Automated Diagnostics and Soft-Repair for Smart Homes

Building America Expert Meeting

NIST, Gaithersburg, MD

04/26/2010

Haorong Li, Assistant Professor

Architectural Engineering, University of Nebraska-Lincoln

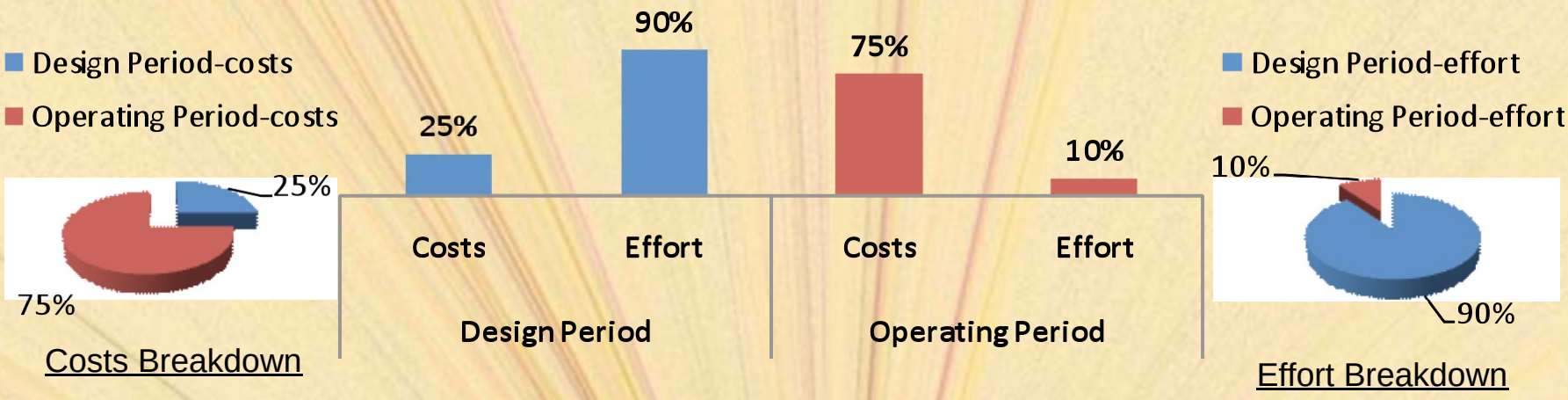
Outline

- Introduction
- Experiences Learned from Light Commercial Systems
- Unique Challenges and Opportunities in Residential Systems
- Strategies for Residential Systems
  - Plug-n-play Diagnostic Solutions for Retrofits
  - Hand-held Diagnostic Tools for Installation Verification, Commissioning and Maintenance
  - Embedded Diagnostics for New Systems

Introduction – The Problem

"Sometimes we can't see the forest for the tree"

- Typical Building System (e.g., HVAC) Lifecycle



Design-focused Academia and Industry

- Design efficiency → practical limits unsurpassable cost-effectively
- Design improvement has no impact on the majority (>90%) of the systems (CEC, 2008)
- Design improvement has little effect in the foreseeable short run (CEC, 2008)
- Design improvement is not an once-and-for-all solution

Better Design – Not an Once-And-For-All Solution

- Building energy systems do not operate as designed due to improper installation/commissioning/developing faults/squandering behavoir

  "the widespread lack of quality system installation and maintenance can increase the actual HVAC system energy use by 20 to 30 percent, regardless of their rated efficiency" (CEC, 2008)

71% of RTUs have some kind of problems that affect performance with an average of 1.9 problems per unit (New Buildings Institute, 2004)

Oversizing is very common and the extent of the oversizing can approach 100% easily (Li, 2008, Proctor et al., 1995 and Neal and O'Neal, 1992)

More than 50% of the RTU units in the field were not properly charged (Proctor and Downey, 1995)

