Balanced Flow Metering and Conditioning Technology for Fluid Systems (Space Liquid Propulsion Systems) for 2006 Instrumentation Symposium for the Process Industries

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Large Rocket Engine Environments

- Very hot (~6000°F)
- Extreme cold (~ -400°F)
- Vibration
- Volatile fluids (liquid oxygen, etc.)
- High pressures (~7,000 psi.)
- Extreme fluid velocities (flow rates, Reynold's numbers > 10^7)
- Fast control loops and failure propagation (<3 seconds to full destruction)
- Industry seldom operates in these regimes

- One failed ground test (turbine meter) ~$200M impact

Problem

- Turbine failure resulted in no LOX flow meter for flight hardware
- Need safe flow metering technology for liquid rocket engines
- Failed past attempts
  - Turbines (work, but severe failure)
  - Vortex shedders
  - Ultrasonic
  - Venturi Tubes (work, but too large for flight)
  - Etc.

NASA Flow Meter Requirements

- Different fluids: LH2, LOX, RP1, etc.
- Different physical states: Gas, Liquid, Multi-Phase
- Wide range (both high and low) in temperature, pressure, vibration and flow conditions
- Very low flow intrusion with near full pressure recovery
- No moving parts
- Minimal piping requirements
- Drop-in replacement of an orifice-plate
- Robust mechanical design
- Highly accurate and repeatable flow measurement
- Easy calibration and maintenance
- Need for high through-put flow areas with low flow restriction

Most needs are common with industrial needs…

Balanced Flow Meter Solution

- NASA patented technology #10/750,628
- Allows engine measurements where none were before
- Ability to condition or measure flow while improving velocity or other profiles
- Provides flow measurement, conditioning, and controlled restriction performance
- Ability to function with minimal straight pipe run
- Measure mass flow rates, fluid volumetric flow rates and density simultaneously
- Sensor set up can provide a triple redundant measurement system
- Successfully fielded by industry

Possible configuration…

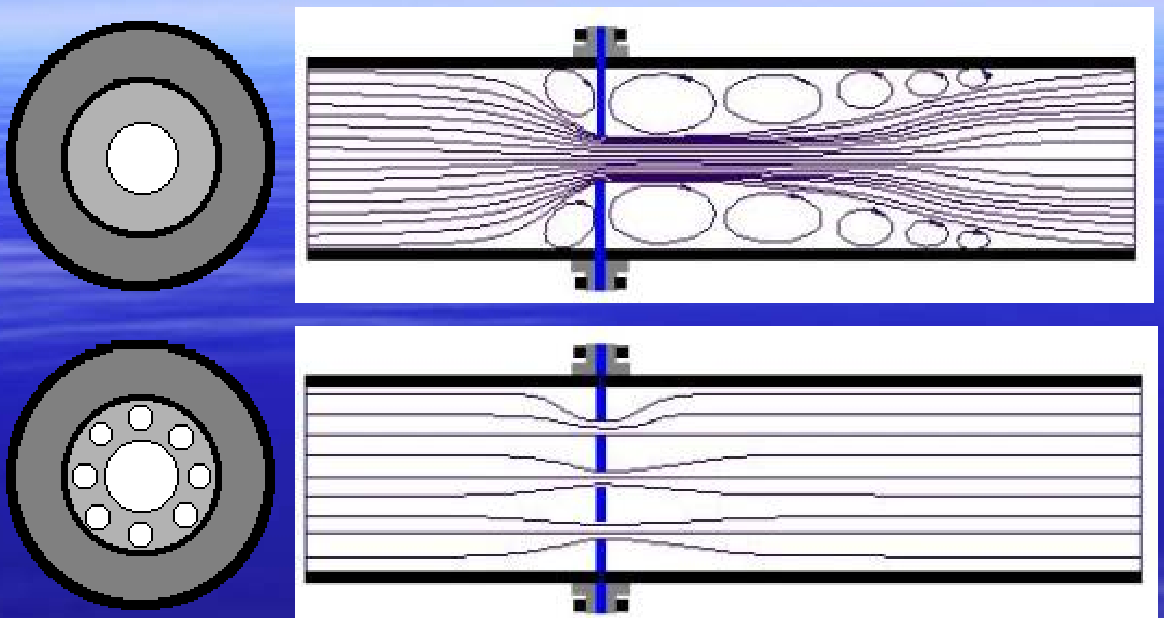
- Beta = 0.9
- 7.5” NDP
- Diff. pressure rated at 150 psi

What is Balanced Flow Technology?

