Controlling Outdoor Air Ventilation in Commercial Building HVAC Systems*

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Presentation Outline

- Importance of ventilation rate
- Controlling ventilation - what does not work
- Measuring outdoor air intake rates
- Performance of CO_2 sensors used in demand controlled ventilation systems

Importance of Ventilation rates

Why is the Outdoor Air (OA) Ventilation Rate Important?

Energy Use and Cost

- Estimated 1 Quad (1 EJ) of energy used annually to condition OA in service sector buildings
  - ~ 18% of total heating and cooling energy
  - Annual U.S. cost ~ $16 billion

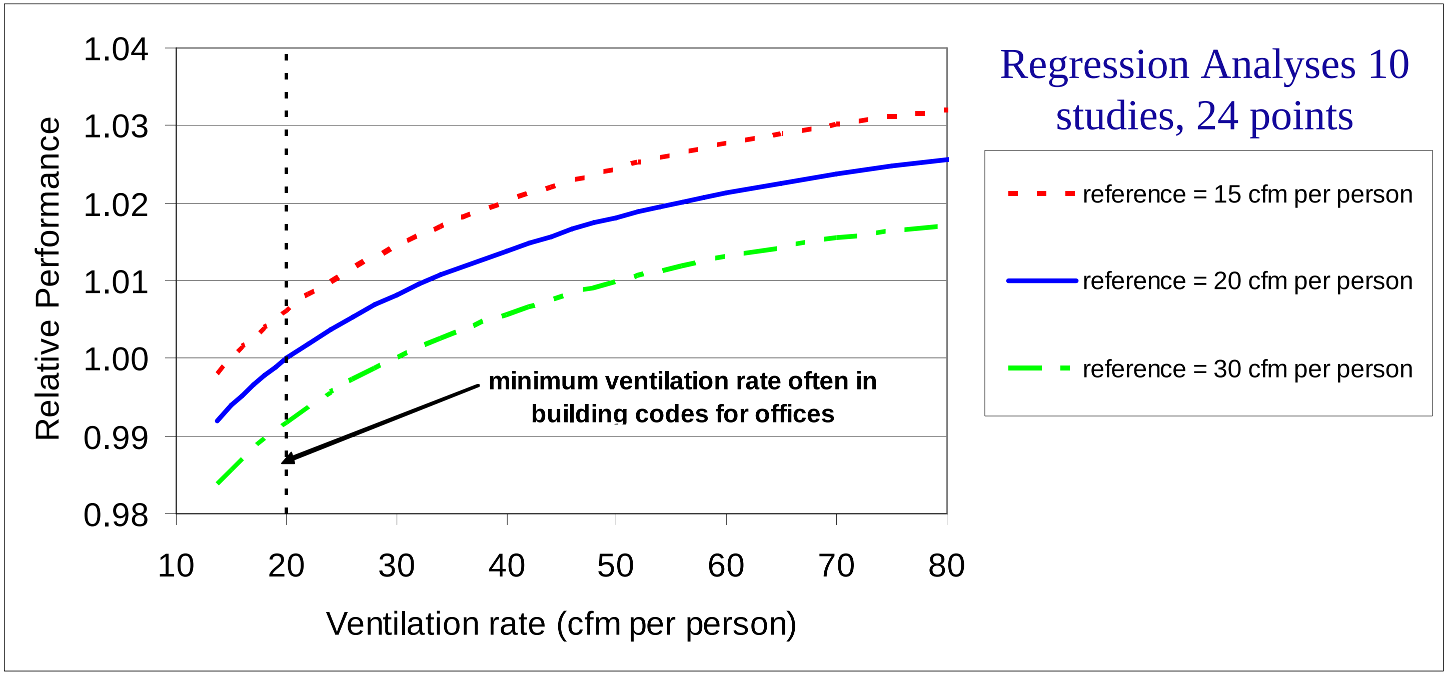
Health

- Sick building syndrome health symptoms
- Communicable respiratory illnesses and absence rate

Work performance

- Small increases in work performance with higher OA ventilation rates

Estimated Relationship of Building Ventilation Rate with Office Work Performance



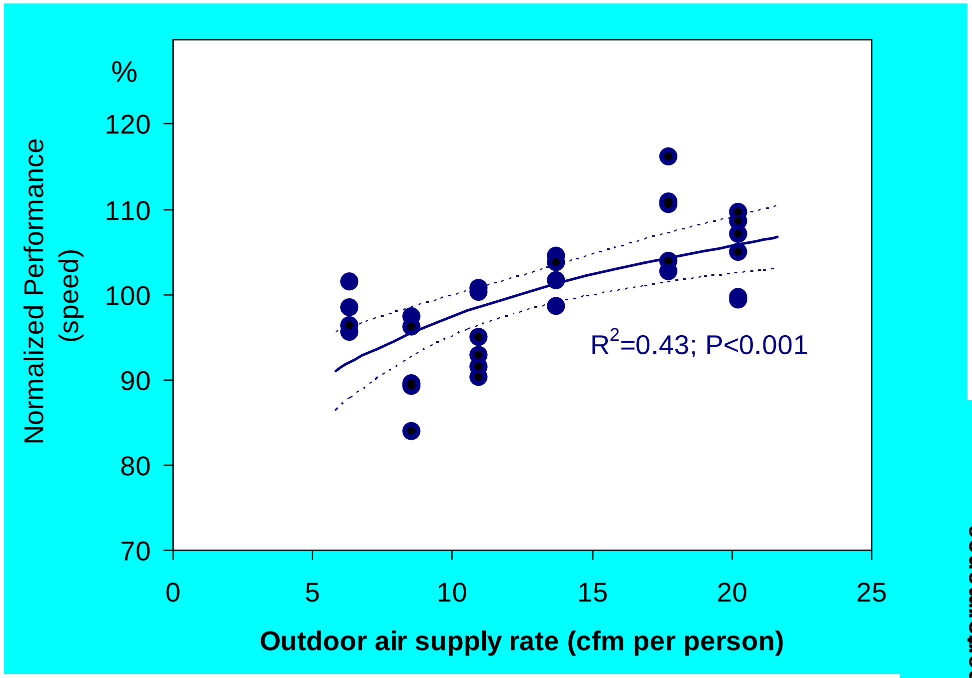
Basis for Estimates

- **Objectively measured performance data; e.g., speed of call center work; accuracy and speed of proof reading and typing**
- **Results of experiments**
- **Controlled for potential confounding**

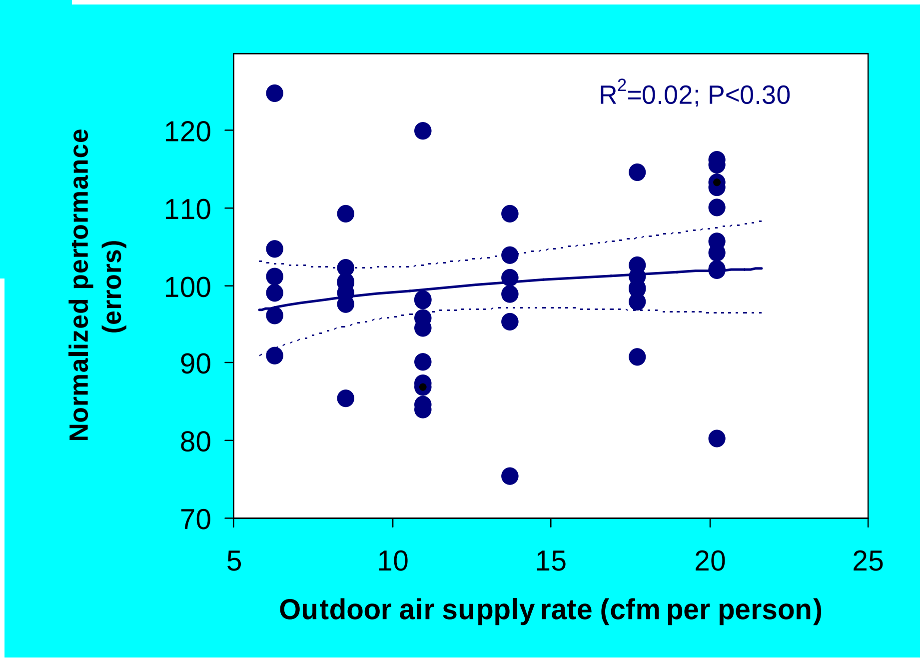
Limitations

- **High remaining uncertainties**
- **Relationship may vary with type of work**

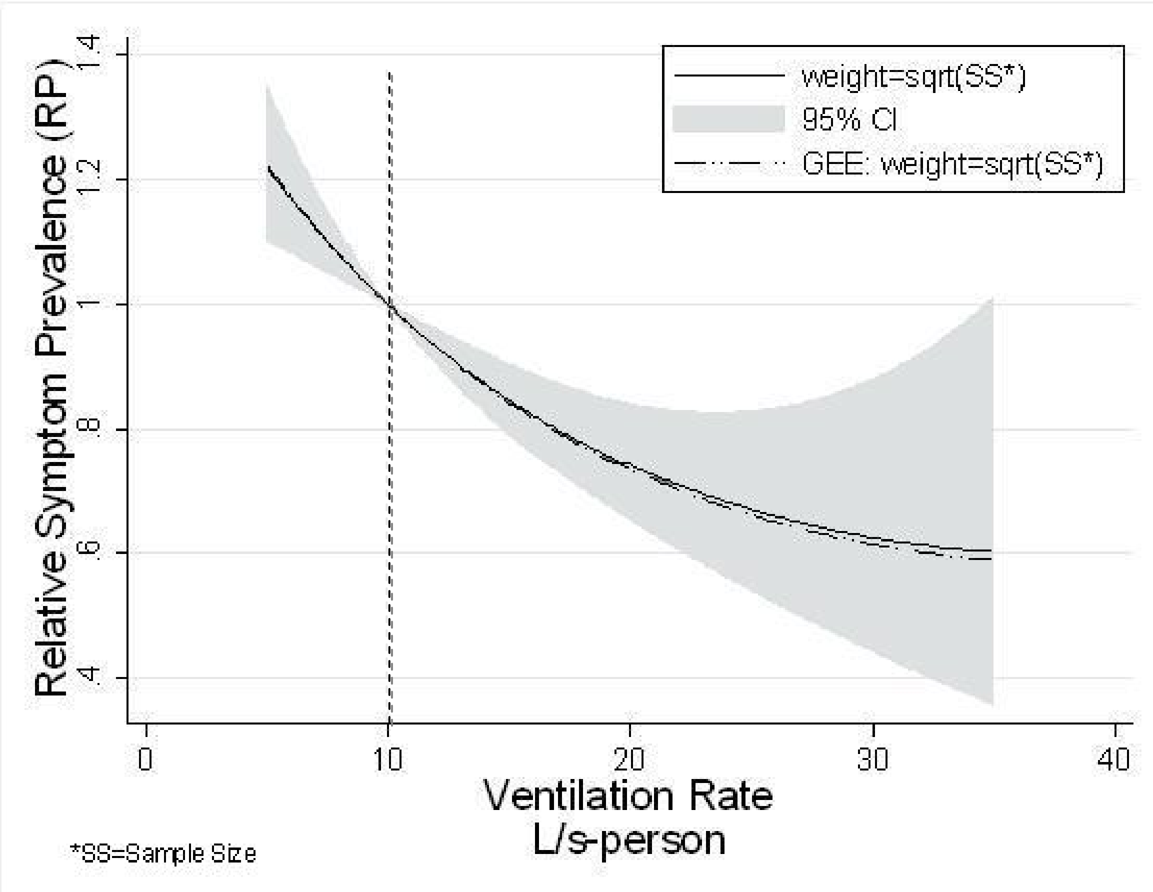
Ventilation Rates and Student Performance



- Experiments in Denmark
- Ventilation rates manipulated
- Reading and math speed and accuracy assessed



Sick Building Syndrome Symptom Prevalance vs. Ventilation Rate



Basis

- Regression analysis of 44 data points from 8 studies

Limitations

- Limited data → wide CI
- Relationship may vary with type of symptom, need more data

Controlling Ventilation Rates: What Does Not Work

What is Wrong with Relying on Occasional Air Balance Data to Set Damper Positions?

Answer: Empirical data indicates that rates of ventilation are often poorly controlled.

U.S. Office Ventilation Rates*

- **Estimated average min. outdoor air supply exceeds code minimum by 40%**
  - **Partly because occupant density was below expectations**
- **However, vent rates are still below code min in 1/3 of offices**

*Analyses of data from 100 building survey

Classroom CO_2 Concentrations Often >> 1000 ppm

CA Survey (201 Classrooms)	
School-Day Mean	1070 ppm
1 hr peak > 1000 ppm	43%
1 hr peak > 2000 ppm	10%
WA, ID Survey (434 classrooms)	
Grab-sample mean	1080 ppm
> 1000 ppm	45%
> 2000 ppm	4%
Maximum	4600 ppm

What Often Does Not Work:

Measuring Supply Air Flow Rate and Subtracting Measured Return Air Flow Rate

WHY?

