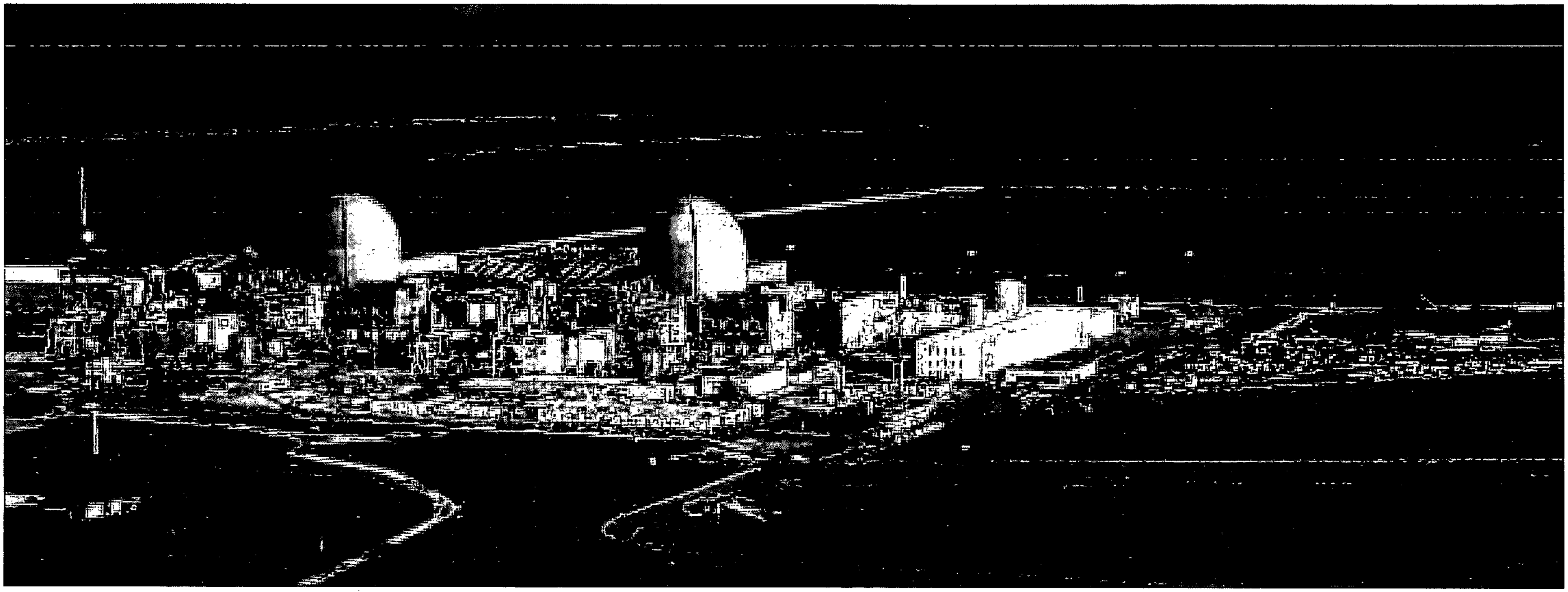
Caldon Ultrasonics



NRC Meeting at Alden Research Laboratory, Inc. Part 1

NON-PROPRIETARY

August 24, 2009

Agenda – Day 1

- Introductory Remarks 8:00 am – 8:15 am
- Tour of Lab with Special Emphasis on Facilities where Calibrations Tests are to be Run
- Description of the Analysis of the Uncertainties in the Lab Measurement (By ARL)
- History of LEFMs and Their Application to Power Plants
- The "Black Box"; How Chordal LEFMs work
- Calibrations Test in the Lab
- Laboratory Calibrations, Practice and Data
- Calibration Test for LaSalle Unit 2
- Witness Sample Data Collection – Preliminary Results (Lab)
- Questions and Answers Lab Tests
- Traceability and Uncertainties
- Summary, Questions and Answers (Day 1)

Agenda – Day 2

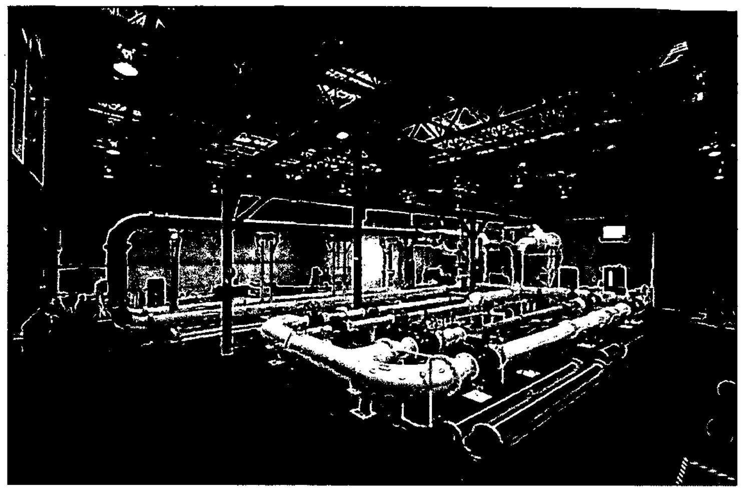
- Purpose and Scope of ER-157 and ER-80
- Summary of Changes to ER-157 Rev. 8
- Coherent Noise Treatment
- Transducer Placement Treatment
- Responses to Recent RAIs
- Reprise of Calibration Results to Date
- Configuration of LEFMs for New Plants
- LEFM Follow Up
- Questions and Answers, Meeting Wrap Up

Introduction to Cameron's Caldon Ultrasonic Technology Center

- Since 2006, Caldon has been part of Cameron's Valves and Measurement Group, Measurement Systems Division

- The Caldon Ultrasonic Technology Center is the center of excellence for ultrasonic technology located in Coraopolis, PA

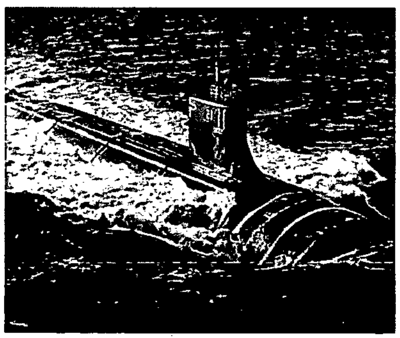
Caldon Ultrasonics Technology Center

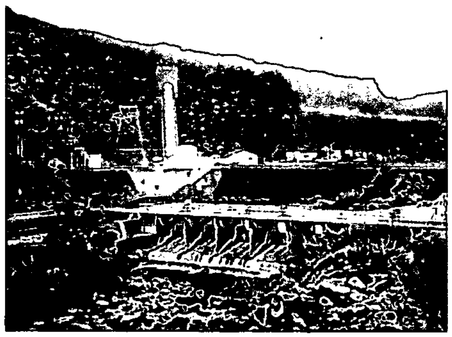


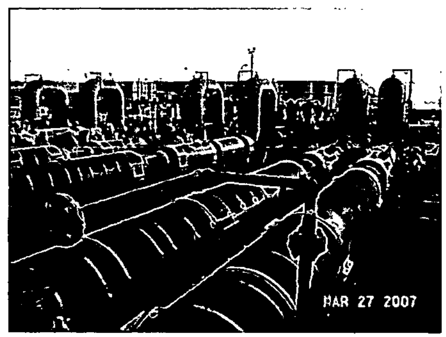
Oil Calibration Facility

Introduction to Cameron's Caldon Ultrasonic Technology Center

- From 1987 to 2005 Caldon was a privately held company
- In 1989 Caldon purchased the Leading Edge Flow Meter (LEFM) from the Westinghouse Oceanic Division
- From 1989 till the present, Caldon has continued and expanded the tradition that Westinghouse began in the early 1960's, of very accurate flow and properties measurements using LEFM technology in difficult and demanding applications