- A thin, multi-hole orifice plate with holes sized and placed per a unique set of equations to produce mass flow, volumetric flow, kinetic energy, or momentum BALANCE across the face of the plate

Chevron-Texaco 18 inch Commercial Plate

How Does It Perform?



Comparison of standard orifice to balanced flow meter, both with 27.1% open area

Results based on compressed gas testing

- 10X better accuracy
- 2X faster pressure recovery (shorter distance)
- 15X noise reduction
- 2.5X less permanent pressure loss
- Exclusively licensed through NASA by A+FlowTek for commercialization

Configurations Tested in 2004


Figure 1 Slotted Configuration

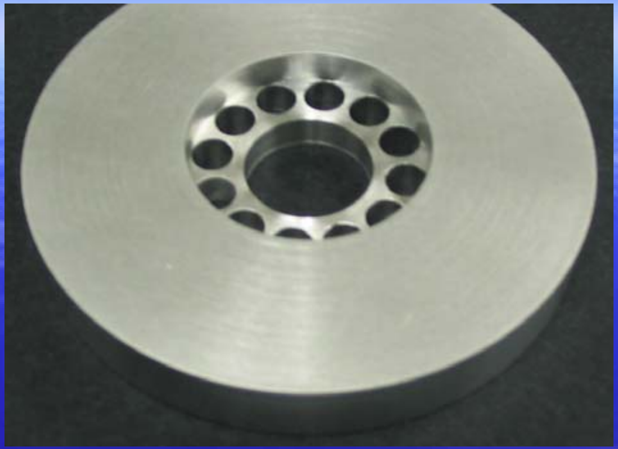


Figure 3 Single Ring of Holes Configuration

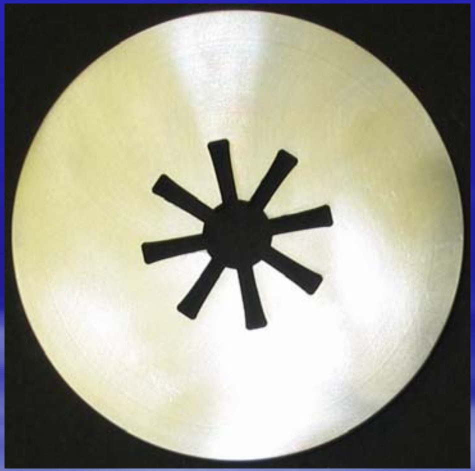


Figure 2 Iron Cross Configuration

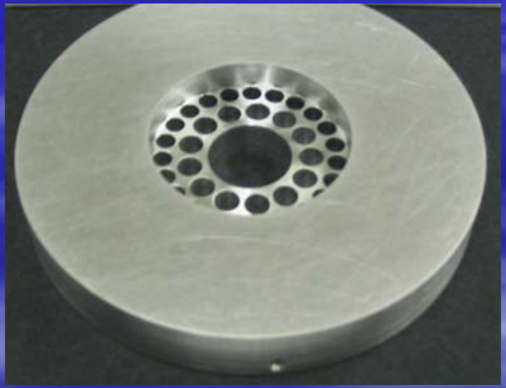


Figure 4 Custom Hole Configuration

Permanent pressure loss, accuracy and discharge coefficient comparable with a Venturi meter!

Balanced Flow Meter Characteristics

- Minimal straight pipe run requirements—BFM has less than 0.5 X pipe diameter straight pipe requirement
- Only requires 0.25 to 0.5 inch thickness and approximately 3 PSI across the plate to condition and monitor flow
- Relatively low cost to build and operate
- Accuracy comparable to Venturi meters

- Cons—similar limitations as standard orifice
  - Not good for pulsing flow
  - Limited turn down
- Testing methods based on American Petroleum Institute (API) Manual of Petroleum Measurement Standards 5.7

How Does it Work?

