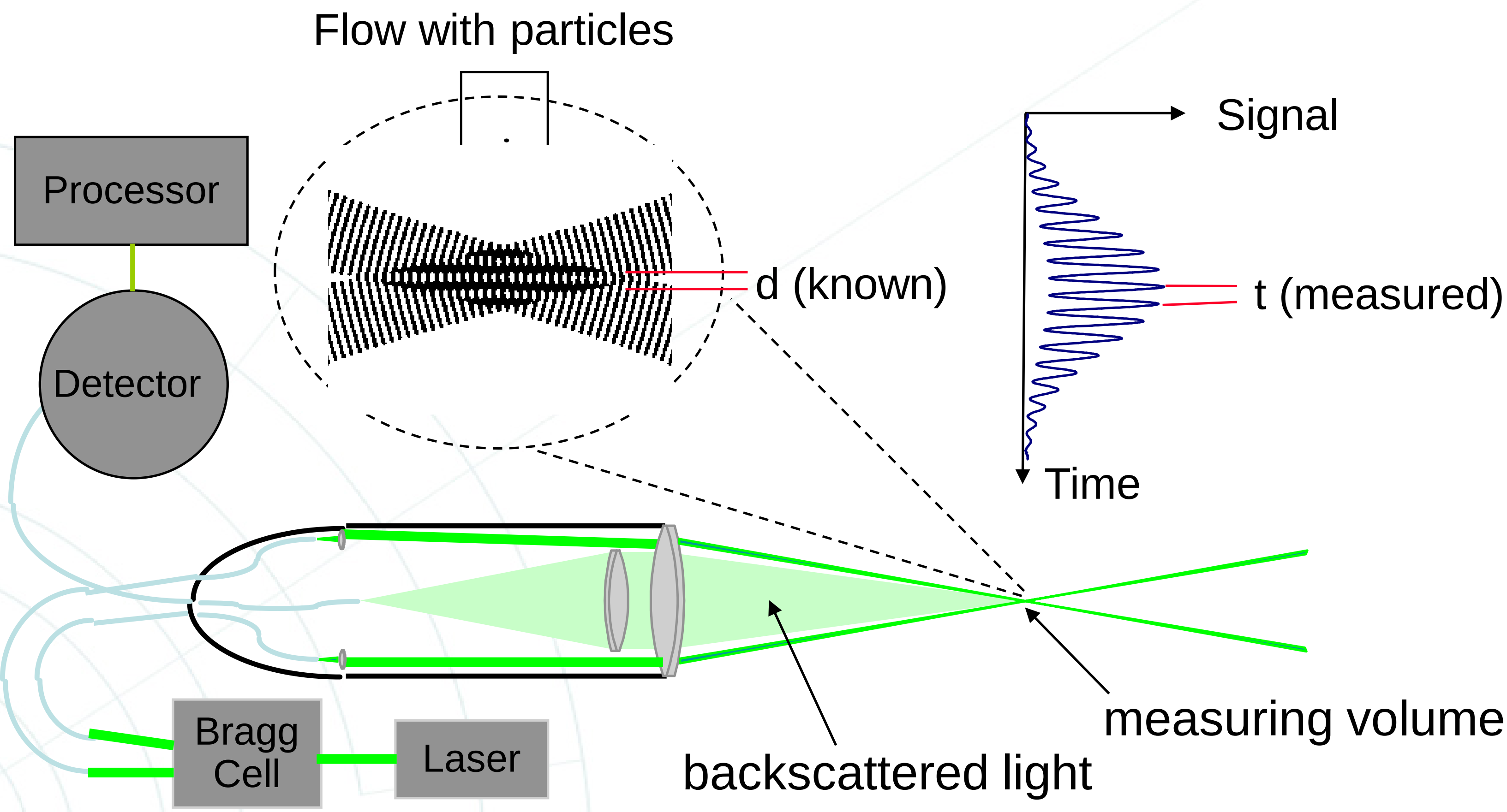
Iosif I. Shinder, Aaron Johnson



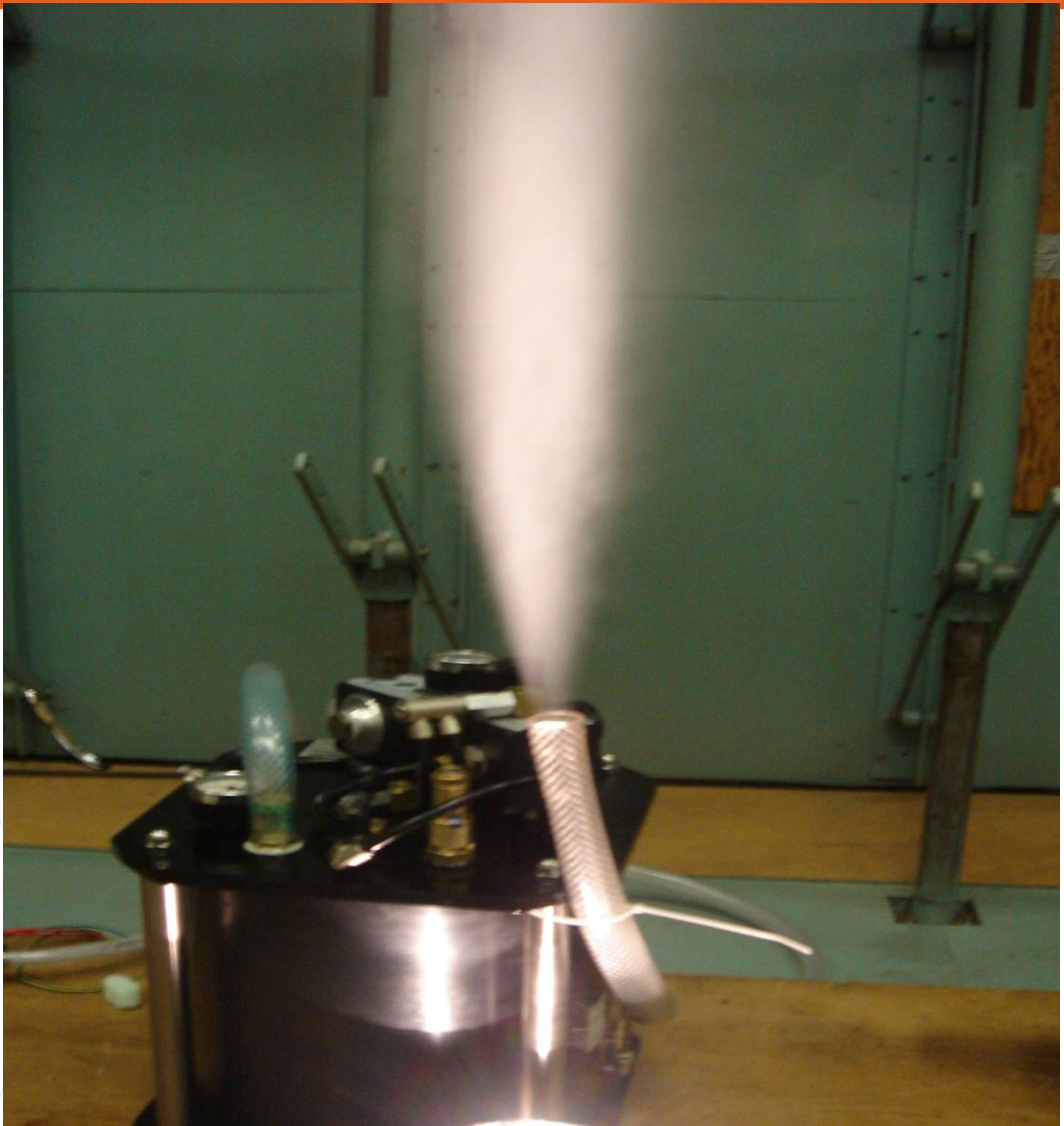
NIST Dual Test-Section Wind Tunnel



Primary Standard. Differential LDV

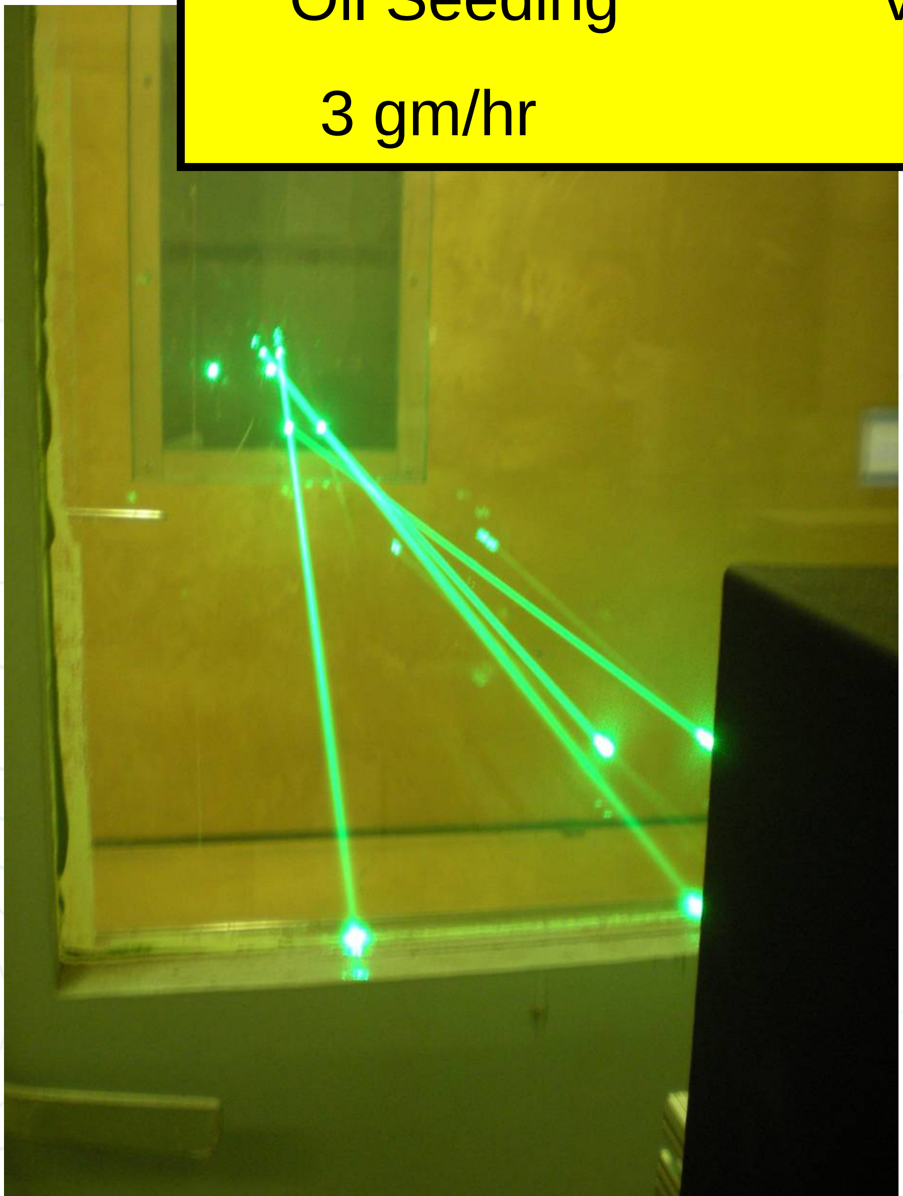


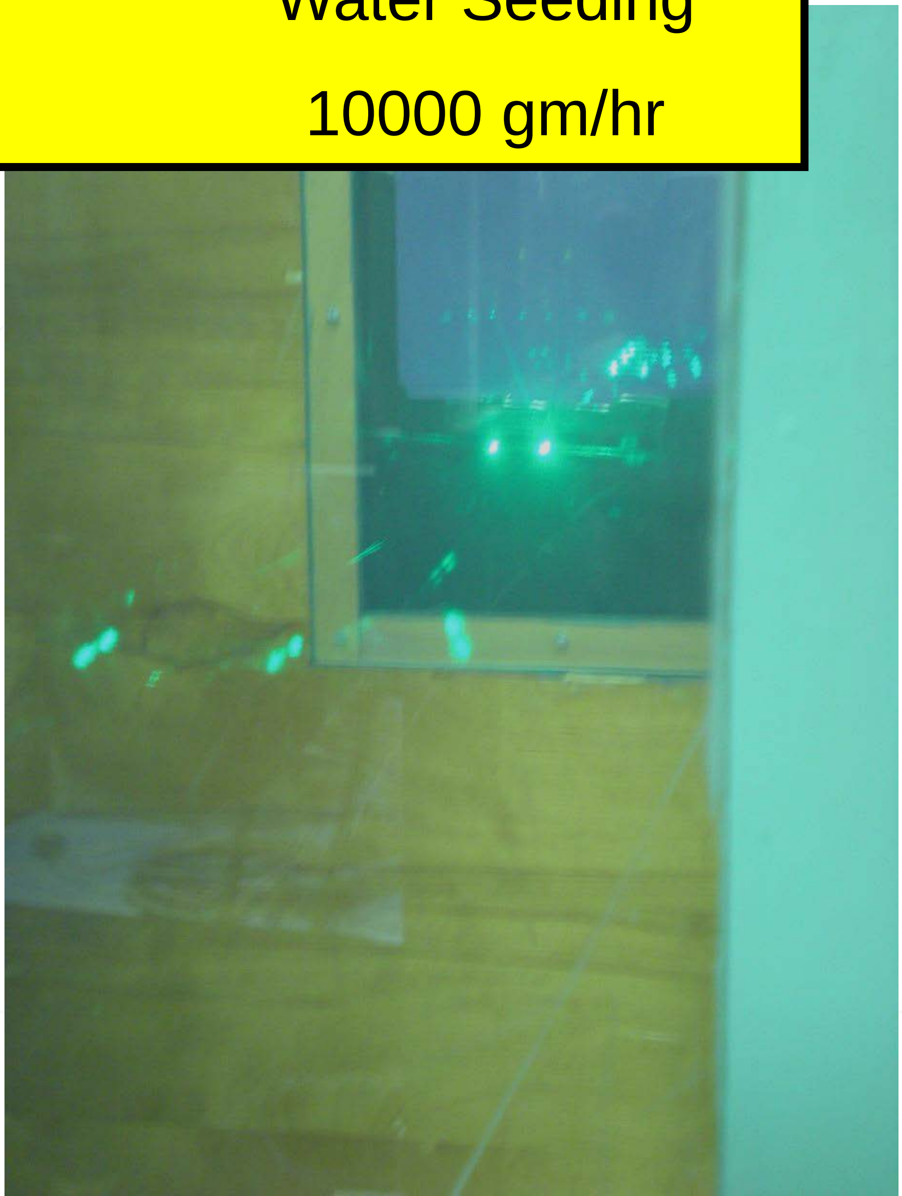