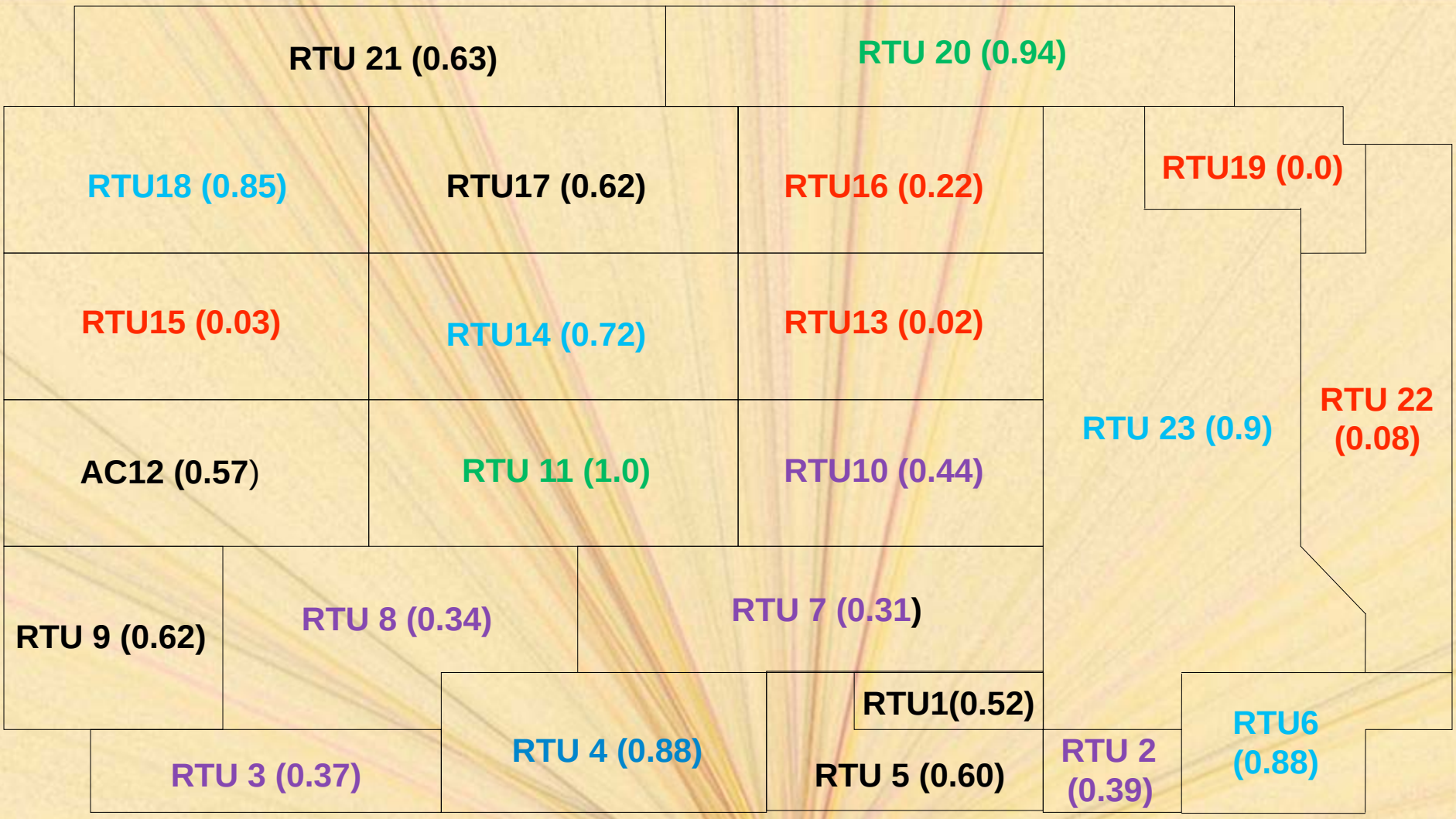
Up to 50% of energy is wasted (Katipamula and Brambley, 2005 and Liu, 2004)

Up to 70% of the service costs can be saved (Li and Braun, 2007)

Waste associated with human-behavior is up to 25% (ACEEE, 2008)