- **Basic design based on multi-hole orifice plate**
- **Basic relation is the Bernoulli equation**
  - **Requires custom Cd calculation**
  - **Long for Bernoulli equation required for high accuracy applications**
  - **Highest accuracy applications require physical properties models**
- **Flow proportional to SQRT of delta P**

Key design factor is the hole distribution

Technical Basis—BFM Hole Layout

- **Plate hole layout basic equation**

$$\kappa\rho AV^n = \text{Constant for each hole} =$$
$$(\kappa\rho AV^n)_1 = (\kappa\rho AV^n)_2 = \ldots = (\kappa\rho AV^n)_I$$

At $\kappa_1\rho_1 \sim \kappa_i\rho_{I,}$

$$A_i/A_1 = (V_1/V_i)^n$$

To simplify, let n = 1

$$A_i/A_1 = V_1/V_i$$

- **Example, given a velocity distribution function**

$$V_r/V_{max} = (1 - R_r/R_{wall})^{1/7}$$

- **Radial velocity ratios**

$$V_1/V_i = ((1 - R_1/R_p)/(1 - R_i/R_p))^{1/7} = A_i/A_1$$

Nomenclature:

- κ: fluid flow correction factor
- ρ: density of fluid
- A: sum of areas at given radius
- V: fluid velocity at radius r
- b: selected balancing constant
- Vmax: velocity at r=0, pipe center
- Rwall: velocity at pipe wall

Technical Basis—BFM Hole Layout Cont.

- **Subsequent radial areas**

$$A_i = A_1((1 - R_1/R_p)/(1 - R_i/R_p))^{1/7}$$

- **Radial area equation**

From $\beta^2 = A_{total} / A_{pipe}$

And multiple holes,

$$A_0 + A_1 + A_2 + \ldots\ldots + A_n = A_{total} = \beta^2 A_{pipe}$$

- **Hole diameters at radius i**

$$D_i = (4A_i/\pi N)^{1/2}$$

Sheer stresses typically lower than standard, single-hole orifice!

Tech Basis-Bernoulli Equation

- **Bernoulli Equation—longer form**

$$(P_a - P_b)/\rho + g(Z_a - Z_b)/g_c + (\alpha_a V_a^2 - \alpha_b V_b^2)/2g_c - h_{fb} = 0$$

- **Equation of Continuity**

$$(\rho AV)_a = m = (\rho AV)_b$$

- **Simplified Bernoulli Equation—assume constant density (incompressible), frictionless fluid (zero viscosity), and no elevation changes**

$$(P_a - P_b)/\rho + (V_a^2 - V_b^2)/2g_c = 0$$

- Equations from ISO 5167-1, API 14.3.1, etc. Derivations in multiple texts.

Tech Basis-Bernoulli Equation

- Beta area ratio

$$(\beta)^2 = A_b/A_a$$

- **Flow Equation**

$$m = C_D Y A_b(2g_c\rho_a(P_a - P_b)/(1 - \beta^4))^{1/2}$$

- **There can be longer equation forms with many other factors, such as expansion factors, compressibility factors, meter correction factors, etc.**

Typical Uncertainties

- **Gas Flow: +/- 0.67% (API 14.3.1)**
- **Liquid Flow: +/- 0.57% (API 14.3.1)**
- **Spec values are EXTREMELY conservative**

BFM Lab Accuracies

- **+/- 2% without calibration**
- **+/- 1.0% long equation**
- **Calculated +/- 0.1% custom equation, calibrated**
- **BFM calculated value: +/- 0.25% (Directly measured)**

MSFC Water Calibration Facility

- National Institute of Standards and Test (NIST) certified
- Volumetric system
- 5000 gallons
- Pump or gravity fed
- Quad deionized water
- 0.25% flow accuracy over unit of time between level sensors
- 0.15% repeatability at given flow set point

MSFC Gas Calibration Facility

- Positive displacement, inverted cylinder system
- NIST certified
- Multiple gases including N, He, Air, Argon, Freon
- 0.01 to 3000 psi operation
- .01 to 400 SCFM
- Accuracy & repeatability???