Oil Seeding



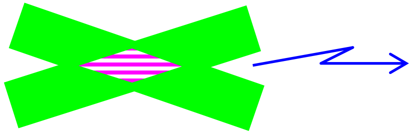
Lasers & Seeding

Oil Seeding	vs	Water Seeding
3 gm/hr		10000 gm/hr



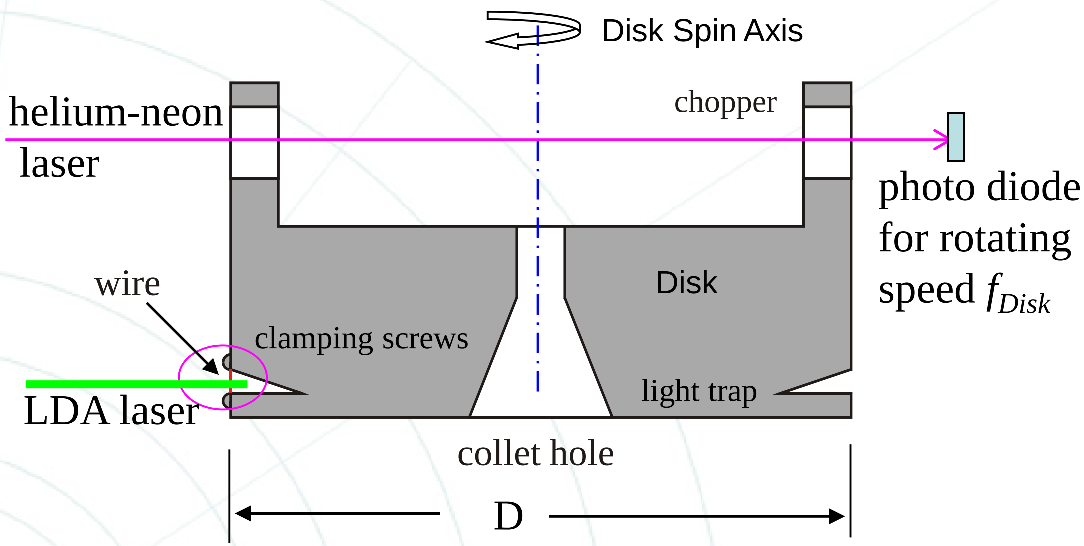


Spinning disk



$$V_{LDA} = d \; f_D$$

$$V_{Disk} = f_{Disk} \; D/2$$



