Conservation of Mass
And Other Crazy Ideas

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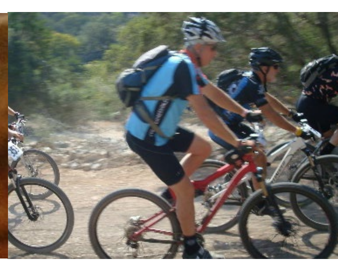
Agenda

History / Background
Commercial Examples
Residential Examples
Fungal Growth Patterns

Every case is different – consult your Building Scientist or Engineer

History / Background

- “Building Commissioning” since early 1990’s when left Lockheed
- Primarily in Hot & Humid climates
- Many, MANY “Lessons Learned”
- That lead to current Expert Witness work (Litigation Engineering)
- Maintain engineering & HVAC licenses plus own rent properties
- List of “hobbies” is long – Dirt Biking, Mtn Biking, Skiing, Windsurfing, Wood working, Machining, Formula SAE car, etc. etc.
- Recently became the “temporary” foster family for an 11 year old boy



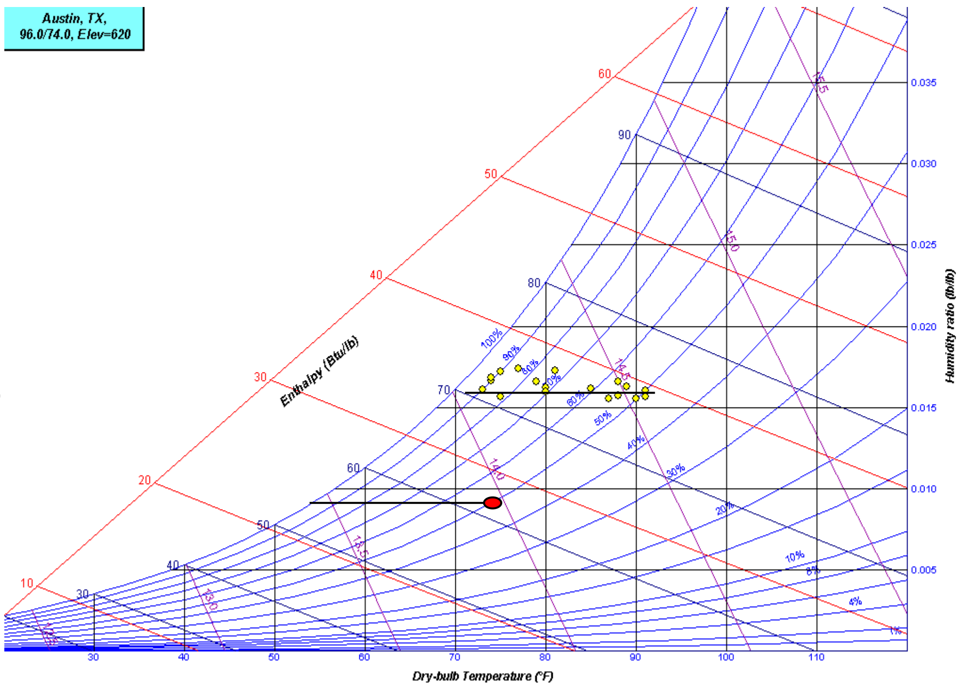

Repeated Commissioning Findings

- Building too humid - HVAC can not control humidity
  - Most people assume that means HVAC is the problem
  - Most assume the HVAC was installed wrong
- Consistently found the HVAC was <u>DESIGNED</u> wrong
  - Air conditioning latent capacity mismatch
  - Building depressurized – especially restaurants
  - Air conditioning oversized – Most common wrong assumption
  - Infiltration due to no/poor air sealing required
- Operated wrong
  - Exhaust fans used to "dehumidify" – see that on internet
  - Poor maintenance
- Crazy Idea #1 – The design MUST match the conditions

Psychrometric Chart

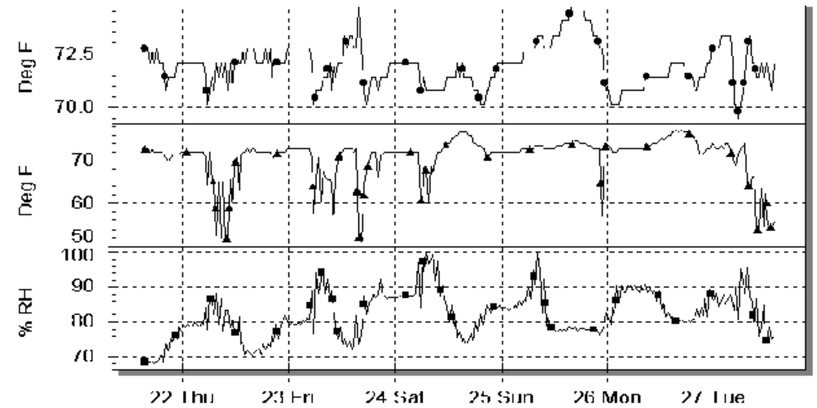
- Properties of "moist air"
  - Bottom is temperature
  - Right is water mass lb_{water} / $lb_{dry\ air}$
  - Curved lines are Relative Humidity
- Know two parameters – can find all others
- RH is widely misunderstood
  - Similar to "wind chill"
- "Magic Point" is 75 F and 50%
  - Dew point of 55 F
- Typical day the dew point is constant near low temperature for the day

- Summer Day
  - Approximately twice the hours at dehumidification condition
- Annual
  - ~ 4100 hours above 55 DP



Finding HUMID Libraries

- Measure, measure, measure
- DO NOT accept "Always done it this way"
  - "Has it ever worked?"
- Needed a way to verify design before construction
  - Very expensive to fix later
- Crazy guy decided engineering principles applied to buildings
  - Conservation of mass
  - Conservation of energy
  - Mathematics
  - Common Sense



