Heating, Ventilating, & Air-Conditioning: Diagnostics & Controls to Improve Air-Handling System Performance

Craig Wray, P.Eng.

Indoor Environment Department
Lawrence Berkeley National Laboratory

Tel: 510-486-4021 Email: CPWray@lbl.gov http://epb.lbl.gov

American Physical Society Short Course

Physics of Sustainable Energy: Using Energy Efficiently and Producing It Renewably

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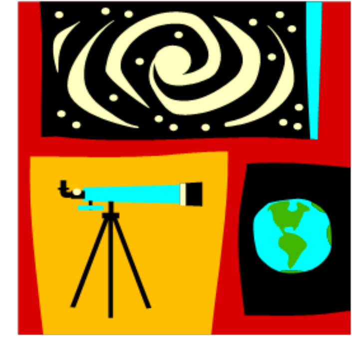
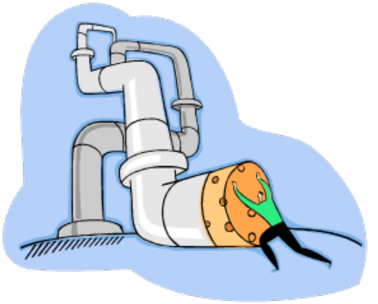
Overview



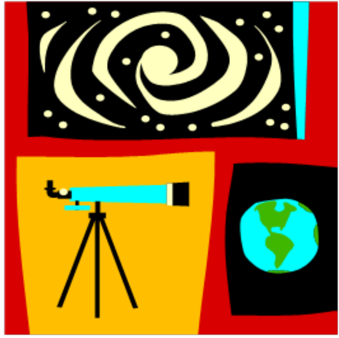
- Background
  - Opportunities for improvement
- Duct Leakage Diagnosis
  - Measuring leakage flows using the DeltaQ test
- Duct Pressure Diagnosis & Control
  - Demand-based reset with DDC/non-DDC controls
- Ventilation Control
  - Intermittent ventilation and efficacy

Opportunities for Improvement



- Duct Leakage and Operating Pressure
  - Thousands of field assembled joints
  - System pressures not uniform or constant; impossible to know location of each leak and pressure difference across each leak
  - Unnecessarily closed dampers restrict flow
  - Large energy savings possible from sealing ducts and optimizing duct static pressures
- Ventilation
  - Standards specify constant ventilation rates
  - Energy intensive process; sometimes can *reduce* IAQ
  - Intermittent ventilation more appropriate in some cases

Overview



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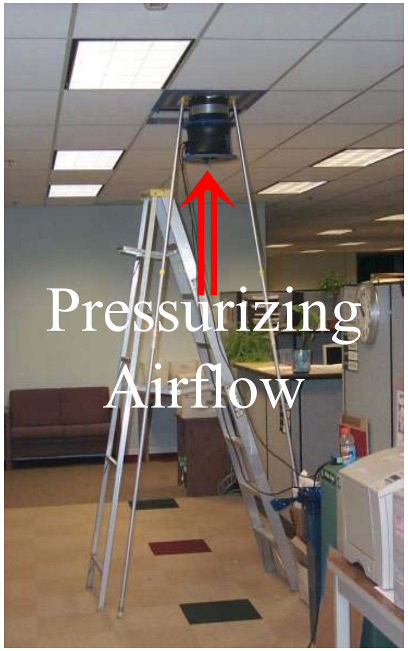
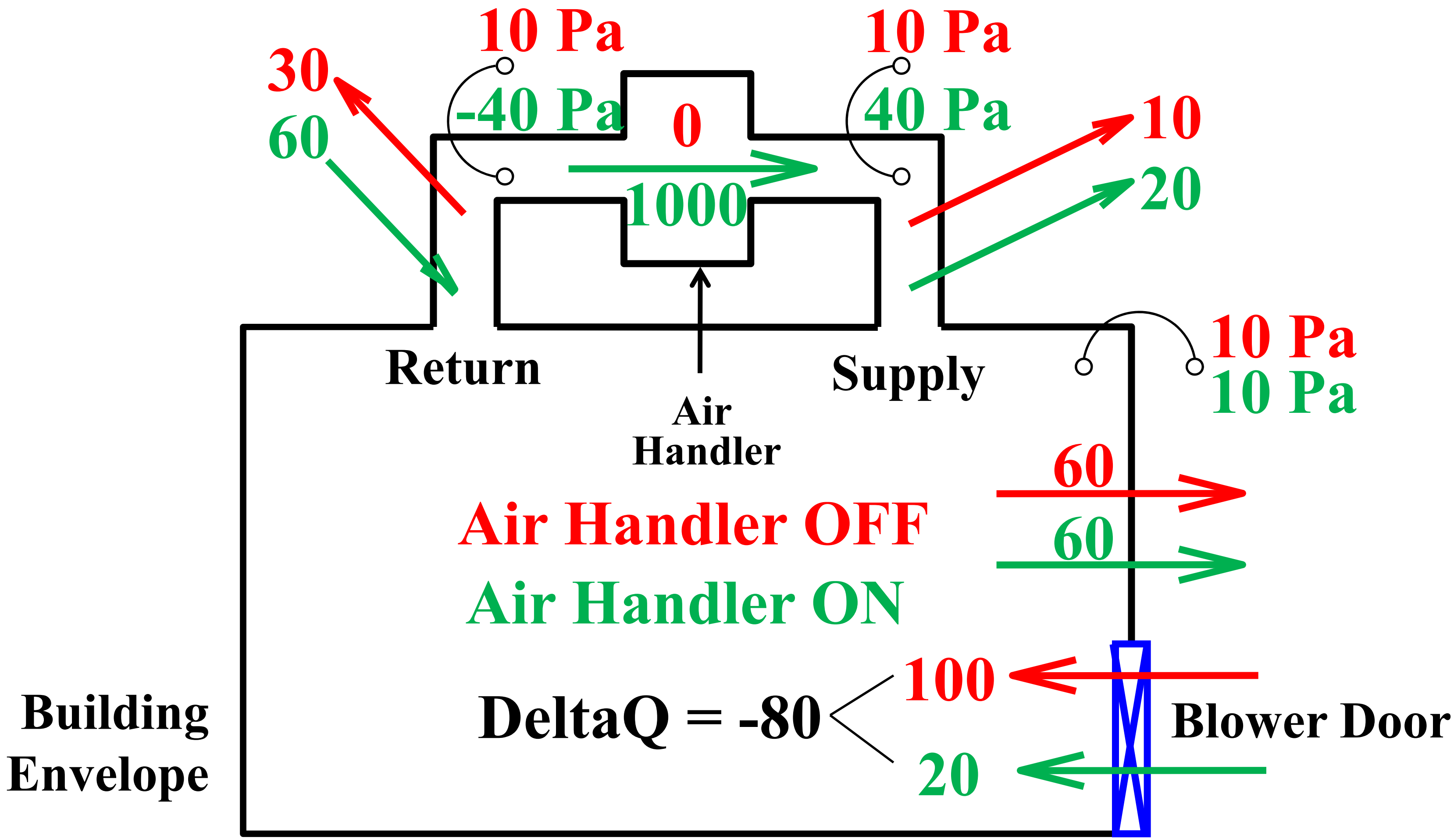
Why Use DeltaQ Duct Leakage Test?

- Fast and easy
  - No register covering (less damage potential)
  - Coincidentally measures envelope leakage
  - Uses familiar equipment (blower door)
  - Self-diagnostic for uncertainty
  - Can be automated
- Accurate
  - Leaks to outside under operating conditions
- BUT…
  - Need a computer
  - Need to operate central blower