Cd and K Factor Comparisons

Balanced Flow Meter plate performance,

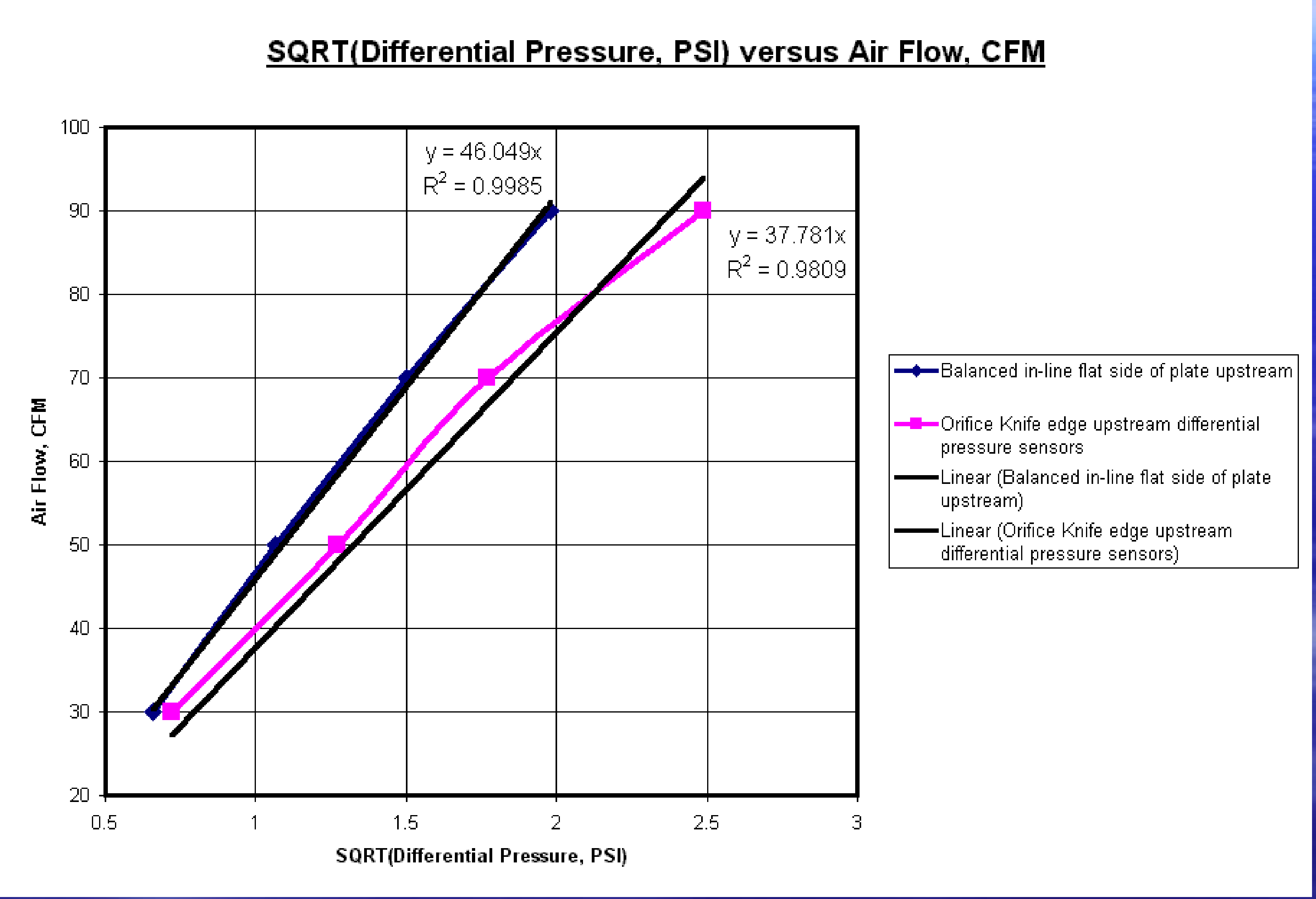
from minimum flows to sonic

BETA	0.25	0.500	0.521	0.650	0.500,fouled	0.500,elbow
Avg Cd	0.892	0.882	0.881	0.911	0.824	0.848
Cd Dev	0.032	0.001	0.009	0.010	0.038	0.008
Avg K Val	287.1	16.3	13.2	4.0	15.65	18.63
K Dev	20.8	0.60	0.53	0.16	1.23	0.38

