Residential Air Conditioning Fault Detection and Diagnostics (FDD) and Protocols to Support Efficient Operation

DOE - Building America Program

Residential Buildings Integration Meeting - July 20-22, 2010

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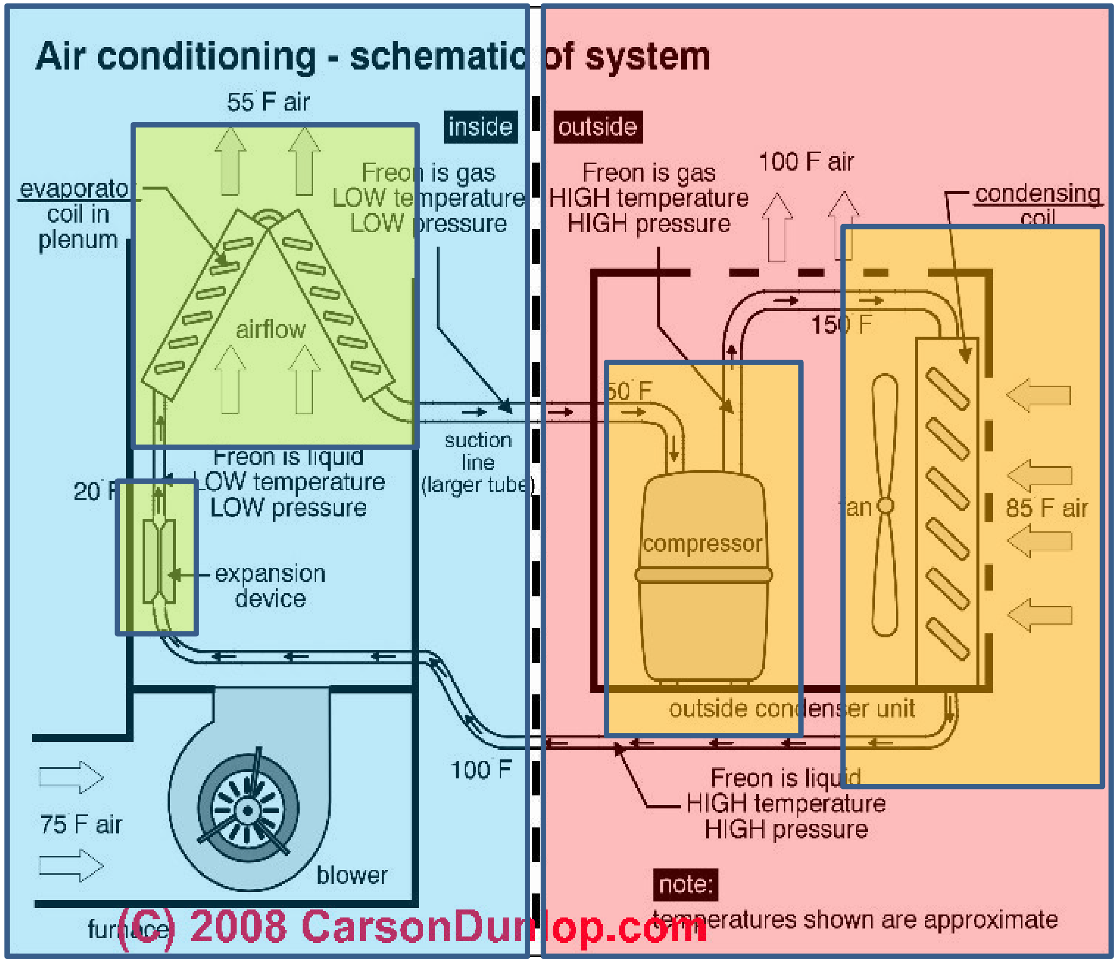
President

Agenda

- Common residential air conditioning systems
- Faults, diagnostic algorithms and factors that impact energy efficiency
- Technical protocols and program designs to measure and improve energy efficiency
- Improved protocols and program designs

Typical Residential "Split System"