Dealing with Humid Buildings

- Hugh Henderson Papers
  - 1998 Latent Degradation Model - ASHRAE #3958
  - 2004 Confirmation of Model – ASHRAE #D-8125
  - April 2004 ASHRAE Journal
- Note - Model for constant ventilation flow systems
  - Most small commercial HVAC systems
- "Too Much Math"
  - Actually requires iterative solution
  - Some parameters not known

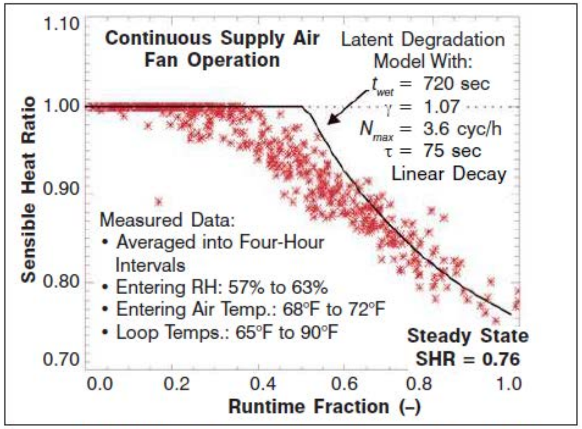


Figure 2: Field data showing the net impact of part-load operation on sensible heat ratio.[2]

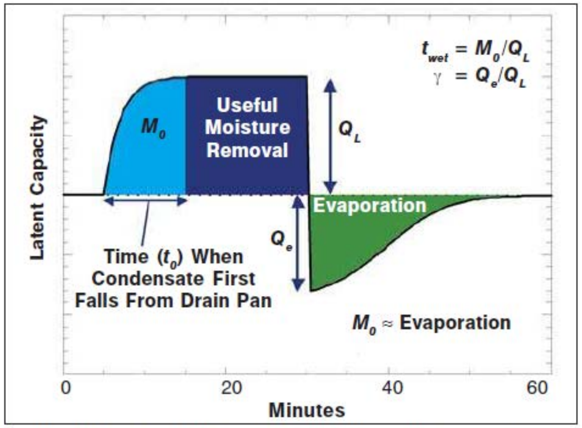
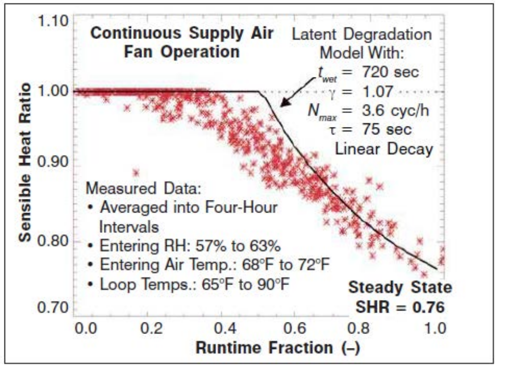
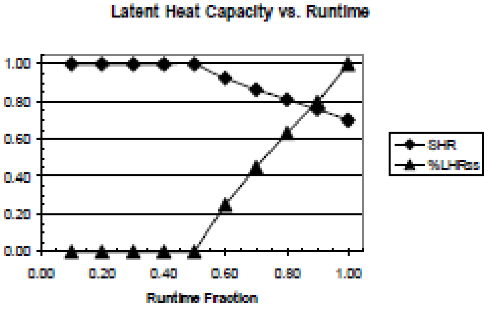


Figure 3: Concepts of moisture buildup and evaporation.

Crazy Browning Paper

- Mass in – Mass out = Mass stored
  - Mass in = ventilation air contains water – lots of water in humid climates
  - Mass out = water removed by HVAC
    - Mass out ≠ water removed by exhaust
  - Mass stored is water remaining in the building – hopefully < zero
- How do we calculate it?
  - Need HVAC detailed performance data
  - Spreadsheet
- What do we get???





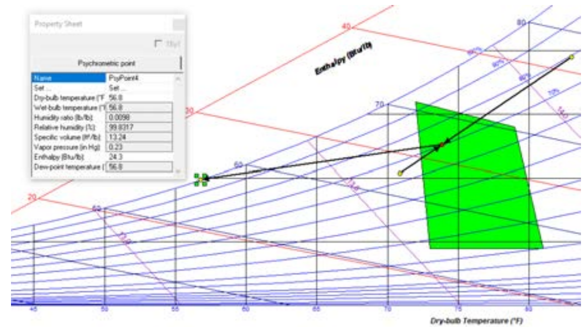
If runtime fraction is ≤ 50% - %LHRss = 0
If runtime fraction is > 50% - %LHRss = 2x-1
q_ℓ = Rated Latent Capacity * %LHRss
mass of water removed per hour = q_ℓ / h_{fg}

idification Estimate					Worst case	ASHRAE Dehumidifcation Load				TDB (F) =	83	TWB (F) =	77.2		@83 OA Rooftop Temp (Condenser)				
					ASHRAE 2001 Houston Inter. Airport					w (lb/lb)	0.0194	TDP =	76		h =	41.2	BTU/lb		
					Indoor Conditions					TDB (F) =	75	TWB (F) =	62.5						
										w (lb/lb)	0.0092	TDP =	55		h =	28.1	BTU/lb		
Review				Water	Max Water	Water	Calc	Calc	Calc					Dwg	Goodm	Goodman			C
ıssumed Sply	Dwg Rtn			Added	Removed	Stored	Entering	Entering	Enthalpy	Submtl	Sbmtl Lvg	Submtl	Sbmtl Lvg	Leaving	Data	Data	Calculate	Calculate	Le
ıirflow (CFM	Airflow (CF	OA DWG	% OA	(lb/hr)	(lb/hr)	(lb/hr)	DB	WB	(BTU/lb)	TC	Enthalpy	SHC	Dry Bulb	WB	TC	SHC	DB	Enthalpy	D
600	450	150	25%	6.9	5.8	1.1	74	67	31.4						17.5	11.38	56.77	24.92	5
t^2 per Dwg				OA + People															