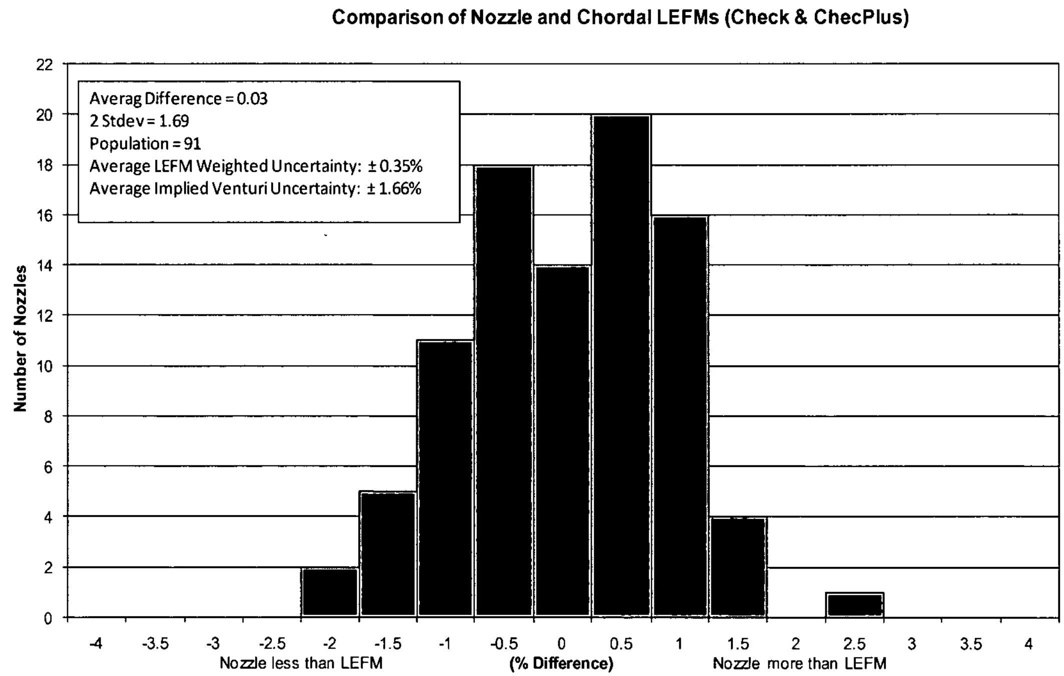


Power Plant Applications and History of LEFMs

- Per Pipe Summary:
  - 143 externals (tests and installations)
  - 35 4-Path chordal meters
  - 69 8-Path chordal meters
  - 4 8-Path chordal fossil meters

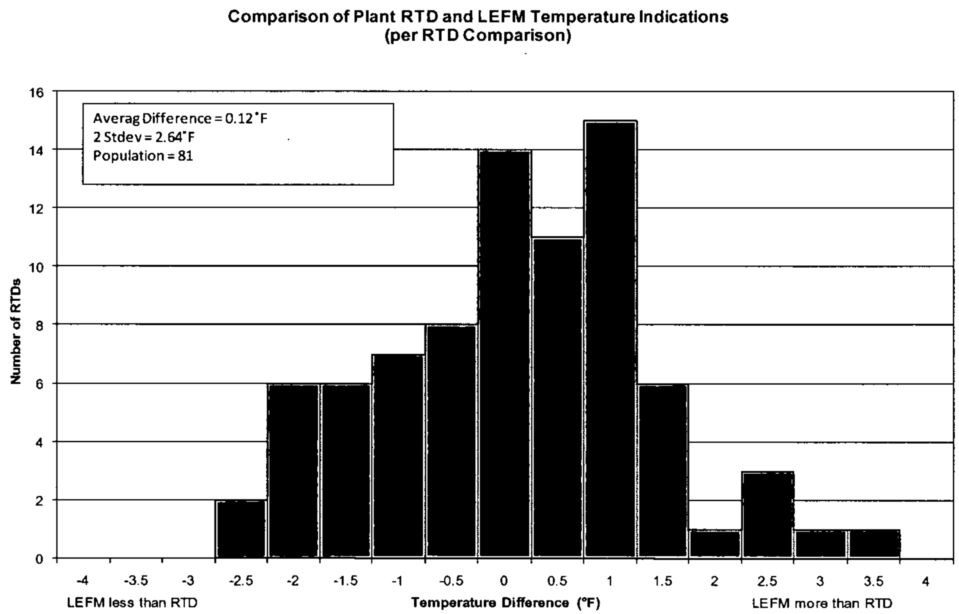
Power Plant Applications and History of LEFMs

- LEFM Check and LEFM CheckPlus Experience - Flow
  - 91 Comparisons
  - Average difference is 0.03%
  - 2 Standard deviations of the differences are 1.69%



Power Plant Applications and History of LEFMs

- LEFM Check and LEFM CheckPlus Experience – Temperature
  - 81 Comparisons
  - Average difference 0.12°F
  - 2 standard deviations 2.64°F



Power Plant Applications and History of LEFMs

- Observations
  - Assumption: LEFM Check and CheckPlus are ±0.5% and ±0.3% accurate
  - The MUR Uprate population suggests venturi accuracy is about ±1.6%
  - Yet there are cases of significant nozzle errors
    - Cofrentes (~1.9% error)
    - Beaver Valley (~1.5% error)
    - Tokai 2 (~2% error)
    - Salem 2, c. 1994 (~3.8% error)
  - The difference cannot be used to justify the accuracy of any of the meters
  - This kind of comparison gives only approximate knowledge of plant power
    - Must establish actual credentials of at least one of the meters we are comparing
  - The remainder of the presentation pertains to the traceable credentials of the LEFM Check and LEFM CheckPlus Systems used for MUR Uprates

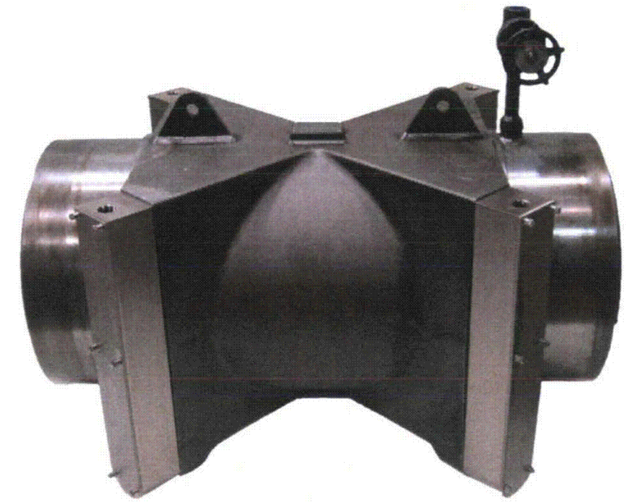
The Black Box: Chordal LEFMs and How They Work

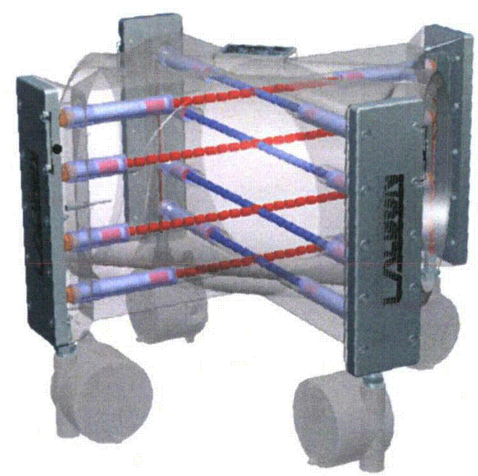
- LEFM Hardware
  - Flow element
  - Transducer housings
  - Transducers
  - Electronics

The Black Box: Chordal LEFMs and How They Work

Flow Element

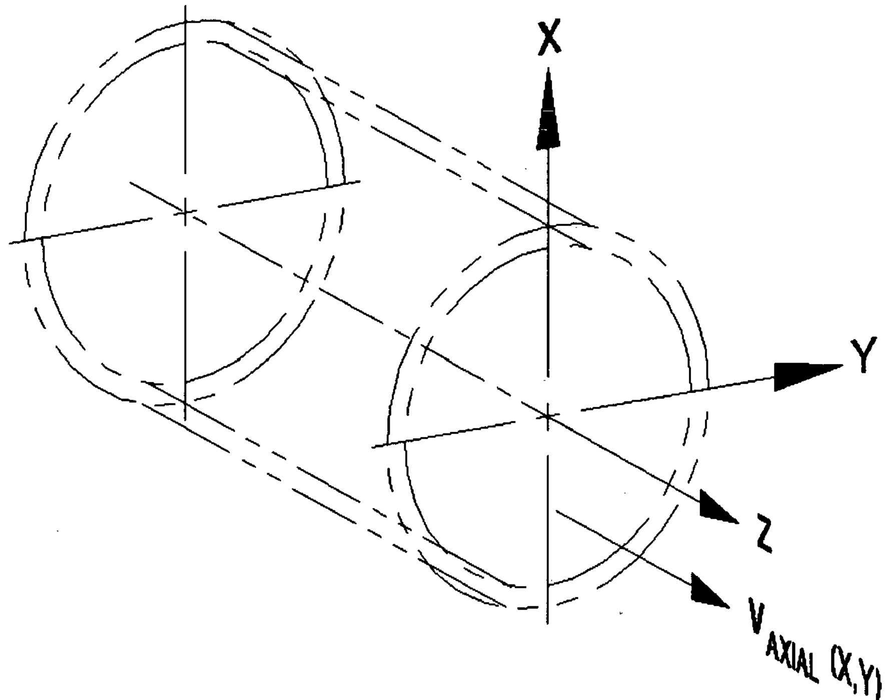
- Fundamentally, a chordal LEFM measures volumetric flow, then converts this measurement to mass flow using sound velocity and fluid pressure to determine fluid temperature and density. A CheckPlus accomplishes this by measuring the transit times of pulses of ultrasound along 8 chords