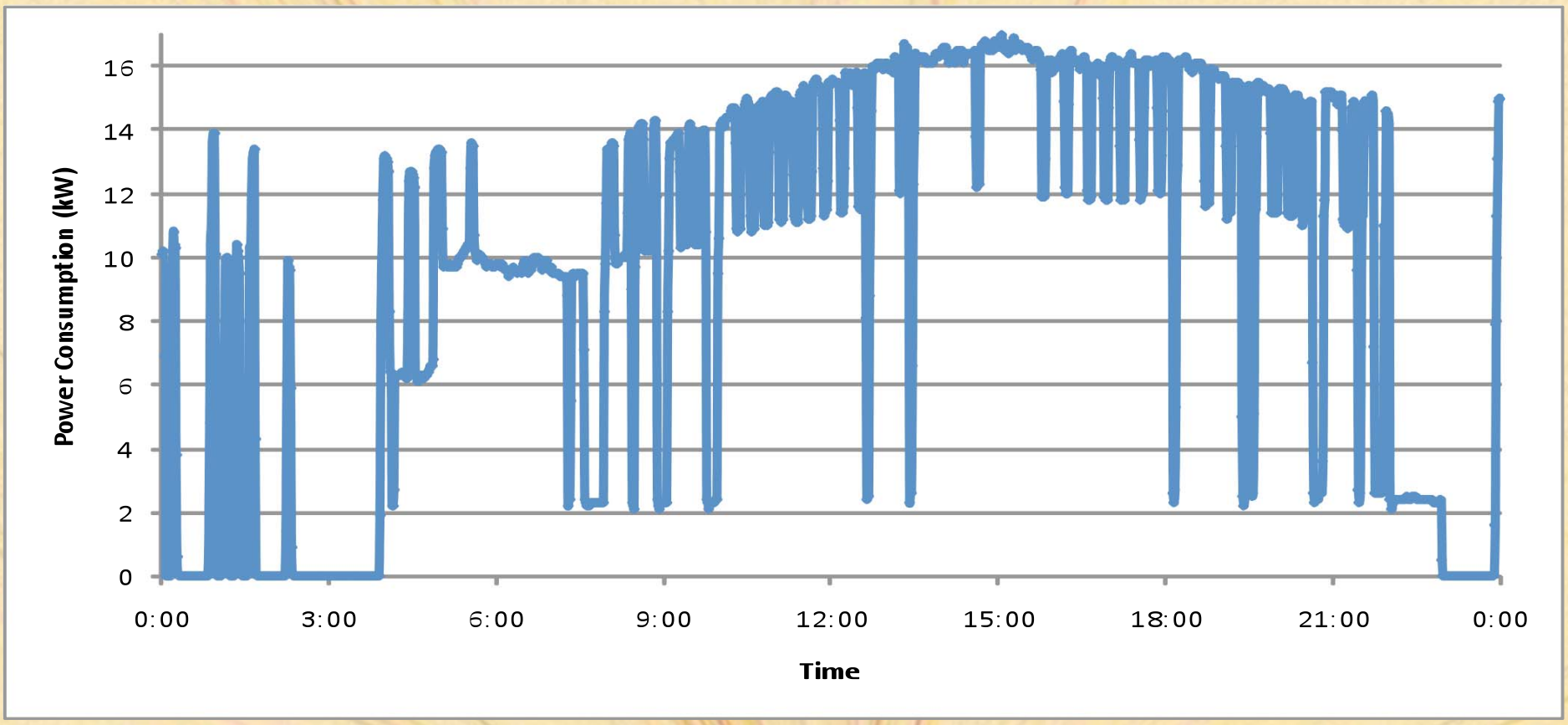
Experience Learned from Light Commercial Systems

Oversizing – A Common Design Problem



RTU Layout and Cooling Runtime Ratio Profile at the Cooling Design Temperature Bin (101 F - 105 F, Weighted Average Runtime Ratio = 0.63) (Residential systems are even worse)