Example Calculation

PACKAGE AIR CONDITIONER

UNIT	AIR CAPACITY				COOLING CAPACITY						
	CFM RANGE (H/L)	O/A CFM	FAN HP	E.S.P.	AMBIENT D.B.	AMBIENT W.B.	ENTER D.B.	ENTER W.B.	SCHEDULED SENS.	SCHEDULED TOTAL	STAGES
RTU	4775/2888	400	3	0.75	105	78	80.00	67.00	105.10	143.55	2
RTU-2	7500/4950	1600	5	0.75	105	78	80.00	67.00	182.20	237.00	2



- Dropbox link at end
- Hot Gas Reheat data

48HC*D24 — 20 TON — COOLING CAPACITIES

48HC24				AMBIENT TEMPERATURE (F) 85 EAT (db) 75	85 / 80	85 / 85	95 / 75	95 / 80	95 / 85	105 / 75	105 / 80	105 / 85	115 / 75	115 / 80	115 / 85	125 / 75	125 / 80	125 / 85
6000 Cfm	EAT (wb)	58	THC	214.4	214.4	242.5	207.0	207.0	234.2	199.0	199.0	225.1	190.2	190.2	215.2	180.6	180.6	204.3
			SHC	186.3	214.4	242.5	179.9	207.0	234.2	173.0	199.0	225.1	165.3	190.2	215.2	157.0	180.6	204.3
		62	THC	226.8	226.8	227.7	217.3	217.3	223.0	206.9	206.9	218.0	195.8	195.8	212.5	183.7	183.7	206.4
			SHC	167.0	197.3	227.7	162.4	192.7	223.0	157.6	187.8	218.0	152.3	182.4	212.5	146.6	176.5	206.4
		67	THC	248.4	248.4	248.4	237.9	237.9	237.9	226.6	226.6	226.6	214.3	214.3	214.3	201.0	201.0	201.0
			SHC	136.5	167.1	197.6	132.2	162.7	193.2	127.5	158.0	188.4	122.5	152.9	183.4	117.2	147.6	178.0
		72	THC	271.9	271.9	271.9	260.3	260.3	260.3	247.9	247.9	247.9	234.5	234.5	234.5	220.1	220.1	220.1
			SHC	105.1	136.0	167.0	100.8	131.7	162.5	96.3	127.1	157.9	91.4	122.1	152.9	86.3	116.9	147.6
		76	THC	—	291.7	291.7	—	279.2	279.2	—	265.7	265.7	—	251.3	251.3	—	235.8	235.8
			SHC	—	110.7	143.7	—	106.5	139.5	—	102.0	134.7	—	97.2	129.7	—	92.1	124.3
		58	THC	225.8	225.8	255.3	217.8	217.8	246.3	209.1	209.1	236.5	199.6	199.6	225.7	189.2	189.2	214.0

Unit	Tons	Dwg Sply Airflow (C	Dwg Rtn Airflow (CF	OA Sched	% OA	Water Added (lb/hr)	Latent case Water Removed (lb/hr)	Water Stored (lb/hr)	Entering DB	Entering WB	Entering Enthalpy (BTU/lb)	TC	Lvg Enthalpy	SHC	Lvg Dry Bulb	Leaving WB	Leaving DP
RTU-1	12.5	4775	4375	400	8%	16.2	42.6	-26.4	75	64	29	66	25.9	21	71.0	59.3	51.6
RTU-2	20	7500	5900	1600	21%	64.8	95.9	-31.1	75	65	30.2	131.95	26.3	30.75	71.2	59.9	52.6
						81.0	138.5	-31.1									
					Interpolation									Interpolation			
					x1	4800	107.7	y1						x1	6000	20.1	y1
					x	5000		y =	109.2					x	7500		30.75
					x2	5400	112.2	y2						x2	8000	34.3	y2

GC Asked for Mechanical Checklist

- Checklist
  - Blanks / Errors
  - Over 10% OA
  - AHRI rating condition (80/67 entering)
  - No Leaving (supply) conditions
  - Supply conditions too humid (>55 F DP)
  - 80% makeup air on restaurant kitchen exhaust
- Calculated
  - More exhaust than ventilation
  - Similar square feet per ton of cooling

GC decided to ask for my review before starting on bid

Hotel Schedule / BBQ Schedule

ROOF TOP UNIT SCHED

MARK	NOM. TONS	...S. & MODEL # ...NE OR EQUAL	FAN				COOLING				GAS
			TOTAL CFM	O/A CFM	E.S.P.	MOTOR B.H.P.	E.A.T. db	E.A.T. wb	TH	SH	MBTU INPU...
RTU-1	17.5	YCH-210	5,625		0.45	3.0			210.0		250.0
RTU-2	17.5	YCH-210	6,000		0.45	3.0			210.0		250.0
RTU-3	17.5	YCH-210	6,000		0.45	3.0			210.0		250.0
RTU-4	8.5	YCH-102	3,000		0.45	2.0			102.0		200.0
RTU-5	8.5	YCH-102	3,000		0.45	2.0			102.0		200.0
RTU-6	17.5	YCH-210	6,500		0.45	3.0			210.0		250.0
RTU-7	17.5	YCH-210	6,800		0.45	3.0			210.0		250.0
RTU-8	17.5	YCH-210	6,200		0.45	3.0			210.0		250.0
RTU-9	17.5	YCH-210	6,475		0.45	3.0			210.0		250.0

PACKAGE AIR CONDITIONER

UNIT	AIR CAPACITY				COOLING CAPACITY						
	CFM RANGE (H/L)	O/A CFM	FAN HP	E.S.P.	AMBIENT D.B.	AMBIENT W.B.	ENTER D.B.	ENTER W.B.	SCHEDULED SENS.	SCHEDULED TOTAL	STAGES
RTU	4775/2888	400	3	0.75	105	78	80.00	67.00	105.10	143.55	2
RTU-2	7500/4950	1600	5	0.75	105	78	80.00	67.00	182.20	237.00	2

AREA	CFM / PERSON	# OF PEOPLE	AREA SQ. FT.	CFM/ SQ. FT.	OCCUPANCY DURATION	ADJUSTED O/A CFM PROVIDED
EMPLOYEES	15	30				450
# OF SEATS/2	20	153				3060
TOTAL OUTSIDE AIR CFM REQUIRED ---------------- 3510						
TOTAL OUTSIDE AIR CFM SUPPLIED ---------------- 3540						