DeltaQ Airflows and Pressures



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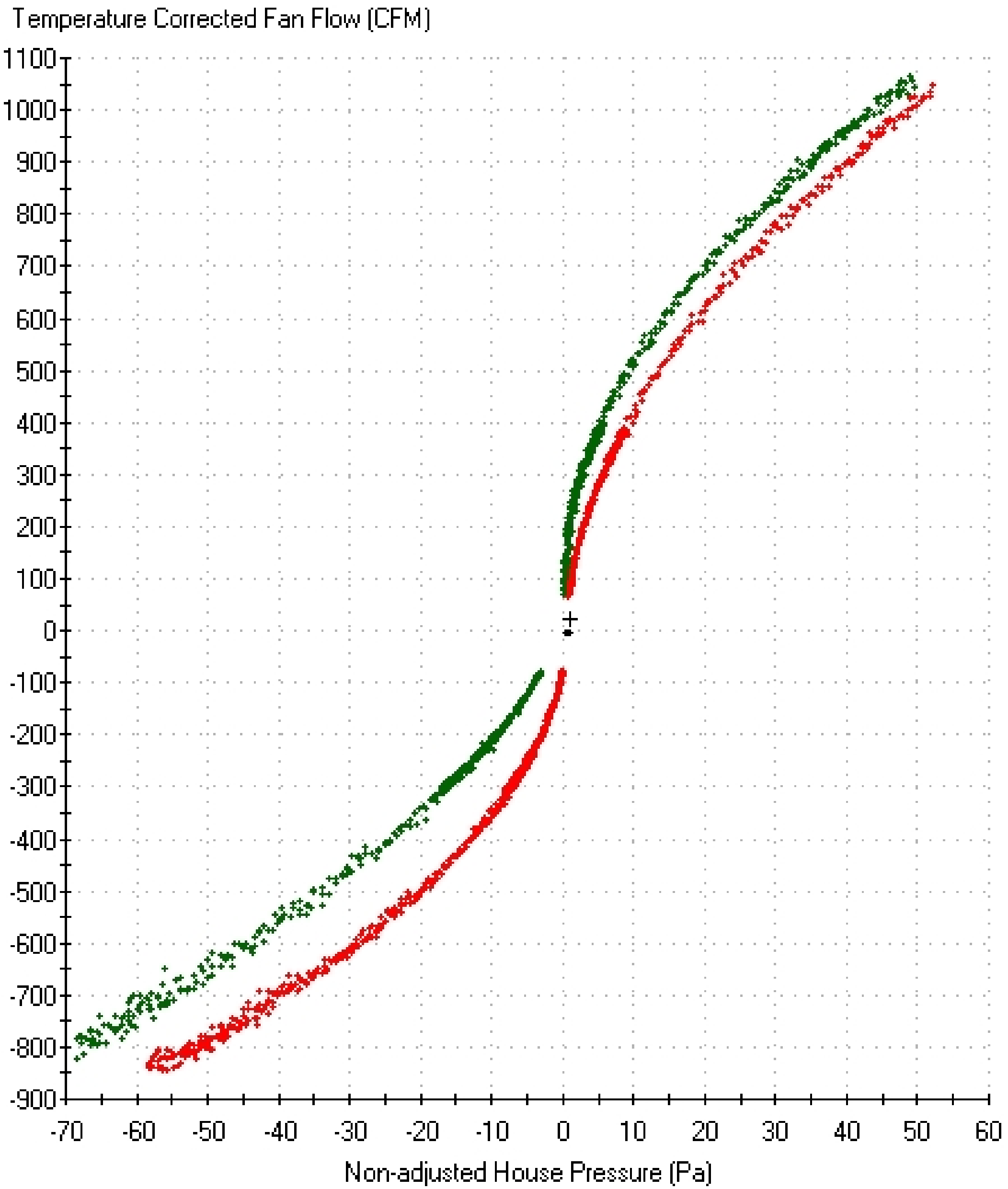


DeltaQ Test Data

- Green = blower on
- Red = blower off
- Difference = DeltaQ

DeltaQ Model

P = Envelope added pressure
P_s = Supply Pressure
P_r = Return Pressure

C_s=Supply leak coefficient
C_r=Return leak coefficient
Q_s=Supply leak flow
Q_r=Return leak flow

$$DeltaQ(P)=Q_{on}(P)-Q_{off}(P) \qquad Q=C(P)^n$$

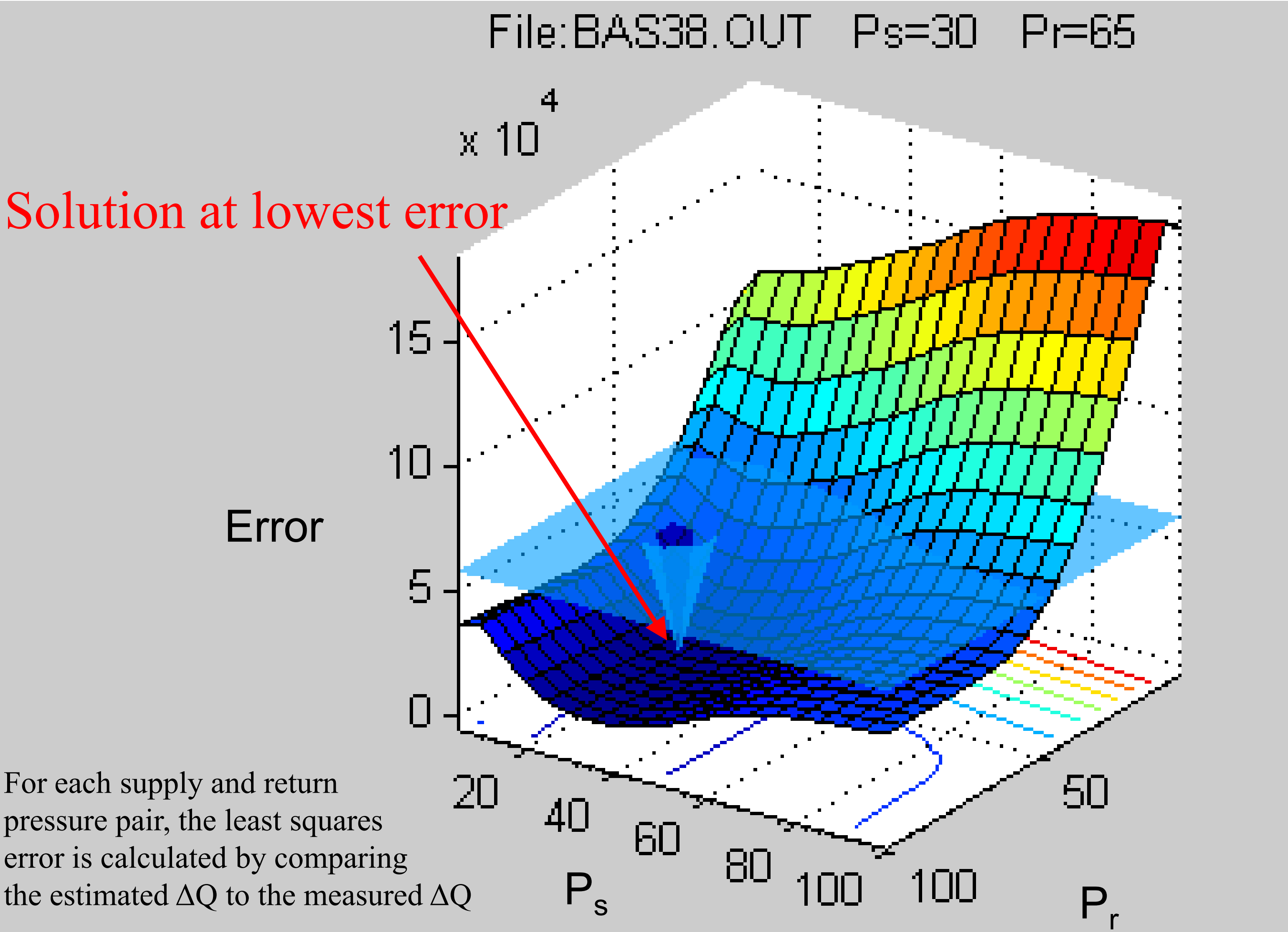
$$Q_{on}(P)=Q_{env}(P) + C_s(P+Ps)^{ns} + C_r(P-Pr)^{nr}$$