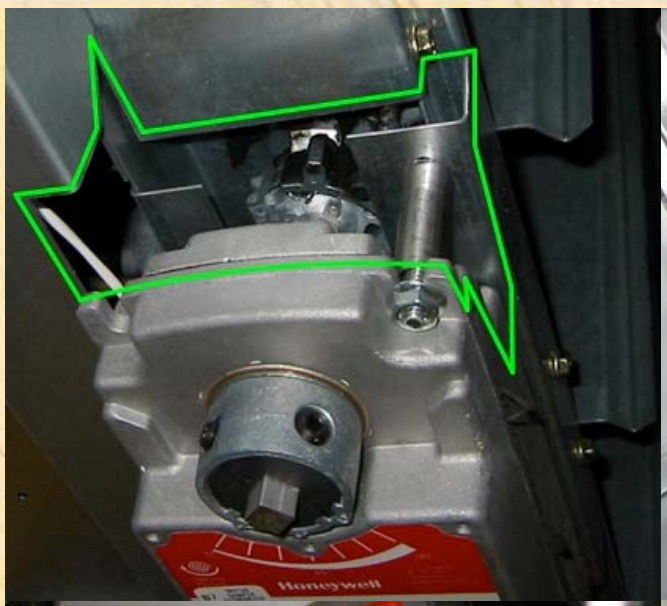
Consequences Caused by Oversizing



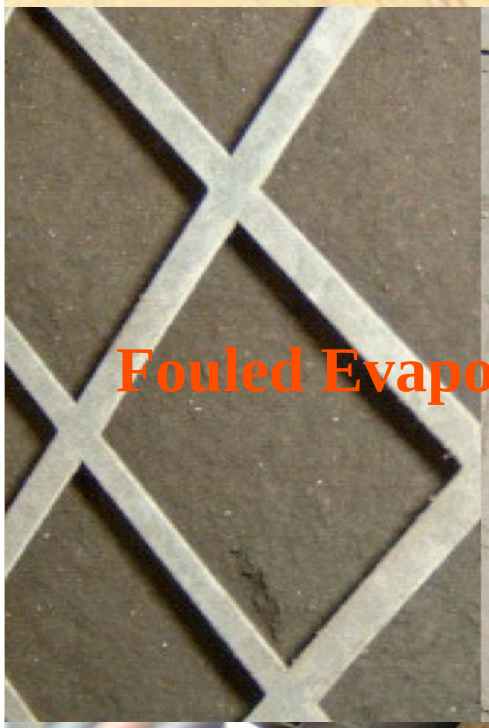
Compressor Cycling: early burnout

Poor humidity control (goods damage, property damage, mold…)

Air Leakage – Improper Installation, Commissioning or Design



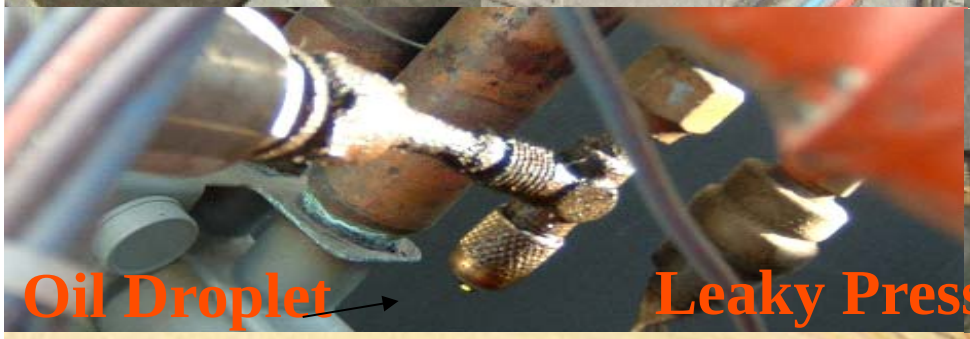
Fouling and Leakage – Operating Faults



Fouled Evaporator Filters

Fouled Condenser

Clean Sensor



Oil Droplet

Leaky Pressure Sensors

Technology Evolution – Where Have the Less Than 10% of the Expert Time and Effort Gone?

"Only the Fit Survive" – Darwin

1. *Prevention-plus-emergence based maintenance ~ 2000 (>95%)*
   - Either too-early or too-late, Problems
     - Do not immediately result in comfort complains → no alarm
     - DO immediately result in higher energy, maintenance, and equipment costs → costly penalty
     - DO ultimately lead to emergency calls → costly repair

2. *Retro-commissioning 2000~present (<5%)*
   - Very costly, feasible only if simple payback period < 3-years
   - Periodical solution, every 3~5 years

The industry is here

3. *Automated fault detection and diagnosis (AFDD) (<<1%)*
   - Around-the-clock protection and optimization
     - Energy savings and longer equipment life
     - Condition-based maintenance and possible soft repair
     - Guaranteed comfort
     - Change in energy use behavior

Automated FDD

"Only the technology, which can be adopted by the market, can change the world"

- Widely used for Critical Systems: Nuclear Plants, Space shuttles
- During the past 20 years, a great deal of attention to HVAC&R
  - Numerous projects sponsored by CEC, DOE, ASHRAE, NSF and the Industry
  - Hundreds of research papers/technical reports
- Few technologies have been successfully adopted by the industry
- Adoption Barriers
  - Inherently Inertial buildings industry (>15 years lifecycle)
  - Cost-effectiveness and scalability
  - Concerns of interference of normal operations
  - Unproven field performance
  - Lack of constructive actionable decisions
  - Lack of real-time interaction between occupants and energy systems

Change, Yes We Can and Should!

“We have an operations-pull market, but our academia and industry are design-focused!”

