Federal Study Quantifies Efficiency Losses Due to Improper HVAC QI

[Poor Installations Undermine Equipment Efficiency]
[U.S. Contribution to the IEA Annex 36 on QI / QM]

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Presentation Overview

Topic	Min
Marketplace realities for subpar installations	~5
Federal study quantifies the problem • IEA Annex 36 QI / QM overview • NIST Contribution	~30
Preserving equipment performance • Manuals & standards … industry practice • Accreditation … industry polices itself	~10
Q & A	?

Key Take Aways *(Spoiler Alert)*

Not following QI practices seriously degrades energy efficiency … 30% and more!

Very influential faults are
1. duct leakage,
2. refrigerant undercharge,
3. oversized equipment with undersized duct,
4. low indoor air flow,
5. refrigerant overcharge.

Effect of multiple faults / errors is additive.

Market Realities … Practitioner 'Rules of Thumb'

500 ft^2 / ton (equipment sizing)

400 CFM / ton (airflow)

0.10 friction rate (duct sizing)

½ CFM / ft^2 (air delivery)

20°F delta across the coil (airflow)

"Beer can cold" (refrigerant charge)

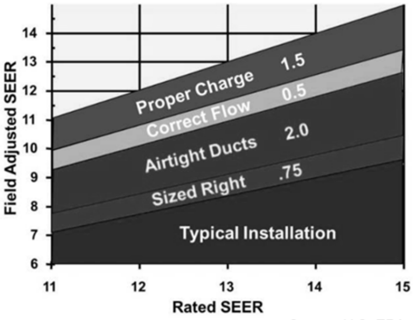
Leads to oversized equipment, undersized ducts, hot / cold rooms, and inefficient operation!

Generally Accepted Wisdom on the Impact of Improper QI / QM

–30% is lost out of the Box !!

Commonly-noted field problems	Magnitude
Refrigerant charge	Up to 30% off of OEM design
Incorrect airflow over the coil	Up to 50% off of design
Equipment size	Routinely 100% too big
Duct sizing	Routinely ½ the requirements
Duct Leakage	Up to 50% of airflow
etc.	

Generally Accepted Wisdom on the Impact of Improper QI / QM



Source: U.S. EPA

Compounding Impacts on HVAC

Geographical- or policy-focused
- Weather / climate issues
- Regional standards / optimizations
- Smart grid applications

Equipment-focused
- Multiple- and variable-speed equipment
- Inverter drives
- Variable refrigerant flow

QI and QM becomes even more important!

… unclear whether small variances are significant,

… whether the variances have an additive impact on equipment performance, and

… whether the deviations (in various applications and geographical locations) have a larger impact than others."

If this information is known, better attention, resources, and effort can be focused on those parameters that are most important in the installation and maintenance of HVAC equipment.

ACCA NIST OAK RIDGE National Laboratory

Glenn C. Hourahan, P.E. Piotr A. Domanski, P.E., PhD Van D. Baxter, P.E.
IEA Annex 36: *QI / QM Sensitivity Analysis (Assessing Efficiency Degradation due to Poor Installations and Maintenance)*

IEA Annex 36
- International collaboration based on QI and QM
  - Quantify impacts on system performance related to varying QI and QM practices / attributes for varied equipment applications.
  - IEA Participants: France (EdF)
    Sweden (KTH, SP, SVEP)
    United Kingdom (DECC)
    US (ACCA, NIST, ORNL)
  - ACCA / NIST / ORNL were co-Operating Agents
  - 4 year effort: Oct 2010 – Oct 2014

Annex 36 Participant	Focus Area	Work Emphasis
France	EdF – Space heating and water heating applications.	Field: Customer feedback survey on HP system installations, maintenance, and after-sales service. Lab: Water heating performance tests on sensitivity parameters and analysis.
Sweden	SP – Large heat pumps for multi-family and commercial buildings. KTH – Fault detection and diagnoses in heat pump systems.	Field: SP – Literature review of operation and maintenance for large heat pumps. Interviews with real estate companies owning heat pumps. KTH - investigations and statistical analysis of 68,000 heat pump failures. Modeling / Lab: Determination of failure modes and analysis of found failures (SP) and failure statistics (KTH).
United Kingdom	DECC – Home heating with ground-to-water, water-to-water, and air-to-water systems.	Field: Monitor 83 domestic geothermal heat pumps and make modifications to improve performance. Lab: Investigate the impact of thermostatic radiator valves on heat pump system performance.
United States (Operating Agent)	NIST – Air-to-air heat pumps in year-round cooling and heating applications.	Lab: Cooling and heating tests with imposed faults to develop correlations for heat pump performance degradations due to faults. Modeling: Seasonal analyses modeling to evaluate the effect of installation faults on heat pump seasonal energy consumption; includes effects of different building types (slab vs. basement foundations) and climates.