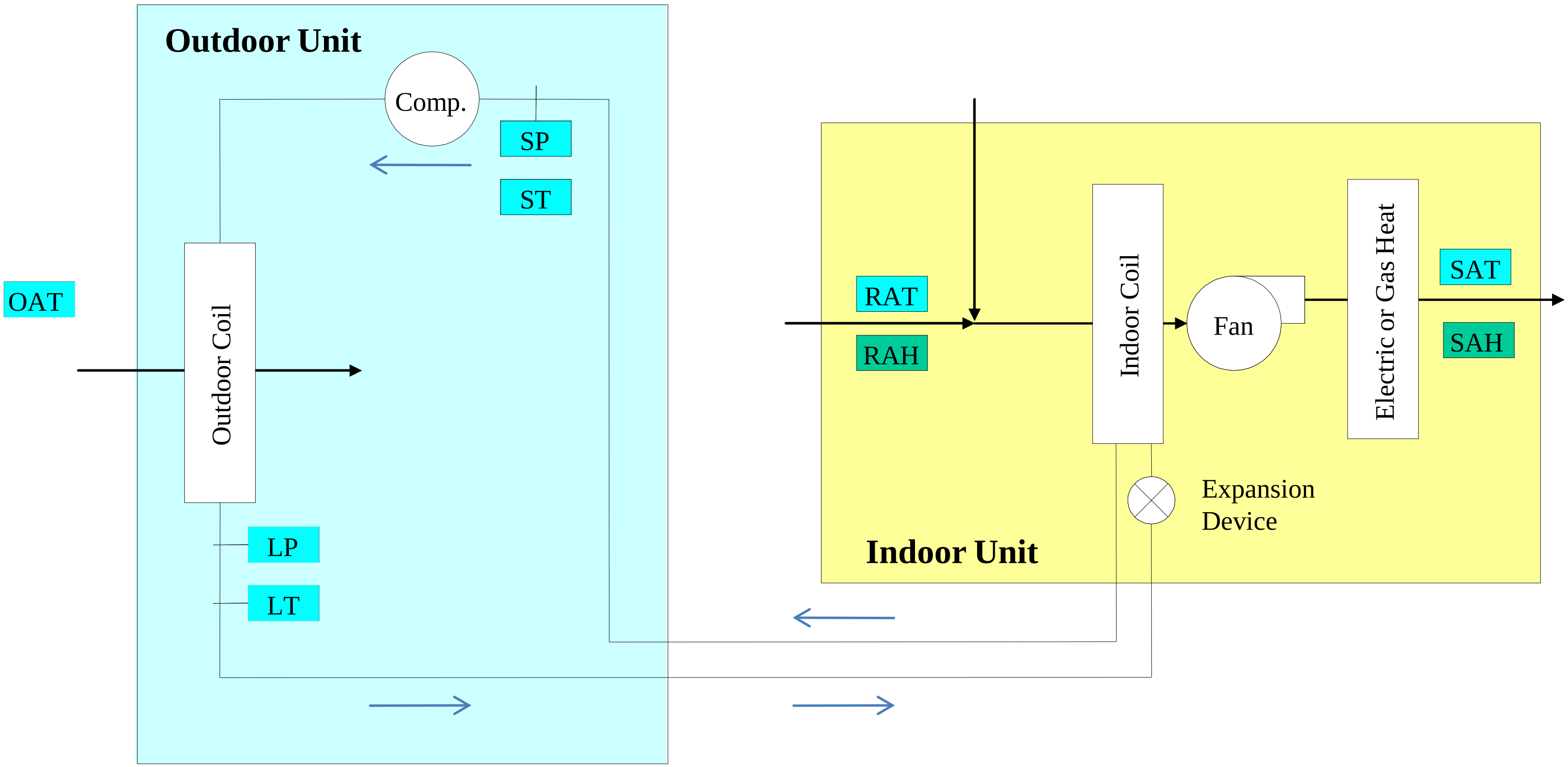
- Outdoor Components
  - Compressor
  - Condenser and fan
- Indoor Components
  - Expansion device
  - Evaporator and fan