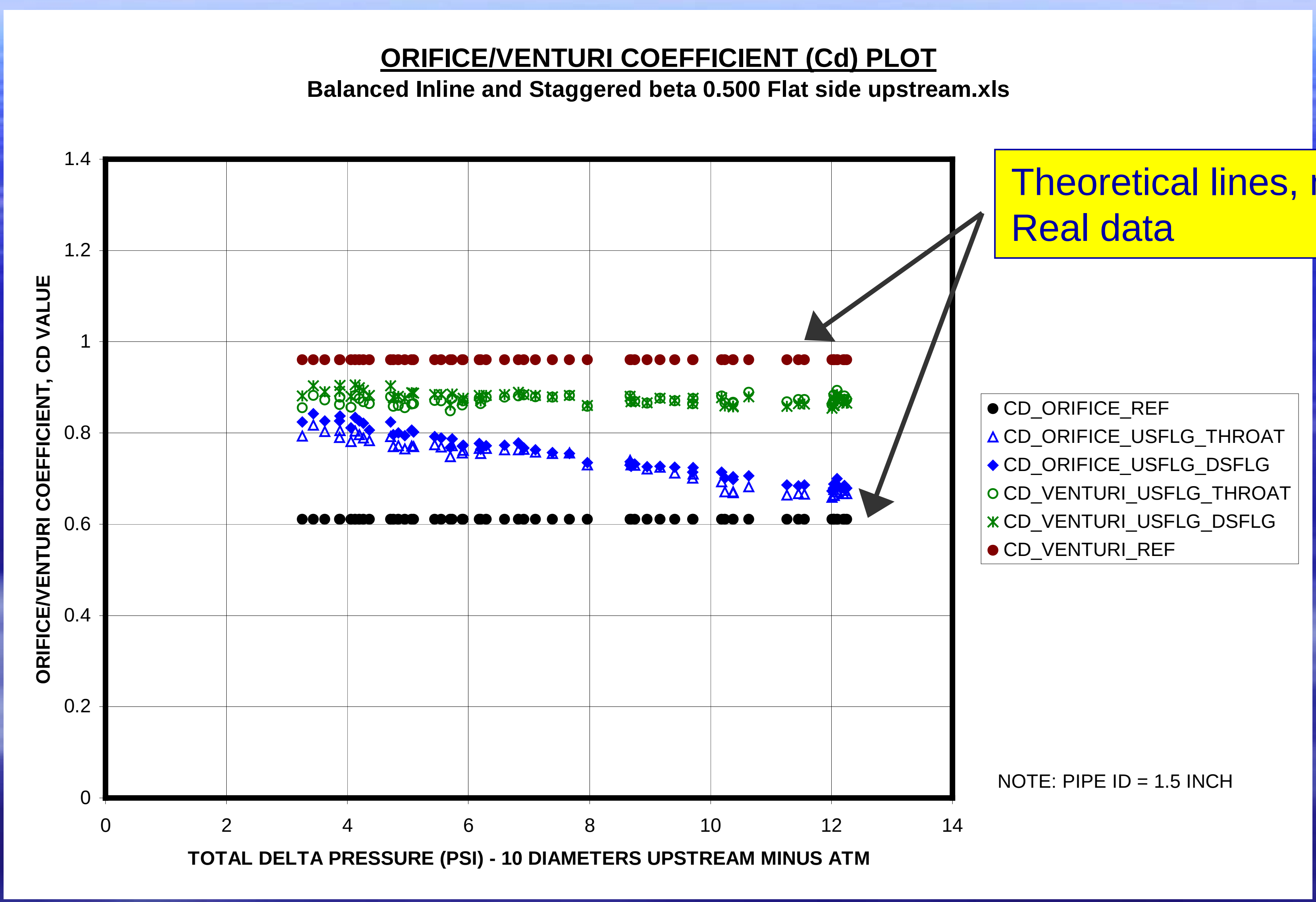
BETA	0.25	0.500	0.521	0.650
Venturi K, Cd=0.96	134.2	5.8	4.7	1.3
Venturi K, Cd=0.80	255.9	12.9	10.7	3.5
BFM K	287.1	16.3	13.2	4.0
Orifice K	669.4	31.5	25.7	7.4

Note: Venturi values do not include downstream losses.