Annex 36 Participants

ACCA → Air Conditioning Contractors of America
DECC → Department of Energy and Climate Change (UK)
EdF → Electricité de France
KTH → Royal Institute of Technology (Sweden)
NIST → National Institute of Standards & Technology
ORNL → Oak Ridge National Laboratory (US)
SP → Technical Research Institute of Sweden
SVEP → Swedish Heat Pump Association

SENSITIVITY ANALYSIS OF INSTALLATION FAULTS ON HEAT PUMP PERFORMANCE

(NIST TECHNICAL NOTE 1848; Sep 2014)

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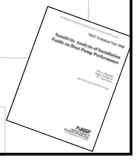

Report can be downloaded from:
www.acca.org/quality

ACCA Quality Installation Standard

ANSI / ACCA 5 QI – 2010 (*HVAC Quality Installation Specification*)

- ❑ **Design Aspects**
  - o Ventilation
  - o Building Heat Gain / Loss Calculations
  - o Proper Equipment Capacity Selection
  - o Geothermal HP Exterior Ground Heat Exchanger
  - o Heating and Cooling Equipment are Matched Systems
- ❑ **Distribution Aspects**
  - o Duct Leakage
  - o Airflow / Hydronic Balance
- ❑ **Equipment Installation Aspects**
  - o Airflow / Water flow through Heat Exchangers
  - o Refrigerant Charge
  - o Electrical Requirements
  - o On-rate for Fuel-fired Equipment
  - o Combustion Venting System
  - o System Controls (thermostat, humidistat, safety controls)
- ❑ **System Documentation and Owner Education Aspects**
  - o Documentation for the Owner
  - o Owner/Operator Education

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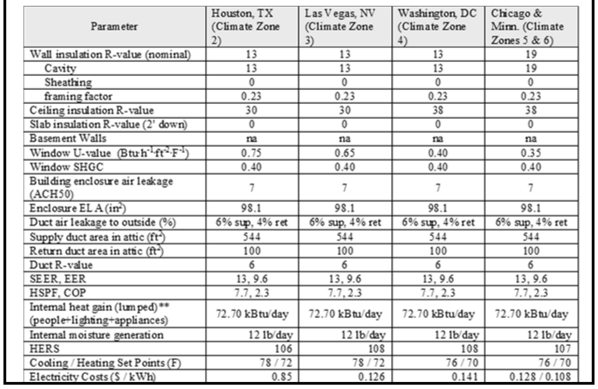
  - o On-rate for Fuel-fired Equipment
  - o Combustion Venting System
  - o System Controls (thermostat, humidistat, safety controls)
  - o Non-Condensable Gases
  - o Undersized TXV (indoor)
- ❑ **System Documentation and Owner Education Aspects**
  - o Documentation for the Owner
  - o Owner/Operator Education

NIST Investigation:
Rez. air-to-air HP w/ electric resistance.

H

Simulated Specifications (HERS Index = 100)



Parameter	Houston, TX (Climate Zone 2)	Las Vegas, NV (Climate Zone 3)	Washington, DC (Climate Zone 4)	Chicago & Minn. (Climate Zones 5 & 6)
Wall insulation R-value (nominal)	13	13	13	19
Cavity	13	13	13	19
Sheathing	0	0	0	0
framing factor	0.23	0.23	0.23	0.23
Ceiling insulation R-value	30	30	38	38
Slab insulation R-value (2' down)	0	0	0	0
Basement Walls	na	na	na	na
Window U-value (Btu·h^{-1}·ft^{-2}·F^{-1})	0.75	0.65	0.40	0.35
Window SHGC	0.40	0.40	0.40	0.40
Building enclosure air leakage (ACH50)	7	7	7	7
Enclosure ELA (in^2)	98.1	98.1	98.1	98.1
Duct air leakage to outside (%)	6% sup, 4% ret	6% sup, 4% ret	6% sup, 4% ret	6% sup, 4% ret
Supply duct area in attic (ft^2)	544	544	544	544
Return duct area in attic (ft^2)	100	100	100	100
Duct R-value	6	6	6	6
SEER, EER	13, 9.6	13, 9.6	13, 9.6	13, 9.6
HSPF, COP	7.7, 2.3	7.7, 2.3	7.7, 2.3	7.7, 2.3
Internal heat gain (lumped)** (people+lighting+appliances)	72.70 kBtu/day	72.70 kBtu/day	72.70 kBtu/day	72.70 kBtu/day
Internal moisture generation	12 lb/day	12 lb/day	12 lb/day	12 lb/day
HERS	106	108	108	107
Cooling / Heating Set Points (F)	78 / 72	78 / 72	76 / 70	76 / 70
Electricity Costs ($ / kWh)	0.85	0.126	0.141	0.128 / 0.108