Potential for Very Large Errors

Example with 15% Accuracy in Supply & Return Flow Measurement

Q(supply) = 1000 cfm

Q(return) = 800 cfm

True Q(outdoor air) = 200 cfm

Measured Q(outdoor air)

Qs - Qr = (1000+150) – (800-120)

= 470 cfm [+135% error]

or

Qs - Qr = (1000-150) – (800+120)

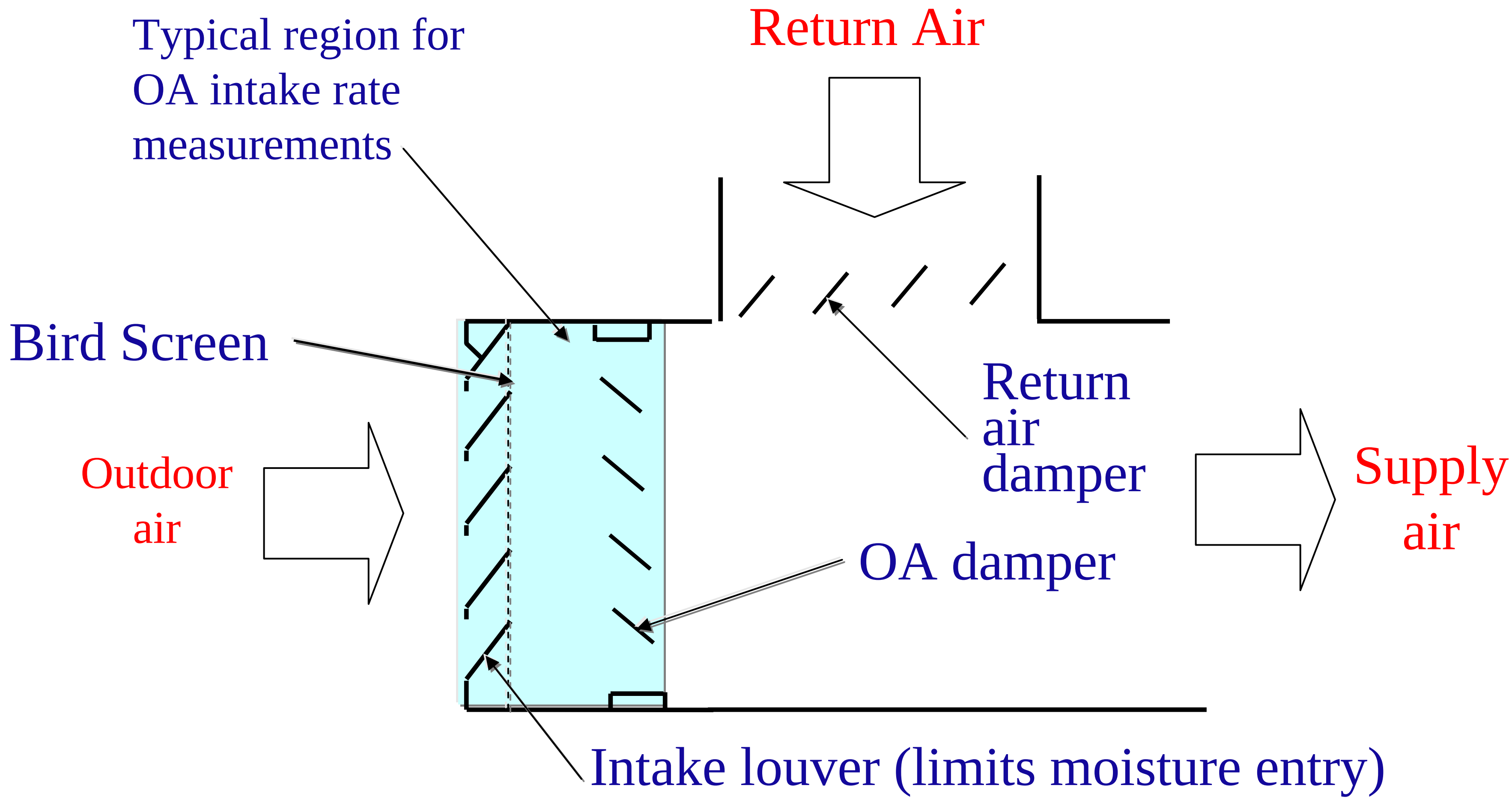
= -70 cfm [- 135% error]

Some Options for Better Control of Ventilation rates

- Separate air handler for outdoor air with air flow measurement system in supply duct
- Measure outdoor air intake rate upstream of where outdoor air mixes with return air
  - Modulate over time to achieve target
- CO_2-based demand controlled ventilation
  - Modulate outdoor air supply rate above a fixed minimum per unit floor area to maintain CO_2 below a target (e.g., 1000 ppm)

Measuring Outdoor Air Intake Rates

Typical OA Intake of a Commercial HVAC System



Why are OA intake measurements challenging?

- Low air speeds (to prevent moisture entry) , near detection limits of many sensors
  - Especially at minimum rates of OA supply
- Spatially variable direction of air flow
- Air flow rates & temperatures vary over time
- Sensors may be exposed to moisture and dust
- Effects of winds
- Limited space

Example of Air Speeds Downstream of a OA intake Louver

With 100% OA:

speed	310 fpm (1.6 m/s)
vel. press	0.006 IWG (1.5 Pa)

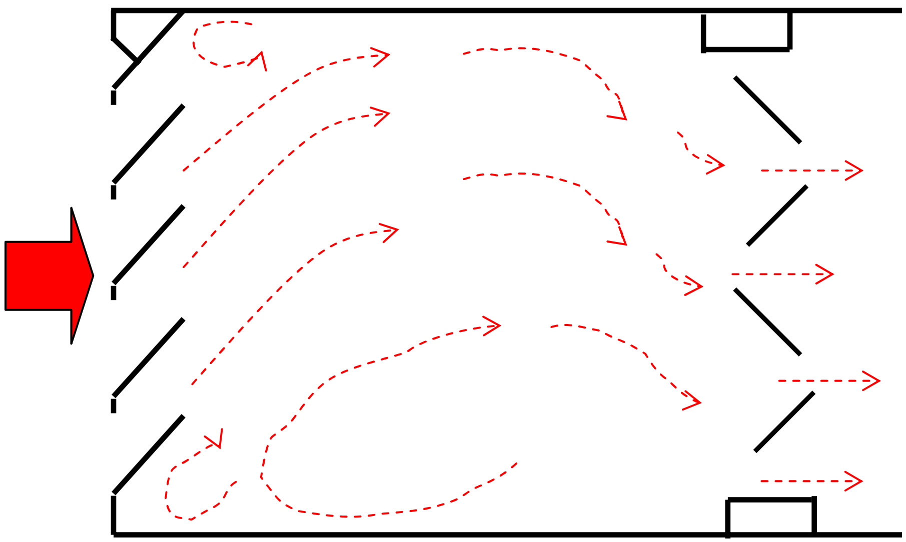
With 20% OA:

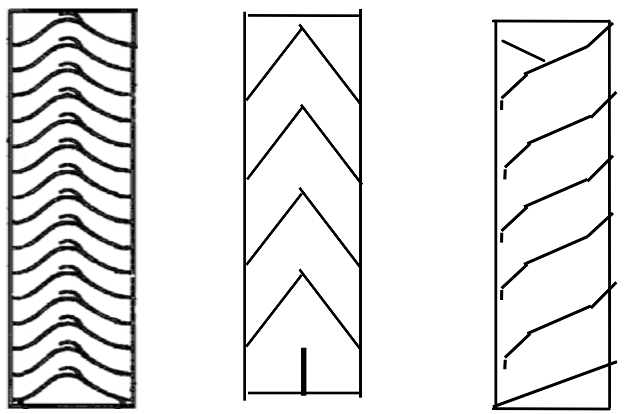
speed	60 fpm (0.3 m/s)
vel. press.	0.0002 IWG (0.06 Pa)

Example of Airflow Profiles at Outdoor Air Intake

Airflow pattern downstream of L3 inferred from observations of smoke transport

Similar but inverted airflow pattern downstream of L2

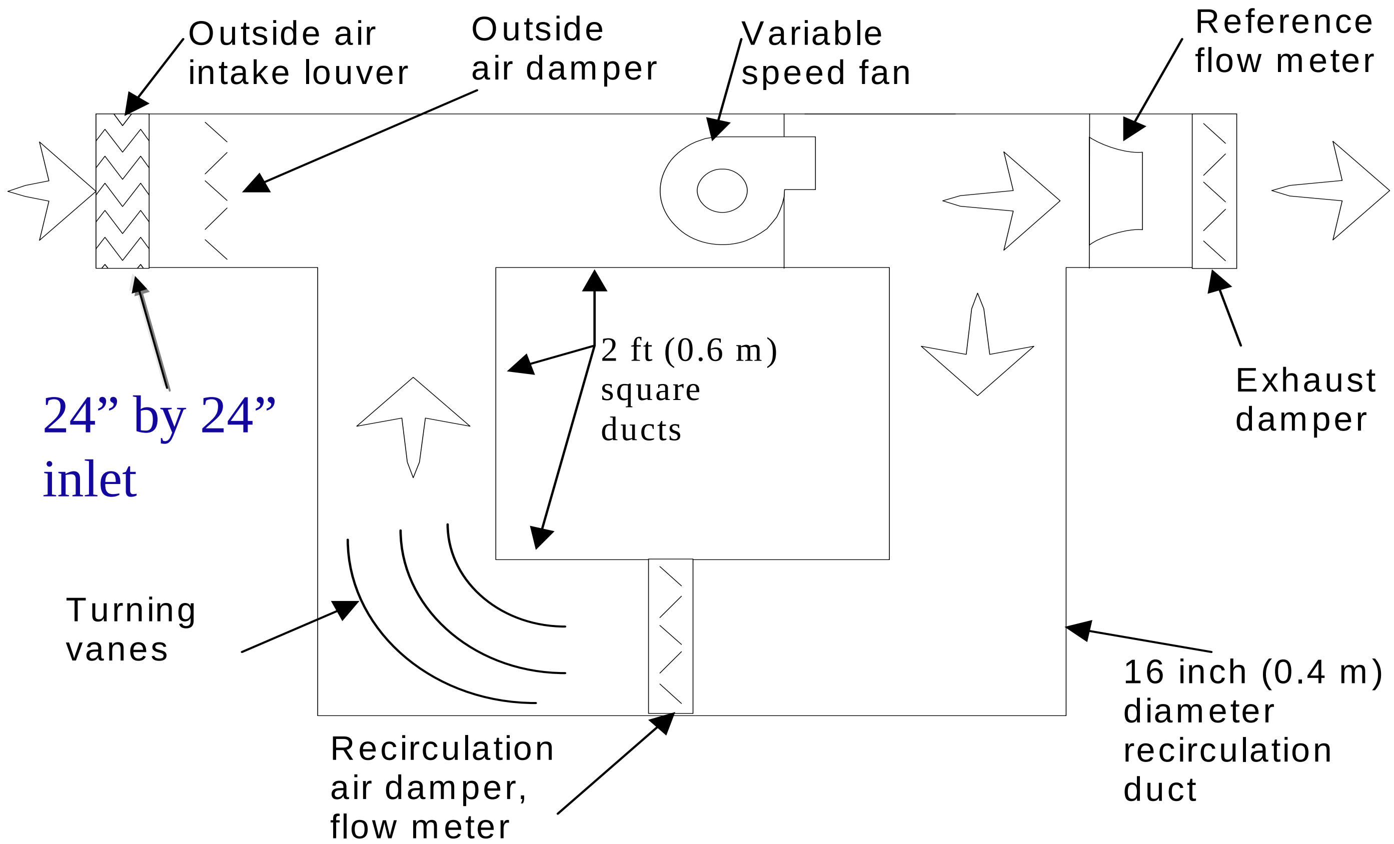




L1 L2 L3

Evaluations of Four Outdoor Air Intake Measurement Technologies

Laboratory-Based Test System



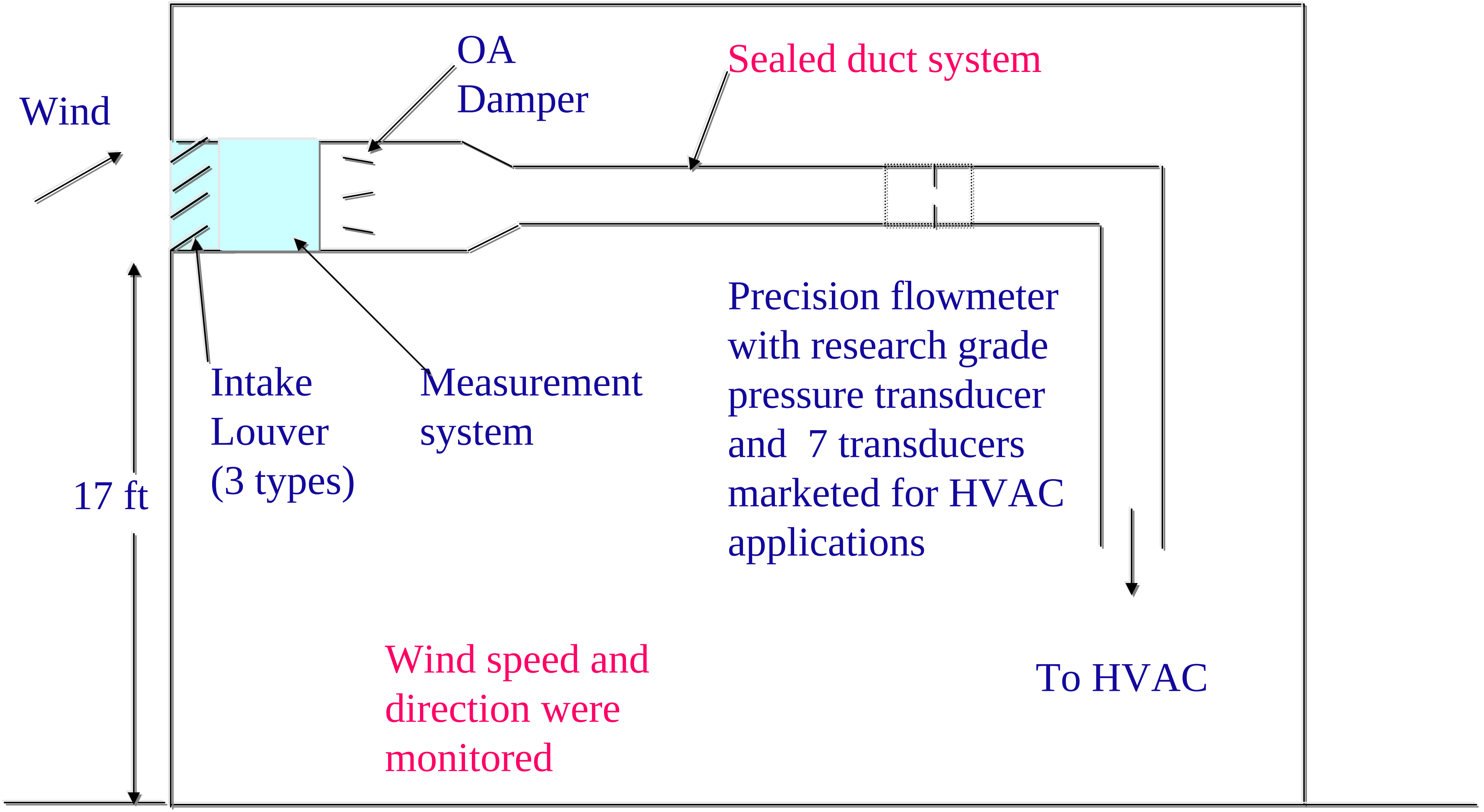
Ref. Flow
0.5% rated accuracy
Few % accuracy in practice