$$C_{LDA} = \frac{V_{Disk}}{V_{LDA}} = \frac{D}{2} \frac{f_{Disk}}{f_D^C \; d}$$

$$V_{NIST} = C_{LDA} \, V_{LDA} = \frac{D}{2} \, f_{Disk} \frac{f_D}{f_D^C}$$

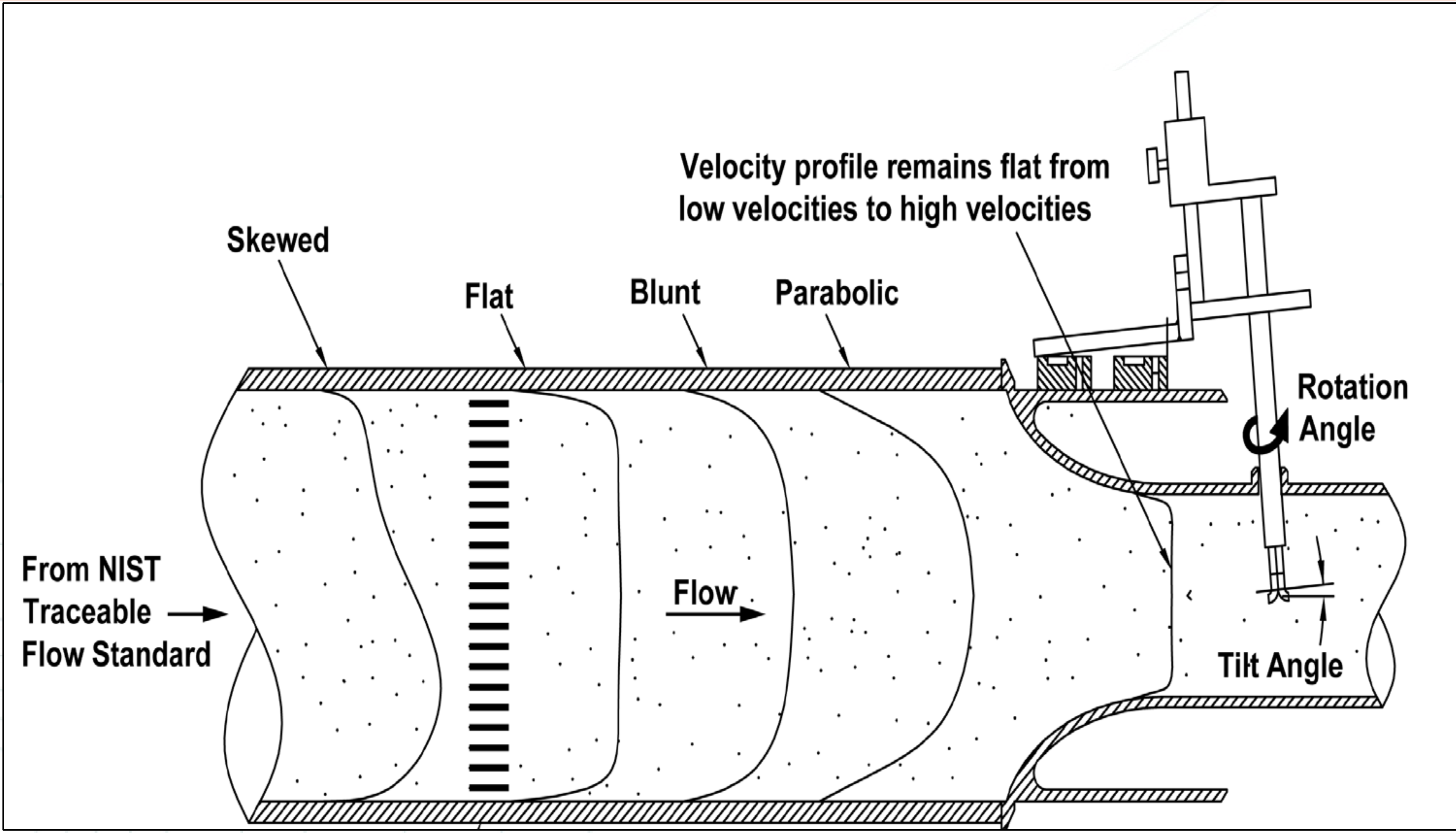
Length D and Time f_{Disk}

NIST Wind Tunnel Capabilities