① CALCULATION IS IN COMPLIANCE WITH IMC & ASHRAE STANDARD 62

ROOFTOP AIR CONDITIONING SCHEDULE

RTU-#	LENNOX MODEL #	COOLING CFM O/S AIR CFM	VOLTS/Ø	EXT. S.P. IN H2O	TOTAL CAPACITY	MIN SENSIBLE CAPACITY	NOM TONS/ EER	MCA MAX FUSE	GAS HEATING INPUT
1	LGH150S4B	5000 1150	208/3	0.8	150 MBTUH	106 MBTUH	12.5 11.0	67 80	130 MBTUH
2,3	LGH120H4B	4000 920	208/3	0.8	120 MBTUH	82.9 MBTUH	10 12	46 50	130 MBTUH
4,5	KGA036S4B	1200 275	208/3	0.8	36 MBTUH	26 MBTUH	3 13 SEER	20 25	65 MBTUH

BUILDING PRESSURIZATION SCHEDULE

EF-1	1100 CFM	RTU-1 O/A	1150 CFM
F-1	2850 CFM	RTU-2 O/A	920 CFM
F-2	2200 CFM	RTU-3 O/A	920 CFM
F-3	850 CFM	RTU-4 O/A	275 CFM
		RTU-5 O/A	275 CFM
		F-4	4040 CFM
TOTAL:	7000 CFM EXHAUST		7580 CFM O/A
BUILDING IS SLIGHTLY POSITIVE WITH ALL EXHAUST FANS OPERATING			

F-5, 6 & 7 ARE INTERMTTANT USE ONLY

Ventilation versus Exhaust

Pressurization Calculation

Supply

Mark	Continuous CFM	Intermitent CFM
RTU-1		50
RTU-2		800
RTU-3		500
RTU-4		300
RTU-5		200
RTU-6		50
MAU-5K	500	
MAU-6K	1485	
MAU-7K	2173	
MAU-8K	1660	
	5818	1900

Exhaust

Mark	Continuous CFM	Intermitent CFM
EF-1		450
EF-2		150
EF-1K		1100
EF-2K		1100
EF-3K		1100
EF-4K		1100
EF-5K	833	
EF-6K	2475	
EF-7K	3621	
EF-8K	2767	
	9696	5000

Highest Building Pressurization Flow

P hi 5818 + 1900 - 9696

-1978 (should always be greater than zero)

Lowest Building Pressurization Flow

P low 5818 - 9696 - 5000

-8878 (should always be greater than zero)

(Does NOT include +/- 10% tolerance on balancing)

Figure 2 – Example conservation of air mass estimate from conservation of air volume. Minimum and maximum pressurization can be estimated from continuous and intermittent flows as shown.

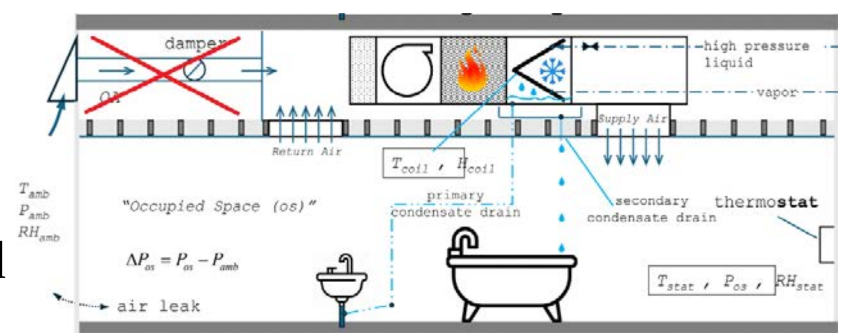
Crazy conservation of air mass.

This building is ALWAYS depressurized

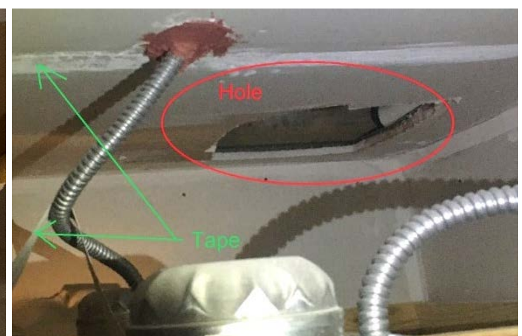
Multifamily Example

- >300 apartment complex in humid climate
  - Mold found ~ 3 years after occupancy
  - Lawsuit filed ~ 5 years after occupancy
- “Return plenum leakage” blamed
  - Pancake AHU’s
  - Gypboard return plenum

- OA supplied to common areas only
  - Building exhaust exceeded OA supply 95% of conditions
  - Entire building depressurized
  - Apartment had exhaust ONLY
  - Each apartment was a fire zone
  - Each apartment is depressurized



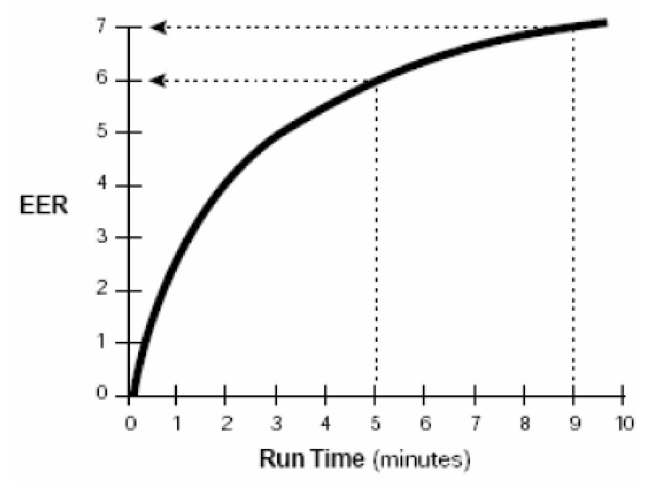
Photos of Findings



Crazy Idea – Depressurized building suck – in so many ways.
Multiple remediations indicates the cause was not corrected.