Test variables
- technology
- OA flow rate
- recirculation flow rate
- inlet louver type
- ΔP across OA damper

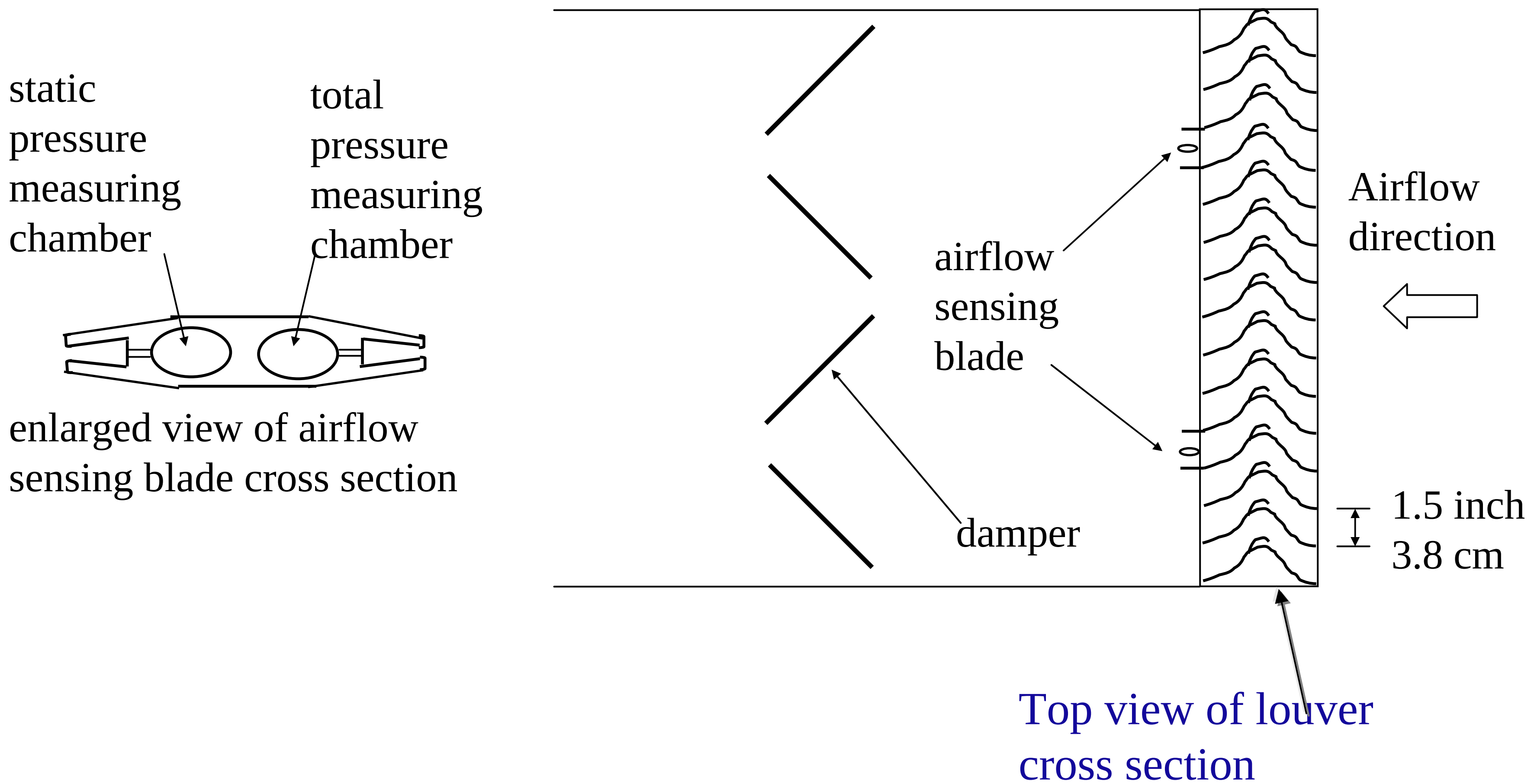
Intake Flow Rate = Reference Flow Rate
(very low leakage test system)

★Note: used research grade pressure transducers

Field-Based Test System

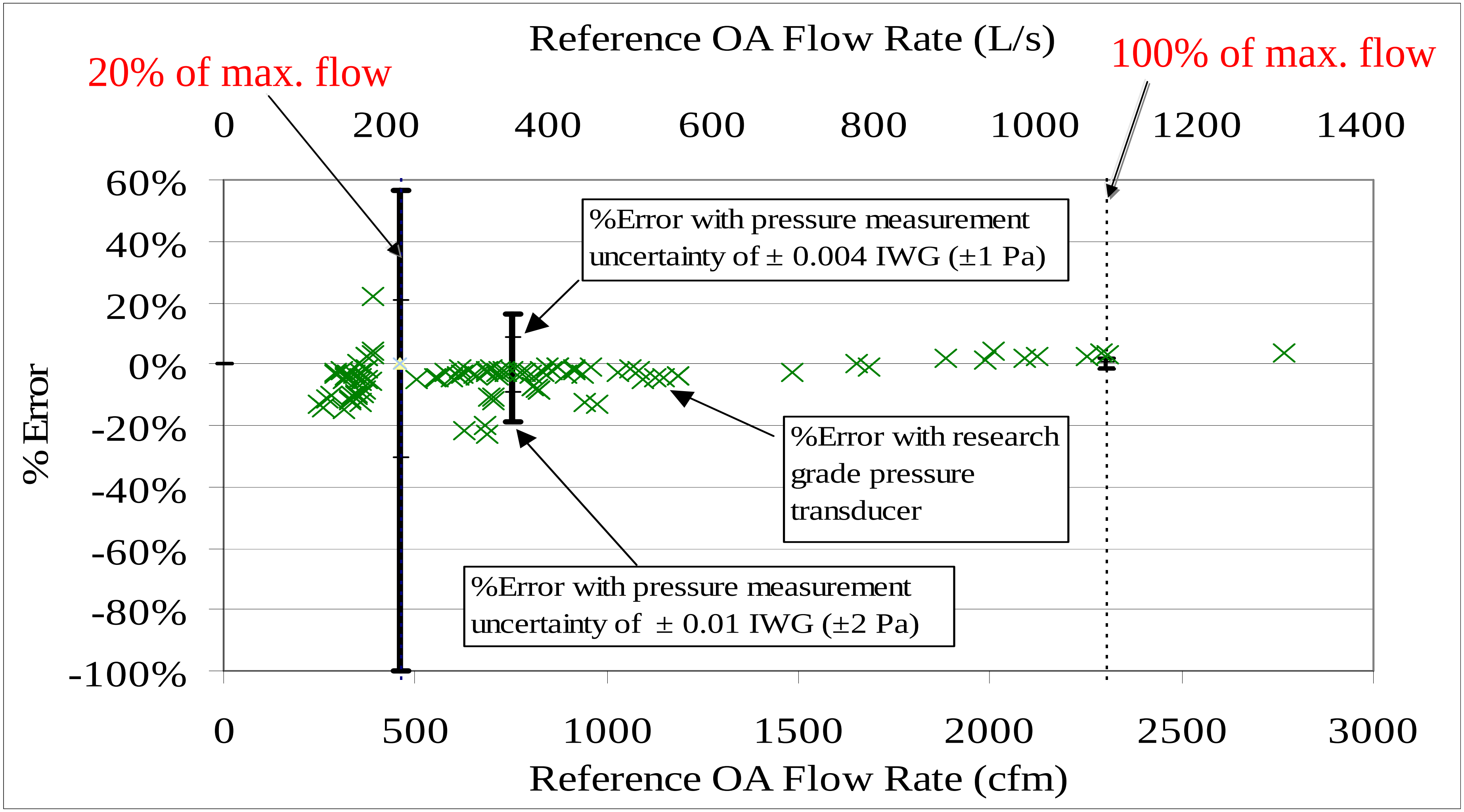


Measurement Technology # 1 Illustration (sensors integrated with louver)



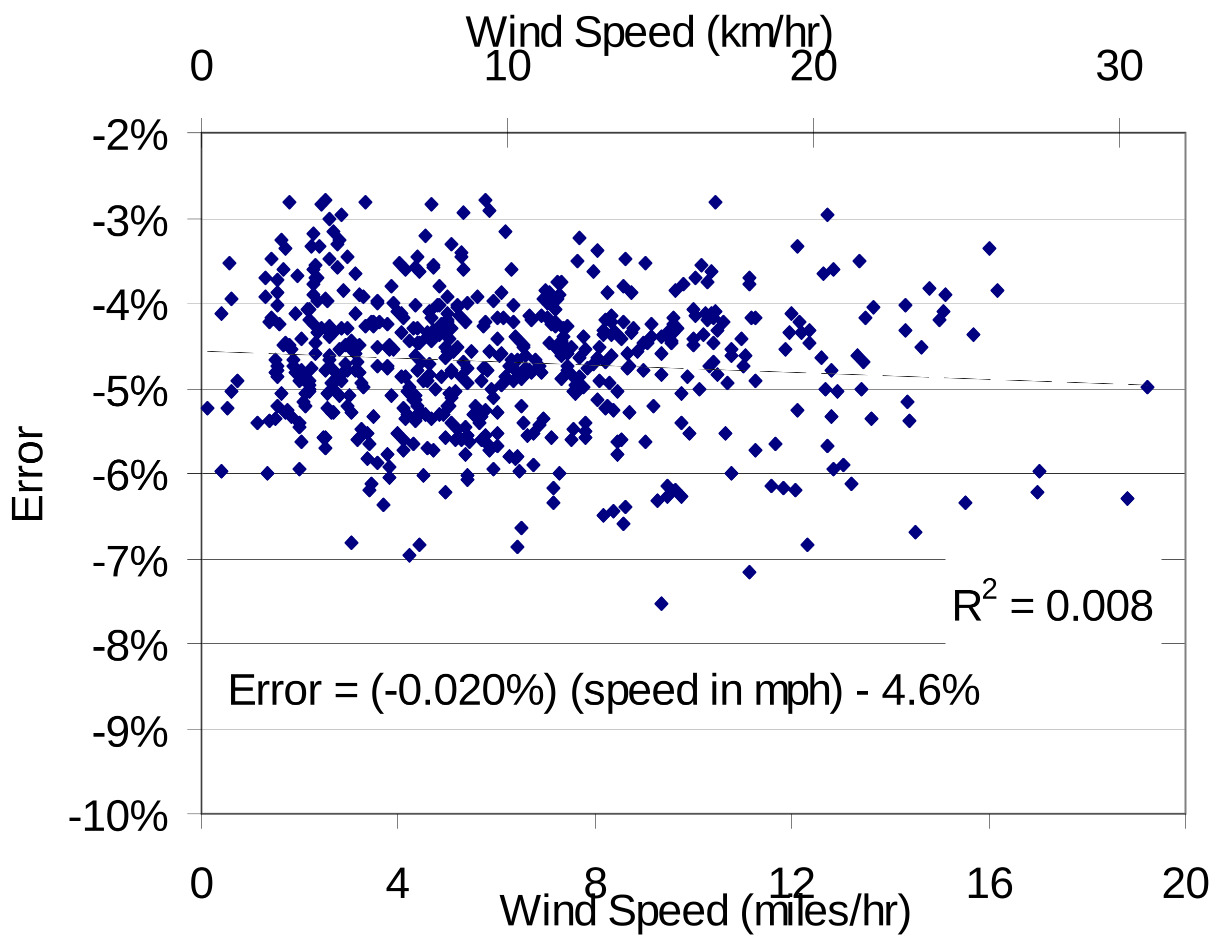
Accuracy of Measurement Technology 1 in Laboratory Studies

with Research Grade Pressure Transducer



Accuracy of MT#1 in Field Study

with Research Grade Press. Transducer



Only 3% to 7% errors in field setting

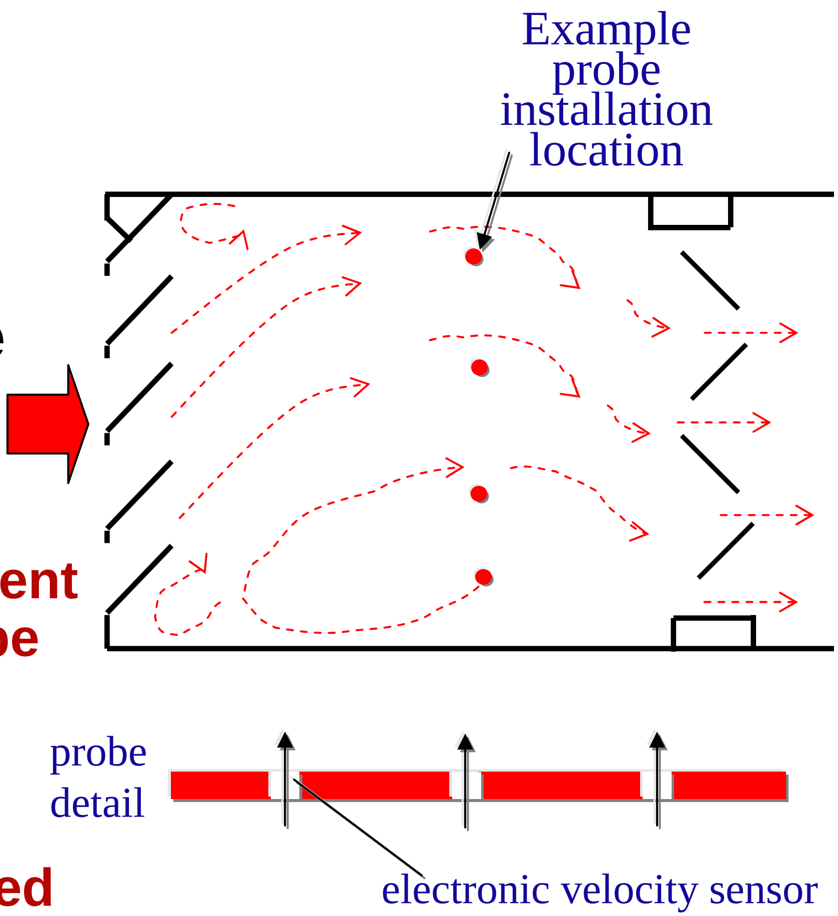
No significant effect of wind speed or direction