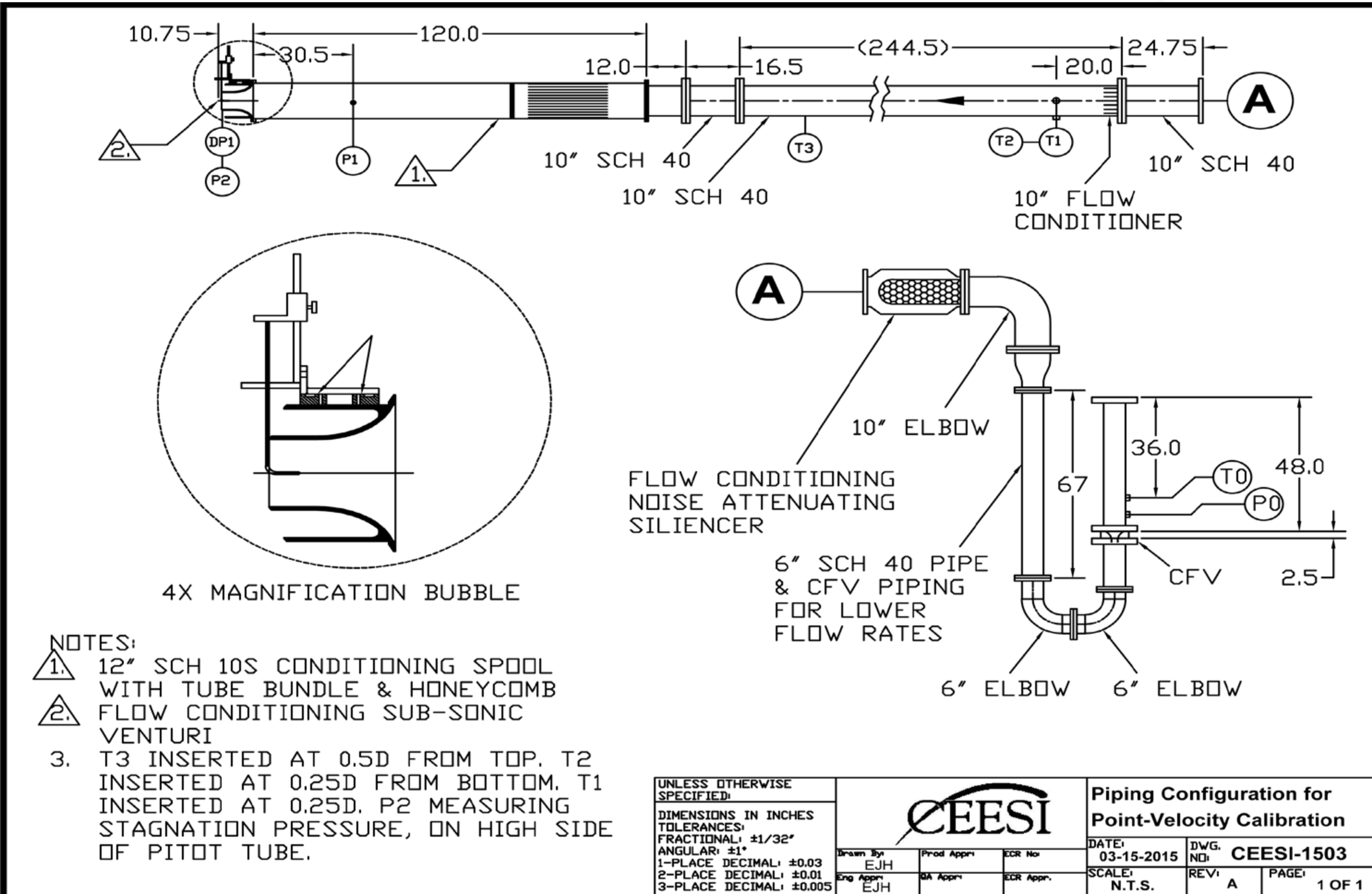
- **Two test sections:**
- **High speed: to 75 m/s (246 ft/sec) 1.2 m high**
- **Low speed: to 45 m/s (147 ft/sec) 2.1 m high**
- **Uncertainties – 0.25% increasing to 2% at low speeds**

NASA's Requirements:
7.6 to 122 m/sec (25 to 400 FPS)