$$Q_{off}(P)=Q_{env}(P) + C_s(P^{ns}) + C_r(P^{nr})$$

$$DeltaQ(P)=C_s((P+P_s)^{ns}-P^{ns}) + C_r((P-P_r)^{nr}-P^{nr})$$

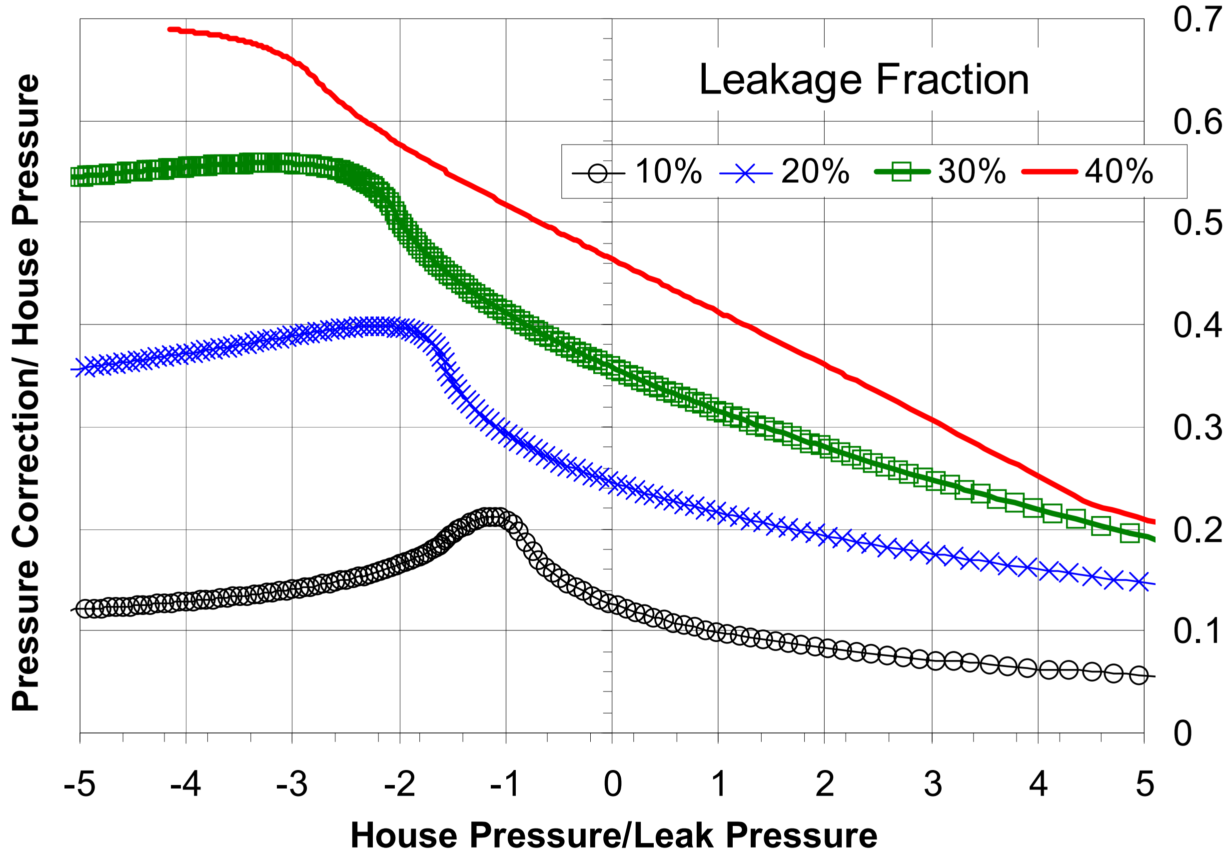
$$DeltaQ(P)=Q_s((1+P/P_s)^{ns}-(P/P_s)^{ns}) - Q_r((1-P/P_r)^{nr}+(P/P_r)^{nr})$$

Pressure Scanning Error Surface



For each supply and return pressure pair, the least squares error is calculated by comparing the estimated ΔQ to the measured ΔQ

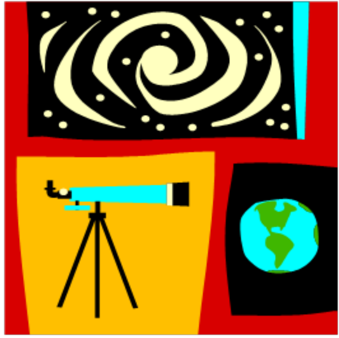
Duct Flow Resistance Correction



Difference between flow through air handler and flow through ducts

Flow through leak

$$1-\left(1-\frac{Q_{r,s}}{Q_{ah}}\right)\left[1\pm\frac{\delta P_{r,s}^{on}}{P_{r,s}}\right)^{1/2} = \frac{Q_{r,s}}{Q_{ah}}\left[1\mp\frac{P-\delta P_{r,s}^{on}}{P_{r,s}}\right)^{n_{r,s}}$$



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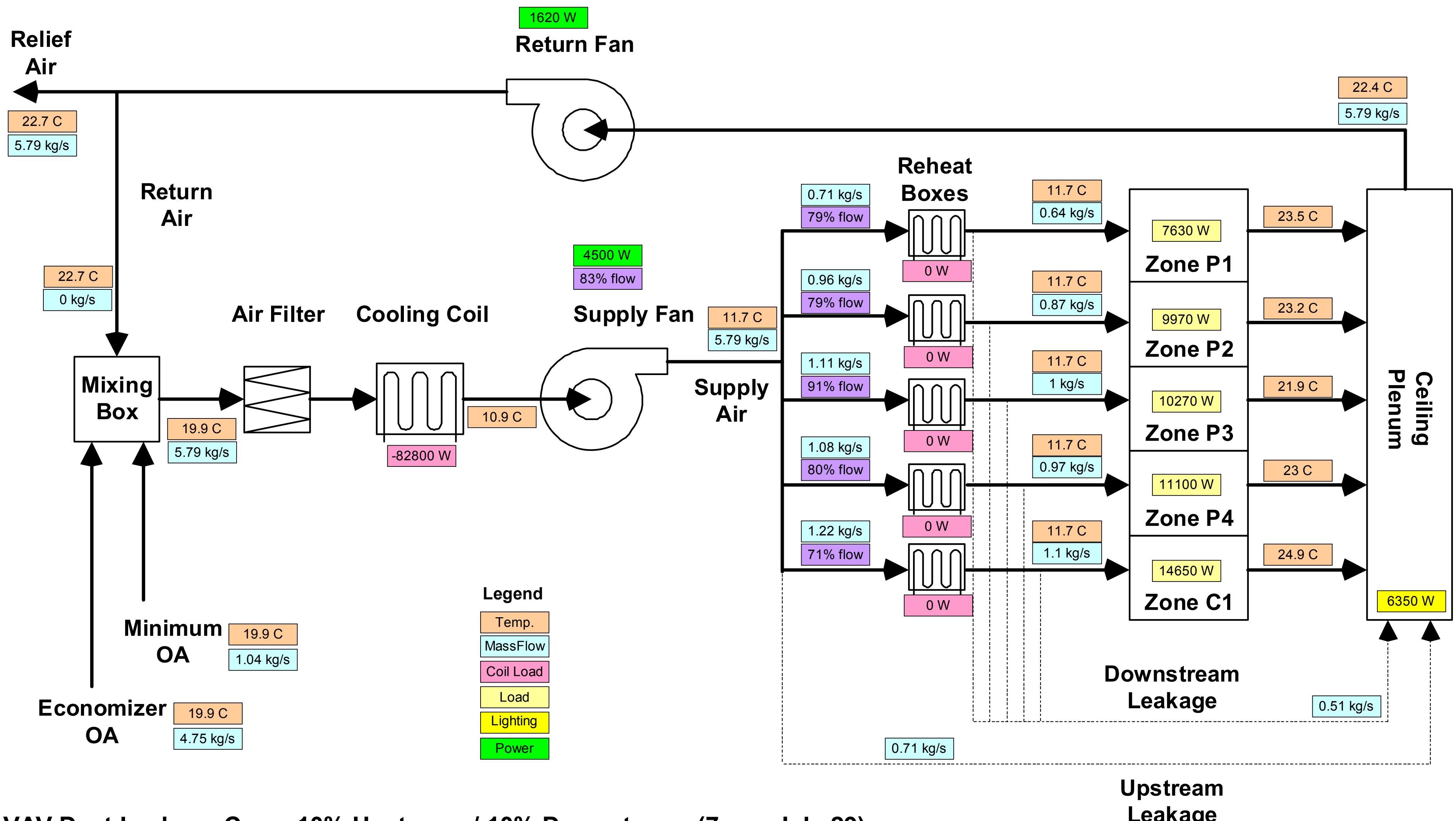
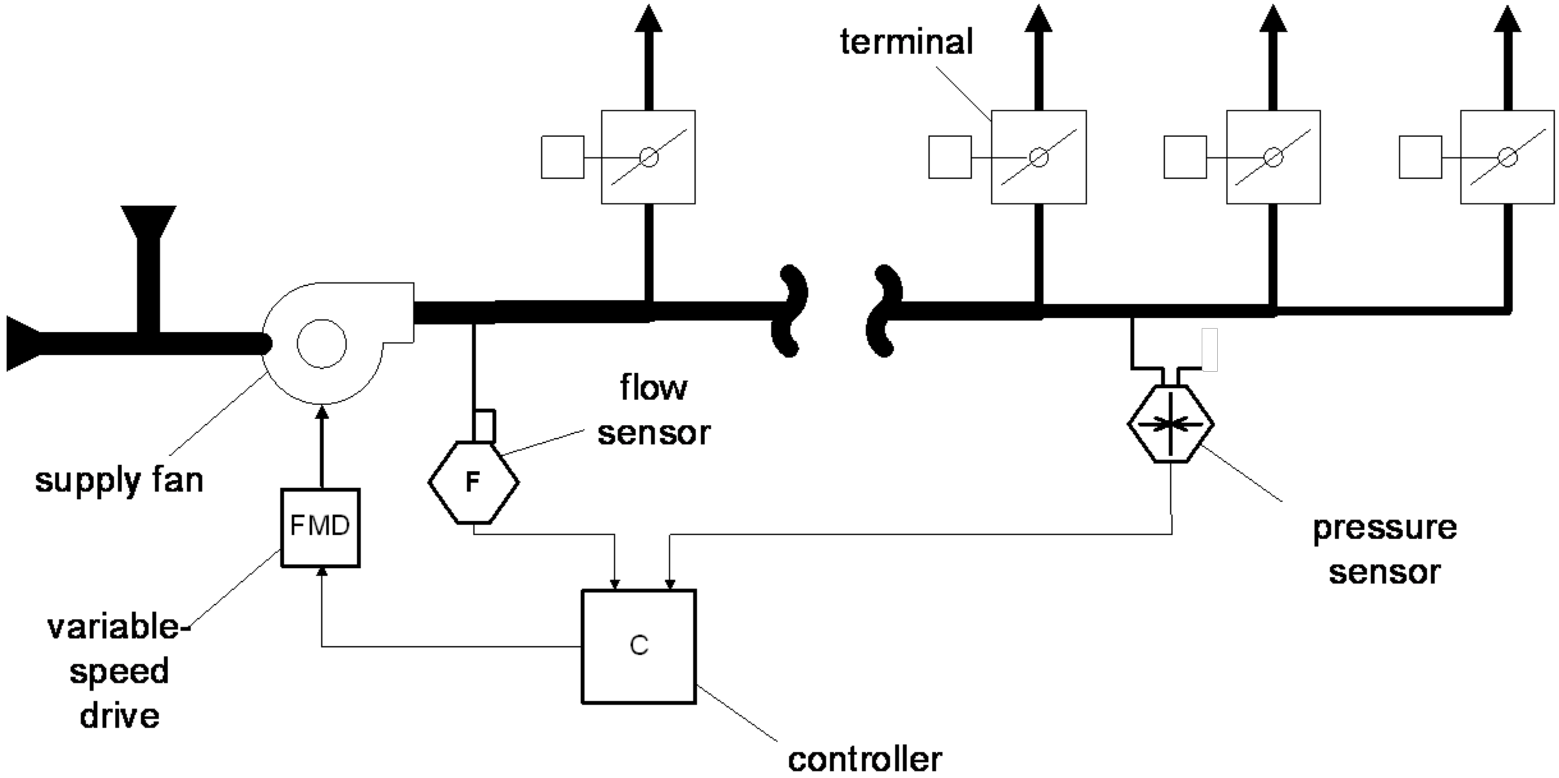
Variable-Air-Volume System Schematic