Measurement Technology #2

Description: **Array of electronic velocity sensors installed downstream of intake louver; tested with several sensor installation locations but only with one louver***

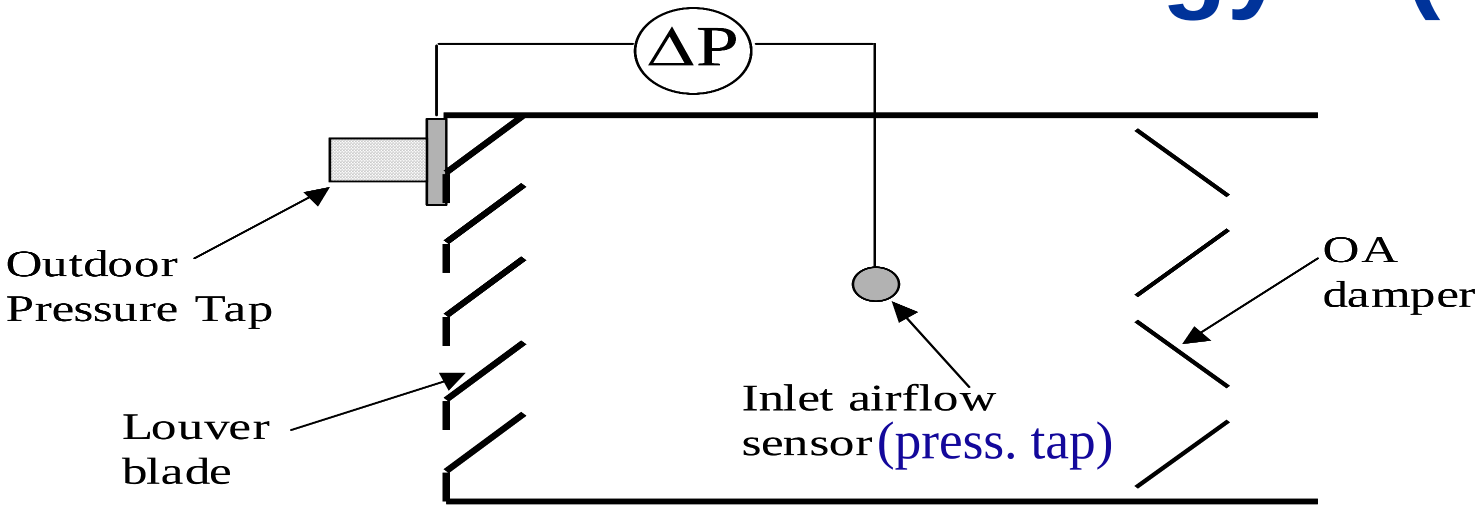
Results (of limited testing):

- **Error ranged from a few percent to > 100% depending on probe installation location & orientation**
- **System should give accurate flows if an accurate field based calibration can be performed**

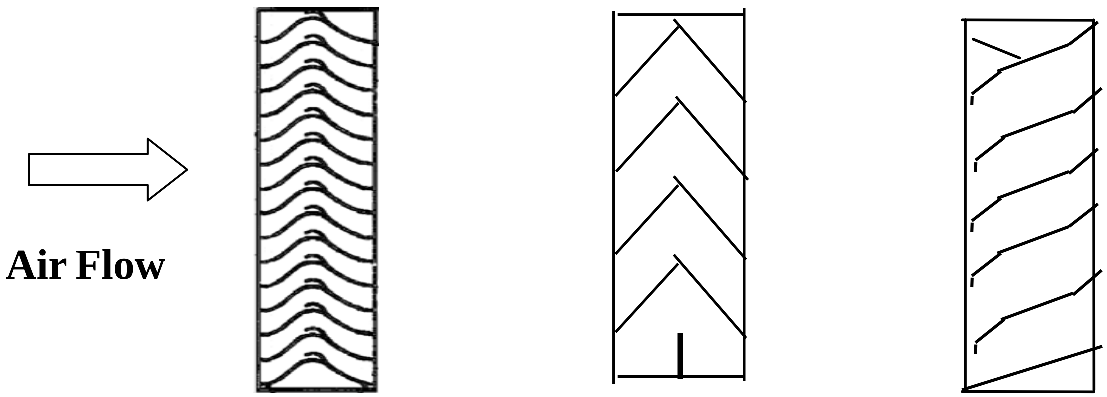


* In actual tests, louver directed air downward

Measurement Technology 3 (MT3)



Evaluated with three intake louvers



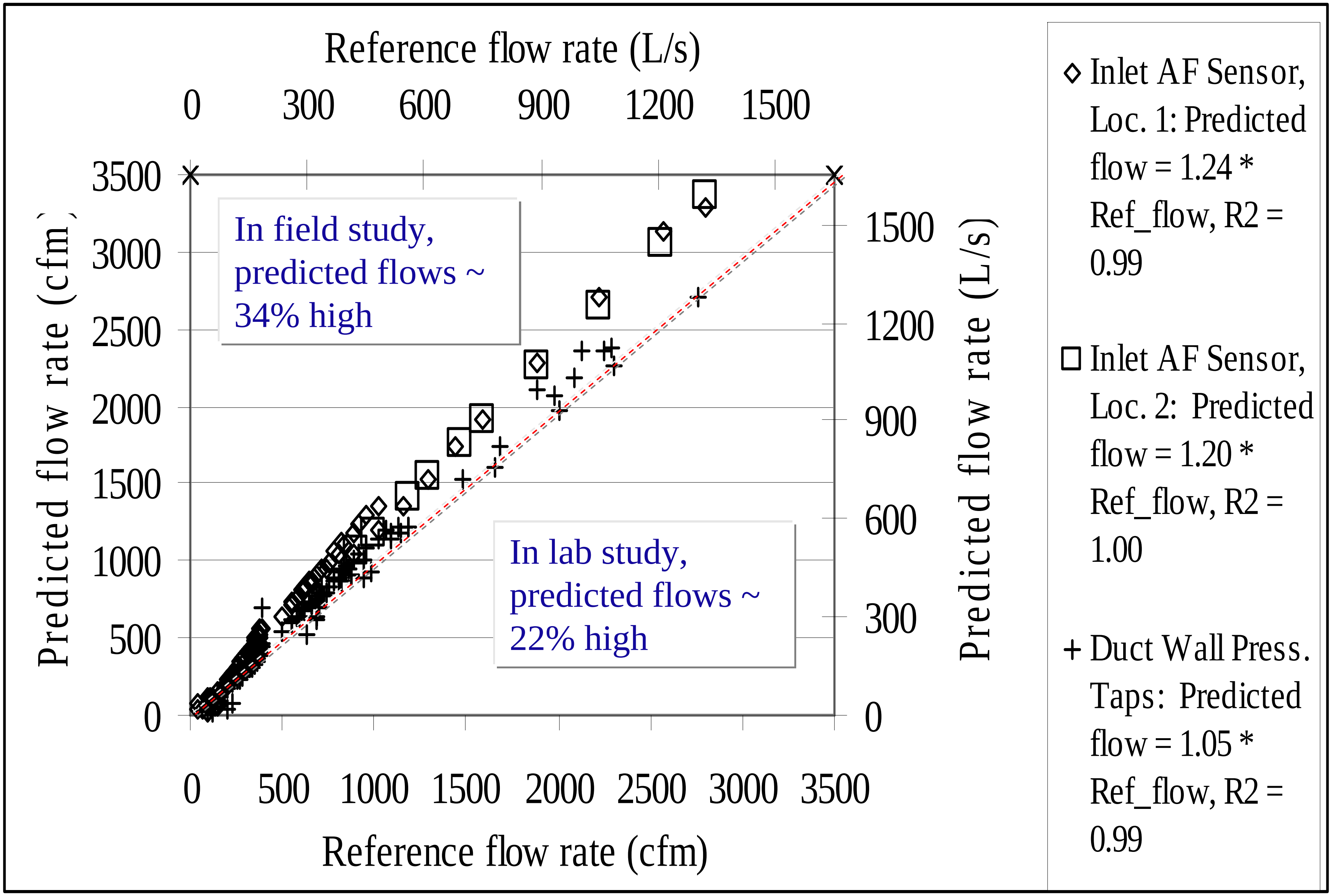
Louver 1 (vertical blade)

Louver 2 (sight proof)

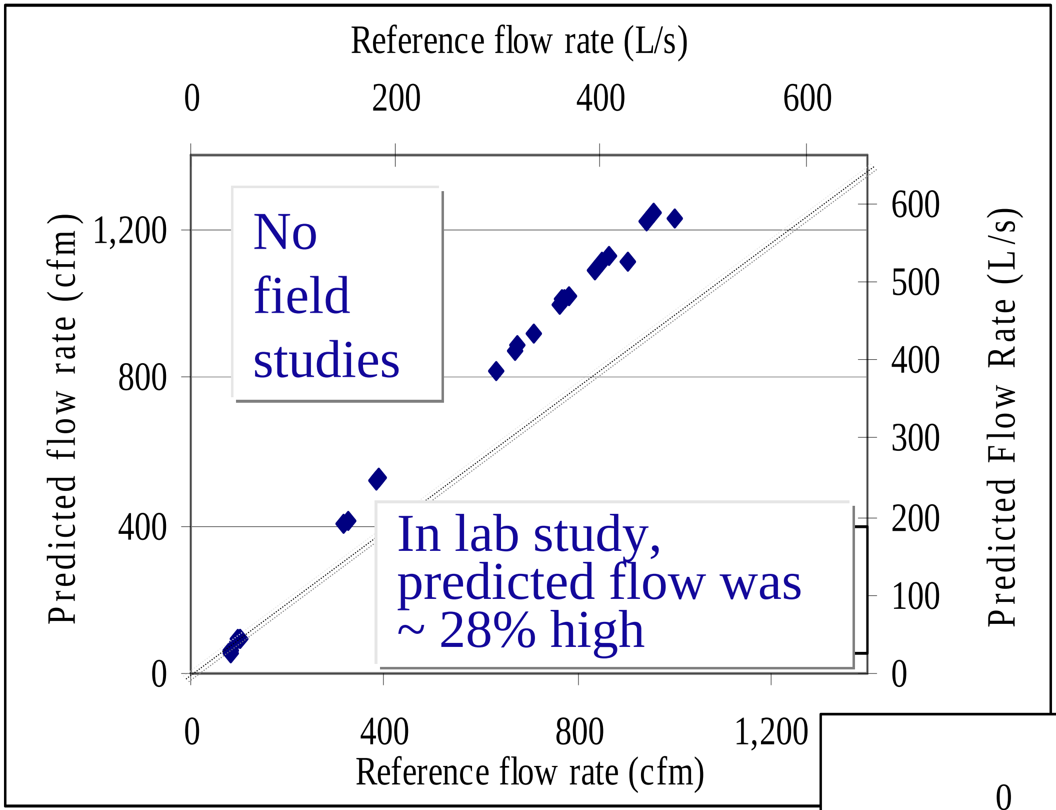
Louver 3 (typical)

Flow Rate determined from measured ΔP and louver manufacturers flow-pressure drop data

Accuracy of MT3 with Louver 1 (vertical blade)
and Research Grade Pressure Transducer