The Black Box: Chordal LEFMs and How They Work

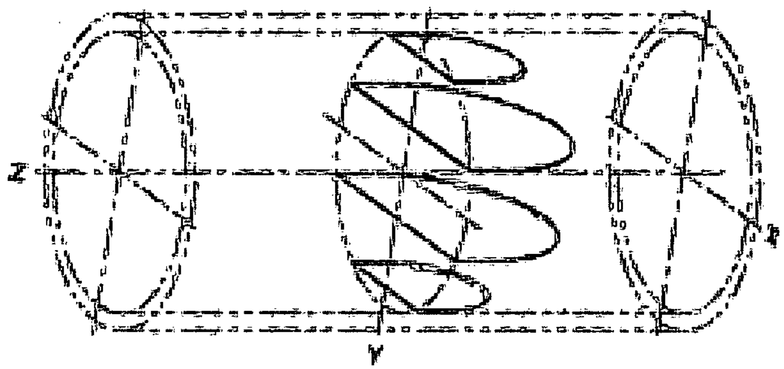
- The volumetric flow in a pipe is given by the integral of the axial velocity over the cross sectional area of the pipe



$$Q = \int V_{axial}(x, y)\,dx\,dy$$

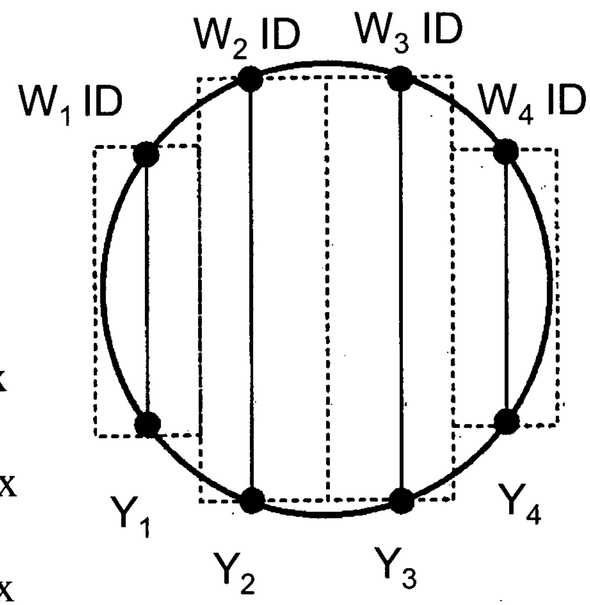
The Black Box: Chordal LEFMs and How They Work

- Chordal LEFMs perform this integration numerically, by measuring the integral of V(x) dx at four pre-selected y positions



At each y, pulse transit times measure ∫v(x) dx

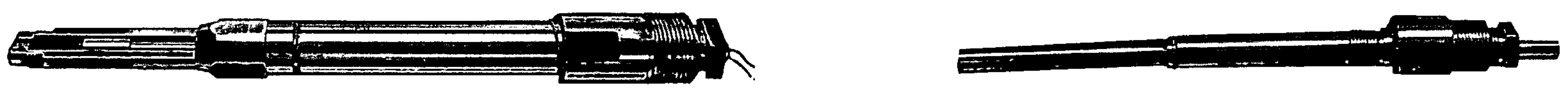
$$
\begin{aligned}
Q = {} & w_1, ID \int^{y_1} v(x)\,dx \\
+ {} & w_2, ID \int^{y_2} v(x)\,dx \\
+ {} & w_3, ID \int^{y_3} v(x)\,dx \\
+ {} & w_4, ID \int^{y_4} v(x)\,dx
\end{aligned}
$$



The Black Box: Chordal LEFMs and How They Work

Transducer Housings

- Pulses of ultrasonic energy are transmitted into the flowing fluid by transducers which are located in wells or housings which serve as a pressure boundary



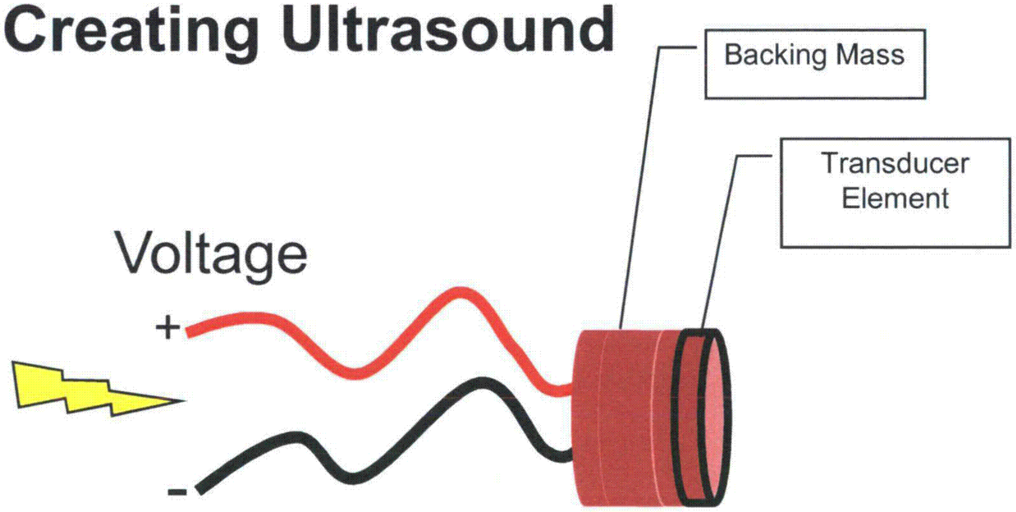
The Black Box: Chordal LEFMs and How They Work

Transducers

- Transducers transform electrical energy into mechanical energy and vice versa
- For nuclear applications transducer frequency is 1.6 megaHertz
- The transmitted pulses typically consist of three or four cycles of 1.6 megaHertz energy

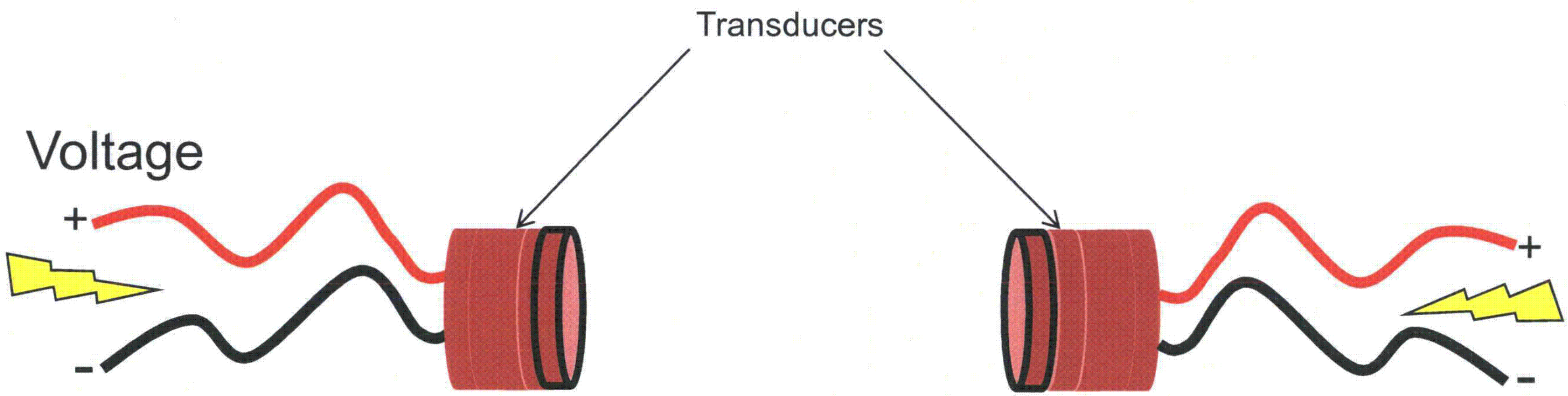
The Black Box: Chordal LEFMs and How They Work