$$W = \frac{Q \cdot \Delta P}{\eta_{system}} \approx \frac{Q^{(1+1/n)}}{\eta_{system}}$$



VAV Duct Leakage Case: 10% Upstream / 10% Downstream (7 am, July 29)

VAV System Control

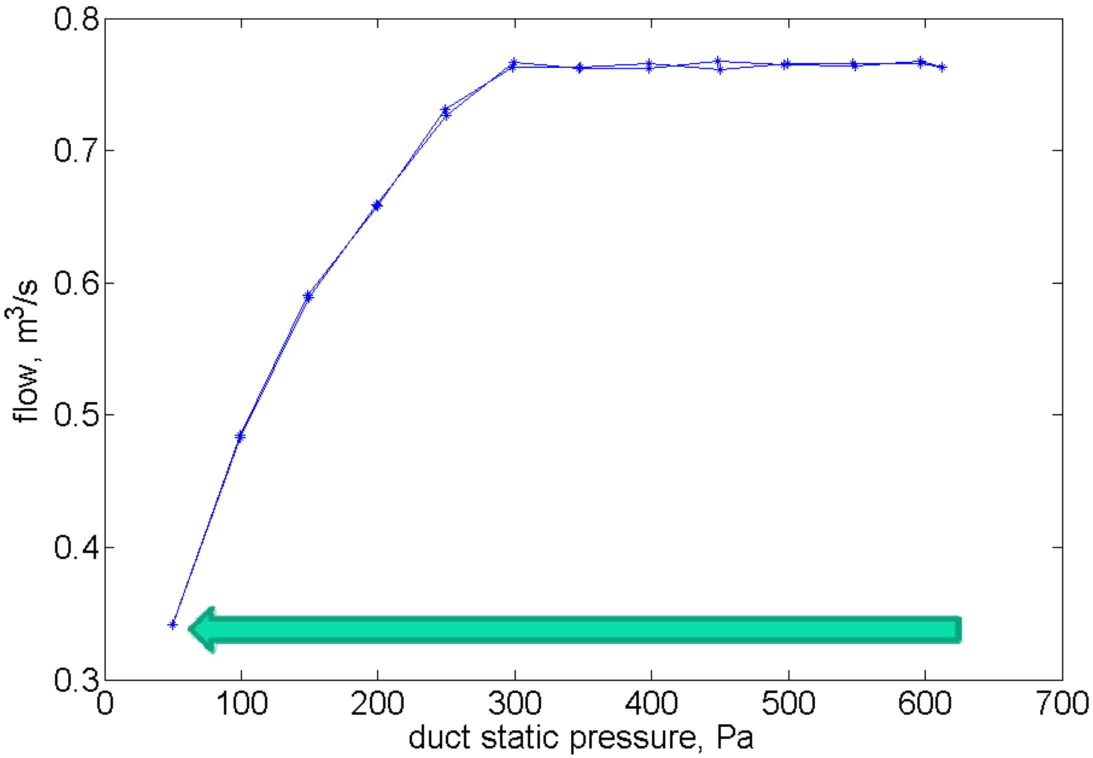


Duct Static Pressure Reset Issues

- DDC systems with reset capability already exist, but suffer from:
  - Inaccurate, open-loop position measurement
  - Failures at terminal boxes
  - Limited bandwidth and limited programming capabilities
- Many systems have pneumatic terminal controls
- Using total supply airflow signal from airflow station expands reset applicability
- Aggregation of terminal box flows makes control more robust to single terminal failure

Diagnostic Principle

- Terminal flows are regulated by thermostat, independent of duct static pressure
- Test Procedure
  - Start at high pressure
  - Incrementally lower pressure
  - Record flow signal at each step
- Complicating Issues
  - Flow stabilizes slowly
  - Zone temperatures can change
  - Noisy measurements
  - Ducts leak (pressure-dependent)



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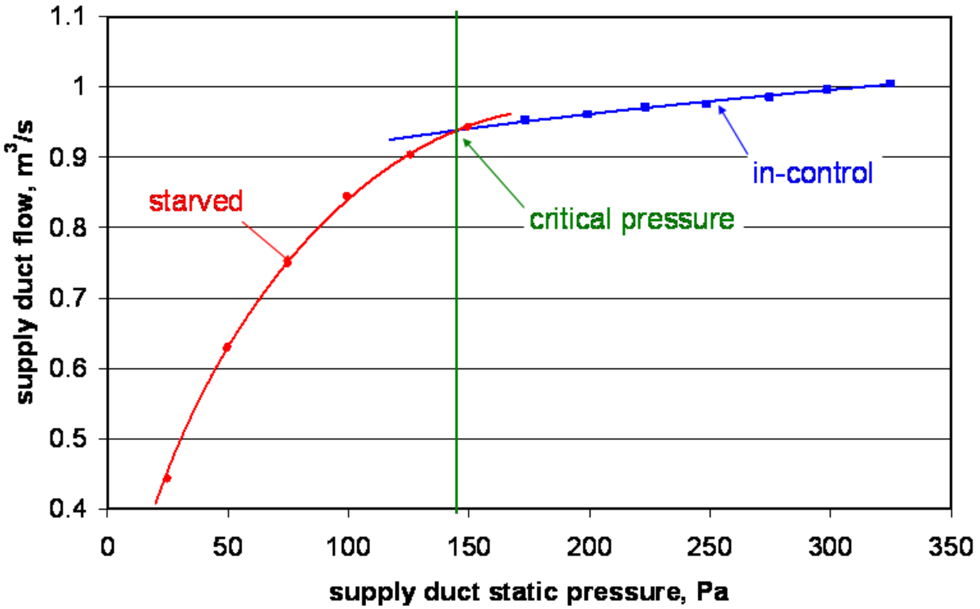
Diagnostic: Dual-Model Estimation

- Model components
  1. Constant component
  2. Time-varying component
  3. Leakage flow
  4. Starved behavior



- "In-Control":

$$Q_c = Q_0 + C_t T + C_p P^N$$

- "Starved": $Q_S = \left(C_0 P^N + C_1 P^{1+N} + C_2 P^{2+N}\right)\left(1 + \frac{C_t T}{Q_0}\right) + C_p P^N$