Alternate Point-Velocity Calibration Methodology

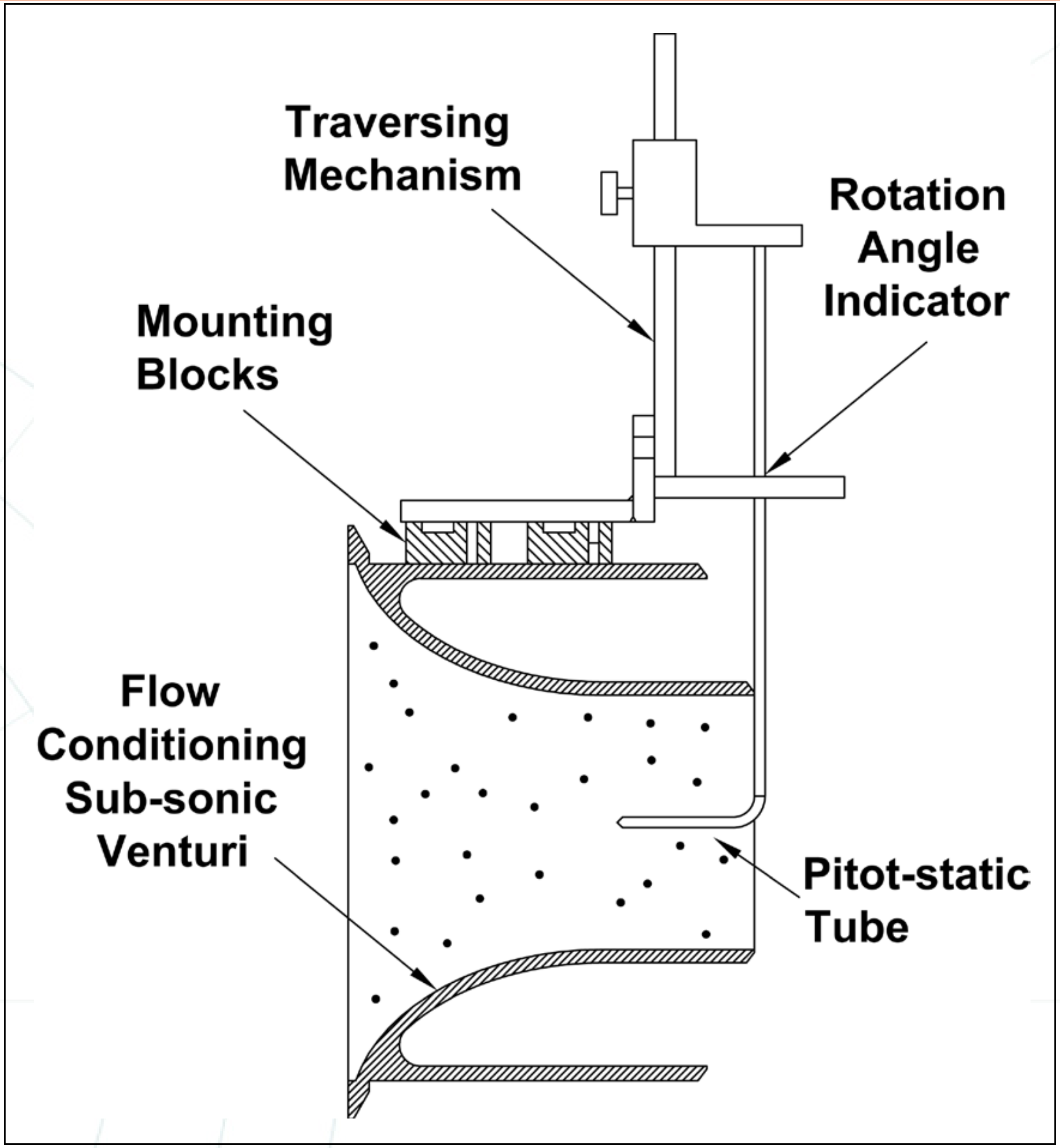


Test Configuration



The Hardware

The Hardware



Step-by-step Alternate Methodology

1. Determine the mass flowrate ($\dot{m}$) from an upstream NIST traceable flow standard.
2. Determine the gas density (ρ) at the calibration location from temperature and pressure measurements.
3. Divide the mass flowrate by the gas density and the throat area (A_{throat}) of the sub-sonic venturi to determine the bulk (average) velocity in the calibration location.

$$V_{Average} = \frac{\dot{m}}{\rho \cdot A_{throat}}$$

4. Correct the average velocity by the projected area of the Pitot-static tube. Note, this does not include the Pitot-static's stem area.

$$V_{Ave-corrected} = V_{Average} \cdot \frac{A_{throat}}{(A_{throat} - A_{Pitot})}$$

Step-by-step Alternate Methodology

5. Using an uncalibrated Pitot-static tube, perform a pitot traverse at the calibrating velocity ranges, while monitoring the flow standard. Apply the equation below to determine individual velocities at each traverse location. If slight variations occur in the flowrate during the pitot traverse, the velocities can be normalized by multiplying by the average mass flow rate during the testing, and by dividing the mass flowrate during the individual traverse point as shown below.

$$V_i = N \cdot K_{initial} \sqrt{\frac{h_{w-i}}{\rho_i}} \left(\frac{\dot{m}_{average}}{\dot{m}_i} \right)$$

Step-by-step Alternate Methodology

6. Determine a Profile Factor (PF) that relates the average velocity in the throat of the sub-sonic venturi to the velocity in the center. Notice how the initial Pitot-static flow coefficient ($K_{initial}$) drops out of the equation.

$$PF = \frac{N \cdot K_{initial}\sqrt{\frac{h_{w-center}}{\rho_{center}}}\left(\frac{\dot{m}_{average}}{\dot{m}_{center}}\right)}{N \cdot K_{initial}\frac{\sum\left[\sqrt{\frac{h_{w-i}}{\rho_i}}\left(\frac{\dot{m}_{average}}{\dot{m}_i}\right)\right]}{n}} = \frac{\sqrt{\frac{h_{w-center}}{\rho_{center}}}\left(\frac{\dot{m}_{average}}{\dot{m}_{center}}\right)}{\frac{\sum\left[\sqrt{\frac{h_{w-i}}{\rho_i}}\left(\frac{\dot{m}_{average}}{\dot{m}_i}\right)\right]}{n}}$$

Step-by-step Alternate Methodology

7. Profile Factors (PF) can be calculated for different velocities, and curve fit to different Throat Reynolds Numbers.

$$PF = f(Re_{throat})$$

8. The Point Velocity Device can be inserted into the center of the sub-sonic venturi, and its flow coefficient can be determined by the following equation.

$$K = \frac{PF}{N \cdot (A_{throat} - A_{Pitot})} \cdot \frac{\dot{m}}{\sqrt{\rho \cdot h_w}}$$

Experimental Results

- Three Pitot-static tubes were tested using the Alternative Methodology.
- The Pitot-static tubes were positioned in the center of the nozzle, and tested from 10 to 115 m/sec.
- The percent deviation between the experimentally determined flow coefficients (K) and theory was determined where:

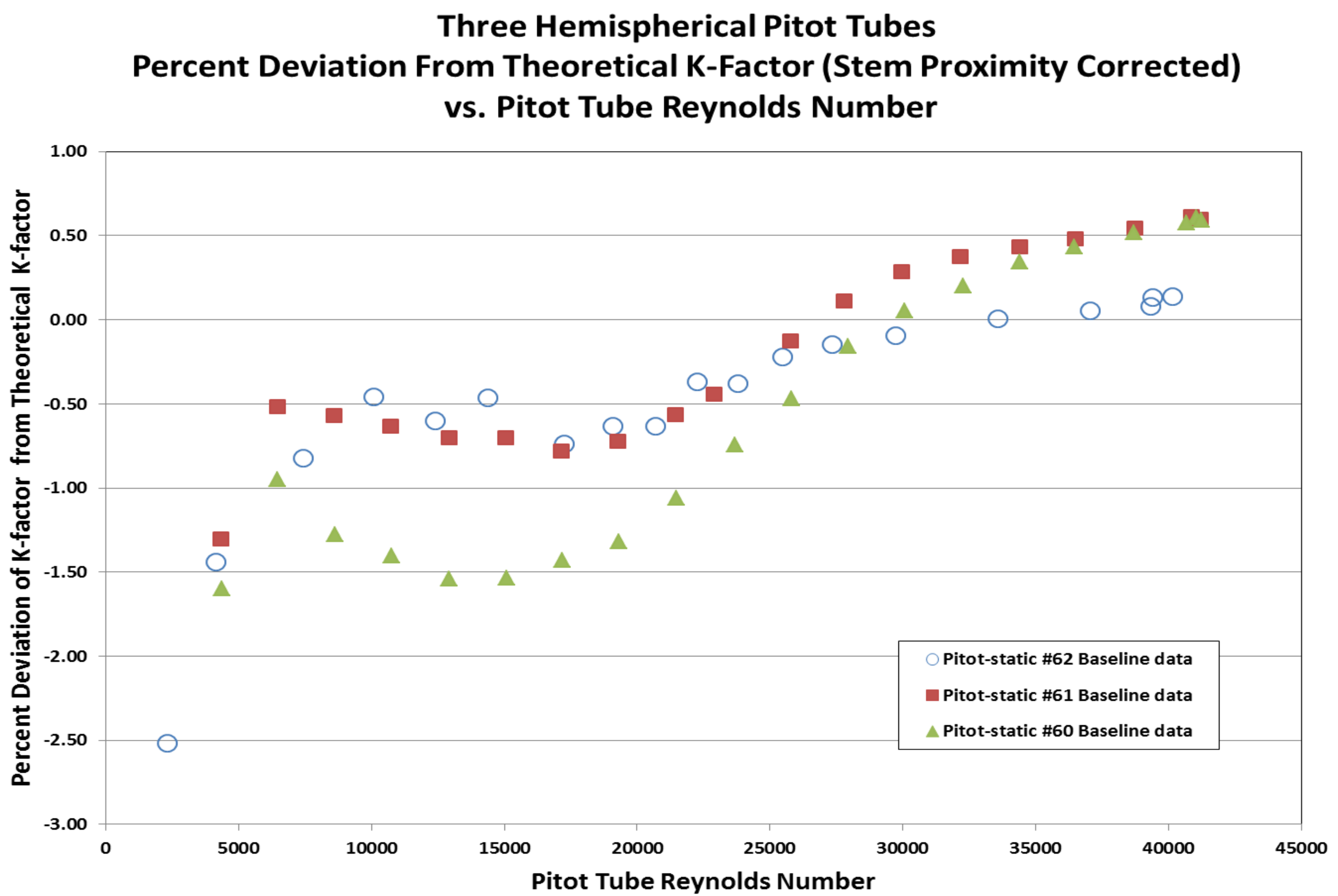
$$K_{theory} = \left\{\left(\frac{\gamma}{\gamma - 1}\right)\left(\frac{P_1}{P_{t-}P_1}\right)\left[\left(\frac{P_t}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]\right\}^{\frac{1}{2}}$$