❑ **Modeling**

H

Heat Pump & House Information

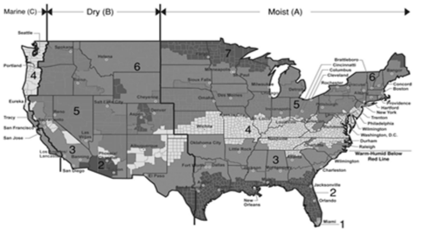
- **Heat Pump ~13 SEER, single speed**
  - – Scroll compressor, TXV
  - – 375 cfm/ton, 0.5 W/cfm, fan in AUTO (cycles) [50.3 L/kJ, 1.06 W/(L/s)]
  - – Heat pump model from EnergyGauge model
- **Home's HERS Index Score 100**
  - – HERS reference home w/ some Building America operating characteristics, ELA = 98.1 in^2 (0.063 m^2)
- **Ventilation** – exhaust only
  - – 58 cfm continuous, 0.4 W/cfm (ASHRAE 62.2) [27.4 L/s, 0.85 W/(L/s)]

Studied Faults: Cooling & Heating Mode

Fault Type	Fault Levels (%)	
	Cooling mode	Heating mode
Heat Pump Sizing (SIZ)	-20, 25, 50, 75, 100	-20, 25, 50, 75, 100
Duct Leakage (DUCT)	0, 10, 20, 30, 40, 50	0, 10, 20, 30, 40, 50
Indoor Coil Airflow (AF)	-36, -15, 7, 28	-36, -15, 7, 28
Refrig. Undercharge (UC)	-10, -20, -30	-10, -20, -30
Refrig. Overcharge (OC)	10, 20, 30	10, 20, 30
Excessive Refrigerant Subcooling (SC)	100, 200	--
Non-Condensable Gases (NC)	10, 20	10, 20
Electric Voltage (VOL)	-8, 8, 25	-8, 8, 25
TXV Undersizing (TXV)	-60, -40, -20	--

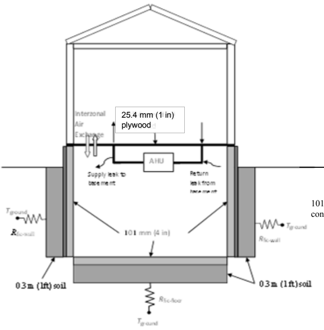
QI

Figure 4.2 – IECC climate zone map

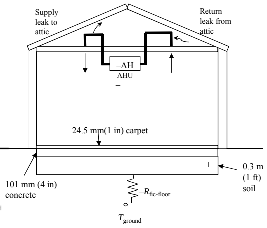


Zone	Climate	Location	Slab-on-grade house	House with basement	HP Size
2	Hot and humid	Houston, TX	Yes	no	3 ton
3	Hot and dry	Las Vegas, NV	Yes	Yes	3.5 ton
4	Mixed climate	Washington, DC	Yes	Yes	2.5 ton
5	Heating dominated	Chicago, IL	Yes	Yes	2.5 ton
6	Cold	Minneapolis, MN	Yes	Yes	2.5 ton

House with a Basement



Slab-on-Grade House



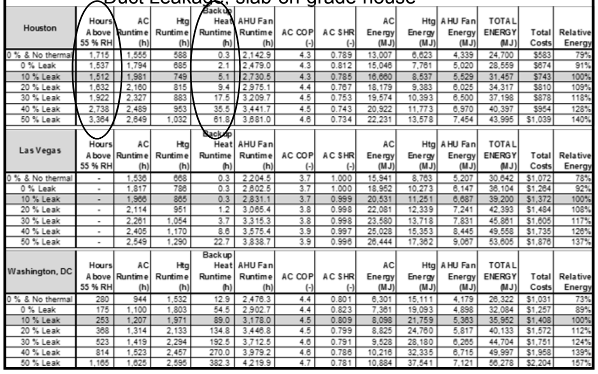
Questions

- **How significant is the effect of individual faults on annual energy use?**
- **What is the effect of simultaneous faults?**
- **How does the effect of faults vary with building type and climate?**

Focus on capacity and energy use while maintaining the target indoor dry-bulb temperature

Table 5.9 – Example of Single-Fault Simulation Results (Annual Energy)