- At critical pressure, both models predict same flow; solve for transition using least squares fit

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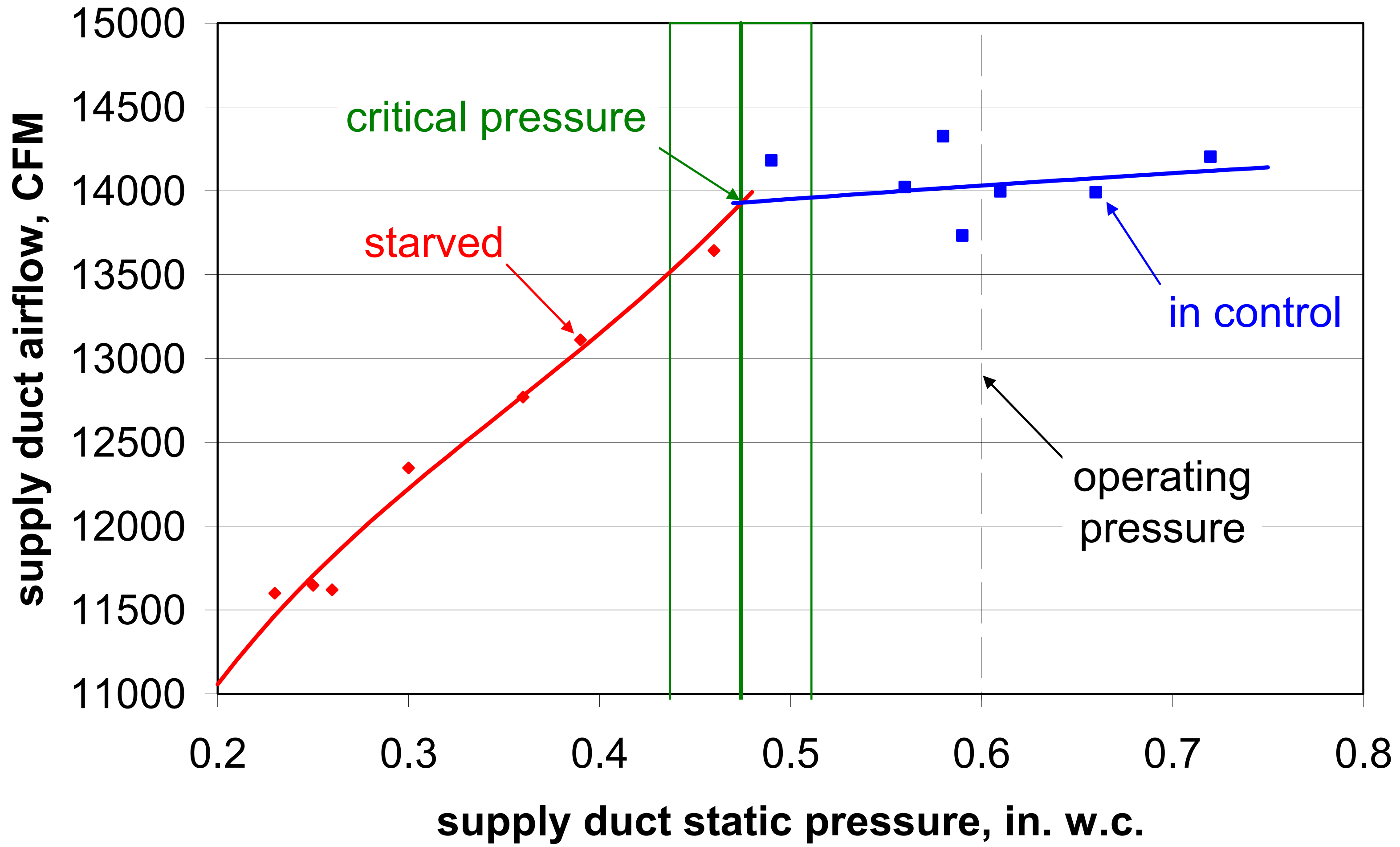
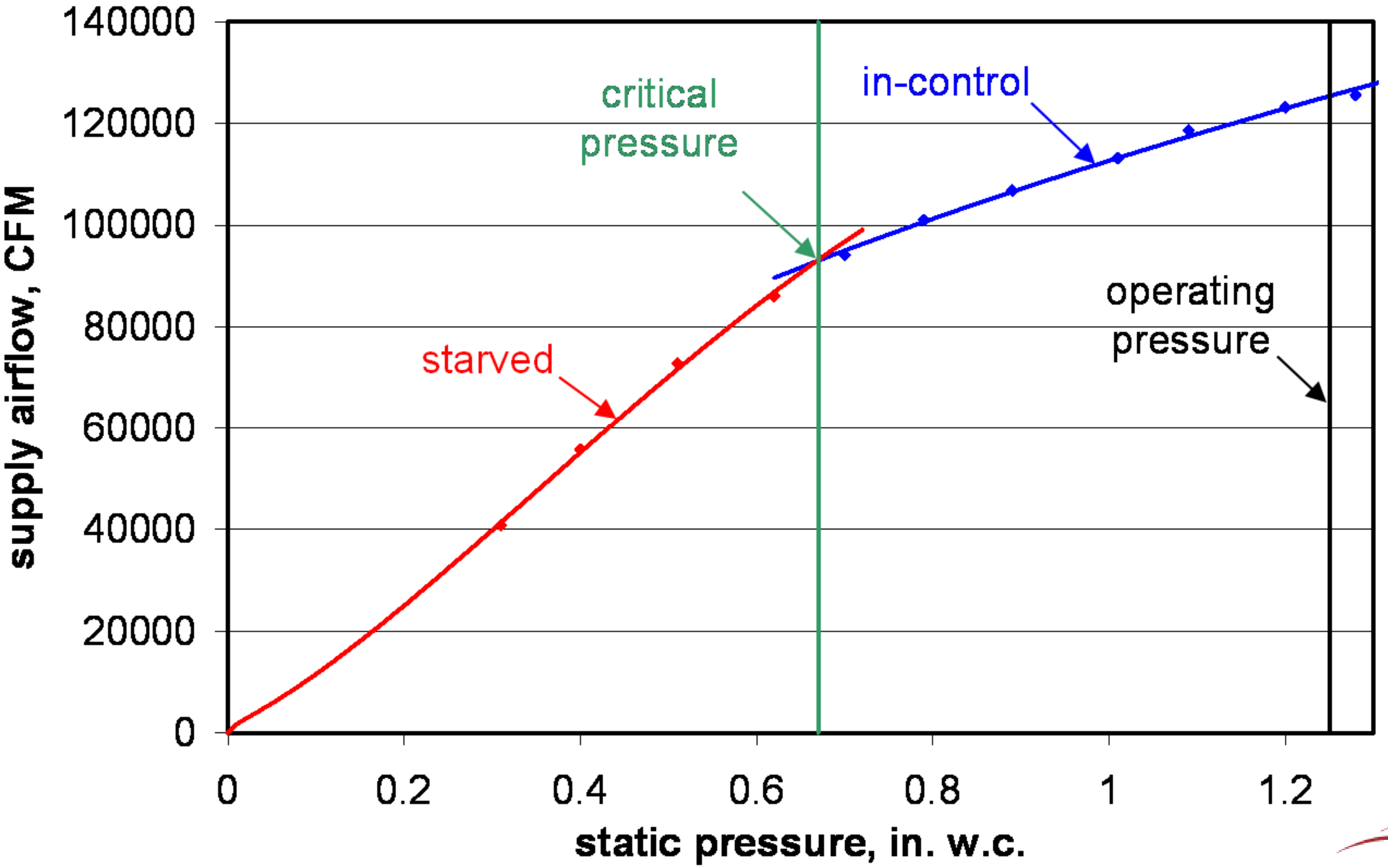
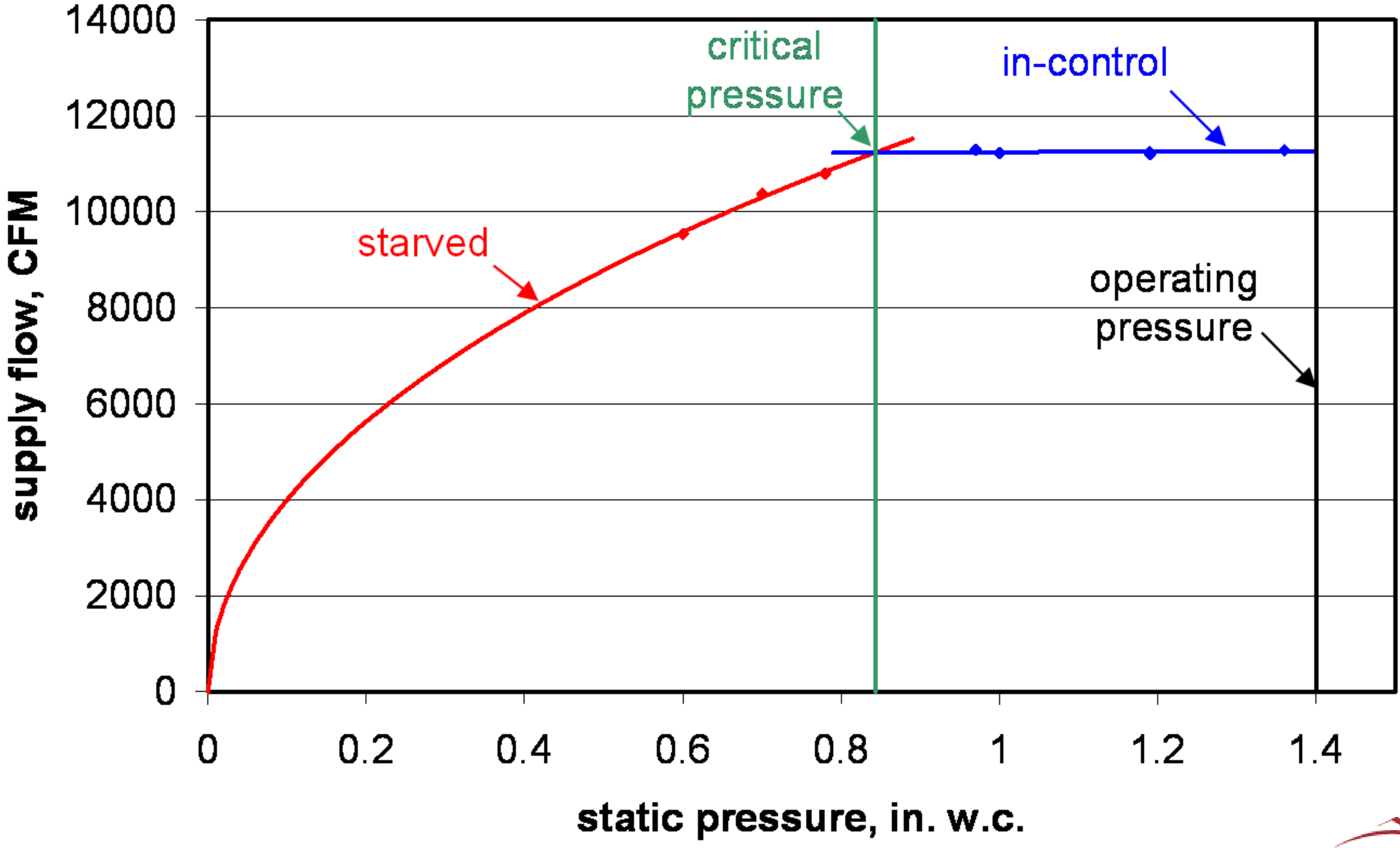