- Change the technology
  - Through changing the design-focused academia and industry
  - Through making the technology readily accessible/affordable for everybody
  - Through developing technology for enabling change in human behavior

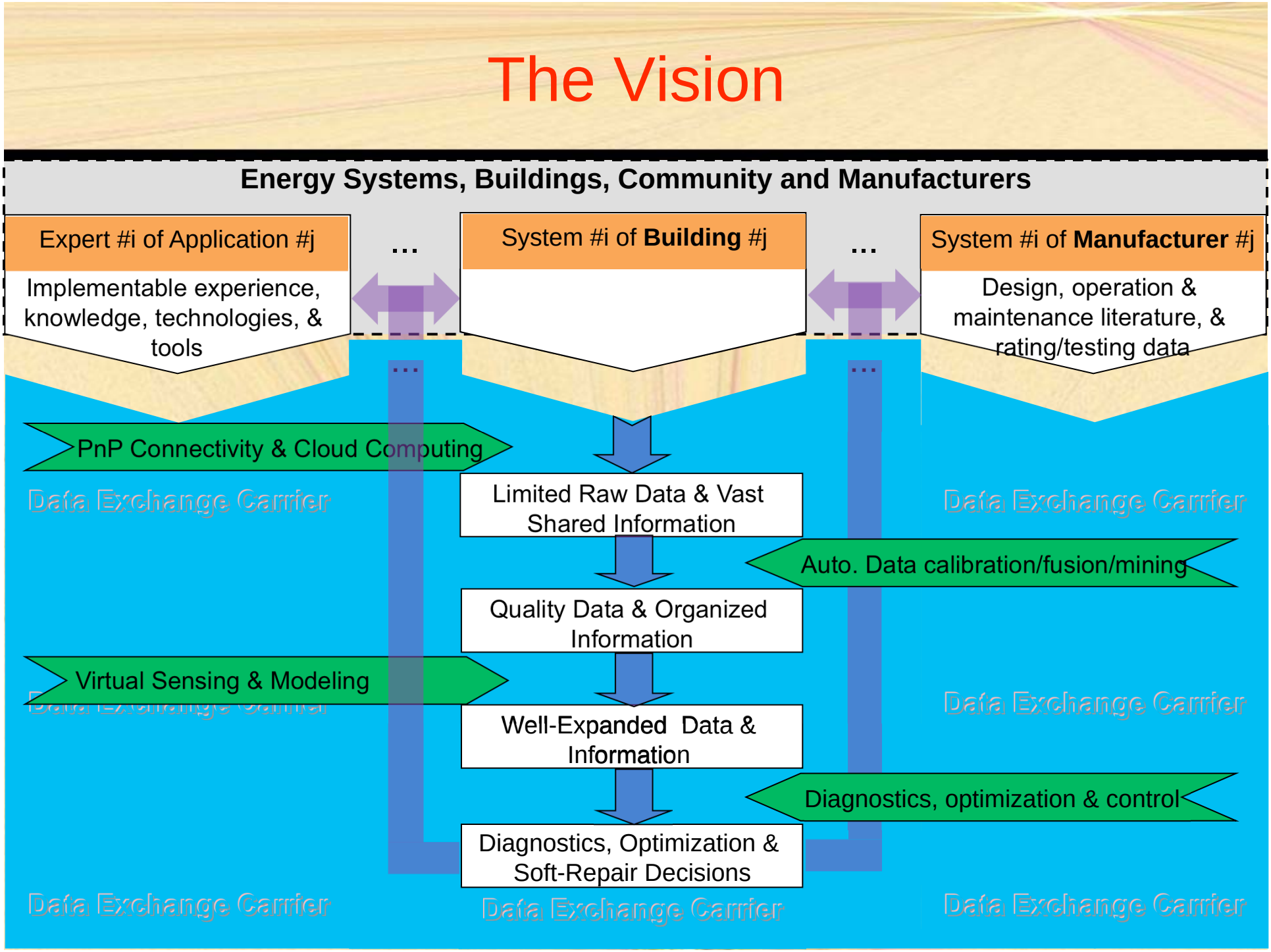
- Change the human behavior
  - Change the design-oriented mindset of policymakers
  - Change the behavior of occupants using feedback
    - Physical comfort and psychological comfort/society responsibility
  - Change the behavior of building operators
  - …

Non-invasive, Low-Cost and Plug-n-Play Smart Buildings Solution

“An idea that is not dangerous is unworthy of being called an idea at all” – Oscar Wilde