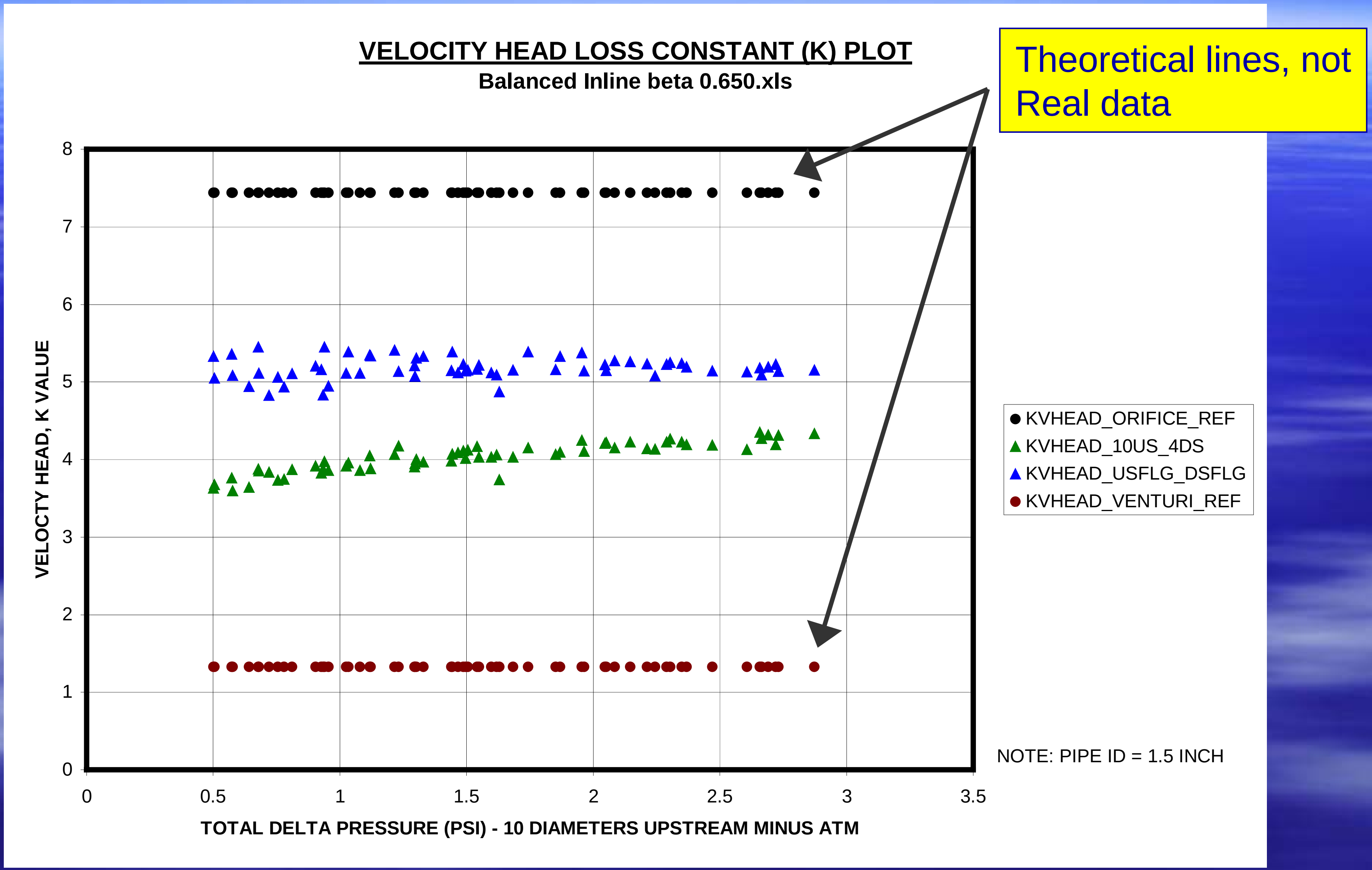
BFM vs. Orifice Flow Equation



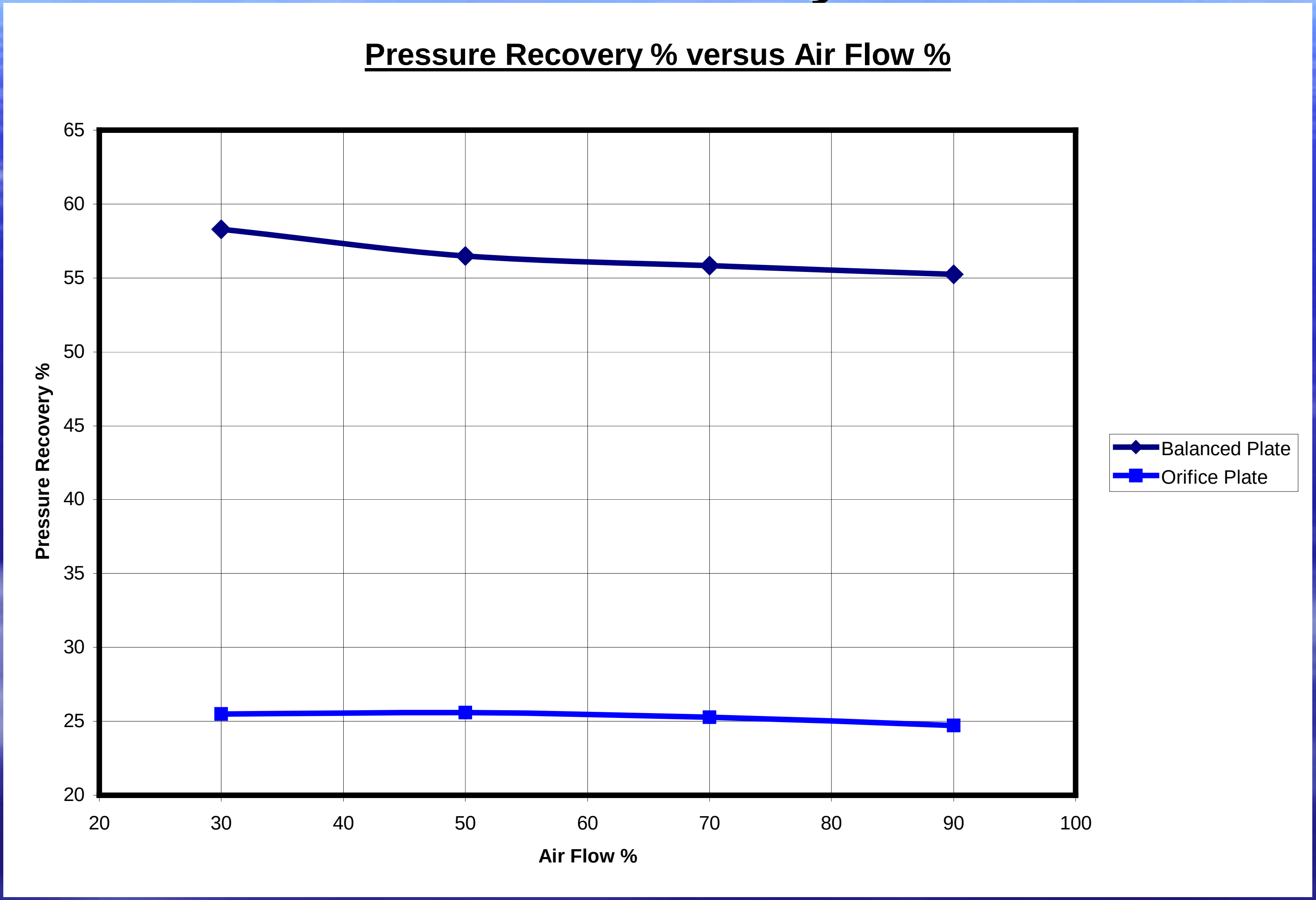
BFM Calibration Cd



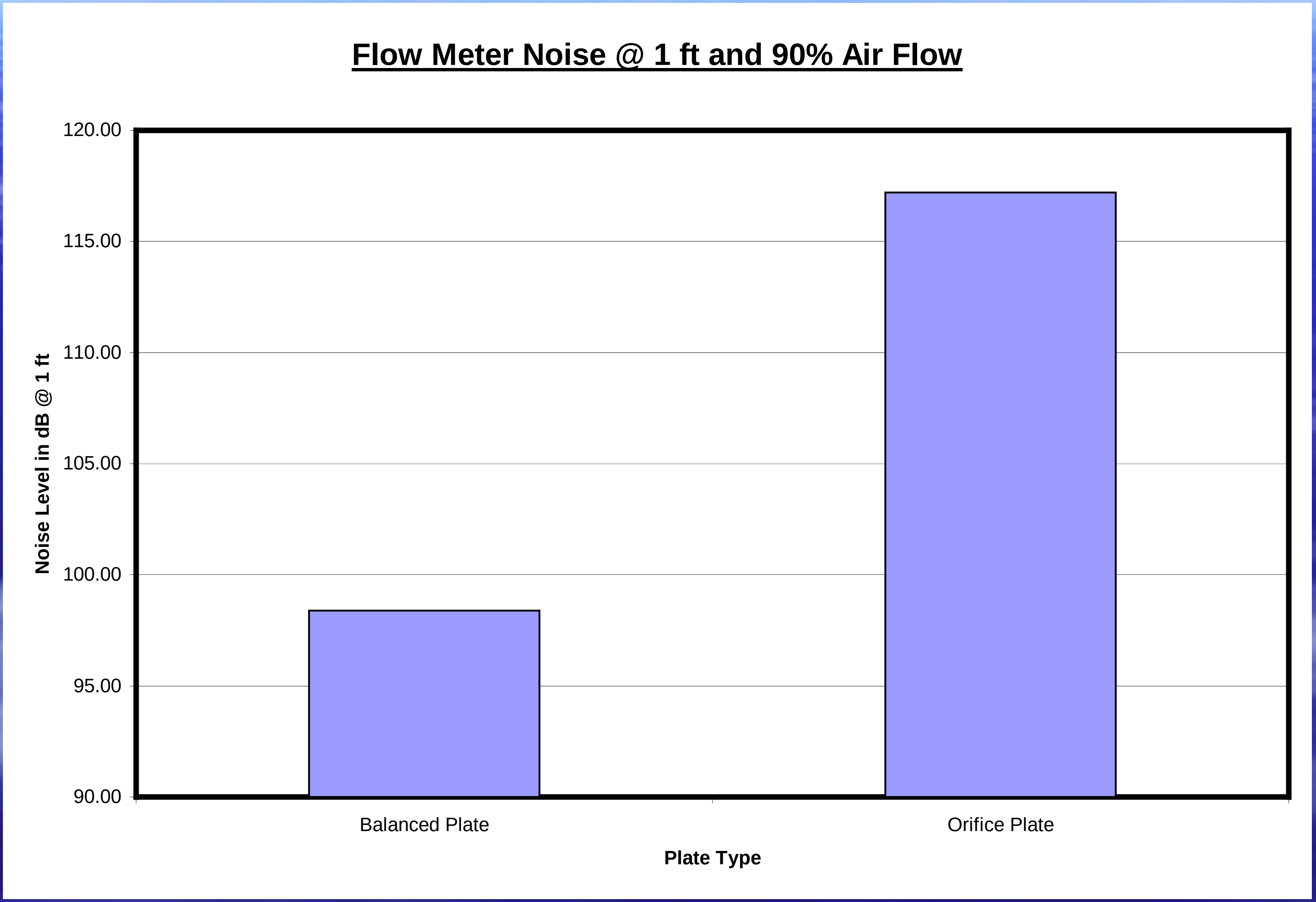
BFM K Factor Plots



BFM vs. Standard Orifice Pressure Recovery



BFM vs. Orifice Acoustic Noise



Why Does This Matter?

- Believe will meet NASA liquid engine flow meter requirements—test program on-going
- Provides safe, rugged, robust flow meter
- Provides drop-in orifice meter replacement
- Increases fluid system efficiency to save $$$
- Provides multiple benefits with relative low-cost
  - Reduced piping requirements
  - Reduced noise generation (EPA regulations)
  - No moving parts, simple design
  - Capable of simultaneous fluid metering and flow profile conditioning
  - Robust calibration—well defined and characterized traditional techniques