Creating Ultrasound



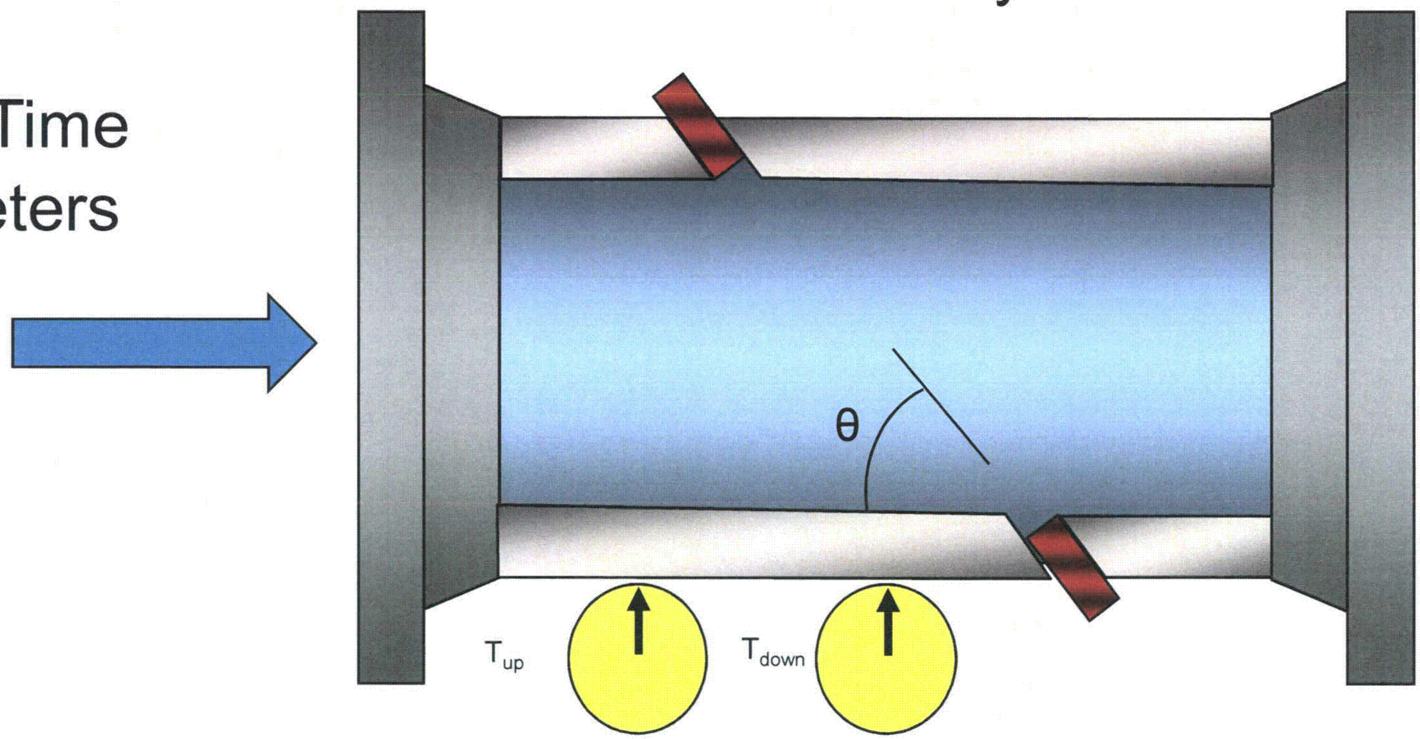
The Black Box: Chordal LEFMs and How They Work

Sensing Ultrasound



The Black Box: Chordal LEFMs and How They Work

Transit Time Flowmeters



The Black Box: Chordal LEFMs and How They Work

- The elapsed times of transiting pulses t_{down} and t_{up} measure two unknowns
  - V, the fluid velocity along the transmission path
  - C, the sound velocity in the fluid at rest

$$t_{down} = L_{path}/(C + V)$$

$$t_{up} = L_{path}/(C - V)$$

The Black Box: Chordal LEFMs and How They Work

- The transit time in the fluid is a function of the average sound velocity and the average fluid velocity projected onto the path

$$t_{down} = L_{path}/(C + V)$$

$$t_{up} = L_{path}/(C - V)$$

$$t_{up}t_{down} = L_{path}^2/(C^2 - V^2)$$

$$\Delta t = t_{up} - t_{down} = 2\, L_{path}\, V/(C^2 - V^2)$$

The Black Box: Chordal LEFMs and How They Work

- The LEFM measures the transit times of ultrasonic pulses traveling in each direction along each chord and uses these data to determine the average fluid velocity and the average sound velocity along each chord

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The Black Box: Chordal LEFMs and How They Work

- The transit time in the fluid is a function of the average sound velocity and the average fluid velocity projected onto the path

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The Black Box: Chordal LEFMs and How They Work

- A critical aspect of the time measurement is pulse detection

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The Black Box: Chordal LEFMs and How They Work

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The Black Box: Chordal LEFMs and How They Work

- The LEFM algorithm
  - The mass flow algorithm is as follows:

$$W_f = \rho \, ^* \, \mathrm{PF}^* \mathrm{F}_{a3} \, (\mathrm{T}) \, ^*(\mathrm{ID}/2) \sum_{i=1}^{4} \frac{\mathrm{w}_i \mathrm{L}_{\mathrm{ffi}}^{\;2} \, (\Delta \mathrm{t}_i)}{\tan(\varphi_i)(t_i + \Delta t_i / 2 - \tau_i)^2}$$

$$\rho = \mathrm{f}_\rho \, (\mathrm{T}, \mathrm{p})$$

$$\mathrm{T} = \mathrm{f}_\mathrm{T} \, (C_{\mathrm{mean}}, \mathrm{p})$$

$$c_{\mathrm{mean}} = \mathrm{F}_{a1} \, (\mathrm{T}) \sum_{i=1}^{4} [w_i \, \mathrm{L}_{\mathrm{ffi}}]/[\mathrm{t}_i + (\Delta \mathrm{t}_i/2) - \tau_i]$$

The Black Box: Chordal LEFMs and How They Work

Definitions

W_f = mass flow rate through the LEFM✓, (lbs/sec)

ρ = mean feedwater density, (lbm/cu. in.)

PF = profile factor, dimensionless

$F_{a3}(T)$ = thermal expansion factor, accounting for the difference in internal diameter and transducer face-to-face distance (L_{ffi}) at operating temperature versus the temperature at which dimensions were measured (in/in/°F)

ID = internal diameter of the spool piece, (in.)

w_i = Gaussian quadrature integration weighting factor for path i, (dimensionless)

φ_I = angle between path i and a normal to the spool piece axis (deg)

L_{ffi} = face-to-face distance between transducer wells of path i, (in.)

t_i = total indicated time of flight of pulse along path i in the direction of the flow,(sec.)

t_{upi} = total indicated time of flight along path i against the direction of flow

Δt_i = the difference in the total transit times of pulses traveling against the flow and with the flow along path i, (sec.); $\Delta t_i = t_i - t_{upi}$

τ_i = total of the non-fluid delays of pulses traveling along path i, (sec.)

T = mean fluid temperature, (°F)

p = fluid pressure, (psi)

c_{mean} = mean sound velocity in fluid, (in/sec)

$F_{a1}(T)$ = thermal expansion factor, accounting for the difference in face-to-face distance (Lffi) at operating temperature versus the temperature at which dimensions were measured, (in/in/°F)

Calibration Tests in the Lab

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Laboratory Calibrations, Practice and Data

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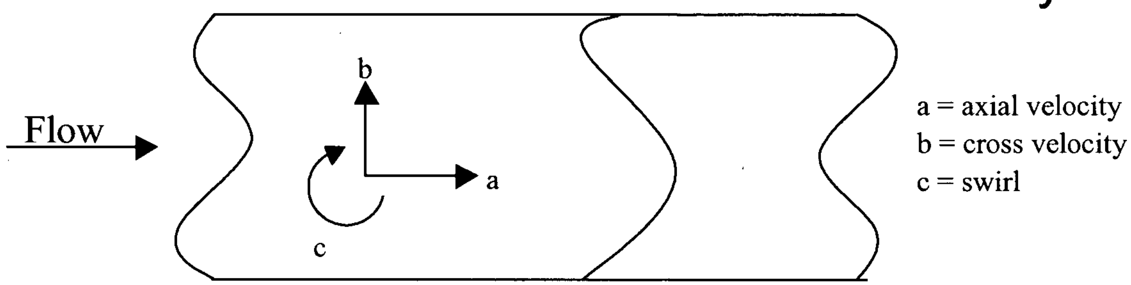
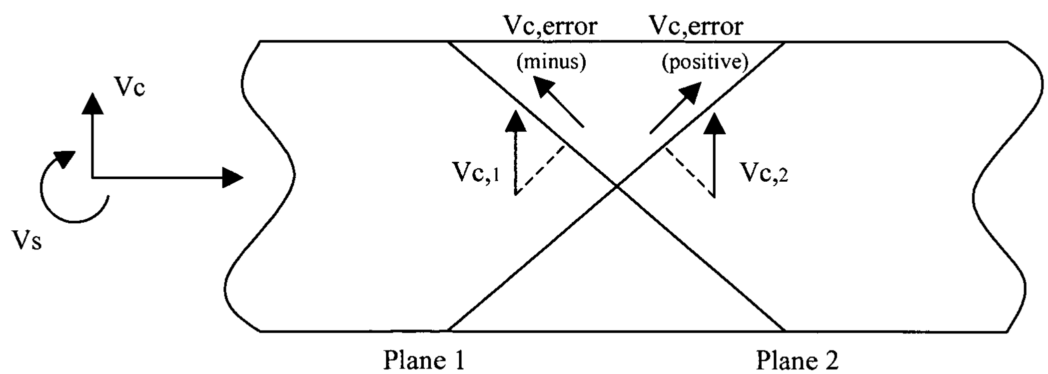
Laboratory Calibrations, Practice and Data