- Low Capital and Installation Costs: ROI < one year
- Non-invasive: no-interruption of normal operation
- Plug-n-Play: – Self-configurable – Self-scalable
- Enabling Core Research Thrust Areas
  - Plug-n-Play Data Exchange Carrier
    - Low-cost connectivity, unlimited data storage/sharing/processing/mining
    - Cloud Computing
  - Automated Calibration/Data Fusion
  - Virtual Sensing and Modeling Technology
  - Automated Diagnostics, Decision-Making and Soft-Repair Technologies

The Vision


Energy Systems, Buildings, Community and Manufacturers
Expert #i of Application #j
Implementable experience, knowledge, technologies, & tools
...
System #i of Building #j
...
System #i of Manufacturer #j
Design, operation & maintenance literature, & rating/testing data
...
...
PnP Connectivity & Cloud Computing
Limited Raw Data & Vast Shared Information
Auto. Data calibration/fusion/mining
Quality Data & Organized Information
Virtual Sensing & Modeling
Well-Expanded Data & Information
Diagnostics, optimization & control
Diagnostics, Optimization & Soft-Repair Decisions
Data Exchange Carrier
Data Exchange Carrier
Data Exchange Carrier
Data Exchange Carrier
Data Exchange Carrier
Data Exchange Carrier

Plug-n-Play Data Exchange Carrier

"A platform of the public, for the public and by the public"

Open to general public (completely free or at very limited costs): Building owners, contractors, operators, equipment manufacturers, utilities, weather station and policy-makers

- Basic Functions
  - Plug-n-play and near-zero-cost connectivity
  - Unlimited data storage/sharing capacity
  - Unlimited computing capacity using cloud computing
  - Configuration wizards and generic tools for
    - Performance monitoring
    - Optimal/adaptive control
    - Diagnostics
    - Reporting and service scheduling
- The larger the number of buildings/systems/users/… connected to this platform
  - The more the amount of shared information and the more powerful the platform
  - The lower the cost for use
  - The more field-proven demonstration
  - The more benefit we can achieve

Automated Calibration/Data Fusion

“Measurements can be very limited but a quality few can beat a mediocre plenty”

- Solution: Onboard measurements diagnostics and Calibration
  - Good sensor but bad locations:
    - Eliminate location-related errors
  - Out-of-calibration
    - Eliminate sensor-inherent errors
  - Sensor failure
    - Avoid using failed measurements
    - Replace failed measurements with alternatives
- How?: “Automated Calibration” in a non-traditional manner
  - Automatically select or create “true values” using onboard existing sensors
  - Using powerful statistic tools

Virtual Sensing and Modeling Technology

“Humanity achieves abundance from deficiency by discovery and invention”

- Virtual Sensing and Modeling Technology
  - Expand limited low-cost meansurements
  - Extract useful information from vast shared and readily available information
- Examples: Based on four onboard air side RTU sensors (OAT, RAT, ZT, DT), manufacturers’ literature, embedded diagnostic alarms and weather info, we can develop
  - Virtual mixed air temperature sensor
  - Virtual air flow rate sensor
  - Virtual cooling/heating/ventilation load sensor
  - Virtual outdoor air ratio
  - Virtual cooling/heating capacity sensor
    - Sensible and latent capacities
  - Virtual fan and compressor power consumption
  - Virtual EER sensor and Virtual SHR sensor
  - Virtual Refrigerant Charge Sensor

Decision-Making and Soft-Repair Technologies

“A solution without actionable decisions is a pure idea”

- Constraint-oriented diagnostics
  - Limited low cost measurements plus virtual measurements
- Fault evaluation
  - Economic impact: energy, demand, maintenance and equipment life
  - Comfort impact
  - Environmental impact
- Adaptive control and soft-repair technologies
  - Temporary soft-repair to minimize fault impact until the receipt of actual repair
    - Optimal service scheduling
  - Ultimate soft-repair without any human intervention
    - E.g., over-ventilation, damper leakage, control-related faults and so on

A Showcase of Diagnosis and Soft-repair for Systems in Big-box Retail

Big-Box Retail: Available Measurements

- Building energy systems are remotely monitored and controlled through a Service Operation Center
- Limited available Measurements for HVAC
  - Four temperatures
    - Out air temperature:
      - Disabled due to inaccuracy, replaced with global OA sensors
    - Return air temperature:
      - Disabled due to wrong location
    - Zone temperature/humidity
    - Discharge air temperature (not accurate in heating mode)
  - Status command
    - Status of cooling and heating stage
    - fan status
  - Set points and schedule

Big-Box Retail – What Can We Do?