Common Degradation Faults

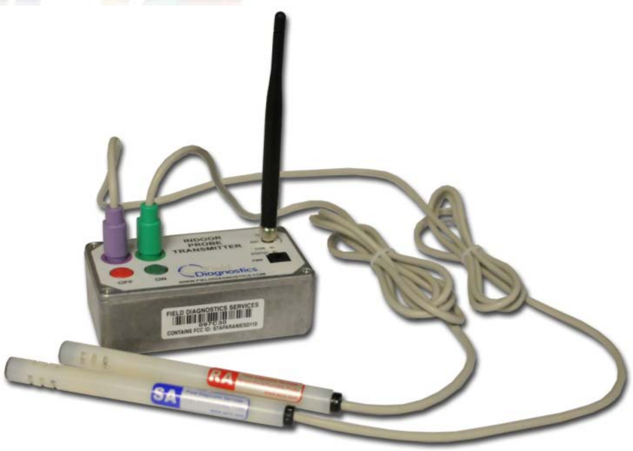
- Compressor
  - Inefficient pump
- Condenser
  - High-side heat transfer problem
- Refrigerant
  - Too little
  - Too much
  - Non-condensibles
- Expansion device
  - Liquid line restriction
- Evaporator and Fan
  - Low-side heat transfer problem
    - Dirty filter
    - Dirty indoor coil
    - Restricted ducts
    - Ineffective fan (e.g. slipping belt)