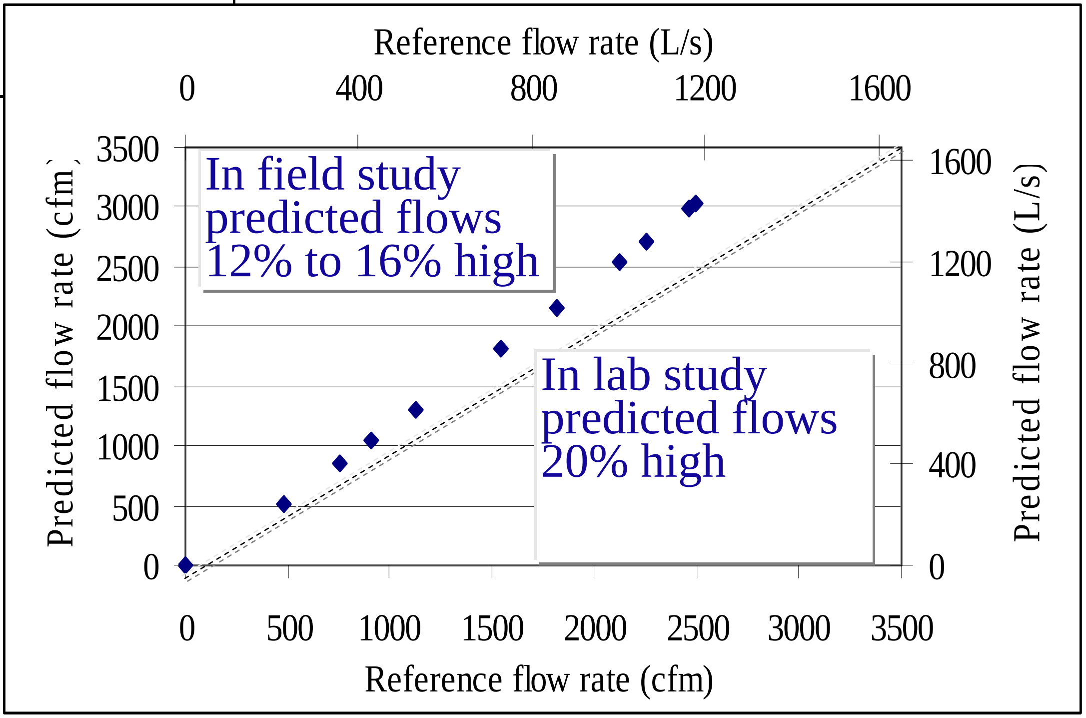


Accuracy* of Measurement Technology 3 with Louver 2 and Louver 3



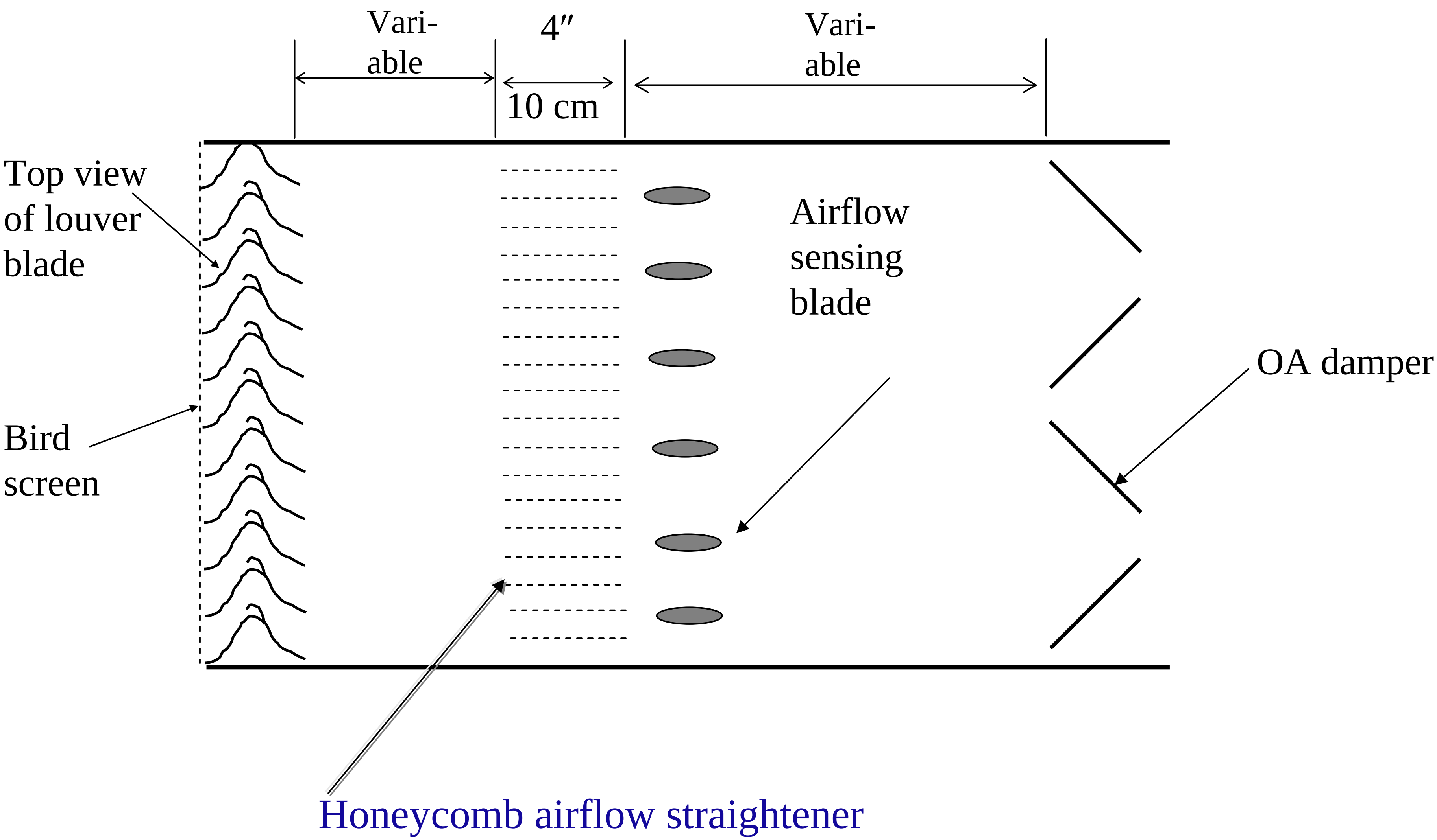
Louver 2 (sight proof)

Louver 3 (typical)



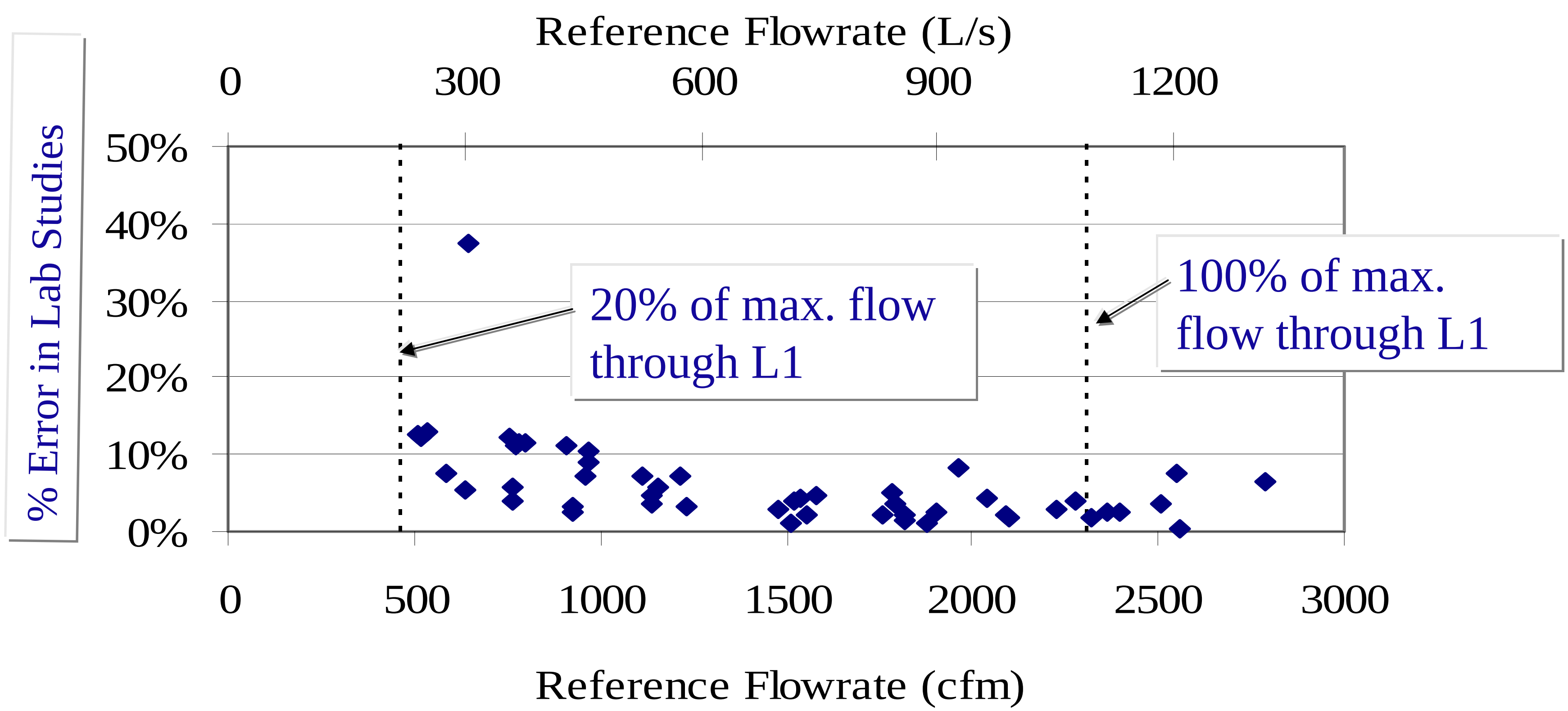
*with research grade pressure transducer

Measurement Technology #4 Illustration



Accuracy of Measurement Technology 4 When Used with Louver 1 (vertical blade)

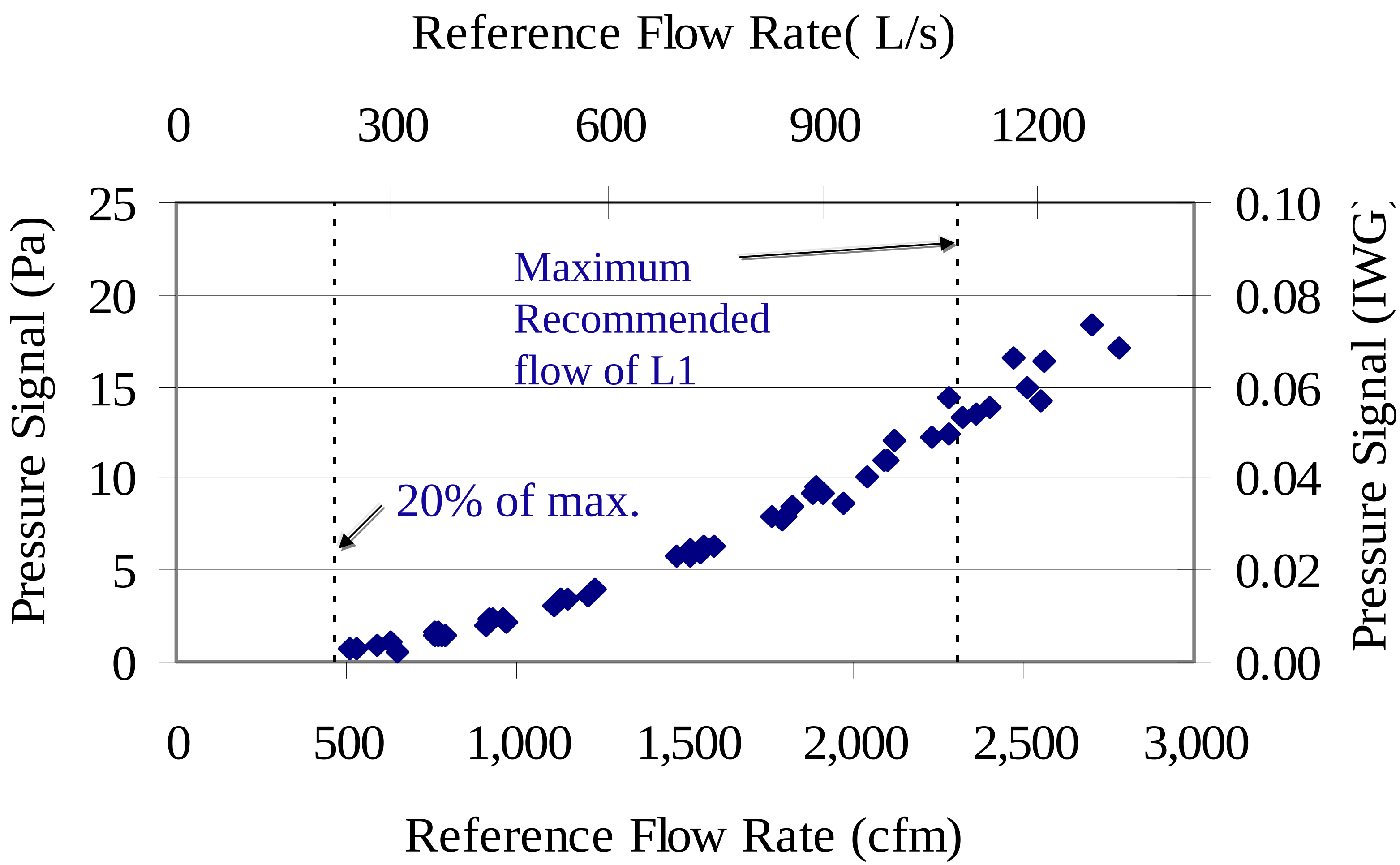
with Research Grade Pressure Transducer



Performance Summary

	MT 4 with vertical blade louver 1	MT 4 with Typical Louver 3
Lab Study	0 to +12% error	-----------------
Field Study	~ - 16% error	+ 105% to 130% error

Small Pressure Signal of MT4

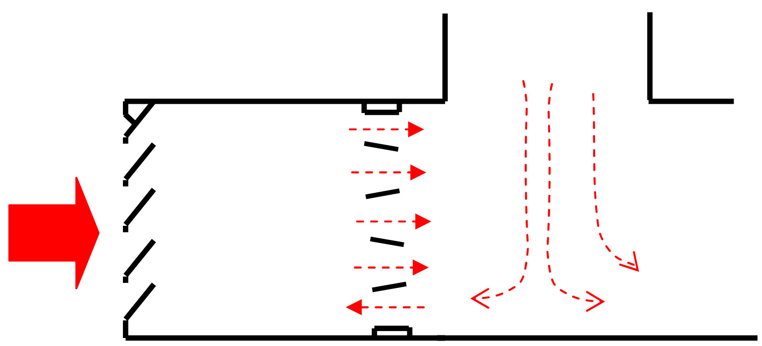


Accuracy of OA Flow Measurement Systems: Summary

- **Main findings:**
  - **MT1, which measures velocities between louver blades, had better than 20% accuracy**
  - **MT2, MT3, MT4: Moderate to large errors in some situations (without accurate field-based calibrations, which are difficult)**
  - **To maintain accurately measurable ΔP signal with MT1, MT3, MT4, separate OA intake systems are required for minimum OA**
  - **Wind did not significantly degrade accuracy of MT1, MT3, MT4**
- **All technologies have pressure drops that are likely to be judged acceptable (< 0.1 IWG)**

Major Causes of Measurement Errors

- Low air speeds → small pressure signals
- Inaccurate pressure transducers
- High spatial variability in air speed and direction at sensor locations
  - Large eddies downstream of OA intake louvers
- Backwards flow through a section of OA damper



“Cures” for Errors from Low Air Speeds

- Two-section OA intake
- Choose louver with high max. air speed
- Measure speed between louver blades, not downstream of louver
- Use highly accurate pressure sensors
- Electronic velocity sensors often maintain accuracy at lower air speeds

Parameter	Louver 1	Louver 2	Louver 3
Max. velocity in louver (fpm)	1856	500	696
Velocity press. (IWG)	0.21	0.015	0.030
Max. vel. downstream of louver (fpm)	575	155	306
Velocity press. (IWG)	0.021	0.001	0.006
20% of max. vel. in louver (fpm)	371	100	139
Velocity press. (IWG)	0.009	0.0006	0.001
Velocity downstream of louver at 20% of max. (fpm)	115	31	61
Corresponding vel. press. (IWG)	0.0008	0.00004	0.0002