- Developing a Data Exchange Carrier to share information among
  - All the systems within a store (HVAC&R)
  - All stores within a location
  - All stores in different locations
  - Weather stations
  - Manual input of equipment manufacturers' literature
- Developing Automated Sensor Calibration algorithms to make full use of the four sensors
  - OAT →DAT →RAT → ZAT
- Developing Virtual Sensors using the four sensors together with manufacturers' , equipment embedded alarms, and weather station data to expand the measurements
  - Virtual OA fraction
  - Virtual heating capacity
  - Virtual cooling capacity
  - Virtual compressor power consumption
  - Virtual EER and SHR
  - Virtual mixed air temperature
  - Virtual air flow rates
  - Virtual building load
  - Virtual fan power consumption
  - Virtual refrigerant charge sensor

Big-Box Retail– Faults Identified

- Generic problems
  - Oversizing (up to 100%)
  - Improper test & balance
  - Outdoor air leakage
  - Excess OA fraction
  - Over circulation
  - Sensor out of calibration
  - Bad sensor location
    - Global OA
    - RAT
    - Some ZT
  - Extremely uneven runtime ratio
  - Failed compressor/heater within warranty period
  - Compressor/heater cycling
- Site-specific problems
  - Low air flow rate
    - Faulty fan,
    - slipping belt,
    - Fouling
    - wrong test & balance
  - High air flow rate: test & balance
  - Low cooling capacity
    - Low flow rate
    - Refrigeration cycle faults:
      - low charge,
      - low compressor efficiency…
- Stuck dampers
- Faulty economizer control
- Bad sensors

Big-Box Retail– Actionable Decisions

"Identification of a problem is good but an actionable solution is better"

- Fault evaluation is performed for each identified problems
- Optimal actionable decisions
  - **Immediate repair** which is more than often the least cost-effective solution
    - Failed compressor/heater within warranty period
    - Control-related faults
  - **Soft-repair** those that are not cost effective to be physically repaired at all
    - Over-sizing
    - Over circulation
    - Outdoor air leakage
    - Bad sensors (OAT)
  - **Optimal Service Scheduling**: Most are not cost effective to be repaired immediately if the severity level is not high enough or a single-purpose site visit is too expensive
    - Improper test & balance
    - Low charge
    - Stuck dampers
    - Fouling
    - Operation issue

Impact of non-optimal design and faulty operations can be minimized by adaptive controls before they are actually repaired

Diagnosis and Soft-repair for Residential Systems

Opportunities, Challenges & Strategies

- More Opportunities than commercial systems
  - Consume more than those in the commercial sector
  - 125 million of homes (vs. 5 million of commercial buildings)
  - Energy-efficiency of residential buildings is lower than that commercial buildings
  - Emergency-based maintenance and no in-house experts
  - Service technicians do not have sophisticated diagnostic tools
- More Challenges
  - Extremely limited measurements
  - No energy management system and connectivity is an issue
  - More cost-sensitive
  - Little available research
  - Scalability
- Our Progressive Strategies for Residential Systems
  - Plug-n-Play Non-Invasive Diagnostics for existing systems
  - Hand-Held Diagnostic Tools for installation verification and service
  - Embedded diagnostics for new systems

Plug-n-Play Non-invasive Diagnostics for Existing Residential HVAC Systems

- Sponsored by DOE to extend our experience in commercial systems to residential systems and the goal is to develop Plug-n-Play Non-Invasive Diagnostics and Decision Support Tools for Residential Systems
- Only use HVAC on-off status, schedule, room temperature, weather and utility information to diagnose
  - HVAC equipment faults
    - Capacity degradation -- Air flow rate degradation
    - Efficiency degradation
  - Building envelop performance
    - Insulation level -- Leakage/Infiltration level
    - Fenestration
  - Occupant behavior
- Advantages
  - Low-cost, Plug-n-Play and Non-Invasive