Transverse Velocities

- An LEFM CheckPlus measures axial velocity ONLY



Velocity Vectors

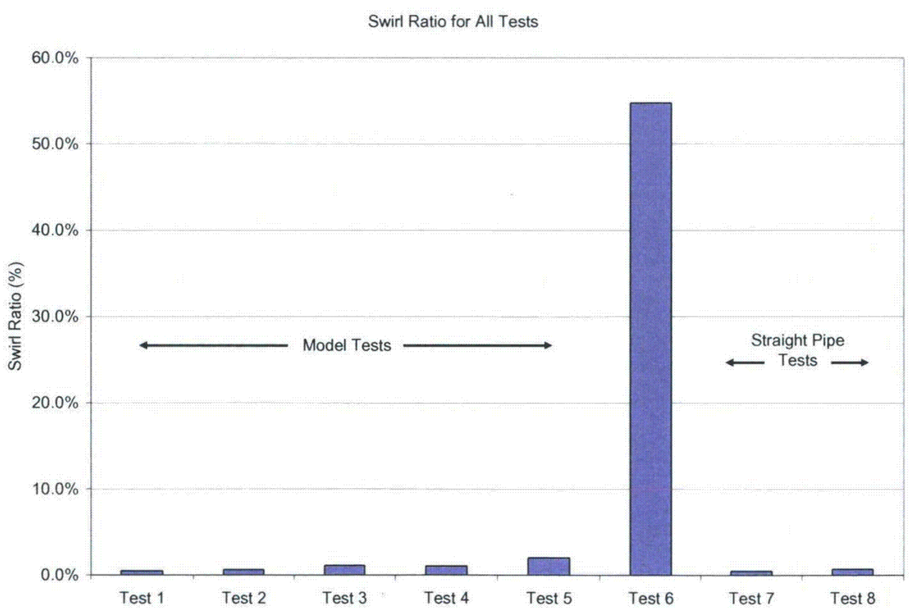


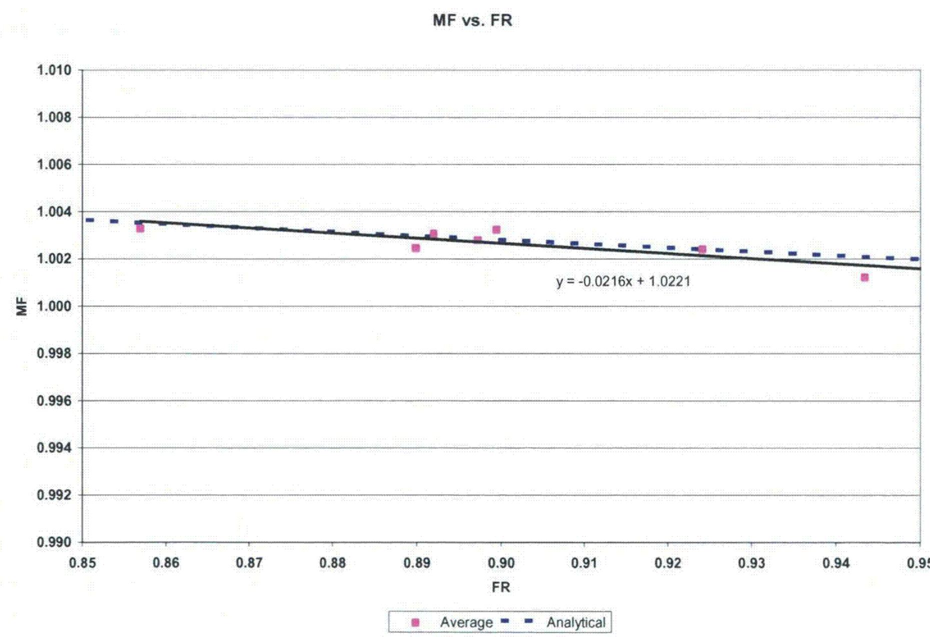
$V_{c,error}$ net = 0 = $V_{c,1}$ error + $V_{c,2}$ error

Cross Flow and Swirl Velocity Errors Cancel

Laboratory Calibrations, Practice and Data

- Calibration tests for Seabrook and other flow elements demonstrate insensitivity of LEFM CheckPlus to swirl





Laboratory Calibrations, Practice and Data

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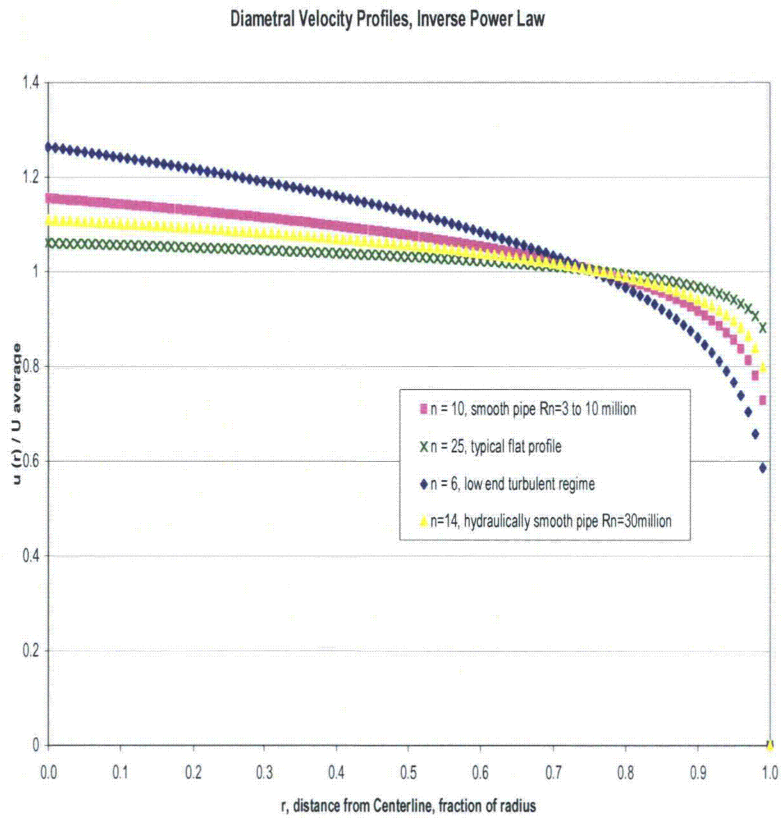
Laboratory Calibrations, Practice and Data

Sensitivity of calibration to axial velocity profile

- By varying its exponent, n, the inverse power law can be used to characterize a nominally symmetrical axial profile *regardless of the Reynolds Number for the flowing fluid or its degree of development*