Field Diagnostics

Refrigeration Cycle Measurements



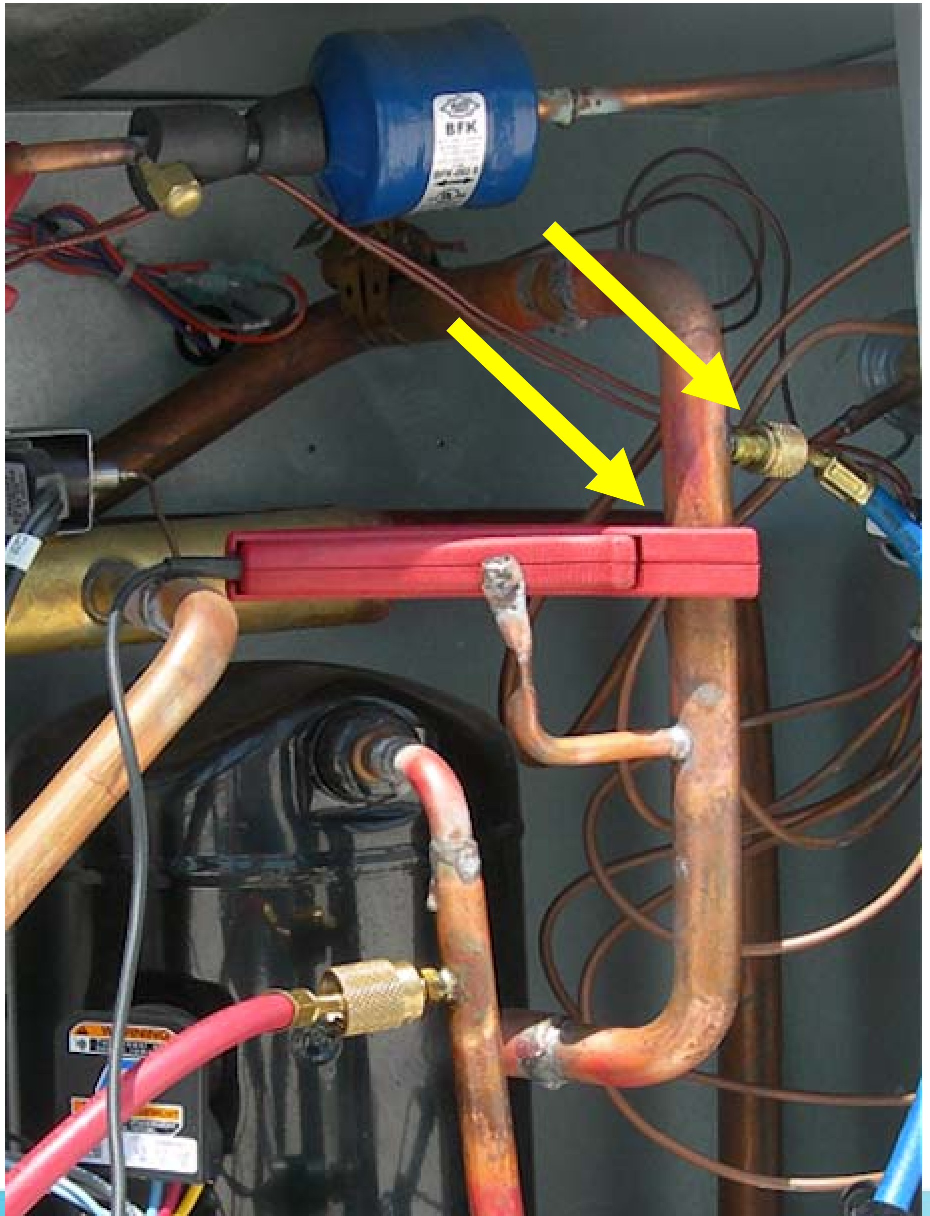
Ref Cycle Measurements



- Outdoor Unit
  - Liquid pressure
  - Suction pressure
  - Liquid temperature
  - Suction temperature
  - Outdoor temperature

Indoor Unit

  - Return air temperature and humidity
  - Supply air temperature and humidity

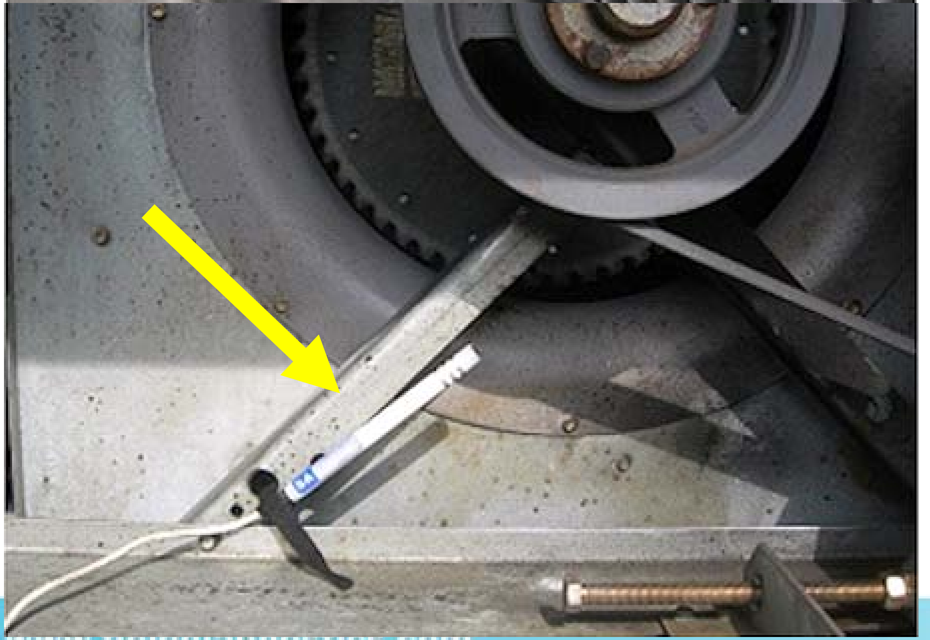


Suction Pressure and Temperature

The *Suction Pressure Hose* is installed on the suction service access fitting.

The *Suction Temperature Sensor Clamp* is installed on the suction line, near the compressor.

Field Diagnostics

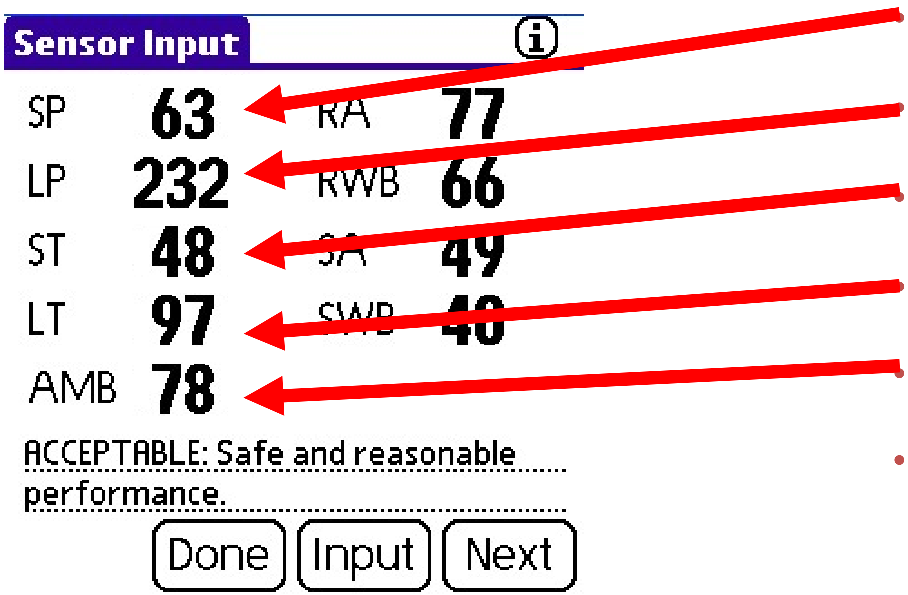


Air-side Temperature and Humidity Sensors

The *Return Air Sensor* measures the temperature and humidity of the air entering the evaporator.