Duct Leakage; slab-on-grade house



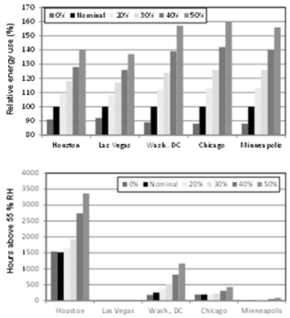
Houston	Hours Above 55 % RH	AC Runtime (h)	Htg Runtime (h)	Backup Heat Runtime (h)	AHU Fan Runtime (h)	AC COP (-)	AC SHR (-)	AC Energy (MJ)	Htg Energy (MJ)	AHU Fan Energy (MJ)	TOTAL ENERGY (MJ)	Total Costs	Relative Energy
0 % & No thermal	1,715	1,555	588	0.3	2,142.9	4.3	0.789	13,007	6,623	4,339	24,700	$583	79%
0 % Leak	1,537	1,794	685	2.1	2,479.0	4.3	0.812	15,046	7,761	5,020	28,559	$674	91%
10 % Leak	1,512	1,981	749	5.1	2,730.5	4.3	0.785	16,660	8,537	5,529	31,457	$743	100%
20 % Leak	1,632	2,160	815	9.4	2,975.1	4.4	0.767	18,179	9,383	6,025	34,317	$810	109%
30 % Leak	1,922	2,327	883	17.5	3,209.7	4.5	0.753	19,574	10,393	6,500	37,198	$878	118%
40 % Leak	2,738	2,489	953	35.5	3,441.7	4.5	0.743	20,922	11,773	6,970	40,397	$954	128%
50 % Leak	3,364	2,649	1,032	61.8	3,681.0	4.6	0.734	22,231	13,578	7,454	43,995	$1,039	140%

Las Vegas	Hours Above 55 % RH	AC Runtime (h)	Htg Runtime (h)	Backup Heat Runtime (h)	AHU Fan Runtime (h)	AC COP (-)	AC SHR (-)	AC Energy (MJ)	Htg Energy (MJ)	AHU Fan Energy (MJ)	TOTAL ENERGY (MJ)	Total Costs	Relative Energy
0 % & No thermal	-	1,536	668	0.3	2,204.5	3.7	1.000	15,941	8,763	5,207	30,642	$1,072	78%
0 % Leak	-	1,817	786	0.3	2,602.5	3.7	1.000	18,952	10,273	6,147	36,104	$1,264	92%
10 % Leak	-	1,966	865	0.3	2,831.1	3.7	0.999	20,531	11,251	6,687	39,200	$1,372	100%
20 % Leak	-	2,114	951	1.2	3,065.4	3.8	0.998	22,081	12,339	7,241	42,393	$1,484	108%
30 % Leak	-	2,261	1,054	3.7	3,315.3	3.8	0.998	23,580	13,718	7,831	45,861	$1,605	117%
40 % Leak	-	2,405	1,170	8.6	3,575.4	3.9	0.997	25,028	15,353	8,445	49,558	$1,735	126%
50 % Leak	-	2,549	1,290	22.7	3,838.7	3.9	0.996	26,444	17,362	9,067	53,605	$1,876	137%

Washington, DC	Hours Above 55 % RH	AC Runtime (h)	Htg Runtime (h)	Backup Heat Runtime (h)	AHU Fan Runtime (h)	AC COP (-)	AC SHR (-)	AC Energy (MJ)	Htg Energy (MJ)	AHU Fan Energy (MJ)	TOTAL ENERGY (MJ)	Total Costs	Relative Energy
0 % & No thermal	280	944	1,532	12.9	2,476.3	4.4	0.801	6,301	15,111	4,179	26,322	$1,031	73%
0 % Leak	175	1,100	1,803	54.5	2,902.7	4.4	0.823	7,361	19,093	4,898	32,084	$1,257	89%
10 % Leak	253	1,207	1,971	89.0	3,178.0	4.5	0.809	8,098	21,759	5,363	35,952	$1,408	100%
20 % Leak	368	1,314	2,133	134.8	3,446.8	4.5	0.799	8,825	24,760	5,817	40,133	$1,572	112%
30 % Leak	523	1,419	2,294	192.5	3,712.5	4.6	0.791	9,528	28,180	6,265	44,704	$1,751	124%
40 % Leak	814	1,523	2,457	270.0	3,979.2	4.6	0.786	10,216	32,335	6,715	49,997	$1,958	139%
50 % Leak	1,165	1,625	2,595	382.3	4,219.9	4.7	0.781	10,884	37,541	7,121	56,278	$2,204	157%

Duct Leakage

Slab-on-grade houses



Significant increase in hours above 55 % RH in Houston

Houston – # of Hours above 55% RH

Duct Leakage 10 – 50%; slab-on-grade house (T'stat turned down 2°F and 4°F)