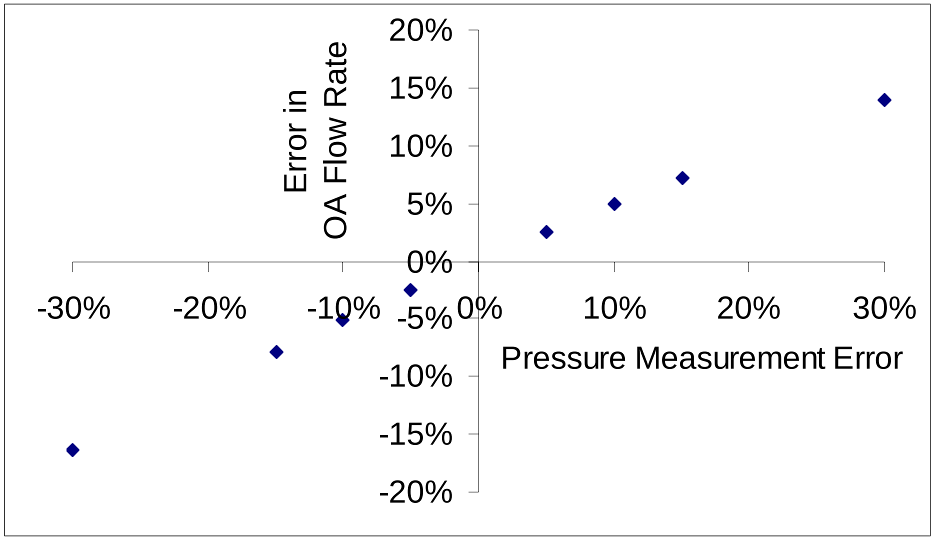
Accuracy of Commercial Pressure Transducers

Pressure Transducer ID	Specifications		In 0.024 - 0.184 IWG Range	
	Pressure range in. of water	Rated accuracy	Expected Max Error % of Reading	Measured Error Range % of Reading
P1	0 – 0.25	1% of FS*	1.3%	0% to 3%
P2+	0 – 0.10	1% FS*	2.1%	4% to 11%
P3+	0 – 0.10	0.25% FS*	0.5%	-16% to 1%
P4	0 – 0.25	1% FS*	1.3%	-61% to 9%
P5+	0 – 0.10	1% FS*	2.1%	-63% to -26%
P6	0 – 0.20	1% FS*	1.1%	-4% to 4%
P7+	0 – 0.10	1% FS*	2.1%	4% to 19%

* FS = full scale   +Only evaluated for pressures < 0.05 IWG

Measured Accuracy

Approximate Required Accuracy



Airspeed Non-Uniformity

downstream of L2 and between blades of L1

Highly Variable
Normalized airspeeds downstream of L2

Inch	2	4	6	8	10	12
1	0.73	0.72	1.05	1.17	1.10	1.22
3	0.47	0.42	0.50	0.49	0.49	0.73
5	0.43	0.42	0.39	0.39	0.39	0.39
7	0.40	0.39	0.39	0.40	0.40	0.40
9	0.59	0.41	0.39	0.39	0.39	0.37
11	0.69	0.42	0.42	0.42	0.41	0.37
13	0.76	0.48	0.39	0.37	0.37	0.36
15	1.13	0.38	0.35	0.37	0.36	0.38
17	1.12	0.62	0.64	0.46	0.45	0.46
19	1.44	0.87	1.38	0.99	0.68	0.67
21	2.54	2.83	2.86	2.83	2.29	2.27
23	4.16	3.88	3.88	4.01	3.98	3.87

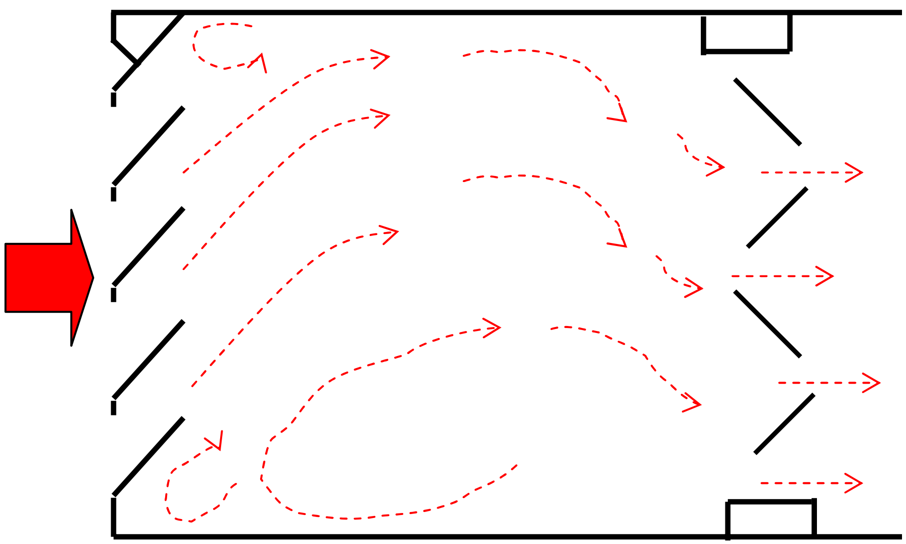
Half-width of louver

Less Variable
Normalized airspeeds inside L1

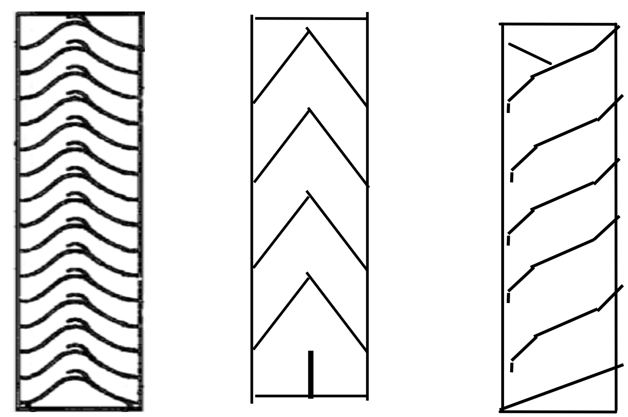
inch from top	Airflow Passage Number 2	5	7	9	12
1	0.75	0.88	0.86	0.92	0.87
2	0.86	0.98	1.04	0.99	0.88
3	1.03	1.00	1.06	0.96	0.97
4	1.02	0.98	1.08	0.97	0.98
5	1.03	1.00	1.06	1.05	1.01
6	1.03	0.99	1.03	1.04	1.03
7	1.04	1.01	1.07	0.98	1.02
8	1.03	1.07	1.08	1.03	1.00
9	1.05	1.08	1.05	0.97	1.01
10	1.04	1.13	0.98	0.96	1.03
11	1.03	1.01	0.90	0.88	1.05
12	1.04	1.14	1.02	1.02	1.04
13	0.98	1.09	1.08	1.03	1.05
14	0.89	1.11	0.97	0.75	0.93

Large Scale Eddies Downstream of Louvers

Airflow pattern downstream of L3 inferred from observations of smoke transport



Similar but inverted airflow pattern downstream of L2

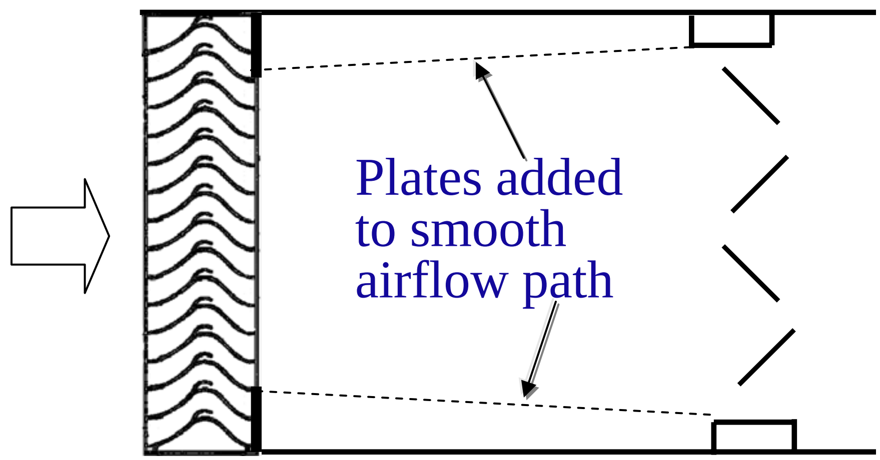


L1 L2 L3

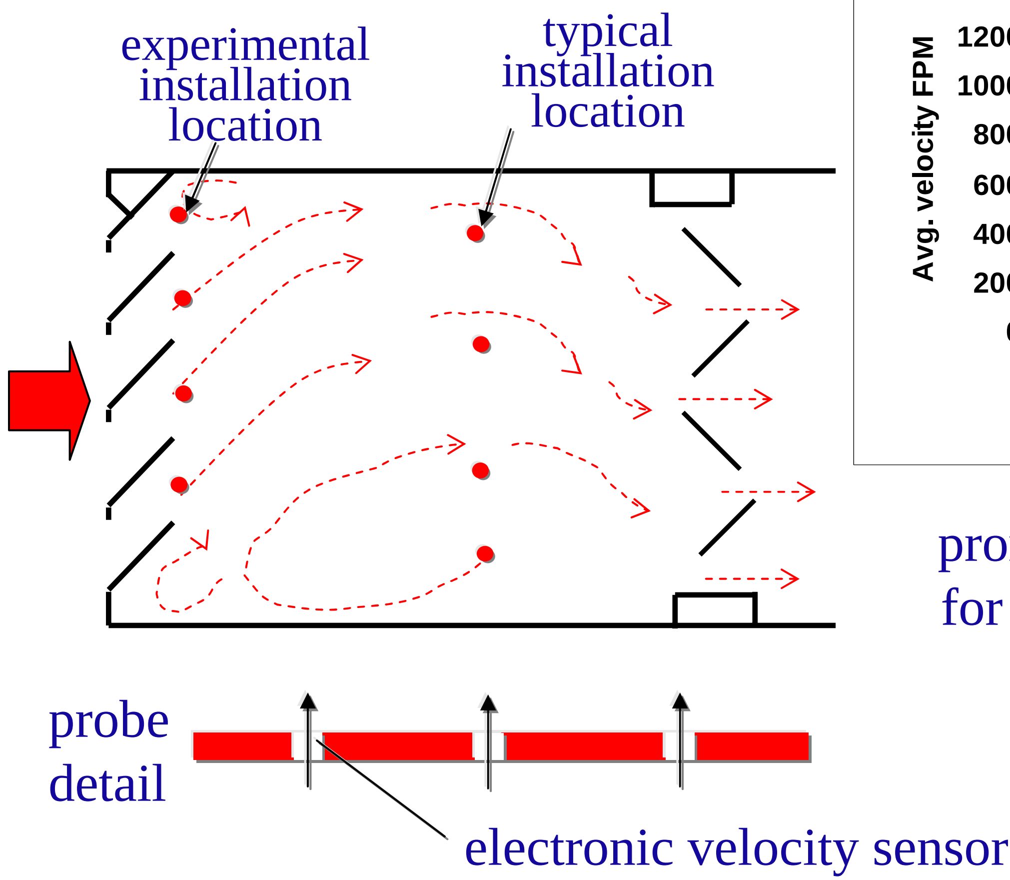
L1 had the most unidirectional downstream flow pattern

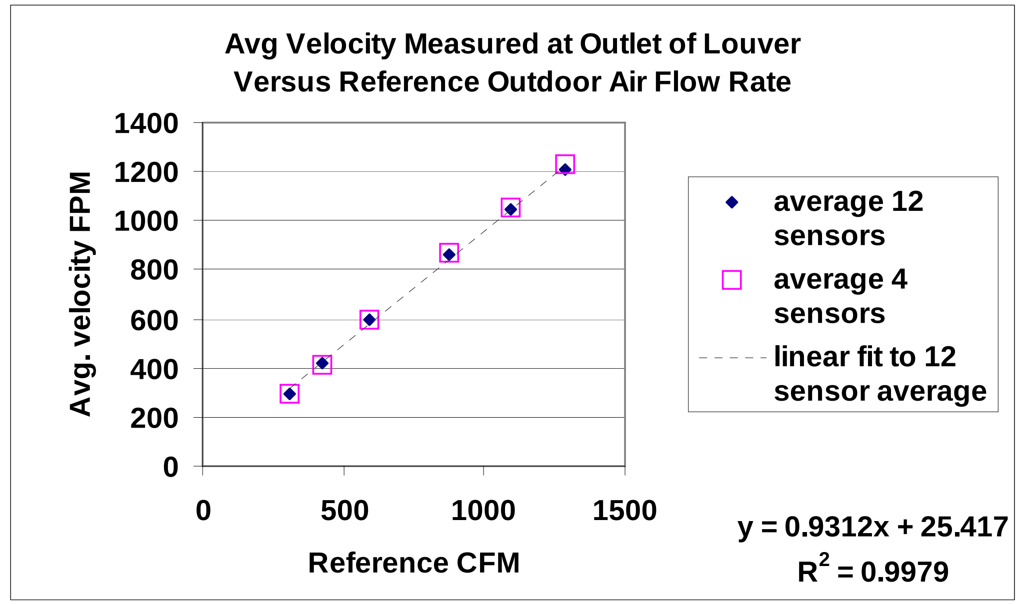
Possible "Cures" for Errors Due to Uneven Velocities and Large-Scale Eddies

- **Use intake louver without a strong outlet velocity component toward duct wall**
- **An airflow straightening device downstream of the louver helps somewhat**
- **Integrate measurement system with specific packages of louvers and OA dampers, and factory calibrate the assembly**
- **Place air speed sensors between louver blades and factory calibrate system**
- **Avoid abrupt contractions and expansions in the cross section of the airflow path between the louver and OA damper**



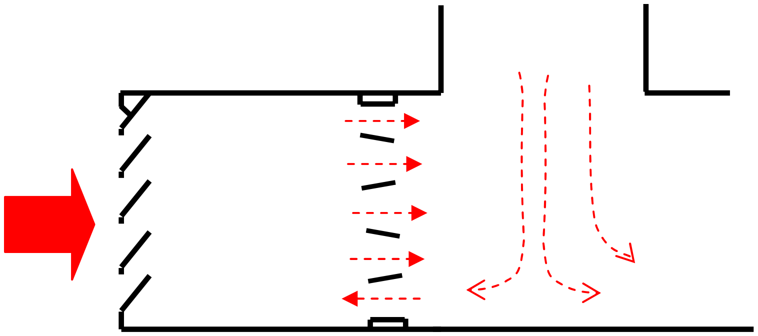
Current Research: Electronic Velocity Sensors Inside Louvers or at the Outlet Face