Residential

- Typically – the ventilation air stops when blower is off
  - Can still use conservation of mass
  - Can't use the Henderson model – some other data available?
- Typically more complicated because of unknowns
  - How is the system operated?
  - How are exhaust fans operated?
- Moisture balance still needed
  - Sensible capacity similar to efficiency v. run time
  - Latent capacity is inverse of sensible capacity (1- $S_{capacity}$)



EPA - Efficiency v run time

Sources of Ventilation

- OA intake – typically ~50 CFM through HVAC blower
- Exhaust fans
  - Kitchen vent hood
  - Toilet exhaust fan
  - Clothes drier
  - “Portable” air conditioner
    - Conservation of energy
    - Conservation of mass (CFM)

“Good” portable AC

- Outdoor air is still loaded with water
- Indoor air is still ~55 F dew point
- Method is still valid but operating conditions variable

Crazy Idea – Engineering principles always apply

Residential Example 1

- Doctor & wife retirement house – wanted a “show place”
  - ~5200 square feet
  - Net Zero – Verified
  - AAC walls - Triple glazed windows - Lots of shading
  - Ground Source VRF Heat Pumps

- Manual J “performed but not applicable”
  - 4 ton peak cooling load - including OA conditioning
  - Installed - 7 tons times two units = 14 tons
  - But “Backup” unit is always running in parallel with Primary unit
- Original units now replaced for about $50,000

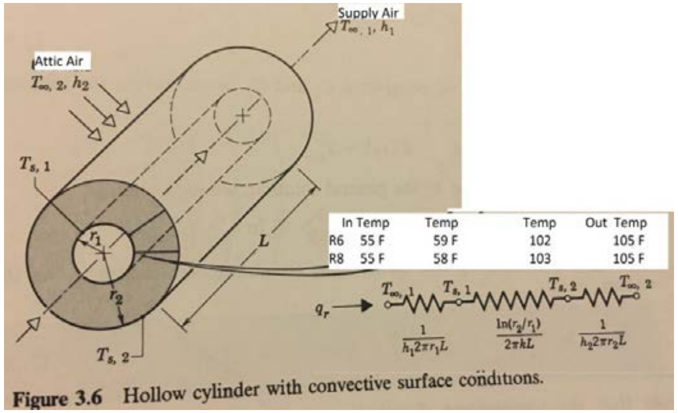
Crazy Idea – Engineering ALWAYS applies &
Newer is not always better

Residential Example 2

- House built in 2012 – Energy Star
- 2 Story 2420 sq foot 4 bedroom near Coast
- Mold Remediation in 2017-2018
  - Many subcontractors sued
  - Entire HVAC replaced including ducts
  - Added more attic vents
  - Additional air sealing (less infiltration)
- Mold returned in 2019 – “Causes”
  - R6 ducts - More attic ventilation
  - Infiltration
  - Original HVAC contractor sued

Crazy Idea 1 – Replacing the entire HVAC system and the mold returns – the original HVAC was not the problem!

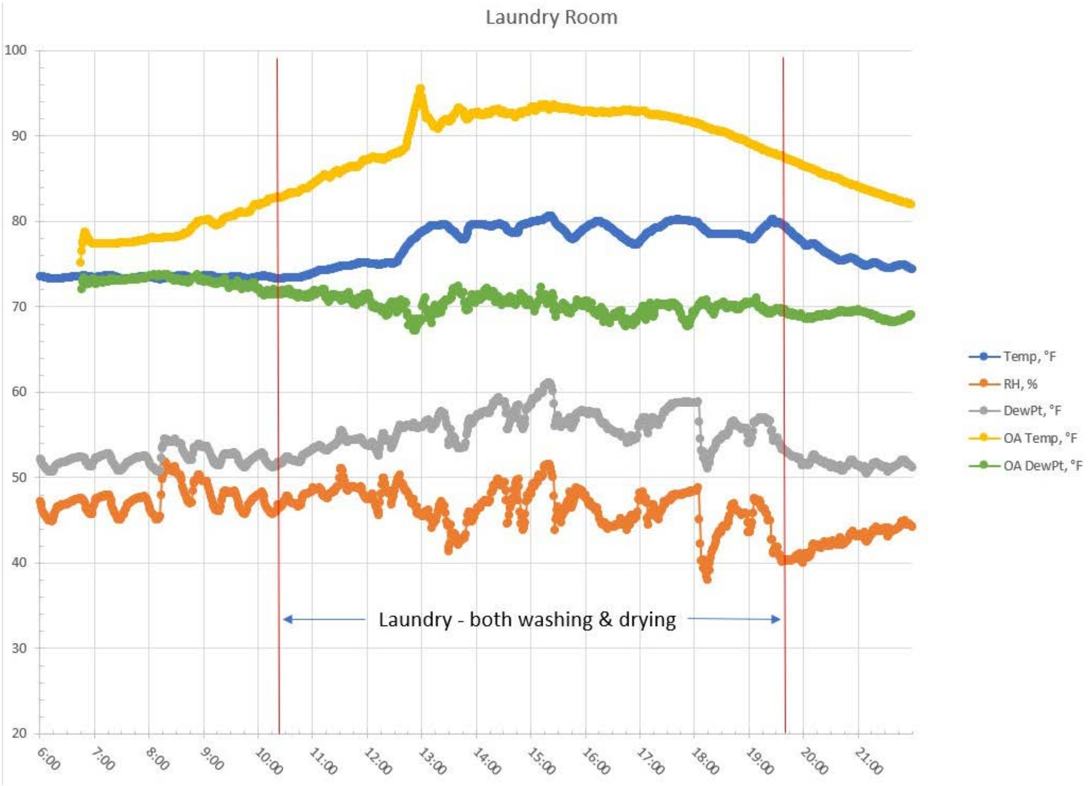
Crazy Idea 2 – If mold came back faster, the “solution” was wrong.