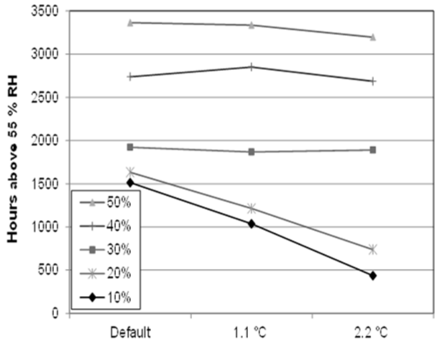


Fig. 5.3

Houston – Incr in Annual Energy Usage

(T'stat turned down 2°F and 4°F)

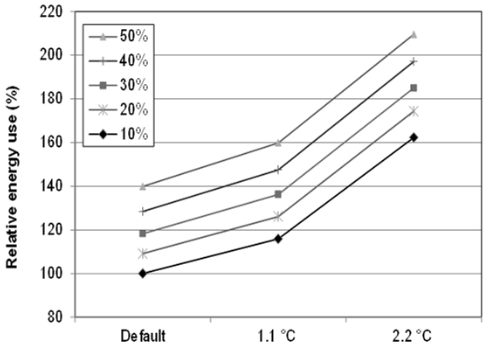
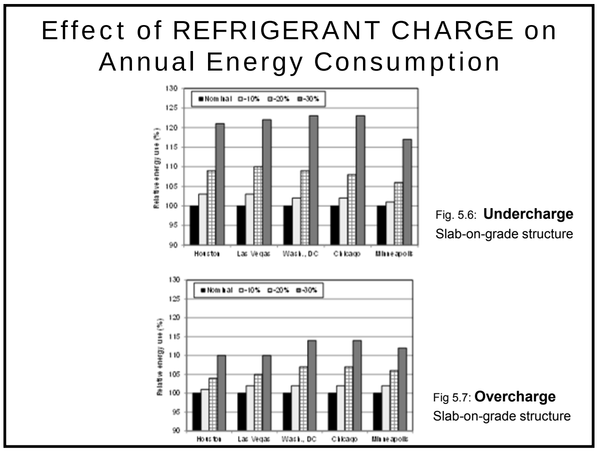


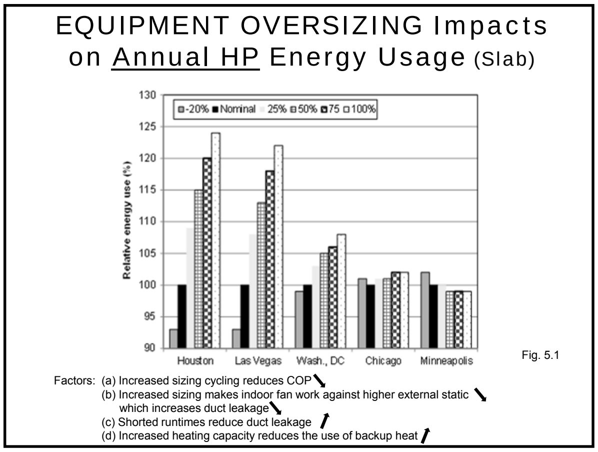
Fig. 5.4



Effect of REFRIGERANT CHARGE on Annual Energy Consumption

Fig. 5.6: **Undercharge**
Slab-on-grade structure

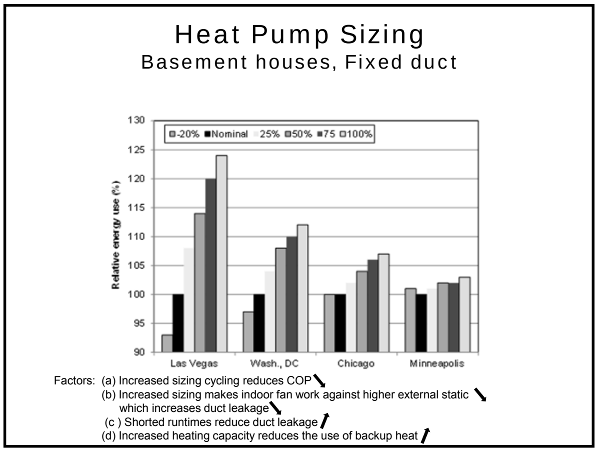
Fig 5.7: **Overcharge**
Slab-on-grade structure



EQUIPMENT OVERSIZING Impacts on Annual HP Energy Usage (Slab)