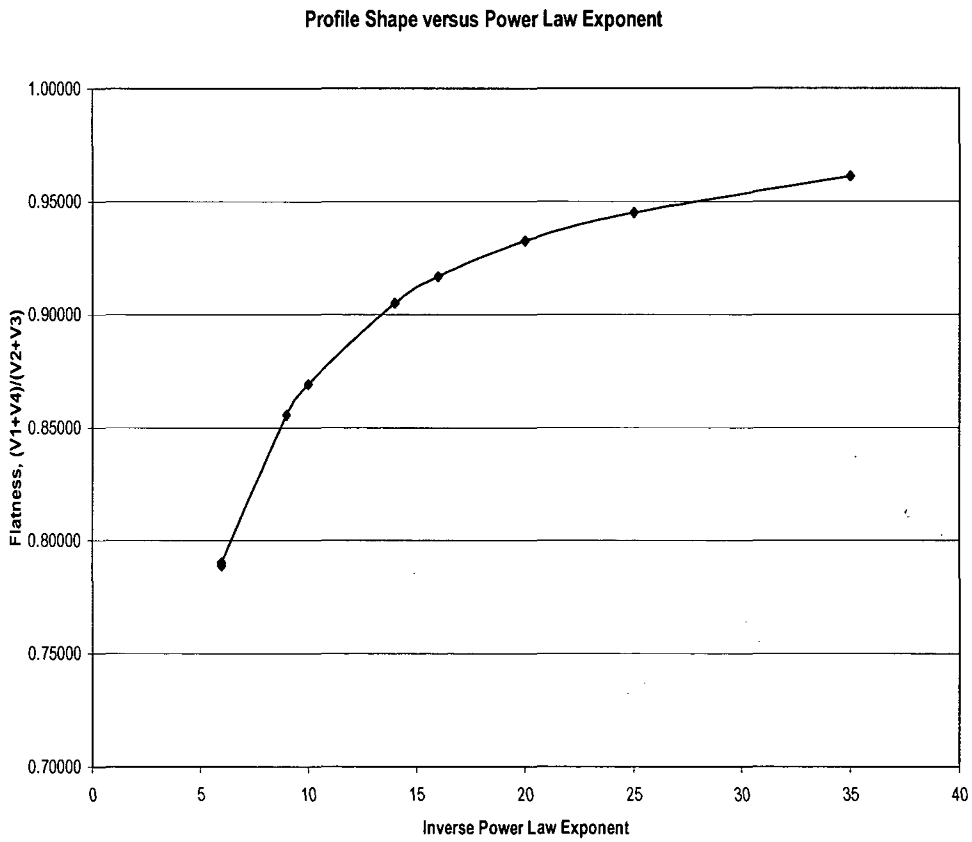
- $V = V_{MAX} (x/R)^{1/n}$



Laboratory Calibrations, Practice and Data

Sensitivity of calibration to axial velocity profile

- FR can be related to inverse power law exponent



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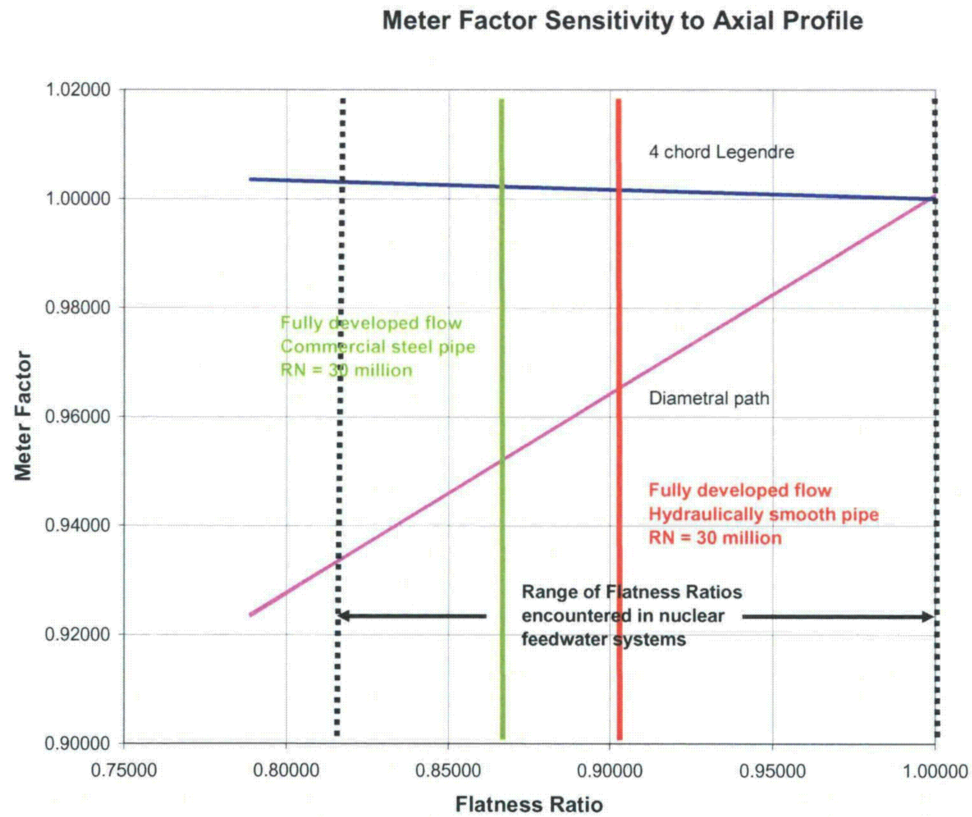
Laboratory Calibrations, Practice and Data

Sensitivity of calibration to axial velocity profile

- The significance of the FR data
  - Flatness ratios measured in-plant can be related to "developed flow profiles" at various Reynolds Numbers



Laboratory Calibrations, Practice and Data

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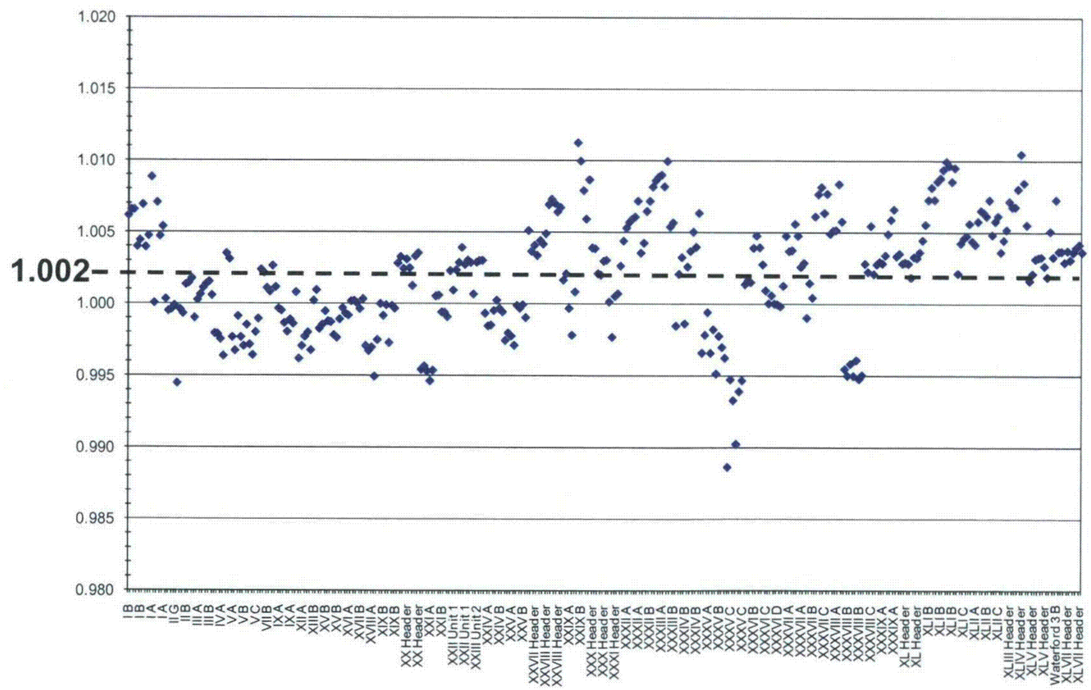
Laboratory Calibrations, Practice and Data

Sensitivity of calibration to axial velocity profile

- Average meter (profile) factor for 75 nuclear meters in 330 hydraulic configurations is 1.002, identical to the theoretical meter factor for 4-path Legendre numerical integration of developed flow profiles in the high Reynolds number regime
- Variability is due to dimensional variations, not hydraulics

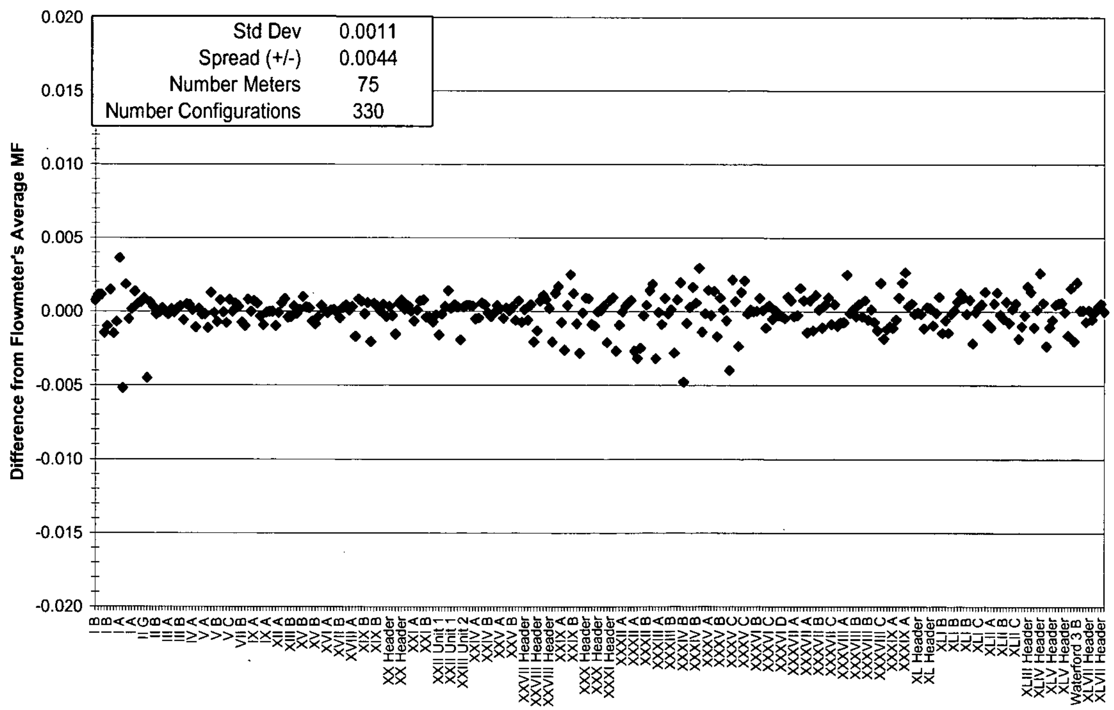


Laboratory Calibrations, Practice and Data

Sensitivity of calibration to axial velocity profile

- Variability is due to dimensional variations, not hydraulics
- Figure shows that variations due to modeling differences are less than ±0.11% (one standard deviation)