The *Supply Air Sensor* measures the temperature and humidity of the air leaving the evaporator.

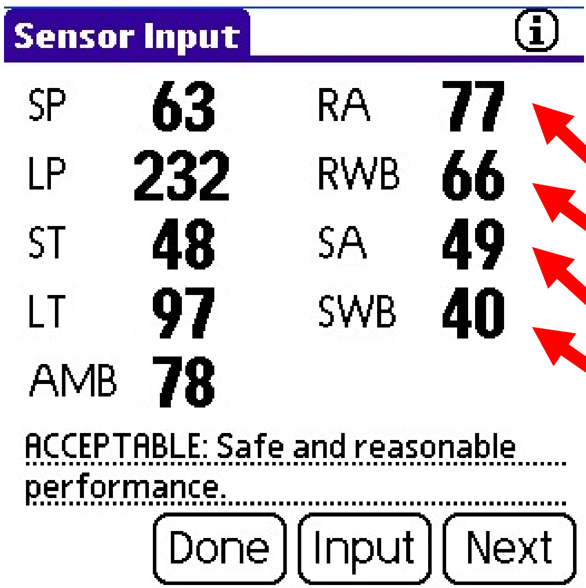
Ref Cycle Measurements



The Service Assistant measures:

- Suction pressure
- Liquid pressure
- Suction temperature
- Liquid temperature
- Ambient temperature
- Return air temperature and humidity sensors
- Supply air temperature and humidity sensors

Ref Cycle Measurements



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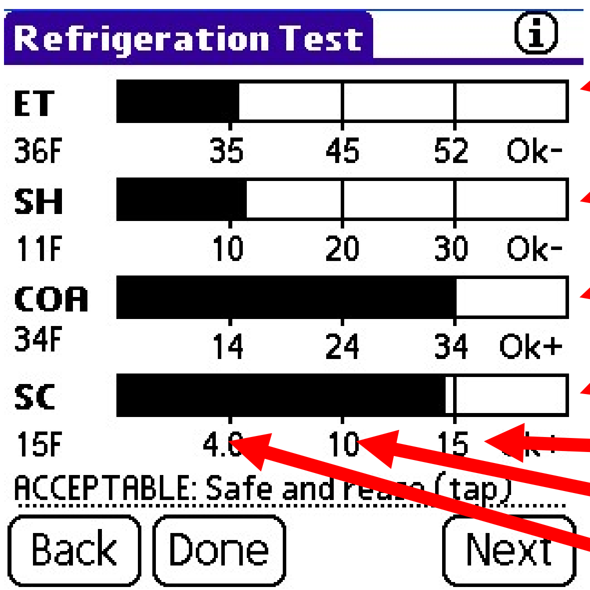
Ref Cycle Performance Indices



The Service Assistant calculates:

- Evaporator Temperature (ET)
- Superheat (SH)
- Condensing Temp over Ambient (COA)
- Subcooling (SC)

- Highest acceptable value
- Goal value
- Lowest acceptable value

Diagnostic Methodology

- Quality measurements
  - Look for unphysical measurement combinations
  - High-side: CT > LT > OAT
  - Low-side: ET < ST < RA
- Calculate performance indices (e.g. ET, SH, COA, SC)
- Calculate fault-free expected values – as function of
  - Equipment type
    - Refrigerant type
    - Expansion device type
    - Efficiency rating
  - Driving conditions
    - Outdoor temperature
    - Evaporator inlet air temperature and humidity
- Determine if differences are significantly high or low
- Combine high and low combinations of the performance indices to isolate the fault