Fig. 5.1

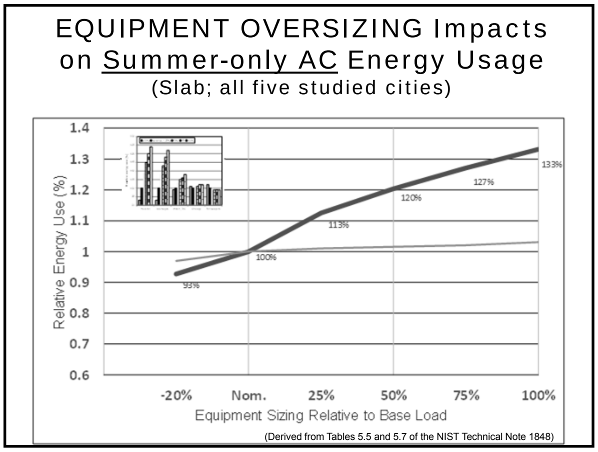
Factors: (a) Increased sizing cycling reduces COP ↘
(b) Increased sizing makes indoor fan work against higher external static ↘ which increases duct leakage ↘
(c) Shorted runtimes reduce duct leakage ↗
(d) Increased heating capacity reduces the use of backup heat ↗



Heat Pump Sizing

Basement houses, Fixed duct

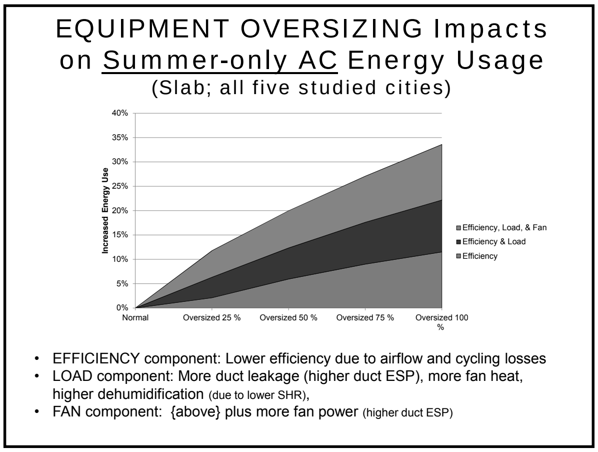
Factors: (a) Increased sizing cycling reduces COP ↘
(b) Increased sizing makes indoor fan work against higher external static ↘ which increases duct leakage ↘
(c) Shorted runtimes reduce duct leakage ↗
(d) Increased heating capacity reduces the use of backup heat ↗



EQUIPMENT OVERSIZING Impacts on Summer-only AC Energy Usage

(Slab; all five studied cities)

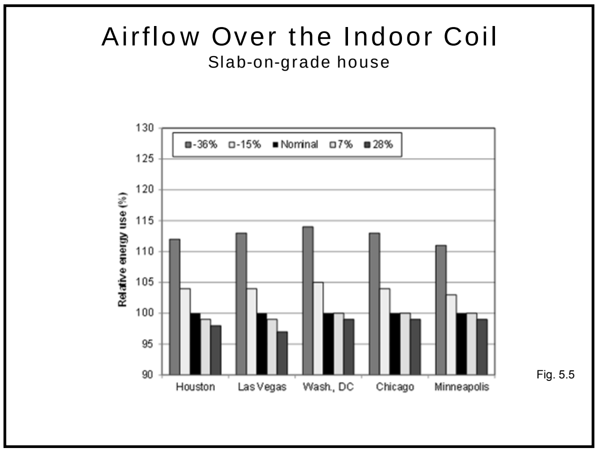
(Derived from Tables 5.5 and 5.7 of the NIST Technical Note 1848)



EQUIPMENT OVERSIZING Impacts on Summer-only AC Energy Usage

(Slab; all five studied cities)

- EFFICIENCY component: Lower efficiency due to airflow and cycling losses
- LOAD component: More duct leakage (higher duct ESP), more fan heat, higher dehumidification (due to lower SHR),
- FAN component: {above} plus more fan power (higher duct ESP)



Airflow Over the Indoor Coil

Slab-on-grade house

Fig. 5.5

Input Voltage

Slab-on-grade house

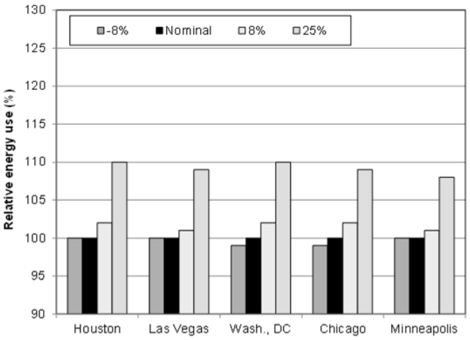


Fig. 5.9

TXV Undersizing

Slab-on-grade houses

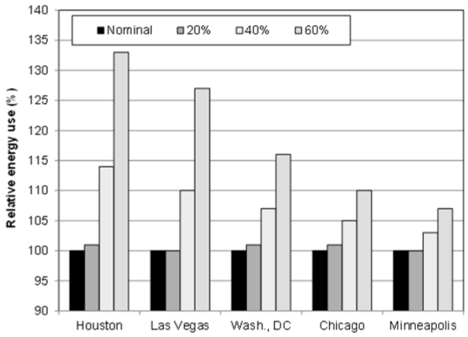


Fig. 5.10

Overview: Single Fault Effects (1)

Except for **duct leakage,** no drastic differences between 'slab-on-grade' and 'basement' structure.