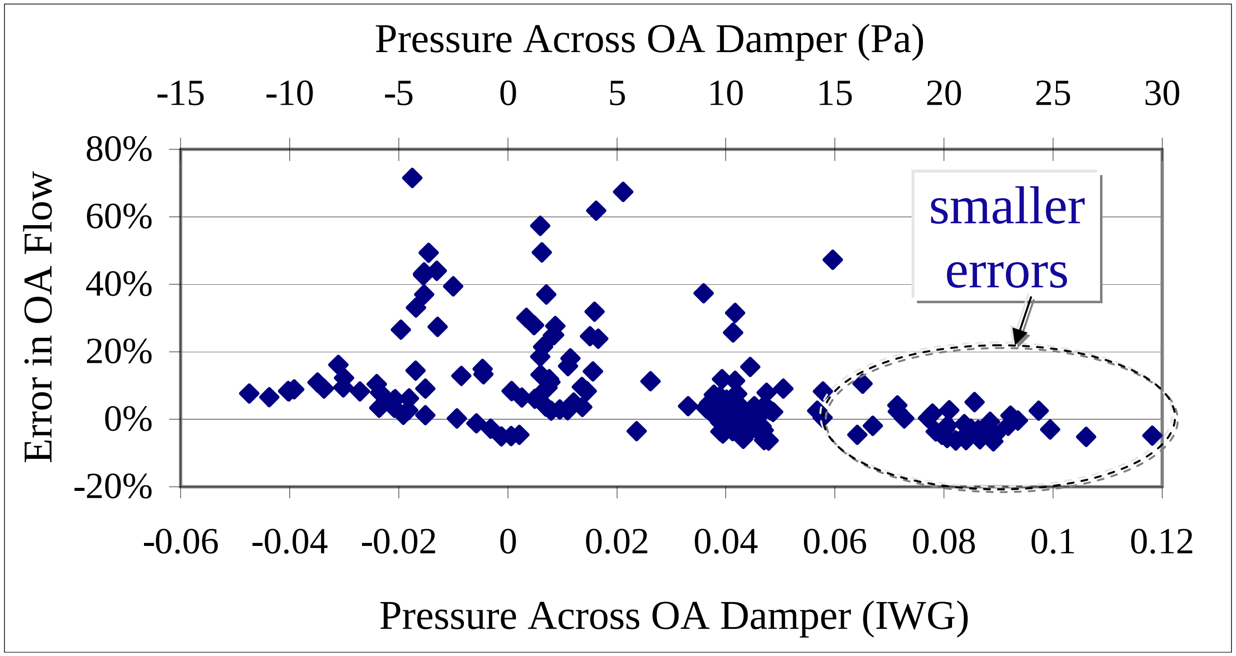
promising method with factory calibration for each combination of louver model and probe installation location

Cure for Backwards Airflow through Portion of OA Damper



Reduced OA flow rate measurement errors with MT4 with positive pressure maintained across OA damper

Maintain > ~0.06 IWG (15 Pa) ΔP across damper eliminated reverse airflow



Outdoor Air Intake Measurements: Take Home Messages

- OA ventilation rates are important and are often poorly controlled
- Don’t rely on supply flow minus return flow
- For better accuracy
  - Select the right louver
    - High maximum air speed
    - Louver outlet flow directed axially
  - Use two-section OA inlet to maintain velocities at minimum OA condition
  - Measure air speed between louver blades
  - If you rely on MT2, MT3, or MT4, an accurate field-based calibration is essential, although difficult
  - Maintain > 0.06 IWG (15 Pa) across OA damper
  - Use highly accurate pressure transducers

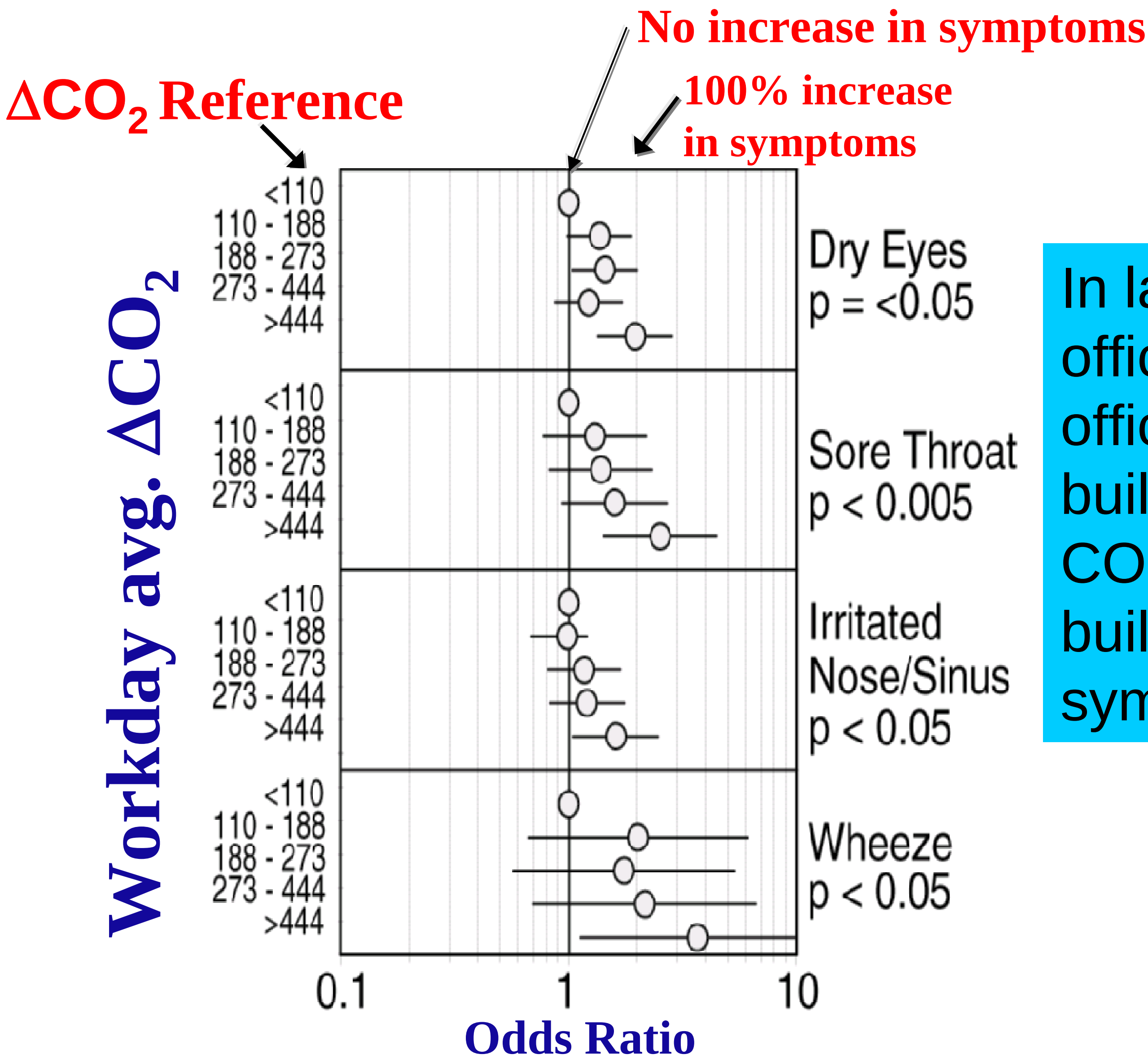
A PILOT STUDY OF THE ACCURACY OF CO_2 SENSORS IN COMMERCIAL BUILDINGS

Background

- Surveys indicate that minimum ventilation rates are poorly controlled in many commercial buildings
- CO_2 sensors/transmitters are used in demand controlled ventilation (DCV) systems
- With DCV, projected cooling energy savings are as high as 20%; projected heating energy savings are even larger
- CO_2 demonstrated as useful predictor of health symptoms, perceived air quality, absence, student performance

Many anecdotal reports of poor CO_2 sensor performance

Example of Relevance of CO_2 to Health



In large survey of office buildings, office workers in buildings with higher CO_2 had more sick building syndrome symptoms

Research Objective and Accuracy Targets

Objective

Determine if CO_2 sensor accuracy, in practice, is generally acceptable or problematic

Typical Indoor Peak Concentrations

Offices 100-building survey

	Peak ΔCO_2 (ppm)
Average	310
Median	269
Max	777

Schools 200-classroom survey

- **57% had peak ΔCO_2 < 575 ppm**
- **School day average ΔCO_2 for all classes = 645 ppm**

(Lenient?) Target Values for Accuracy

Offices

62 ppm (20% of avg. peak ΔCO_2)

54 ppm (20% of med. peak ΔCO_2)

Schools

120 ppm

(~ 20% of average ΔCO_2)

Methods

- Measured accuracy of CO_2 sensors in CA commercial buildings
- 44 sensors
- 9 buildings
- 6 “brands”

Multipoint Calibration Checks

Challenge sensor with 5 primary standard calibration gases
269 ppm ± 7% to 1180 ppm ± 2%

Calculate zero-offset and slope error

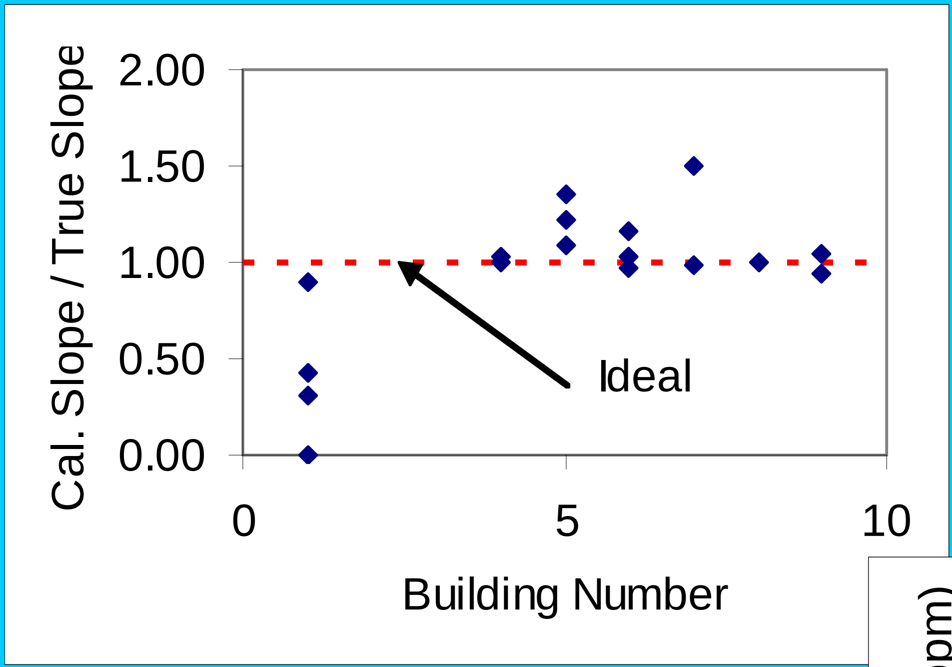
Compare predicted errors at 600 & 1000 ppm to targets

Single Point Calibration Checks

Compare sensor reading to concentration measured simultaneously at same location with calibrated reference instrument with estimated ± 30 ppm accuracy