Summary of Nuclear Meter Calibrations



Calibration Test for LaSalle Unit 2

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Calibration Test for LaSalle Unit 2

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Calibration Test for LaSalle Unit 2

- The calibration test plan is spelled out in ALD-1123 Rev. 2 dated 08/20/09 (pass out)

Calibration Test for LaSalle Unit 2

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Traceability and Uncertainties

- Traceability is defined as a process whereby a measurement can be related to a standard via a chain of comparisons. Certain requirements apply:
  - The standard must be acceptable to all parties with an interest in the measurement and is usually a standard maintained by a national laboratory such as the National Institute of Standards and Technology.
  - The chain of comparisons must be unbroken—the field measurement must be connected, by one or more links directly to the standard.
  - Every link in the chain involves a comparison that necessarily carries with it an uncertainty. Hence the total uncertainty of the measurement must reflect the aggregate uncertainties of each link of the comparison chain.
  - There can be no unverified assumptions in the chain of comparisons; it is clearly not possible rationally to assign an uncertainty to an assumption that has no quantitative basis.

Traceability and Uncertainties

- The Chordal LEFM✓ + Algorithm
  - The mass flow algorithm is as follows:

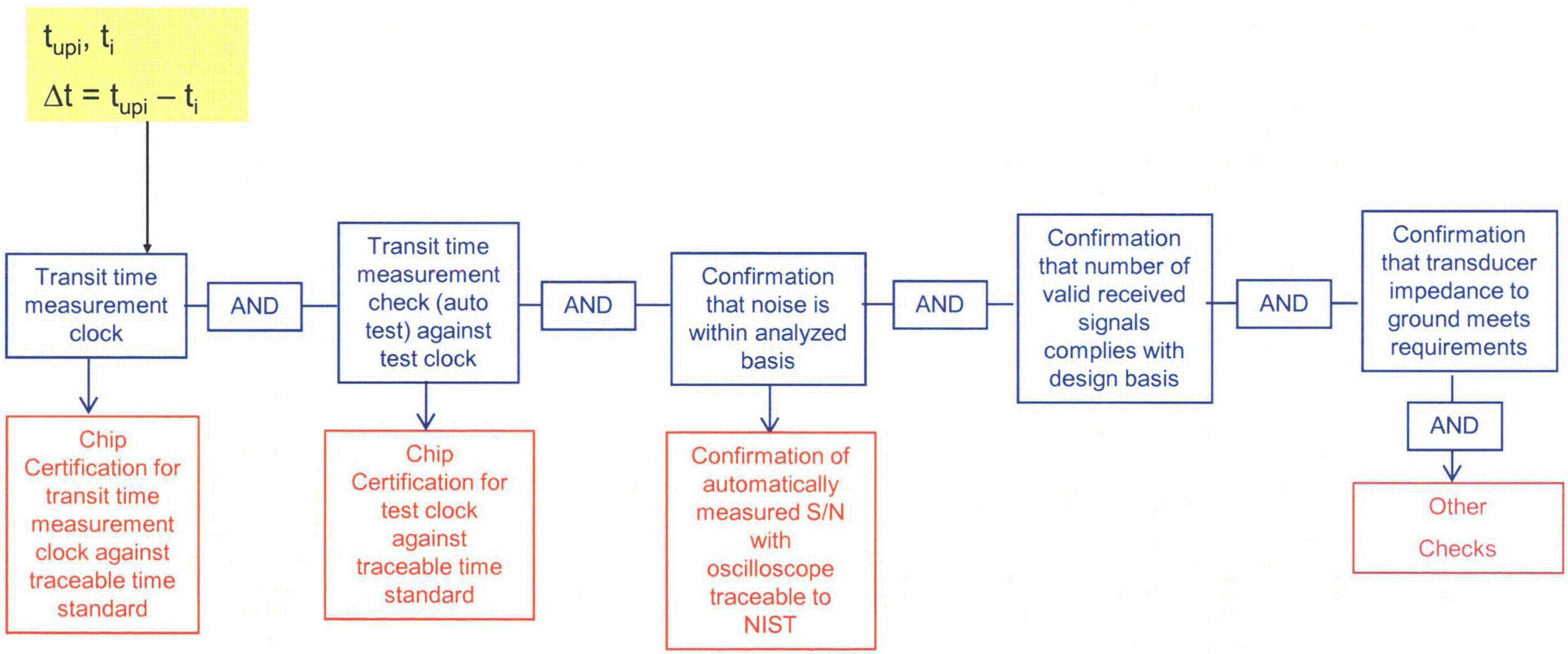
$$W_f = \rho * \mathrm{PF}^* \mathrm{F}_{a3}\,(\mathrm{T})\,^*(\mathrm{ID}/2) \sum_{i=1}^{4} \frac{\mathrm{w}_i \mathrm{L}_{\mathrm{ffi}}{}^2\,(\Delta \mathrm{t}_i)}{\tan(\varphi_i)(t_i + \Delta t_i / 2 - \tau_i)^2}$$

$$\rho = \mathrm{f}_\rho\,(\mathrm{T}, \mathrm{p})$$

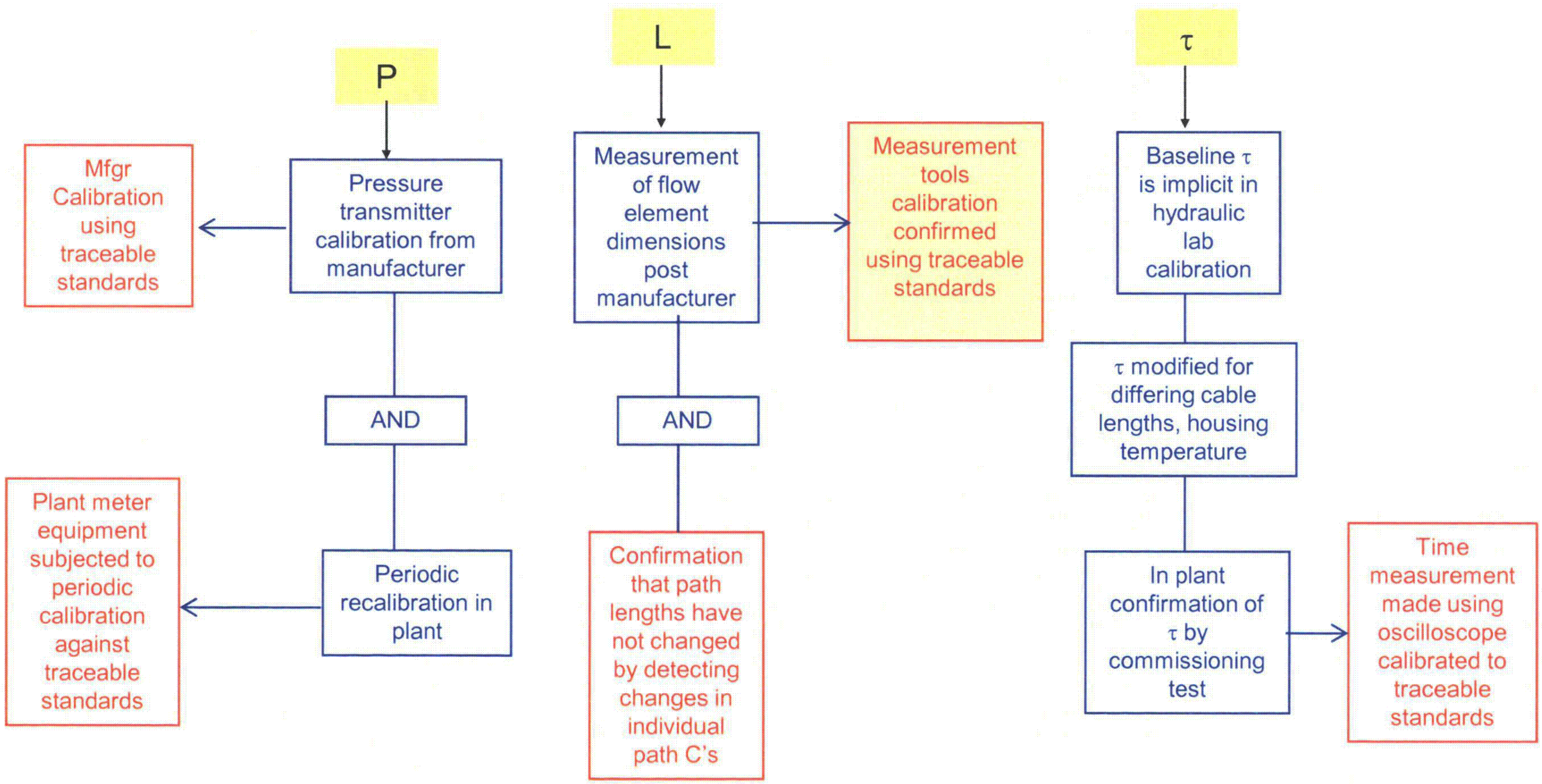
$$\mathrm{T} = \mathrm{f}_\mathrm{T}\,(C_{\mathrm{mean}}, \mathrm{p})$$