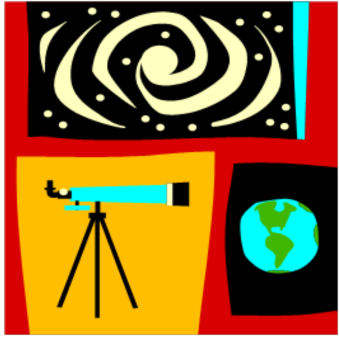
UCOP



supply airflow, CFM
140000
120000
100000
80000
60000
40000
20000
0
0
0.2
0.4
0.6
0.8
1
1.2
static pressure, in. w.c.
critical pressure
in-control
starved
operating pressure

County of Alameda





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Intermittent Ventilation: When Steady Won't Always Do

- Ventilation (for acceptable IAQ) should not always be constant
- May be periods of the day when outdoor air (OA) quality is poor and one wishes to reduce amount of OA entering building
- Economizer operation can over-ventilate a space from IAQ point of view; energy savings can be achieved by reducing ventilation rates at other times to account for over-ventilation
- Demand charges or utility peak loads may make it advantageous to reduce ventilation for certain periods of the day
- Some HVAC equipment may make cyclic ventilation more attractive than steady-state ventilation
  - Example: residential or small commercial systems that couple ventilation to heating and cooling system operation

What's The Problem?

- Constant target ventilation (A_{eq})
- Intermittent ventilation with cycle time (T_{cycle}), over-ventilation (A_{high}) for fractional time f_{high}, and under-ventilation (A_{low}) for fractional time f_{low}
- *Equivalency* = same dose for constant contaminant source
  - Sherman & Wilson (1986); Std 136
- Means to demonstrate equivalency not obvious:
  - Designers want flexibility to use intermittent ventilation, but also want to follow standards & guidelines
  - Average not always same as constant

Efficacy is Link

- Provide calculation method to assess equivalency
  - Find the temporal ventilation effectiveness ("efficacy") of a given pattern of ventilation
- Definition: $\varepsilon = \dfrac{A_{eq}}{f_{low}A_{low} + (1 - f_{low})A_{high}}$
- Typical Use: $A_{high} = \dfrac{A_{eq}/\varepsilon - f_{low}A_{low}}{(1 - f_{low})}$

Hyperbolic Cotangent?

$$\varepsilon = \frac{1 - f_{low}^2 \mathrm{N} \cdot \coth(\mathrm{N} / \varepsilon)}{1 - f_{low}^2}$$

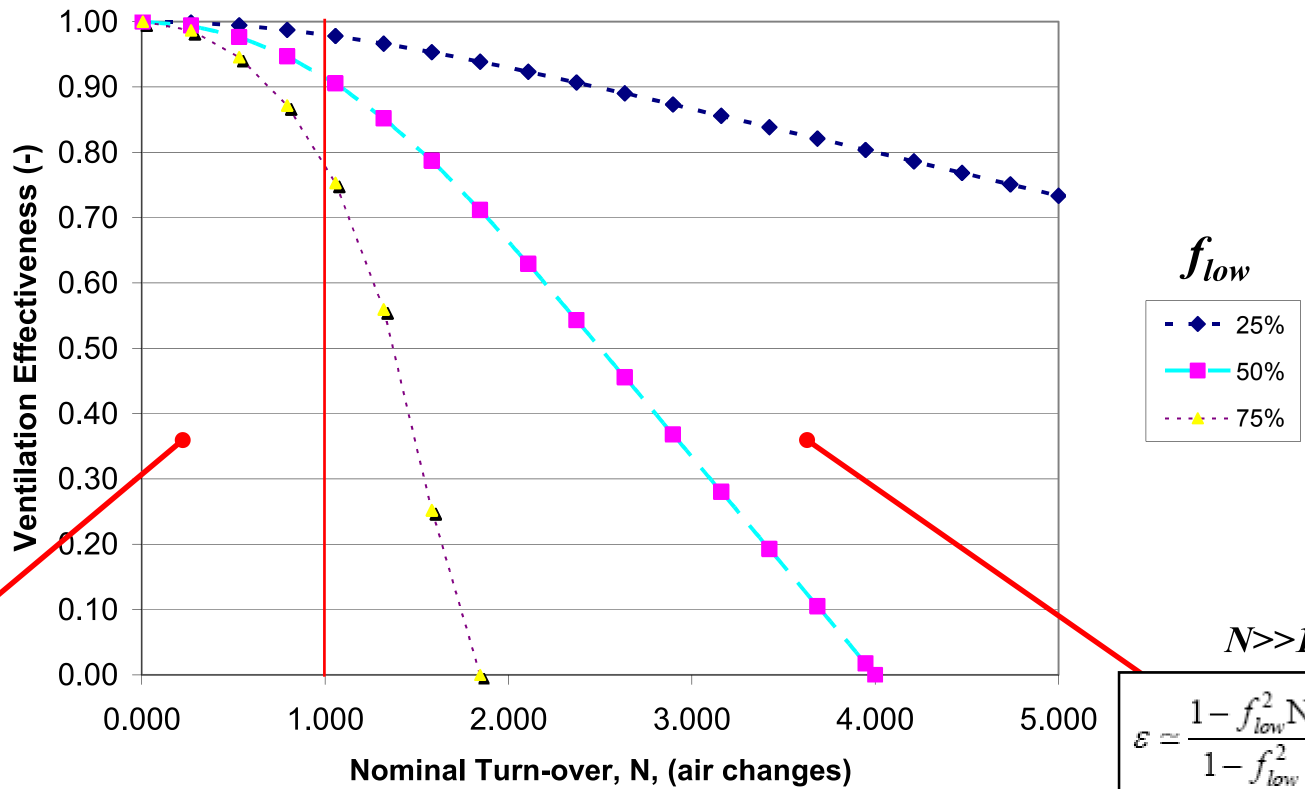
- Nominal Turnover: $\mathrm{N} \equiv \frac{(A_{eq} - A_{low}) \cdot T_{cycle}}{2}$
- Fraction of time under-ventilated: f_{low}
- Recursive equation → numerical solution
- Use efficacy for design