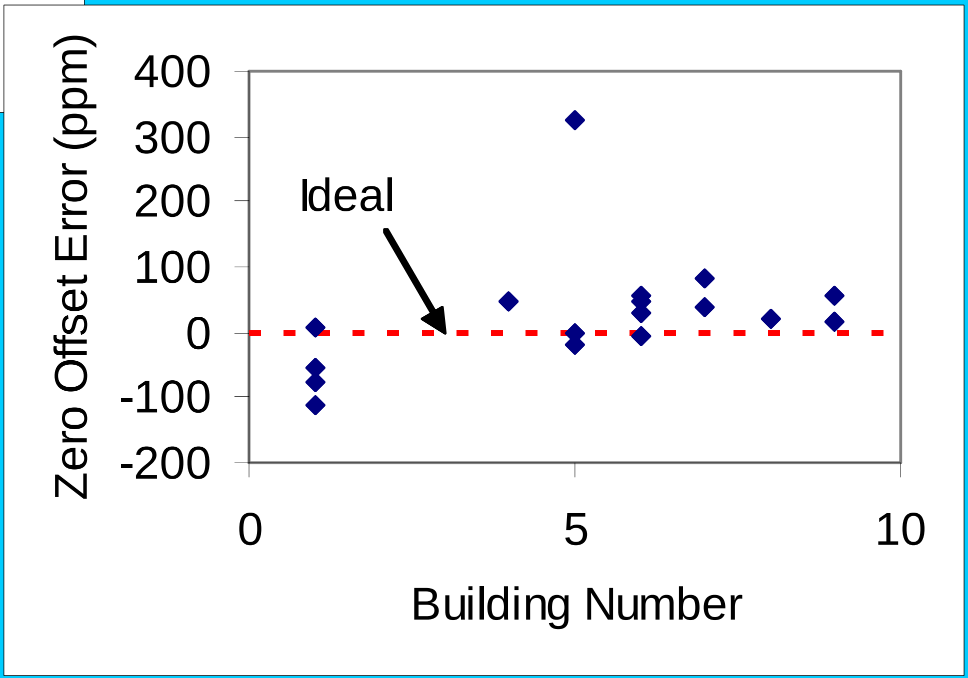
Compare errors to targets

Results – Multipoint Calibration Checks

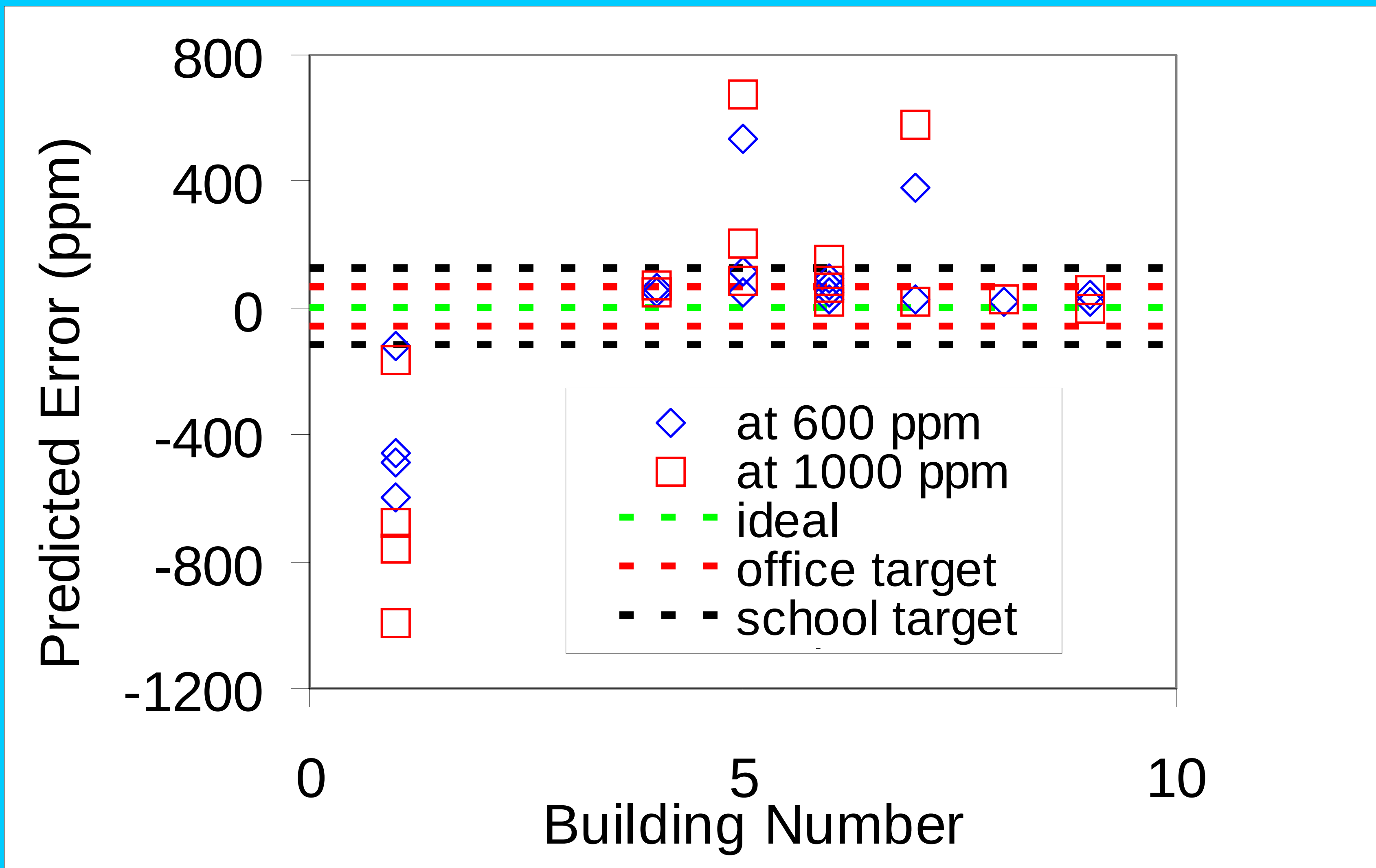


Error in Sensor Gain

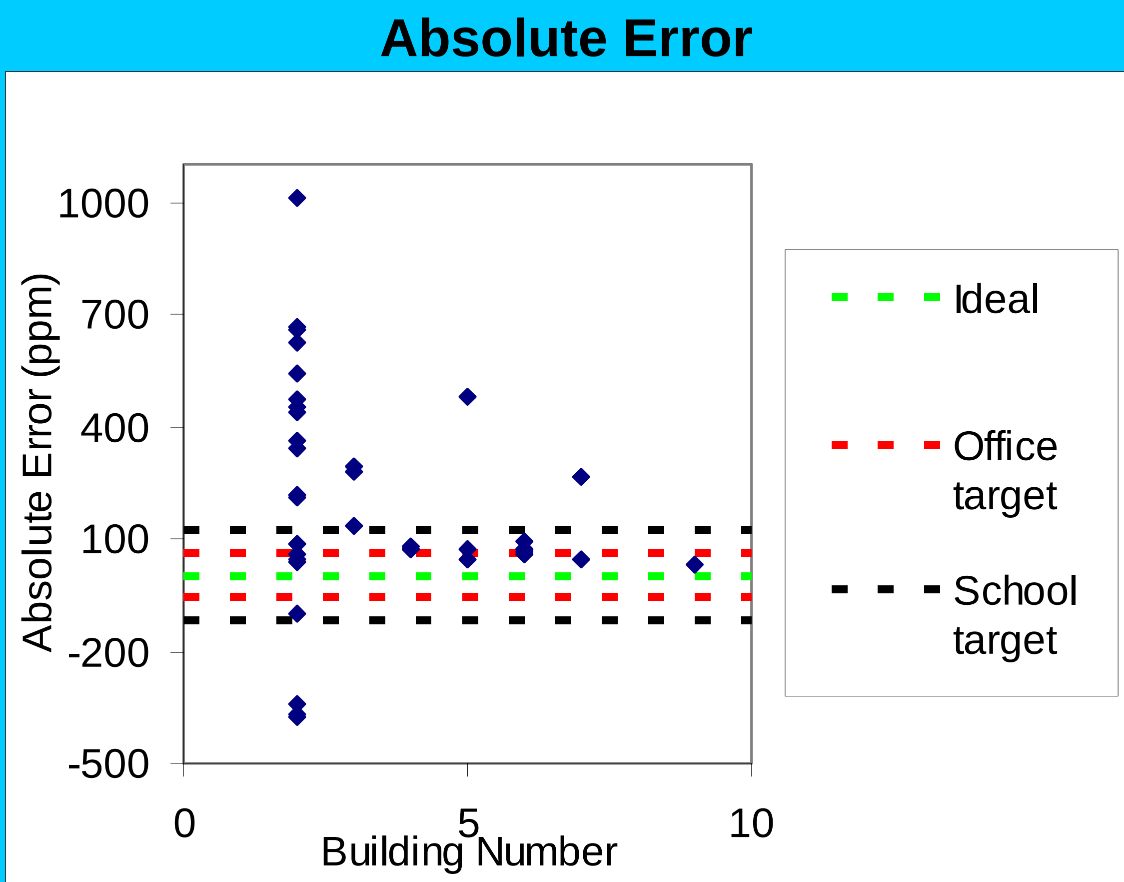
Zero Offset Error

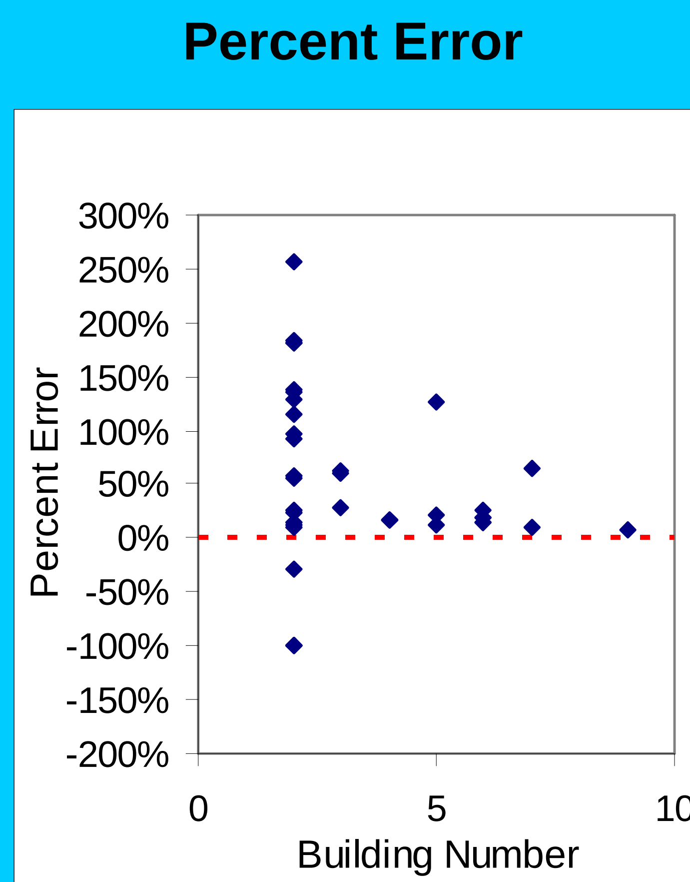


Results- Multipoint Calibration Checks



Results – Single Point Calibration Checks

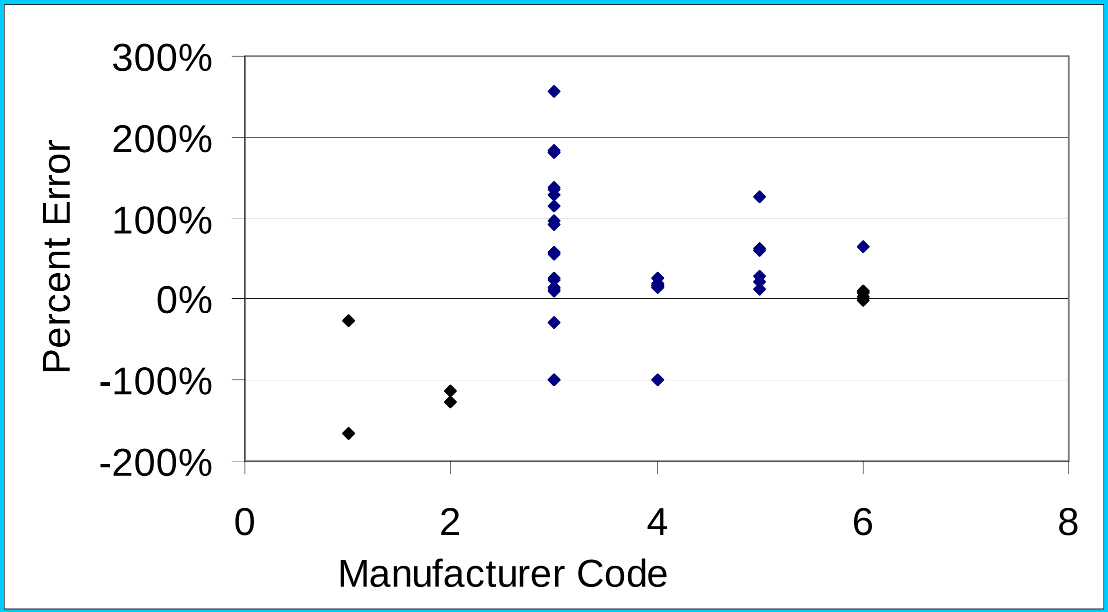




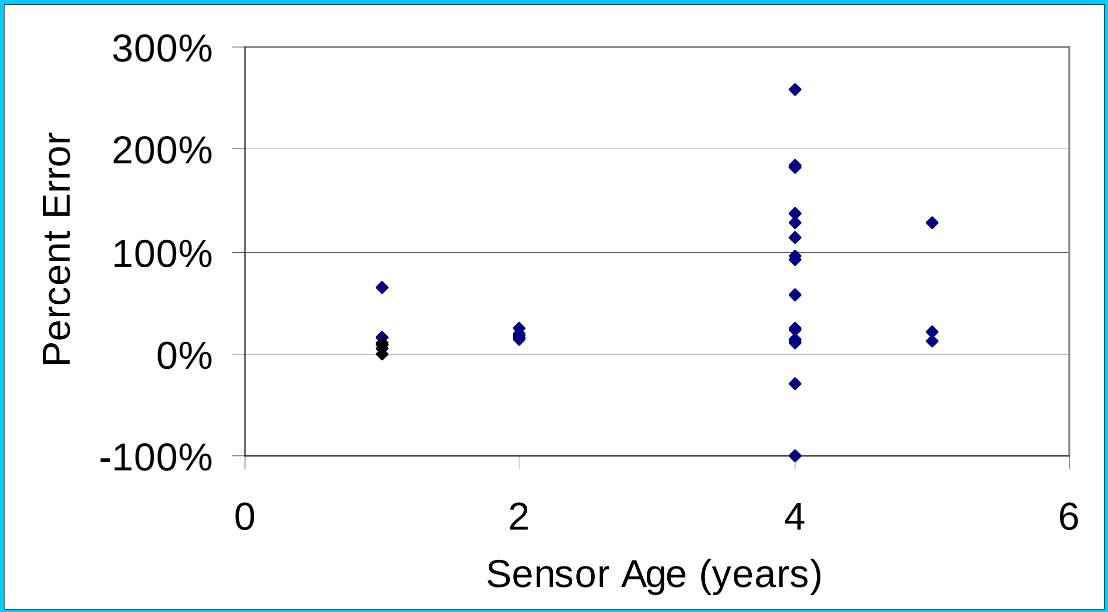
Absolute value of error

Average	**256 ppm**	**68%**
Median	**173 ppm**	**43%**

Accuracy vs. Manufacturer Code and Sensor Age



No Clear Trend (insufficient data)



No Clear Trend (insufficient data)

Pilot Study of CO_2 Sensors:
Summary and Conclusion

Summary

- accuracy of CO_2 sensors used in commercial buildings is frequently less than is needed to measure peak indoor-outdoor CO_2 concentration differences with less than a 20% error

Conclusion

- need more accurate CO_2 sensors and/or better sensor maintenance or calibration procedures

Recommendation

- Current users of CO_2 sensors for demand controlled ventilation should perform frequent sensor calibrations

Demand Controlled Ventilation

Current & Pending Research

Current

- Iowa Energy Office is performing detailed laboratory studies of the accuracy of new CO_2 sensors

Pending

- Lawrence Berkeley National Lab to perform larger study of in-situ sensor accuracy, sensor installation locations, and alternatives to use of low cost distributed CO_2 sensors

Acknowledgments

- Support from U.S. Department of Energy
  - Evaluation of OA measurement methods
  - Pilot study of CO_2 sensor accuracy
- Support from California Energy Commission
  - Current research on use of electronic sensors inside or at outlet of louvers
  - Probable future support for research on demand controlled ventilation
- Contributions of colleagues to research implementation
  - David Faulkner
  - Doug Sullivan
- Reviews and advice
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