$$c_{\mathrm{mean}} = \mathrm{F}_{a1}\,(\mathrm{T}) \sum_{i=1}^{4} [w_i\ \mathrm{L}_{\mathrm{ffi}}]/[\mathrm{t}_i + (\Delta \mathrm{t}_i/2) - \tau_i]$$

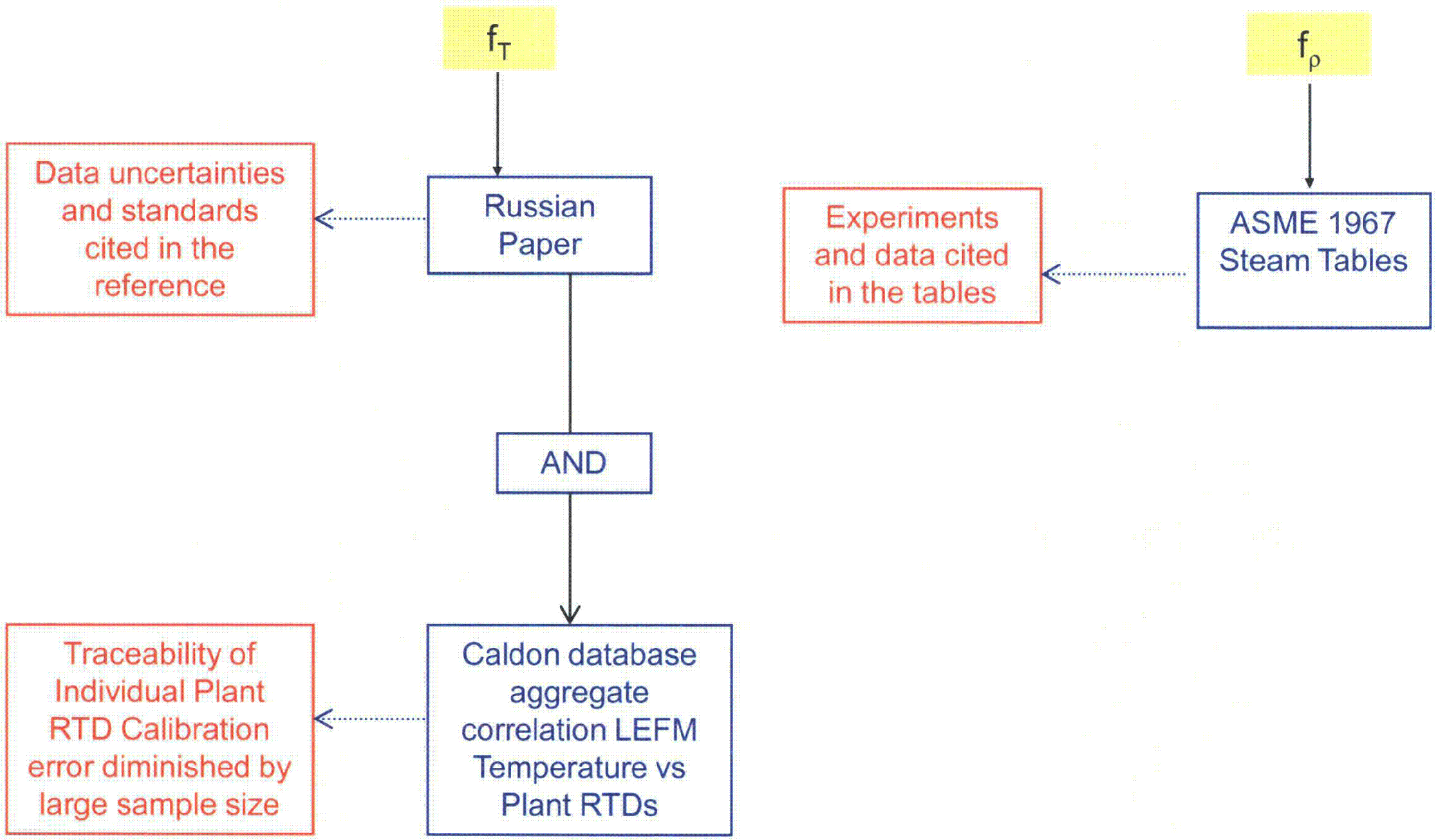
Traceability and Uncertainties



Traceability and Uncertainties



Traceability and Uncertainties



Traceability and Uncertainties

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Traceability and Uncertainties

- Uncertainties and their Bases
  - Appendix A of ER-157P provides the basis for the analysis of uncertainties for each LEFM Check or CheckPlus application
  - A spread sheet analysis is performed for each plant using plant specific numbers for PF, times-of-flight, dimensions, pressure instrument data etc.

Uncertainties

Power Algorithm

$$P_R = W_{FT}\,(h_s - h_{fw}) \pm P_{LOSS}$$

$$\mathrm{W_F} = \rho(\mathrm{p}, \mathrm{T_{fw}}) \cdot \mathrm{Q}$$

$$Q = (PF)(F_{A3})\left(\frac{ID}{2}\right)\left(\sum_{i=1}^{4} \frac{w_i\, L_{ffi}^2\, \Delta t_i}{\left[(\tan\phi_i)(t_i + \frac{\Delta t_i}{2} - \tau_i)^2\right]}\right)$$

$$h_{fw} = h(p,\ T_{fw})$$

$$T_{fw} = T\,(c_{fw},\ p)$$

Uncertainties

Sensitivity Coefficients

M = f (X, Y, Z)

$$dM = \left.\frac{\partial f}{\partial X}\right|_{YZ} dX + \left.\frac{\partial f}{\partial Y}\right|_{XZ} dY + \left.\frac{\partial f}{\partial Z}\right|_{XY} dZ$$

$$\frac{dM}{M} = \left\{\frac{X}{M}\left.\frac{\partial f}{\partial X}\right|_{YZ}\right\}\frac{dX}{X} + \left\{\frac{Y}{M}\left.\frac{\partial f}{\partial Y}\right|_{XZ}\right\}\frac{dY}{Y} + \left\{\frac{Z}{M}\left.\frac{\partial f}{\partial Z}\right|_{XY}\right\}\frac{dZ}{Z}$$

$$\frac{dM}{M} = \left[\left(\left\{\frac{X}{M}\left.\frac{\partial f}{\partial X}\right|_{YZ}\right\}\frac{dX}{X}\right)^2 + \left(\left\{\frac{Y}{M}\left.\frac{\partial f}{\partial Y}\right|_{XZ}\right\}\frac{dY}{Y}\right)^2 + \left(\left\{\frac{Z}{M}\left.\frac{\partial f}{\partial Z}\right|_{XY}\frac{dZ}{Z}\right)^2\right]^{1/2}$$

Uncertainties

Loop Power Uncertainty in Sensitivity Format

$$dP_{LOOP}/P_{LOOP} = (1/\rho)\ \{\partial\rho/\partial T|_p\ dT_{fw} + \partial\rho/\partial p|_p\ dp_{fw} + d\rho_{corr}\} + dQ/Q$$

$$[1/(h_S - h_{fw})]\ \{\partial h_s/\partial p|_M\ dp_s + \partial h_S/\partial M|_p\ dM\} +$$

$$[1/(h_S - h_{fw})]\ \{\partial h_{fw}/\partial p|_T\ dp_{fw} + \partial h_{fw}/\partial T|_p\ dT_{fw} + dh_{corr}\} +$$

$$dP_{LOSS/LOOP}/P_{LOOP}$$

Uncertainties

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Uncertainties

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Uncertainties - Continued

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