Air Change Rates & Turn-Over Times

ach (1/h)	*Turn-Over Time (h)*	*DESCRIPTION*
0.15	6.67	Infiltration rate of *new homes*
0.25	4.00	Infiltration rate of *commercial buildings*
0.3	3.33	Ventilation requirement of *almost empty commercial buildings* [from Std 62.1-2004]
0.5	2.00	*Office space* requirement [from Std 62.1-2004]; also *large home* [from Std 62.2-2004]
0.7	1.43	Ventilation requirement for *small homes*
1.0	1.00	Infiltration rate of *older homes*
2.0	0.50	*Conference room* requirement [from Std 62.1-2004]
4.0	0.25	*High density space* (e.g., theater lobby)

Efficacy Trends

Efficacy for Different Under-Ventilation Fractions



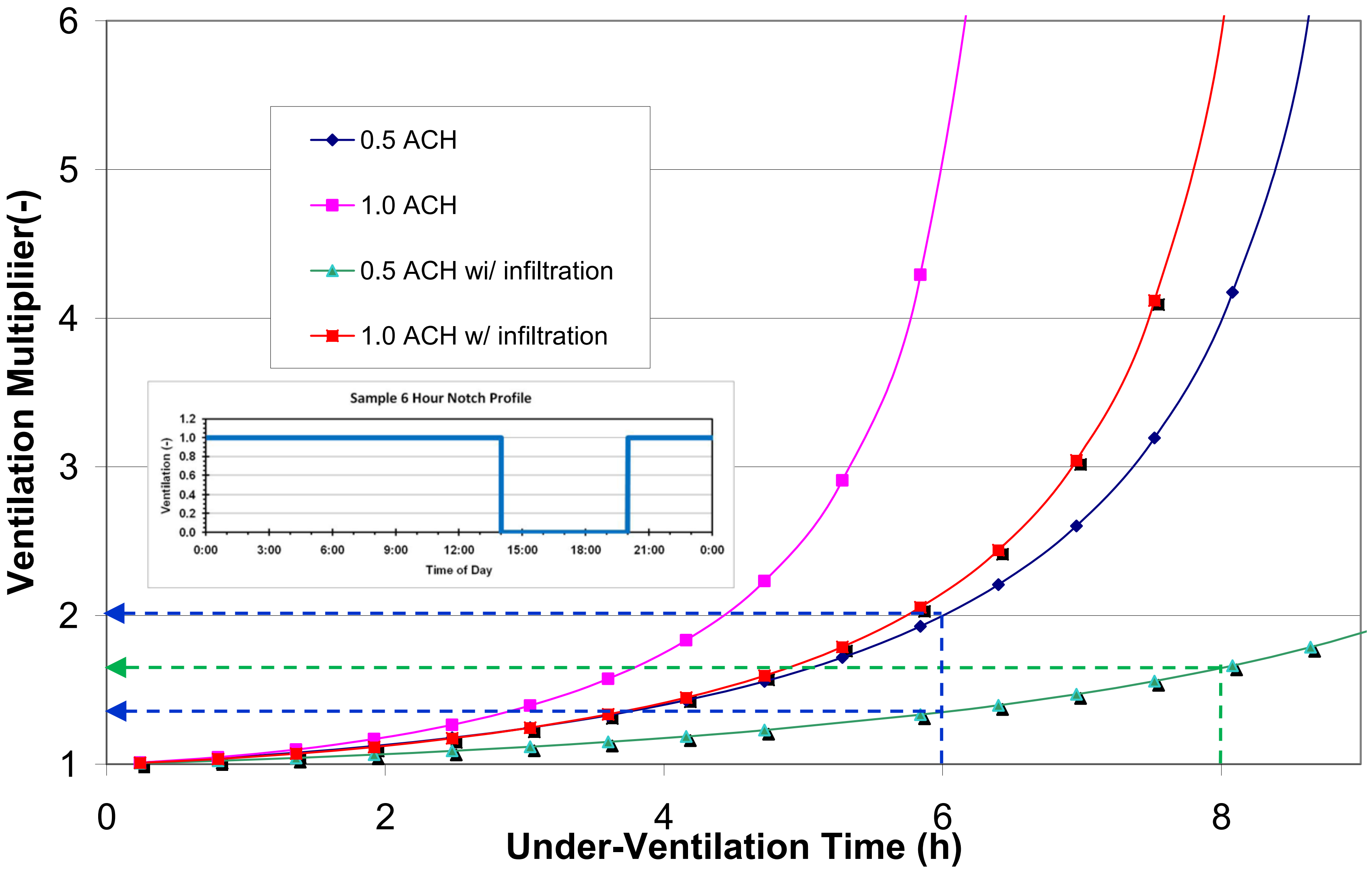
N<<1

$$\varepsilon \simeq 1 - f_{low}^2 N^2$$

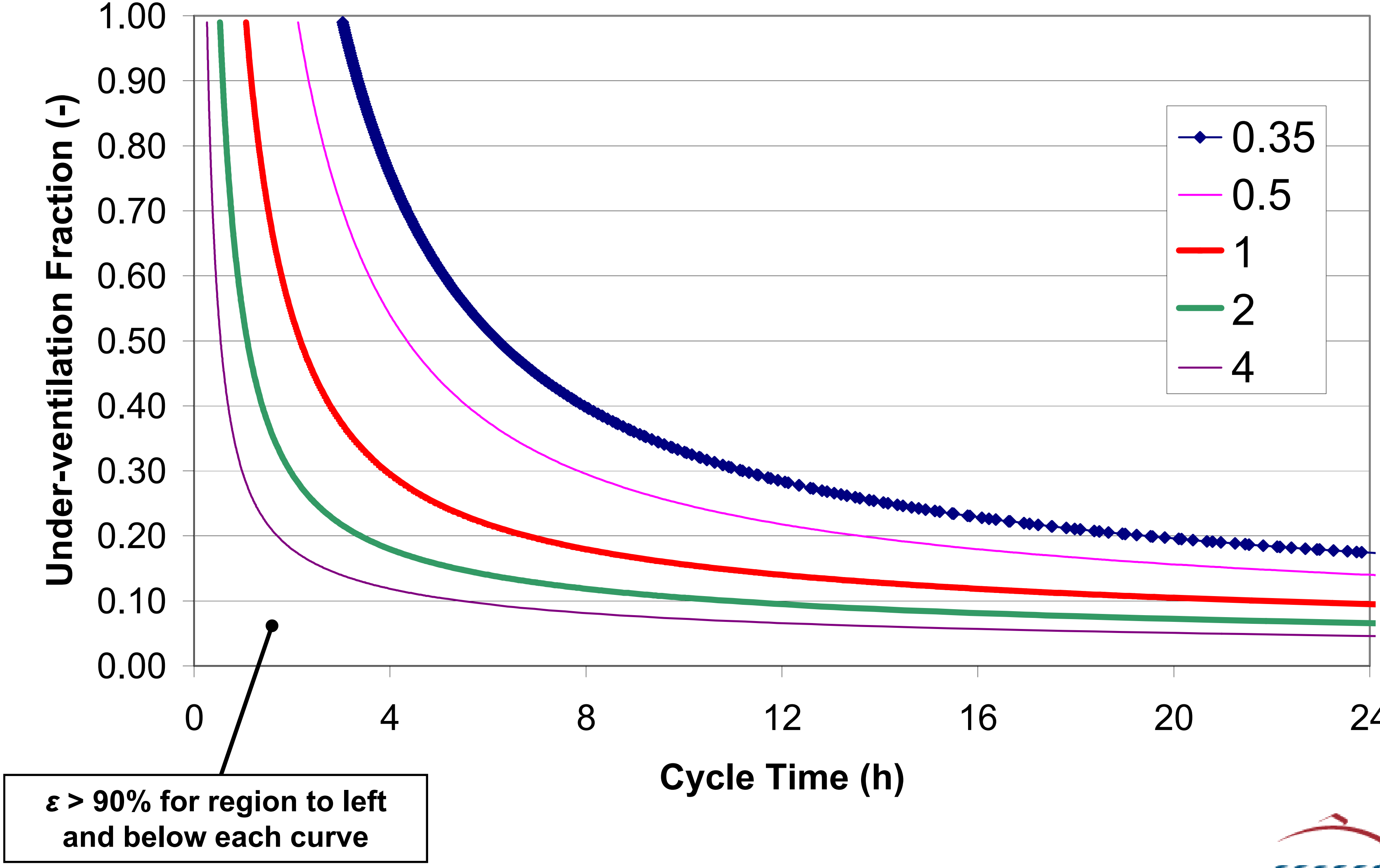
N>>1

$$\varepsilon \simeq \frac{1 - f_{low}^2 N}{1 - f_{low}^2}$$

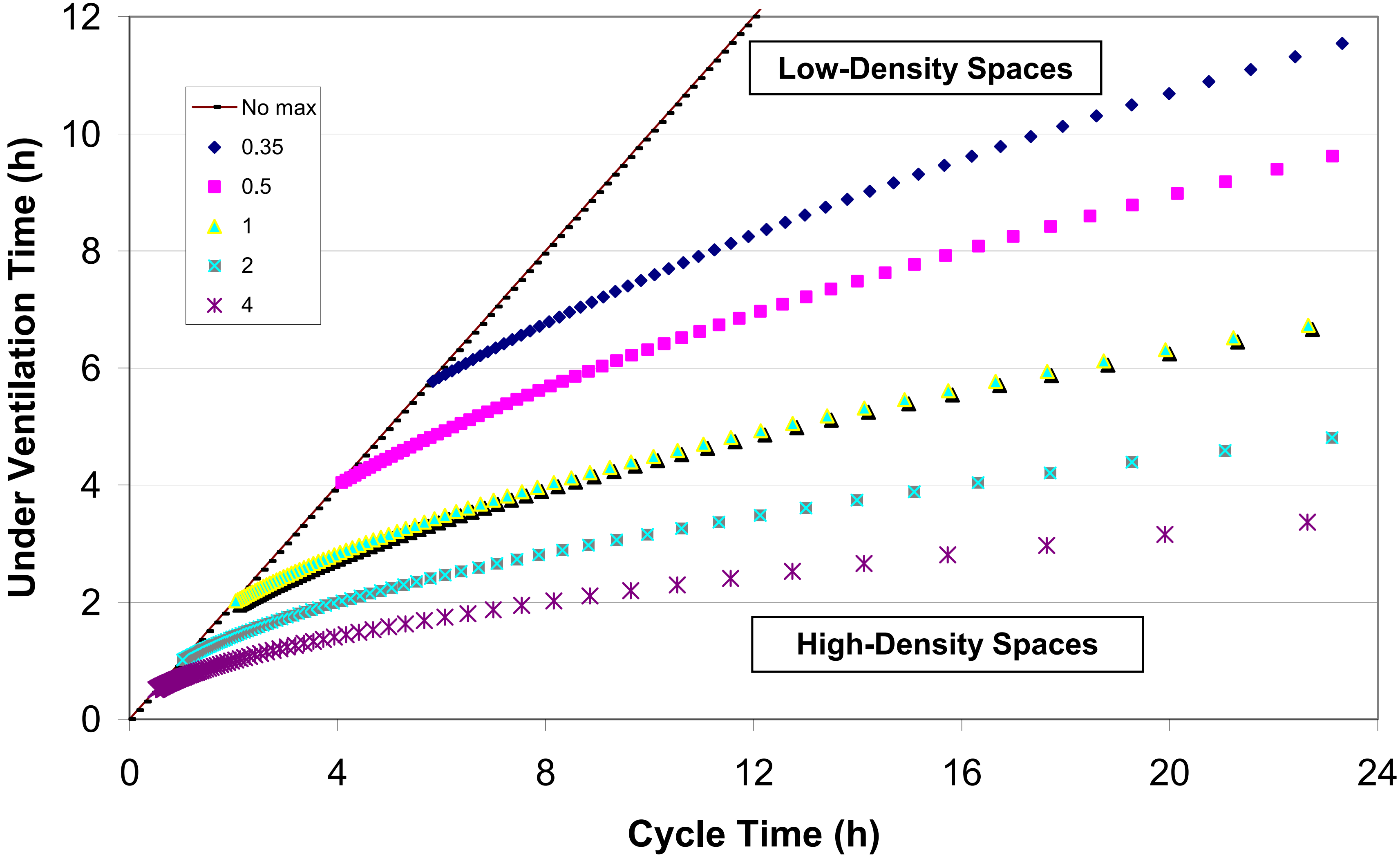
Notch Ventilation at Various Air Change Rates



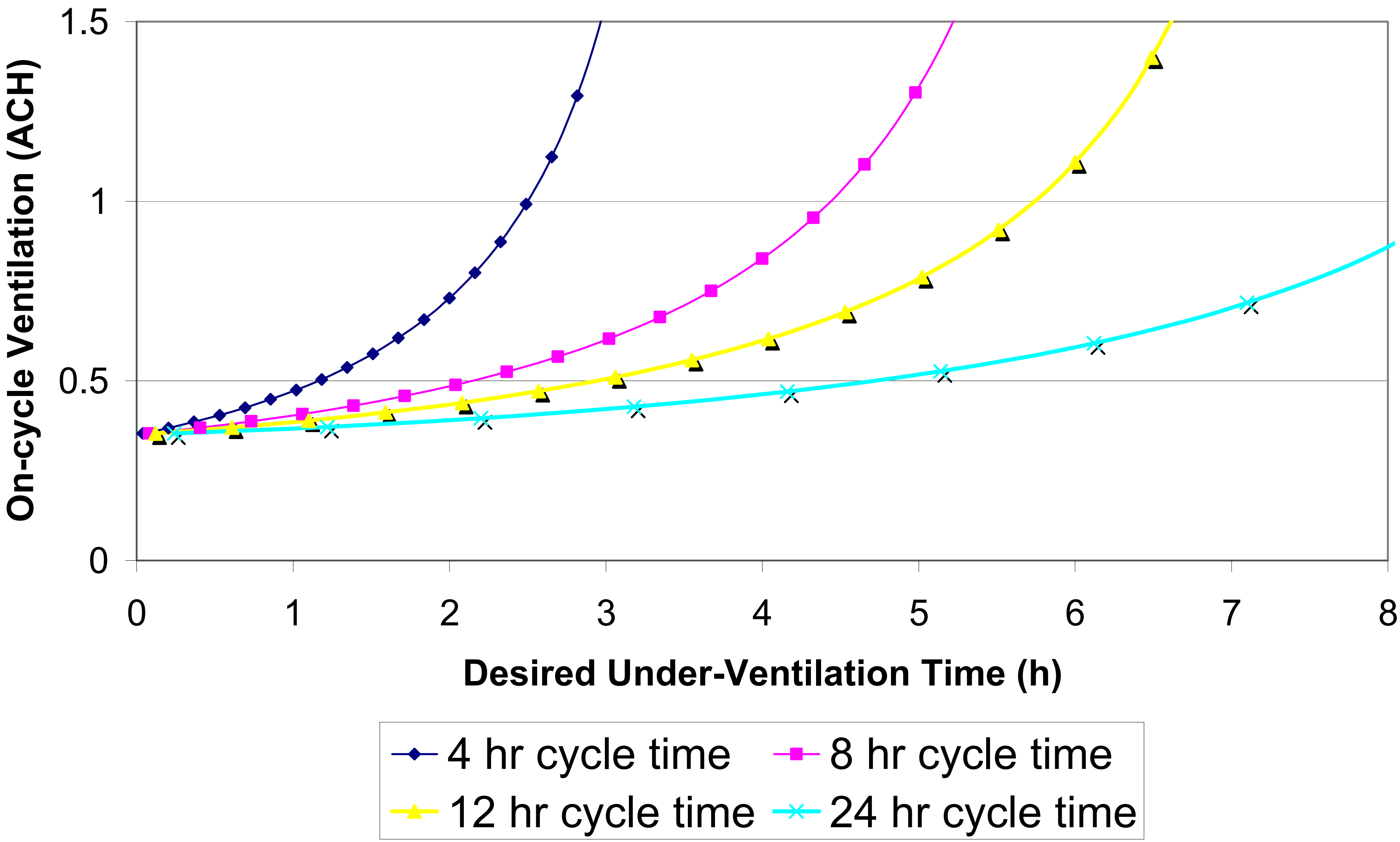
90% Efficacy at Various Air Change Rates



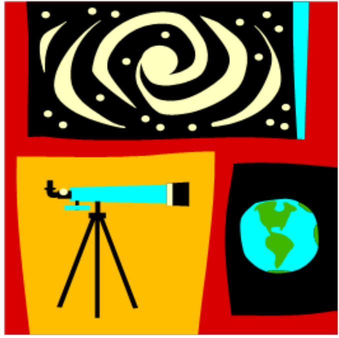
Maximum Under-Ventilation



Capacity Required for 0.35 ach



Questions?



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