Experimental K-factors vs. Theory

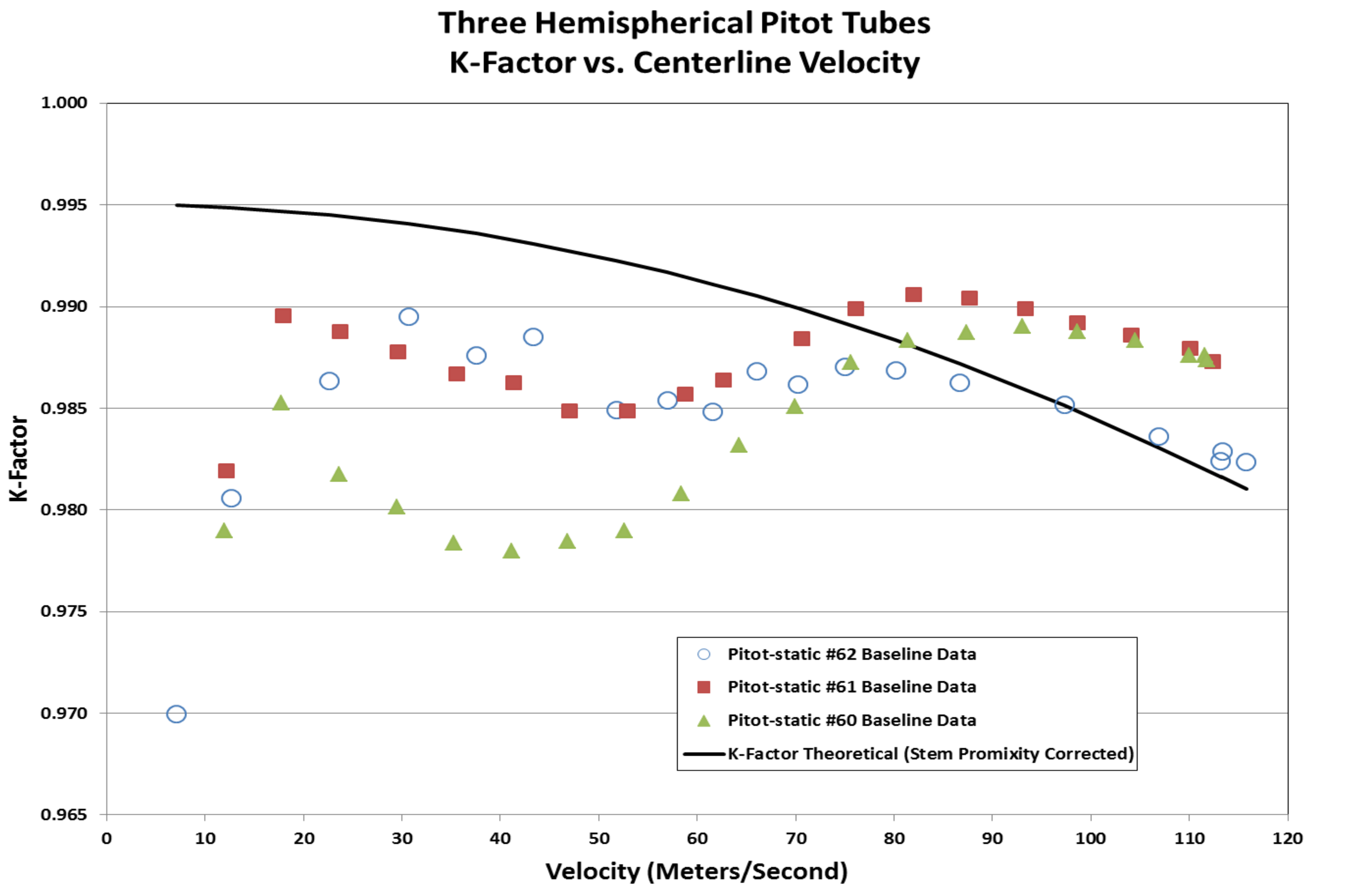
Summary of the Percent Deviation between Experimentally determined Flow Coefficients and Theroetical Flow Coefficients		
Pitot-static Tube No.	Perent Average Deviation*	Percent Standard Deviation*
#60	-0.5	0.84
#61	-0.2	0.58
#62	-0.5	0.62
Averages:	-0.4	0.7

* Over the entire velocity range tested

K-factor vs. Pitot Tube Reynolds Number



K-Factor vs. Velocity



Uncertainty

The following equation was used to determine the Pitot-static Tube's flow coefficient (K) uncertainty.

$$\frac{U_e(K)}{K} = \sqrt{\left[\left(\frac{\partial K}{\partial \dot{m}}\right)\frac{U(\dot{m})}{\dot{m}}\right]^2 + \left[\left(\frac{\partial K}{\partial V_{pf}}\right)\frac{U(V_{pf})}{V_{pf}}\right]^2 + \left[\left(\frac{\partial K}{\partial P_1}\right)\frac{U(P_1)}{P_1}\right]^2 + \left[\left(\frac{\partial K}{\partial T_1}\right)\frac{U(T_1)}{T_1}\right]^2 + \left[\left(\frac{\partial K}{\partial h_w}\right)\frac{U(h_w)}{h_w}\right]^2}$$

Where:

$\dot{m}$=mass flow rate from the Critical Flow Venturi, pounds-mass/sec

V_{pf}= Velocity profile factor in the sub-sonic venturi

P_1= Static pressure in the sub-sonic venturi, psia

T_1= Absolute sub-sonic venturi temperature, °R

h_w = Differential pressure produced by the Pitot-static tube, "H_2O

Uncertainty

Applying the appropriate sensitivity coefficients the equation above yields.

$$\frac{U_e(K)}{K} = \sqrt{\left[\frac{U(\dot{m})}{\dot{m}}\right]^2 + \left[\frac{U\left(V_{pf}\right)}{V_{pf}}\right]^2 + \left[\frac{1}{2}\frac{U(P_1)}{P_1}\right]^2 + \left[\frac{1}{2}\frac{U(T_1)}{T_1}\right]^2 + \left[\frac{1}{2}\frac{U(h_w)}{h_w}\right]^2}$$

Applying the test uncertainties the equation above yields.