- **Duct leakage →** The most influential fault on performance
  - Impact: ~30% energy penalty
  - Significant increase of indoor RH in humid climates
- **Refrigerant undercharge →** The 2nd most influential fault
  - 20% energy penalty at 30% undercharge
  - 2 – 3% penalty at 10% undercharge
- **Equipment oversizing** (with undersized ductwork) →
  Summer & Winter HP usage:
  - 20% energy penalty in warm climates (Houston, Las Vegas)
  - 2% or less energy impact in Chicago, DC, Minneapolis

  Summer (only) AC usage (all climates):
  - 7 – 13% energy penalty for **each 25%** oversized

Overview: Single Fault Effects (2)

- **Refrigerant overcharge →** also significant increase
  - 10 to 15% energy penalty at the 30% overcharge fault level.
- **Low indoor airflow →** also consistent increases
  - 10 to 15% energy penalty at the -30% fault level.
- **Undersized cooling TXV →** most pronounced in localities with a high number of cooling mode operating hours
  - 14% more energy used in Houston (40% undersize)
  - 3% energy penalty in Chicago.
- **Improper voltage** & **Non-condensables** → Penalty impact is under 4% (for the studied ranges).

  [Obviously, all these faults have a substantial impact on 1st *cost*, *equipment durability*, *degraded moisture control capability*, and *comfort*.]

Double Faults Example (1)

Multi-fault Set: 10 **(Houston)**		**- 15% Airflow**	**- 36% Airflow**
		104%	**112%**
15% Undercharge	**105%**	**107%**	**111%**
30% Undercharge	**121%**	**123%**	**127%**

Impacts < Additive

Double Faults Example (2)

Multi-fault Set: 5 **(Houston)**		**20% Duct Leakage**	**40% Duct Leakage**
		109%	**128%**
10% Noncondensibles	**102%**	**112%**	**131%**
30% Noncondensibles	**104%**	**113%**	**133%**

Effects Additive

Double Faults Example (3)

Multi-fault Set: 3 (Houston)		20% Duct Leakage	40% Duct Leakage
		109%	128%
15% Undercharge	105%	**115%**	**136%**
30% Undercharge	121%	**132%**	**156%**

Effects Amplified

Double Faults Examples (4 and 5)

Multi-fault Set: 3 (Washington, DC)		20% Duct Leakage	40% Duct Leakage
		112%	139%
15% Undercharge	105%	**117%**	**146%**
30% Undercharge	123%	**137%**	**172%**

Effects Amplified

Multi-fault Set: 3 (Minneapolis)		20% Duct Leakage	40% Duct Leakage
		113%	140%
15% Undercharge	103%	**116%**	**144%**
30% Undercharge	117%	**132%**	**162%**

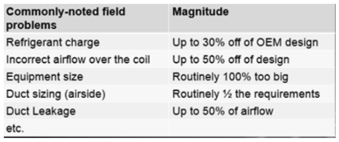
Effects Amplified

Triple Faults

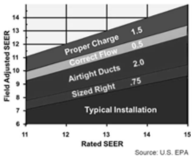
Triple faults not studied … resource constraints, insufficient data for modeling.

"It is reasonable to assume that the effect of a triple fault will be at least as high as that of any of the possible three fault pairs considered individually; however, ***the effort of the third fault can increase the effect of the other two faults in an additive manner****."*

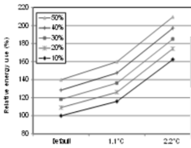
Field Problems Can Be Much Worse Than Anyone Ever Thought …

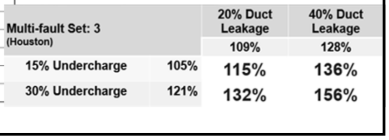


Commonly-noted field problems	Magnitude
Refrigerant charge	Up to 30% off of OEM design
Incorrect airflow over the coil	Up to 50% off of design
Equipment size	Routinely 100% too big
Duct sizing (airside)	Routinely ½ the requirements
Duct Leakage	Up to 50% of airflow
etc.	