Low ET - Diagnostic Logic Example

- Liquid line restriction
  - Low ET
  - High SH
  - High SC
- Low refrigerant charge
  - Low ET
  - High SH
  - Low SC
- Low-side heat transfer problem
  - Low ET
  - Low SH

Field Diagnostics

Impact of Faults on Efficiency

Changes in rooftop operation due to refrigerant leakage				
(% leakage)	**% Change in Capacity**	**% Change in COP**	**Change in T_{sh} (F)**	**Change in T_{hg} (F)**
3.5	3.0	**2.7**	3.5	3.3
7.0	3.8	**2.8**	7.0	6.1
10.5	5.6	**3.6**	9.9	8.4
14.0	8.0	**4.6**	11.1	10.0
Changes in rooftop operation due to liquid line restriction				
(% AP)	**% Change in Capacity**	**% Change in COP**	**Change in T_{sh} (F)**	**Change in T_{hg} (F)**
5	3.5	**3.0**	5.5	5.8
10.0	5.2	**3.7**	8.7	8.8
15.0	8.8	**5.1**	11.9	12.2
20.0	17.2	**8.7**	16.0	16.6

Smart Maintenance For Rooftop Units
By Mark Breuker, Todd Rossi, Ph.D., and Jim Braun, Ph.D.
ASHRAE Journal November, 2000

Field Diagnostics

Impact of Faults on Efficiency

Changes in rooftop operation due to compressor valve leakage				
Fault Level (% A lJ)	**% Change in Capacity**	**% Change in COP**	**Change in T_{sh} (F)**	**Change in T_{hg} (F)**
7	7.3	**7.9**	-3.6	0.2
14	9.6	**10.5**	-4.8	0.0
28	12.5	**14.0**	-7.2	0.1
35	21.3	**23.8**	-11.8	0.6
Changes in rooftop operation due to condenser fouling				
(% area block)	**% Change in Capacity**	**% Change in COP**	**Change in T_{sh} (F)**	**Change in T_{hg} (F)**
14	3.1	**4.3**	0.8	2.2
28	4.8	**7.7**	4.2	2.6
42	7.4	**12.2**	8.0	3.1
56	10.9	**17.9**	11.2	4.5
Changes in rooftop operation due to evaporator fouling				
(% A airflow)	**% Change in Capacity**	**% Change in COP**	**Change in T_{sh} (F)**	**Change in T_{hg} (F)**
12	6.7	**6.0**	2.1	1.5
24	13.6	**12.3**	3.9	3.2
36	19.4	**17.4**	5.5	5.1

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Measuring Efficiency

- Efficiency = Net Capacity / Total Power
- Gross Capacity
  - Air-side: m_A * [$h_{RA}(T,RH)$ - $h_{SA}(T,RH)$]
  - Ref-side: m_R * [$h_{LL}(P,T)$ - $h_{SL}(P,T)$]
- Net Capacity = Gross Capacity – Indoor Fan Heat
- Total Power = Compressor + Indoor Fan + Outdoor Fan
- Efficiency is a function of the driving conditions:
  - Outdoor temperature (OAT)
  - Evaporator inlet air temperature and humidity

Efficiency Index (EI)

- **Objective**
  - Measure efficiency
  - Make best use of existing thermodynamic/diagnostic measurements
  - Account for variable driving conditions
- **Approach**
  - Use manufacturer’s compressor performance data to obtain compressor power and refrigerant mass flow rate (m_R)
  - Calculate refrigerant enthalpy (h) from suction and liquid line pressure and temperature measurements
  - Assume fan power in proportion to compressor
  - Normalize for driving conditions by computing the ratio of the efficiencies from:
    - Actual performance indices
    - Expected performance indices for a similar no-fault unit under the same driving conditions (“Normal” model required)

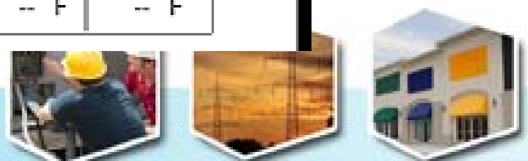
Example Performance Report

Performance Parameter	Pre-Test Value	Post-Repair Value	Realized Savings
Efficiency Index (EI)	86%	97%	$246
Capacity Index (CI)	75%	88%	
Potential Annual Savings	$409	$163	

The following values were used for Potential Annual Savings calculation: Annual Runtime 1500 hrs/year, Electrical Cost 17.7 cents/kWh.