	In Temp	Temp	Temp	Out Temp
R6	55 F	59 F	102	105 F
R8	55 F	58 F	103	105 F

Figure 3.6 Hollow cylinder with convective surface conditions.

Are Laundry Exhaust Fans Good or Bad?



- No exhaust fan
- Little exterior wall
- Dew point peak ~60F
- Exhaust fan likely to INCREASE dew point
- 100 CFM exhaust = 4 lb/hr water into house

Crazy Idea – Don't install exhaust laundry exhaust fan.
Crazy Idea 2 – Put all exhaust fans on a timer.

Building Water Damage Model

- Building materials absorb and desorb water constantly
- As long as below “critical” water content – no problem
  - Different materials have different critical level
- Above critical level – damage starts occurring
- When building is pressurized – drying at least some time
  - Wind, exhaust fans, etc. will overcome pressure at some conditions
  - Both wetting and drying occur
  - Time to “damage” greatly extended
- When building is depressurized – there is no drying
  - Water absorbed but never desorbed
  - Critical water content will be reached – damage will occur

Fungal Growth Patterns

- Three primary requirements for mold
  - Mold spores – everywhere
  - Nutrient – wood, paper, dust, etc.
  - Available water – primary means to control mold
  - Others not as critical

- Wise person once said – find the mold, found the water
  - ‘Steve Brick’ sometime last century
- There is also a time component
  - Too soon - mold is not very detectable
  - Too late – mold everywhere does not help identify source

Mold Source ?

- Fiberglass pipe insulation

Mold Source ?

- Return plenum

Mold Source ?

- Kitchen vent hood cabinet

Mold Source ?

- Ceilings
  - Family room
  - Closet


Diffusion of Water from Attic

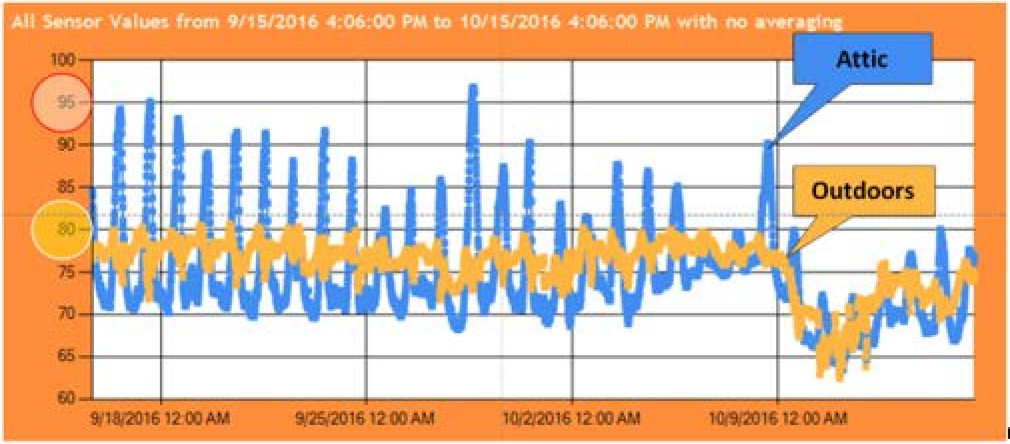


Figure 11 - **Measured Outdoor Air Dew Point v Attic Dew Point for a vented attic in Orlando FL (credit Lew Harriman Mason-Grant Consulting)**

Figure 12 shows a portion of the 1996 National Institute of Standards and Technology (NIST) paper by Burch et. al. Note that the 1996 NIST paper actually states on page 46 next to last paragraph "… the ceiling construction functions as a "pass through system" where moisture readily flows through it from the roof cavity to the indoor environment where it is removed by the air conditioning equipment. …"

Vented roofs cause moisture problems south of the Mason-Dixon Line and east of Interstate 35 in Texas. Venting a roof in a hot-humid and mixed humid climate is a very, very bad idea.

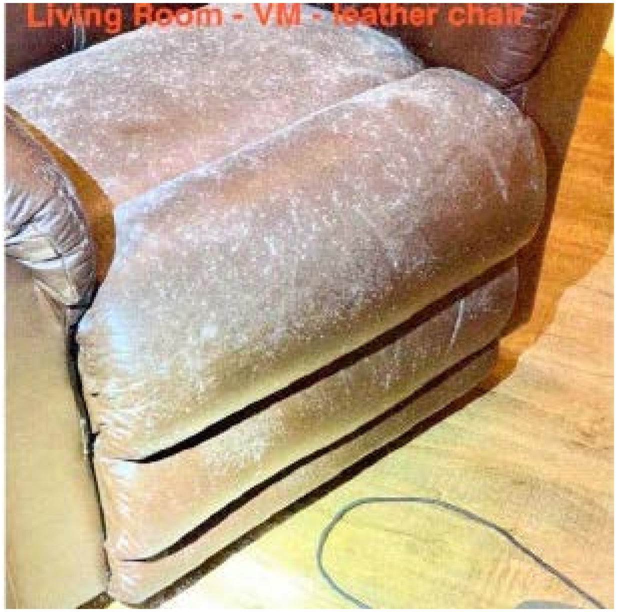
Mold Source ?

- Supply Plenum

Mold Source ?

Refrigerator door

Leather Chair



Thank You!