Source: U.S. EPA





Multi-fault Set: 3 (Houston)		20% Duct Leakage	40% Duct Leakage
		109%	128%
15% Undercharge	105%	**115%**	**136%**
30% Undercharge	121%	**132%**	**156%**

"The goal of the NIST study was to assess the impacts that HVAC system installation faults had on equipment electricity consumption. The effect of the installation faults on occupant comfort was not the main focus of the study, and this research ***did not seek to quantify any impacts*** *on* ***indoor air quality****, or* ***noise generation*** *(e.g., airflow noise from air moving through restricted ducts).*

Additionally, the study ***does not address*** *the effects that installation faults have on* ***equipment reliability / robustness*** *(number of starts/stops, etc.),* ***maintainability*** *(e.g., access issues),* ***or costs*** *of initial installation and ongoing maintenance."*

Landmark Study !

Okay, remember this also !!

- Quantifies efficiency losses (>30%)
- Losses are additive for multiple faults (>>30%)
- Applies to Unitary Equipment
  - Residential and Commercial
  - Split Systems and Packaged
- Results being embraced
  - Utility Commissions
  - State Energy Offices
  - Electric COOP Boards
  - Utilities

NIST Technical Note 1848

Sensitivity Analysis of Installation Faults on Heat Pump Performance

NIST

www.acca.org/quality

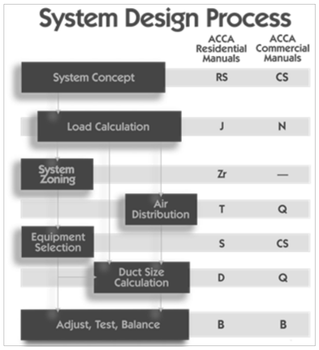
Obviously, without an emphasis on ensuring quality installations (QI) …

HVAC Systems do not properly perform and …

Customers Don't Get What they Paid For !!

Industry Resources

Design Manuals **QI / QM Standards**



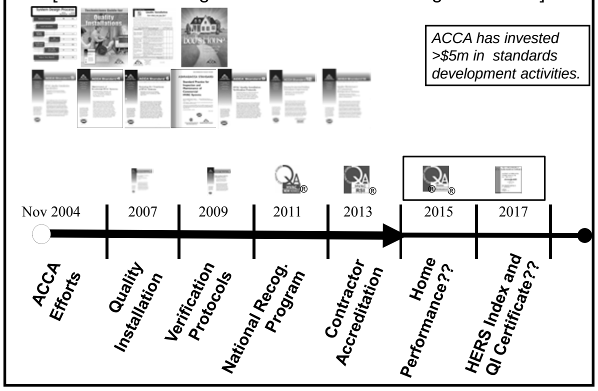
System Design Process

	ACCA Residential Manuals	ACCA Commercial Manuals
System Concept	RS	CS
Load Calculation	J	N
System Zoning	Zr	—
Air Distribution	T	Q
Equipment Selection	S	CS
Duct Size Calculation	D	Q
Adjust, Test, Balance	B	B

Advancing Contractor Accreditation

[aka: The Long Path to "Establishing the Bar"]

ACCA has invested >$5m in standards development activities.



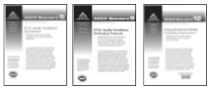
ACCA 5 QI / ACCA 9 QIvp / ACCA 12 QH …

Basis for QA Contractor Accreditations

New Homes
Started in 2011
600+ accredited contractors nationwide

Residential Service and Installation
Started in 2013
150+ (and growing) contractors nationwide

Home Performance
pending



EPA EnergyStar^{TM} Programs

New Homes

- EnergyStar Certified New Homes (v3; eff. Jan2012)
  - Aligned with ACCA's QA New Homes Program

Existing Homes

- Energy Star Verified HVAC Installation (ESVI; pending)
  - Seeking to align with ACCA's RSI Program

QA Program: Contractor Accreditation

HVAC (New Homes)

HVAC (Existing Homes)
RSI Certificate - $45

Application and Annual Fee:
$ 600 ACCA Member
$ 800 Non-member

Foundation: Contractor Accreditation Requirements

QA Contractor Elements	Trade License	Business Registration	Insurance • G/L • Auto • Workers Comp.	Certifications • EPA (Section 608)

Information on the QA Program can be found at: **www.QAContractors.org**

Why is ACCA Promoting?

(aka: the “value proposition”)

- Differentiate quality-focused contractors
- Levels the playing field for professional contractors
- Raises the contractor performance bar
- Industry guides the effort …
  (beats even more regulations from the government)
- Helps stakeholder groups meet efficiency goals

- **Oh … and it helps to ensure that the <u>customer receives</u> what s/he thought s/he was getting all along.**

<u>**No** QI / QM</u> …
No energy efficiency

<u>**Know** QI / QM</u> …
Know efficiency
(and comfort, and performance, and durability, and etc.)

Discussion