Diagnostics Parameter	Pre-Test			Post-Repair		
	Goal	Value	Evaluation	Goal	Value	Evaluation
Evaporating Temp (ET)	40 F	23 F	Lo	42 F	36 F	Ok-
Suction Superheat (SH)	20 F	6 F	Lo	20 F	30 F	Ok+
Condenser Over Ambient (COA)	21 F	5 F	Lo	22 F	15 F	Ok-
Subcooling (SC)	10 F	6 F	Ok-	10 F	10 F	Ok
Indoor Air Temp Difference (ITD)	19 F	5 F	Lo	17 F	26 F	Hi
Condenser Temp (CT)	-- F	84 F	N/A	-- F	89 F	N/A

Measurement	Pre-Test	Post-Repair	Measurement	Pre-Test	Post-Repair
Suction Pressure (SP)	46 psig	62 psig	Supply Air (SA)	67 F	46 F
Liquid Pressure (LP)	154 psig	165 psig	Return Air Wet Bulb Temp (RWB)	60 F	62 F
Suction Temp (ST)	29 F	65 F	Supply Air Wet Bulb Temp (SWB)	56 F	38 F
Liquid Temp (LT)	78 F	79 F	Ambient Temp (AMB)	79 F	74 F
Return Air (RA)	72 F	72 F	Air off Condenser Temp (AOC)	-- F	-- F



Residential Air Conditioning Energy Efficiency Improvement Example Savings Calculation

<table>
<tr><th>City</th><th>CDD (65F base)</th><th>AC Energy (kWh/year)</th><th>Factor</th><th>EI</th><th>Efficiency Improvement Opportunity</th><th>Recovery</th><th>Energy Savings (kWh/year)</th></tr>
<tr><td>Fort Collins, CO</td><td>497</td><td>1741</td><td>3.50</td><td colspan="4">Baseline Data</td></tr>
<tr><td>East Denver (Stapleton)</td><td>698</td><td>2443</td><td rowspan="3">3.50</td><td rowspan="3">81%</td><td rowspan="3">19%</td><td rowspan="3">80%</td><td>371</td></tr>
<tr><td>West Denver (Lakewood)</td><td>435</td><td>1523</td><td>231</td></tr>
<tr><td>Boulder</td><td>552</td><td>1932</td><td>294</td></tr>
<tr><td>Average</td><td></td><td></td><td></td><td></td><td></td><td></td><td>299</td></tr>
</table>



Simple FDSI Tune-up Protocol

- **Test all or suspect units**
  - **Pay "Audit" incentive if test-in passes**
- **Repair problem units and test-out**
  - **Pay "Performance Improvement" incentive if test-in fails and test-out passes**

Measure	Incentive
Refrigeration Cycle Audit	$25
Refrigeration Cycle Performance Improvement (single circuit)	$125