- Dropbox link –
  - https://www.dropbox.com/scl/fo/6xzpguqrb7s72enmi2y8e/AC37H4By0Q9_CA0V9AF38kk?rlkey=uj4257xtn9nh0drsd5cejblxa&st=zdewzsji&dl=0
  - https://www.researchgate.net/publication/26901105_Conservation_of_Mass_An_Old_Principle_That_Needs_More_Usage_in_Hot_Humid_Climates
    Check minute versus hours UNITS!!!
  - https://core.ac.uk/download/pdf/79624059.pdf - Check Units

Stages Duct Leakage Testing

- Our duct are so good they don't need to be tested
- Ducts can't be leak tested (ASTM E1554)
- The test is WRONG!
- Duct can't possibly be sealed as specified so the current leakage should be accepted as is

- This wasn’t included in our bid – it will cost extra (Testing MUST be specified)
- See – I told you we would take care of you

Duct Leak Testing Truths

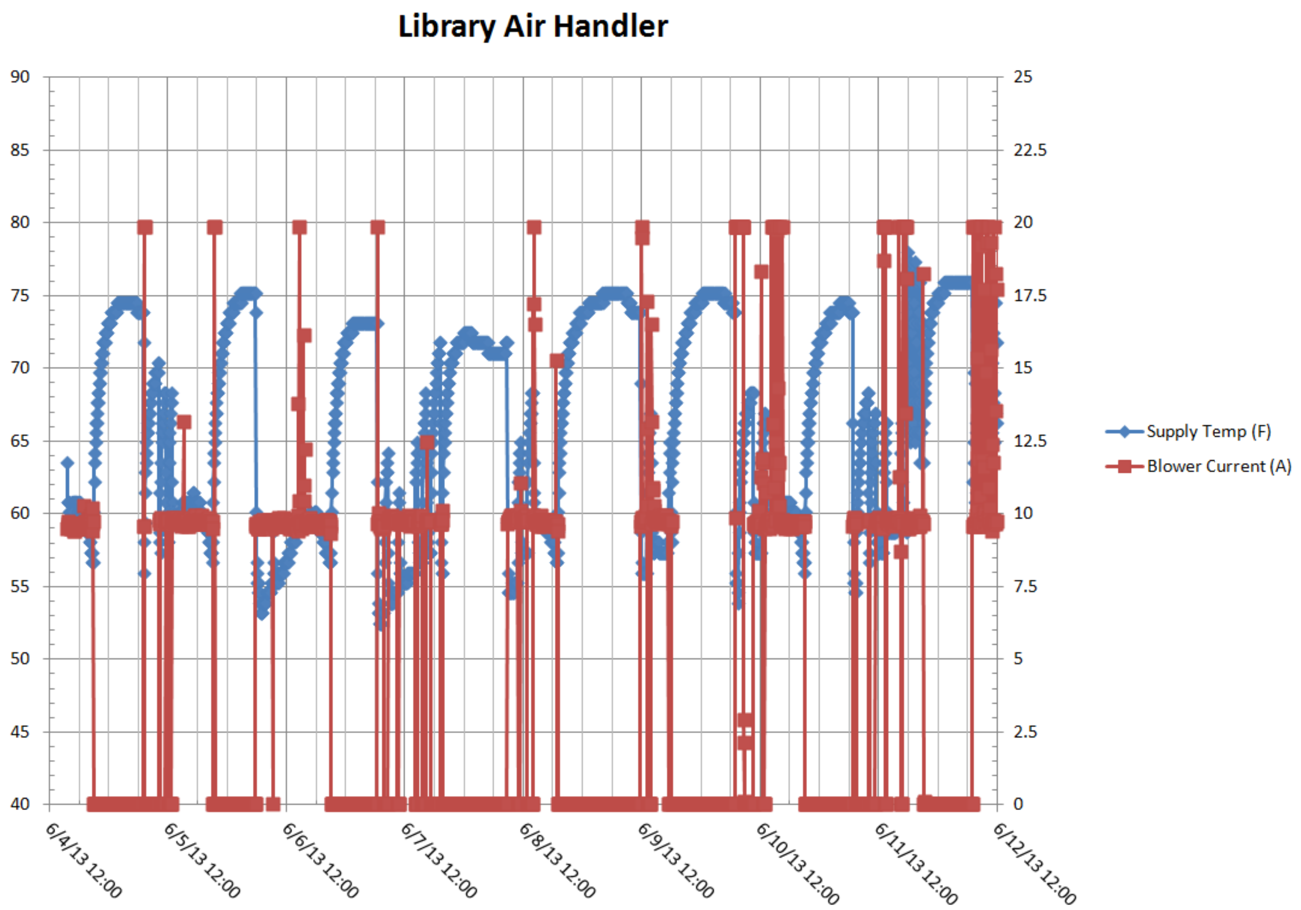
- If the contractor can't show duct leak test experience –
that contractor is NOT qualified

- If it can't be sealed as tight as a duct
or it can't be tested to be sealed as tight as a duct –
the ***DESIGN*** should **NOT** show it to be used as a duct
(E. G. - plenum ceilings, Under Floor Air Distribution,
building cavities, panned joists, etc)

- Duct should be tested at rough-in (for contractor's benefit)
and a final (for Owner's benefit)

- Ducts CAN and MUST be sealed – but it requires effort
during design, installation and verification

What's Wrong Here?