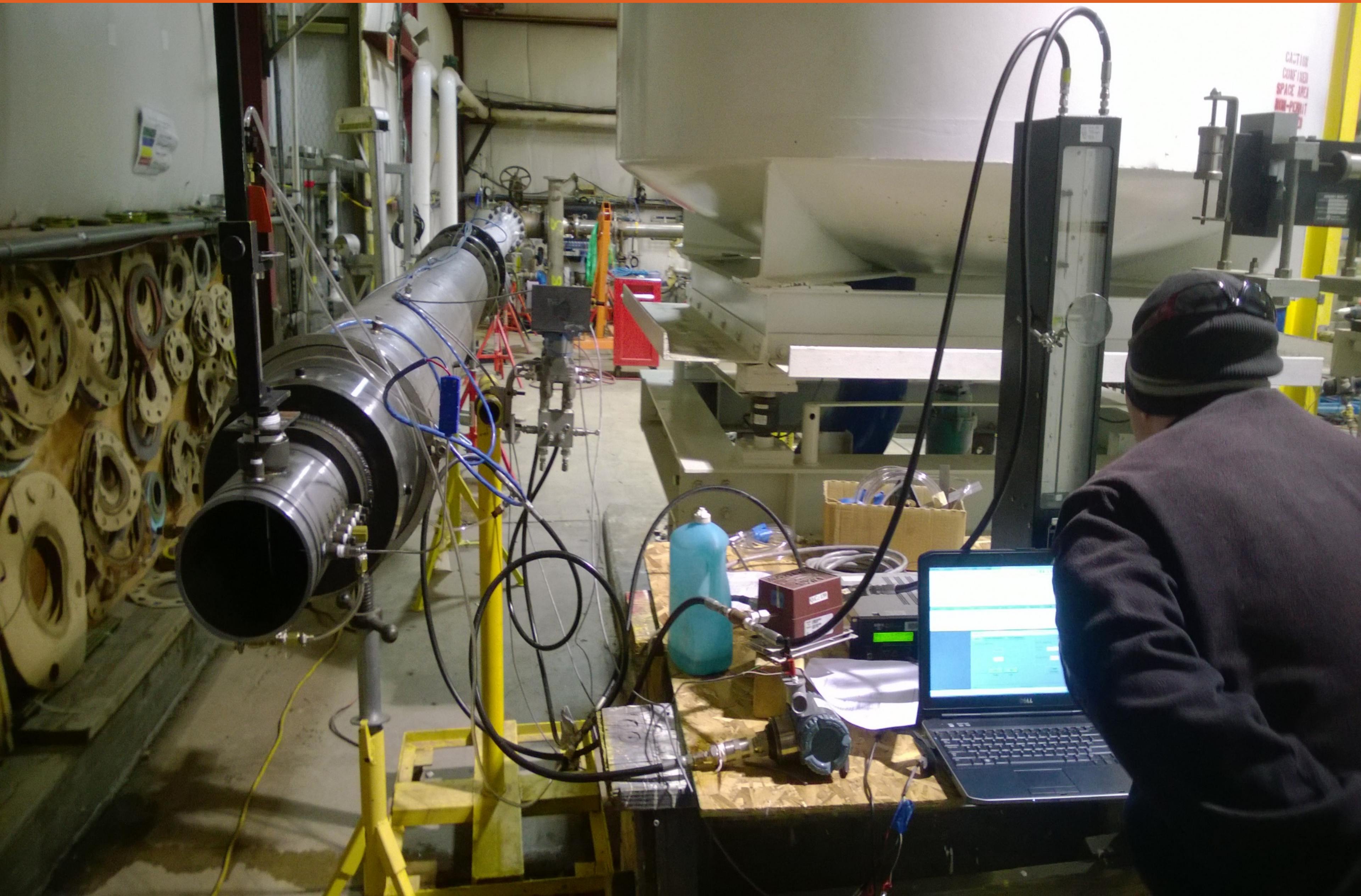
$$\frac{U_e(K)}{K} = \sqrt{[0.35]^2 + [0.1]^2 + \left[\frac{1}{2}\cdot 0.1\right]^2 + \left[\frac{1}{2}\cdot 0.1\right]^2 + \left[\frac{1}{2}\cdot 1.0\right]^2} = 0.62\%$$

The expanded uncertainty of the Pitot-static flow coefficient (K) at two-sigma is 1.24%

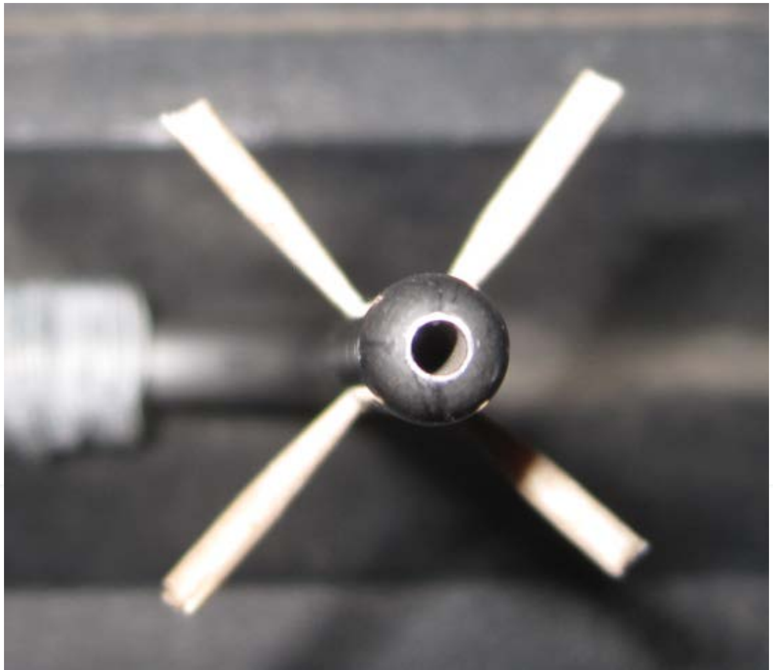
Results

- Individual averages of all three experimentally determined flow coefficients were within the estimated uncertainty of 0.62% at one sigma of the theoretically calculated flow coefficient.
- Flow coefficient deviations were likely a result of imperfections in the Pitot-static tube’s surfaces and geometry, and the turbulence levels during testing.
- Better uncertainty could be achieved using more accurate DP transducers which contributed greatly to the uncertainty budget.
- ±0.5% DP transducers would have produced a 0.9 % uncertainty at two sigma.