  - Typical +/- 0.15% accuracy of measured flow throughout measurement range
  - Reduced pump energy requirements
    - High pressure recovery
    - Low permanent pressure loss

Lessons Learned

- Always double check flow meter vendor claims, flow equations, and calibration techniques
- There are hundreds of emerging flow metering technologies—stringently define your unique requirements
- Determine best calibration method for your application—in-situ system level calibration vs. typical individual component calibration
- Test/Calibrate as you intend to use the meter—If possible, test your new meter!
- Follow standards for instrument placement, uncertainties, etc., but not for plate thickness!

Useful References

- The Consumer Guide to Differential Pressure Flow Transmitters by David W. Spitzer and Walt Boyes, Published by Copperhill and Pointer, Inc., ISBN 1-932095-03-9
- API Manual of Petroleum Measurement Standards 5.7, Testing Protocol for Differential Pressure Flow Measurement Devices
- API Manual of Petroleum Measurement Standards Ch. 14—Natural Gas Fluids Measurement, Section 3—Concentric, Square-Edged Orifice Meters, Part 1—General Equations and uncertainty Guidelines
- API Manual of Petroleum Measurement Standards Ch. 14—Natural Gas Fluids Measurement, Section 3—Concentric, Square-Edged Orifice Meters, Part 2—Specification and Installation Requirements
- ISO 5167-1 Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full, Part 1: General principles and requirements
- ISO 5167-1 Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full, Part 2: Orifice Plates
- The measurement, instrumentation, and sensors handbook, John G. Webster, CRC Press & IEEE Press

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