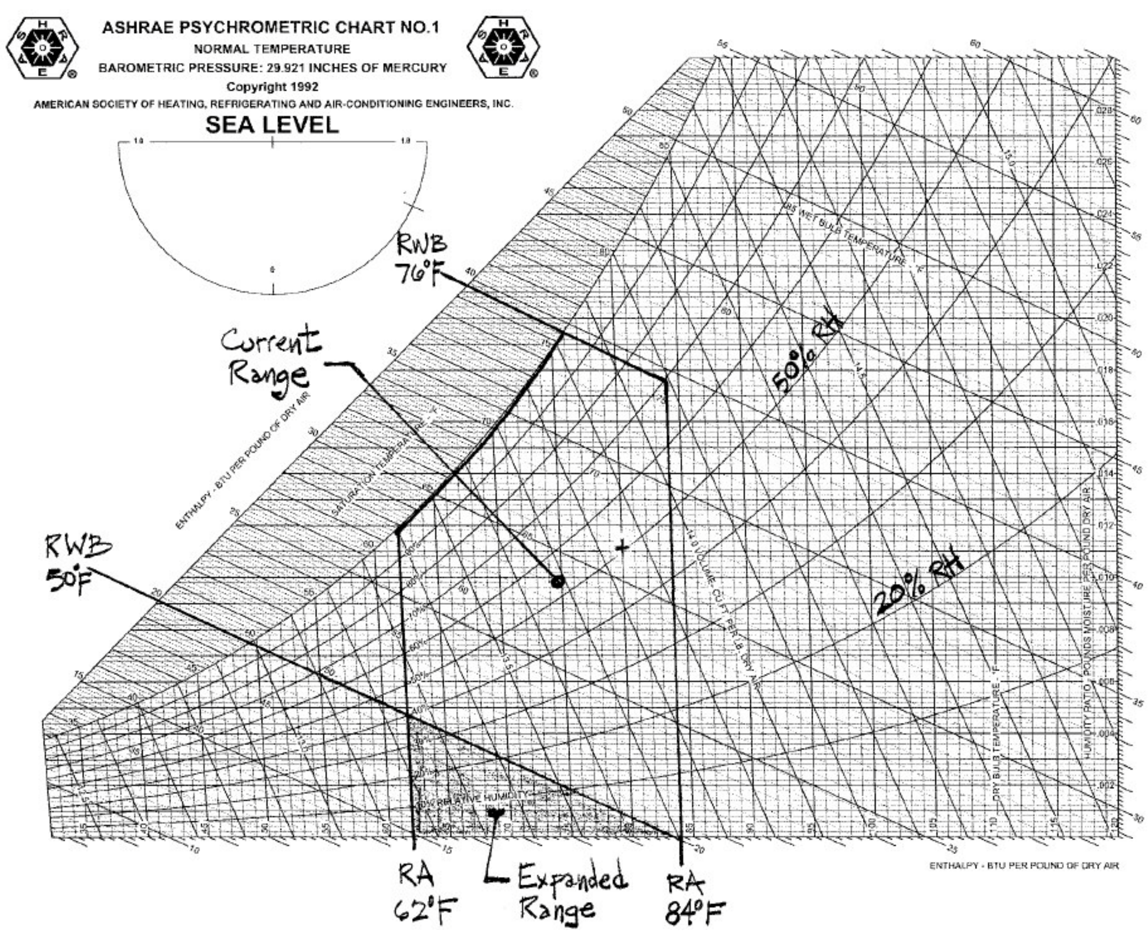
Ref Cycle Pass/Fail Criteria

- Correct unit information
  - SEER or EER is entered correctly
  - Capacity is entered correctly
- Diagnosis is "Safe and Reasonable"
- EI (efficiency index) is at least 90

Weaker RCA Tune-up Protocol

- Refrigerant Charge and Airflow
  - Does not directly consider broader set of possible faults
- Protocol is based on common new unit refrigerant charging algorithm
  - Other faults more reasonable to assume not present, for example:
    - Clean indoor and outdoor heat exchanger / filters
    - Expansion device not restricted
    - Compressor effectively pumping
- Only uses 1 of 4 performance indices (SH or SC) to determine correct charge levels and pay incentive
  - Low efficiency degradation threshold to engage corrective action
- Weak program design
  - Can pay incentives to adjust charge when SH or SC off because of other faults
  - Corrective action may not achieve desired efficiency improvement

Protocol Challenge: Hot/Dry Climates



- Standard protocol has problems in hot/dry climates where indoor coils are more likely to be dry
- Fixed orifice expansion device units have expected superheat (SH) values of zero
- Innovative algorithm adapts diagnostics and efficiency estimator to these conditions
  - See "Expanded Range"

Next Generation Protocols

- Look for opportunities to replace units when appropriate
  - Incentivized tune-up provides opportunity to test units and improve performance
  - When unit performance problems are beyond tune-up scope to repair – move to replacement scenario
    - Help make business case to customer
    - Automate Manual-J sizing calculations
    - Administer new unit incentives
  - Bigger savings achieved and more contractor revenue generation (promotes more production)
- Embedded 24/7 “Smart Grid” monitoring solutions
  - Find problem units remotely
  - Incentivize repairs
  - Manage workflow via PDA platform



Conclusion

- HVAC equipment performance provides significant opportunity to improve residential energy efficiency
- Efficiency is dependent on common service tasks, for example:
  - Clean indoor and outdoor coils
  - Clean filters
  - Correct refrigerant charge
- FDSI has effective technology and program platform to:
  - Measure equipment performance
  - Standardize and document customized field protocols for program implementation
  - Implement and administer scaled programs