Similar Testing (Added a Throat Extension)



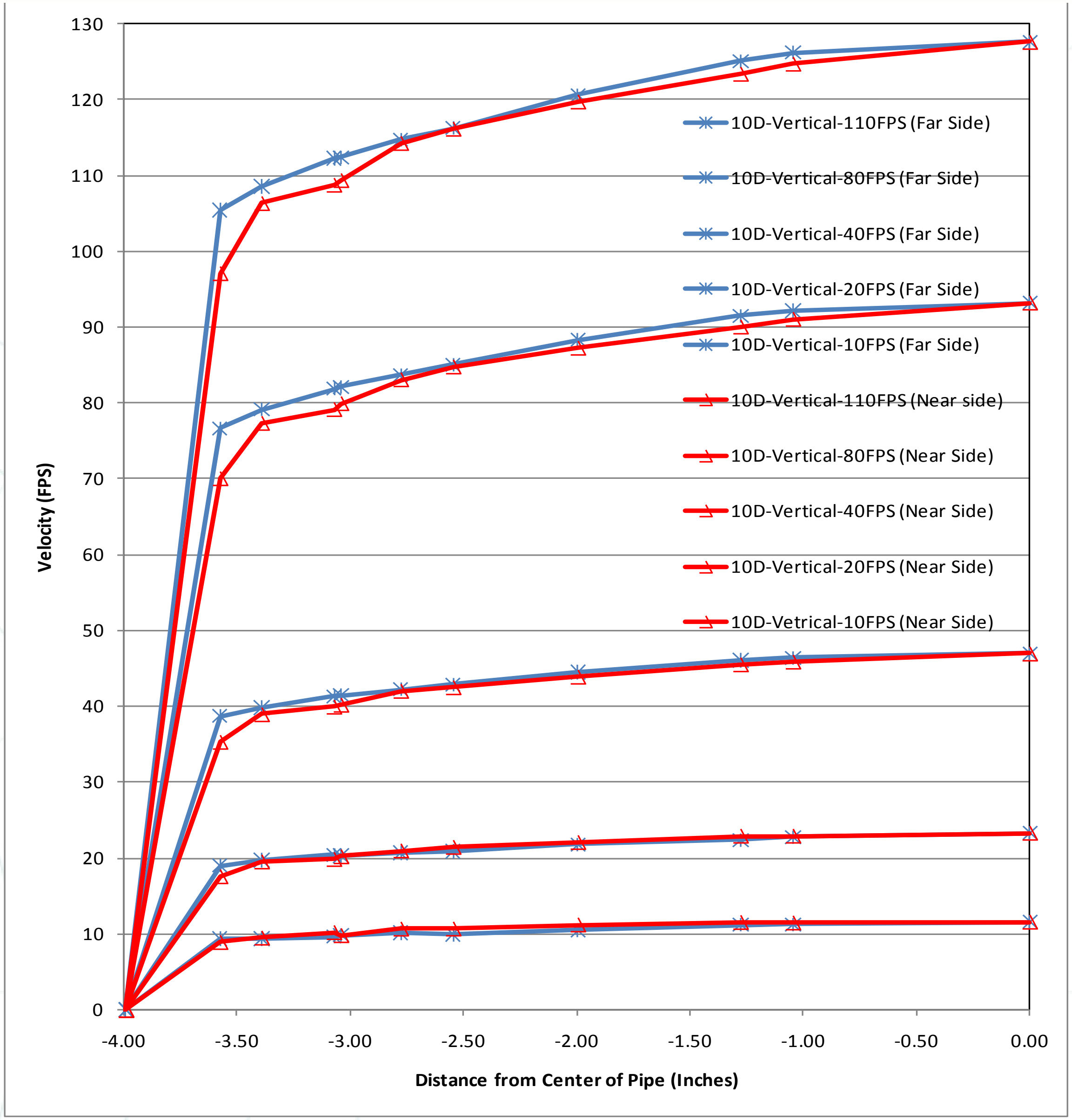
Extended Throat & Close-up of Pitot Tubes



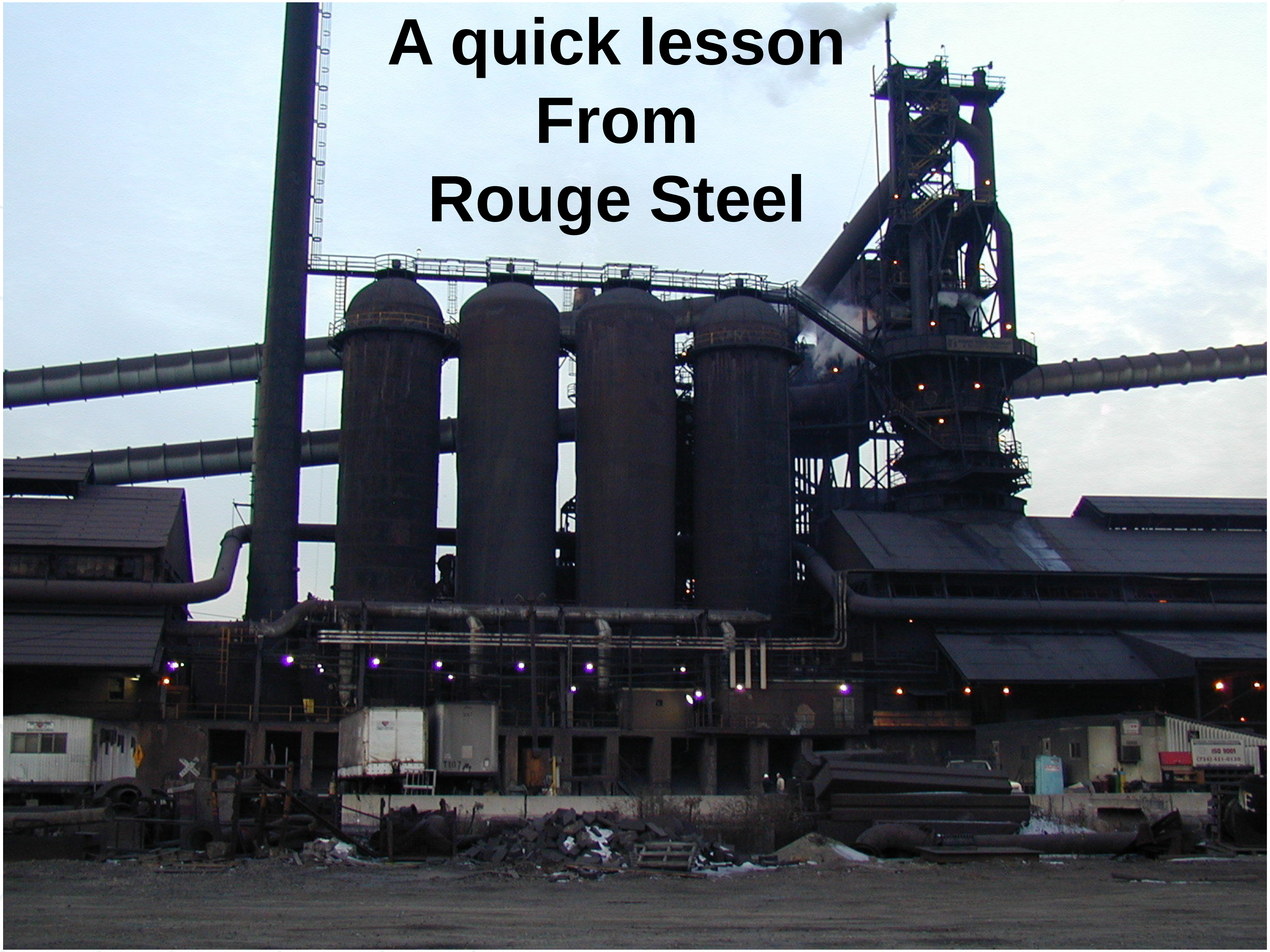
Checking For Leaks

Checking For Leaks

Don't Forget about Blockage



Stack Flow Measurement



Flare Gas

Stack Flow Measurement

Stack Flow Measurement

Stack Flow Measurement

Questions?

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