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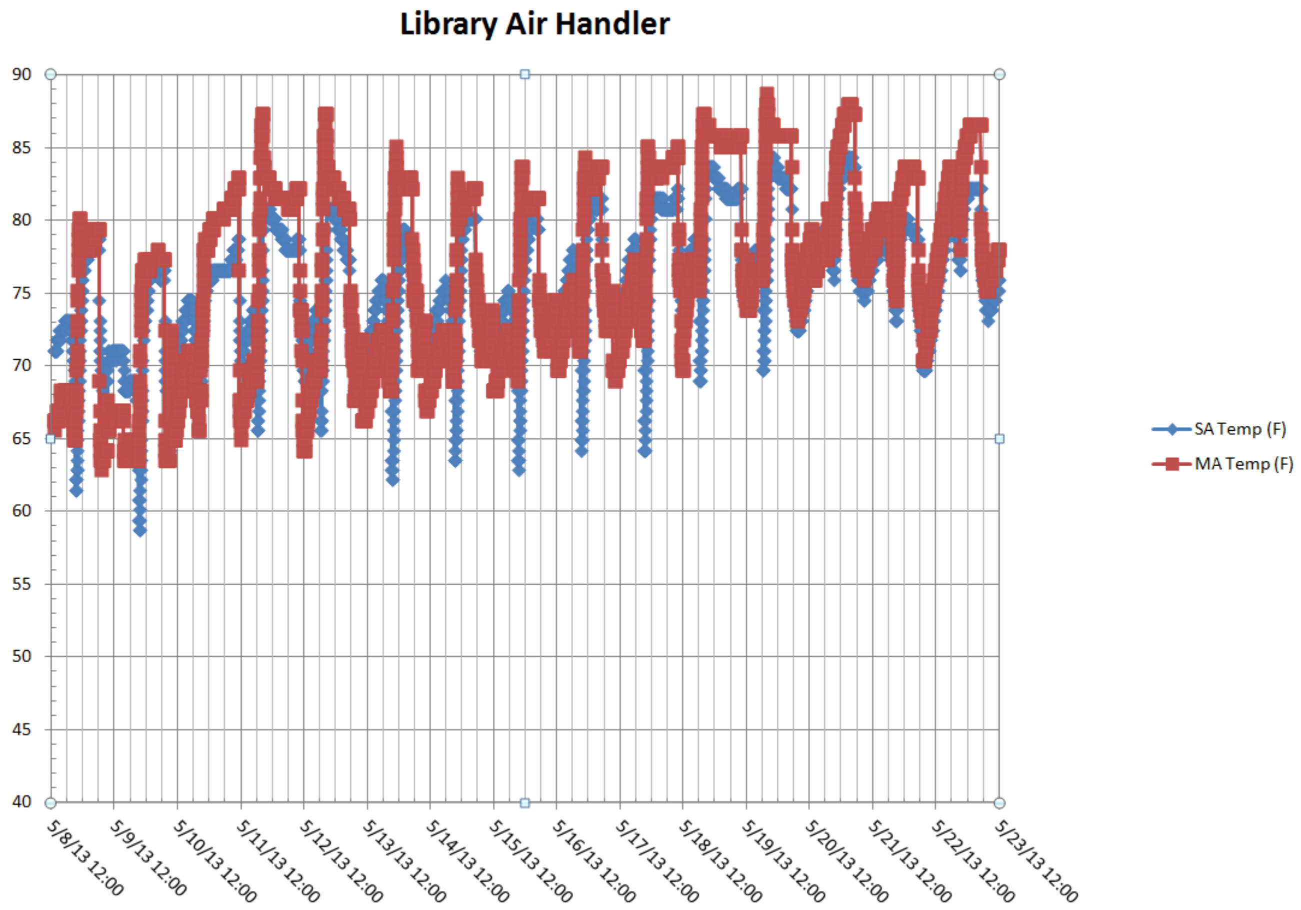
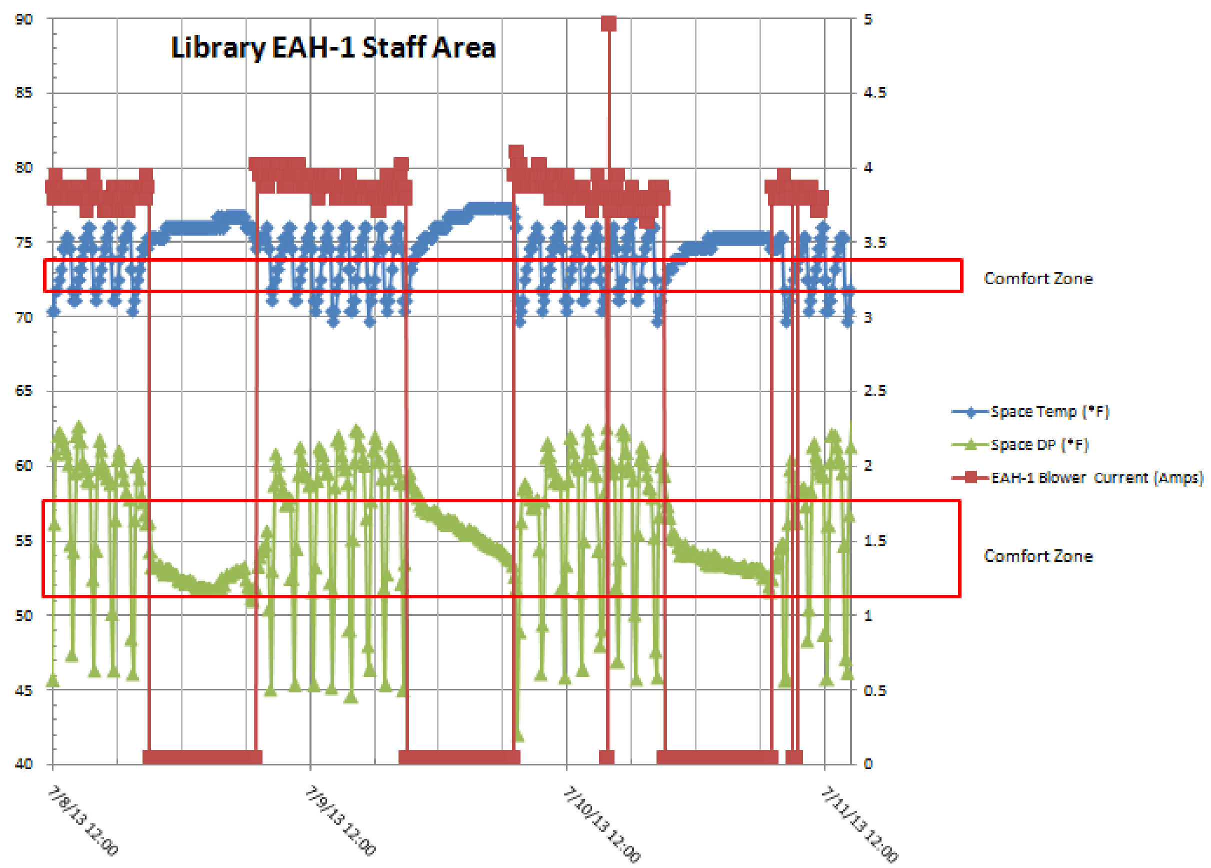


What's Wrong Here?



Sq Ft per ton Metric

- Why as we build more energy efficient buildings – do they need MORE air conditioning???