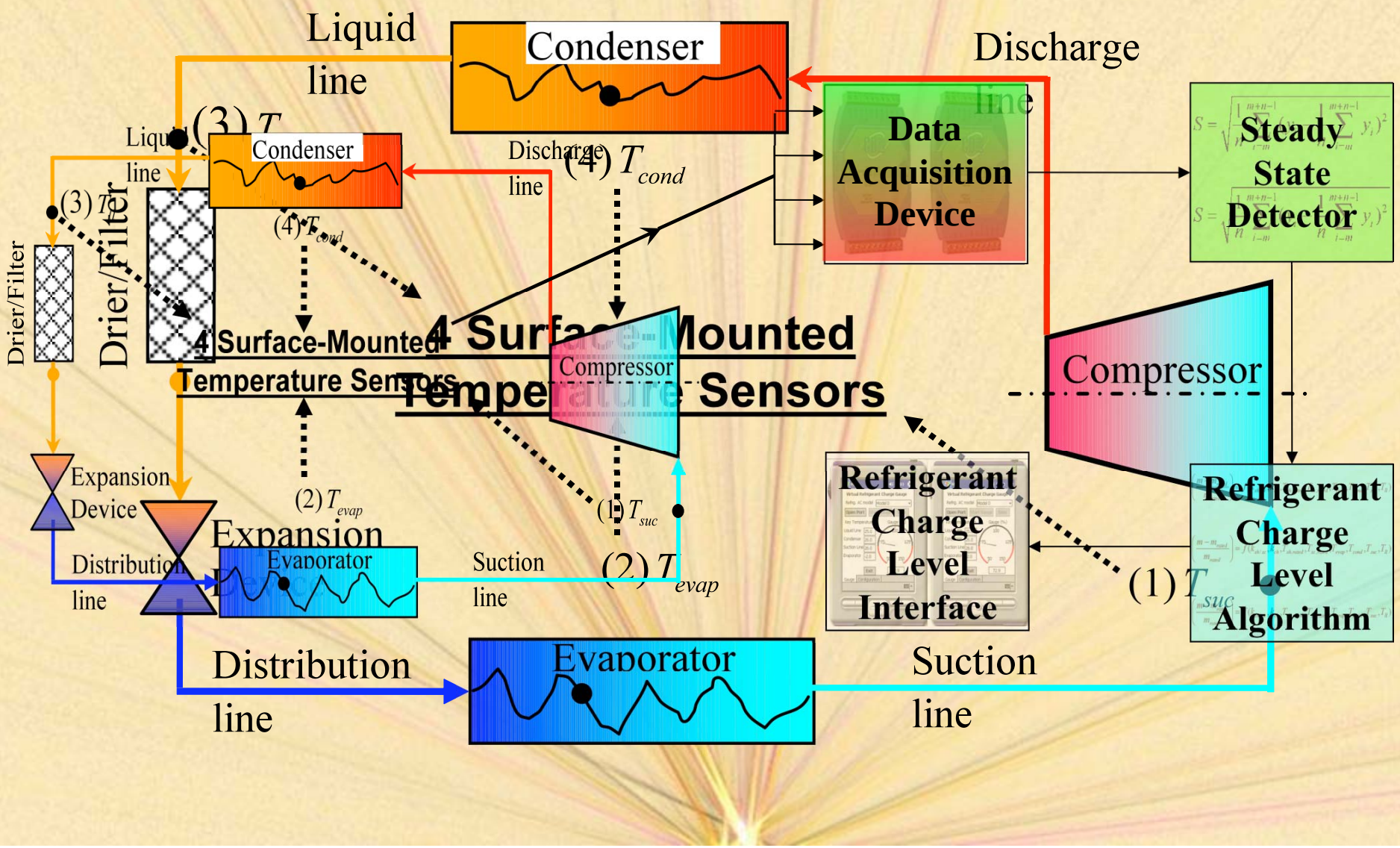
A Real Story for My Own Home

- Last summer, my home AC failed to cool my house
  - The blower, condenser fan and compressor seemed running
  - Little air and little cooling effect
- Potential Consequence
  - Service technicians were not available until four days later and
  - It could cost me more than $300 to fix it and four days of discomfort…
- It ended up costing me only $50 without a single-day of discomfort
  - Soft-repair by re-programming the thermostat
    - Fan on mode
    - Setpoint at 76 F for one hour + 82 F for one hour + 76 F for one hour + 82 F …
  - Smart service scheduling
- The whole process could be automated if we had an FDD-enabled home energy automation system or thermostat installed

Hand-Held Diagnostic Tools for Installation Verification and Service

- Economically feasible for Installation, Service and Commissioning Technicians
  - $50-$500
- Approaches
  - Wireless Sensing Modules
  - Capable of Communicating with iPhone / Wireless Router
  - Component Performance Data - compressor map & expansion device performance map
  - Decoupling-Based Diagnosis Algorithms
- Advantages
  - Affordable as a tool
  - Sophisticated algorithms
  - Improved service productivity and quality

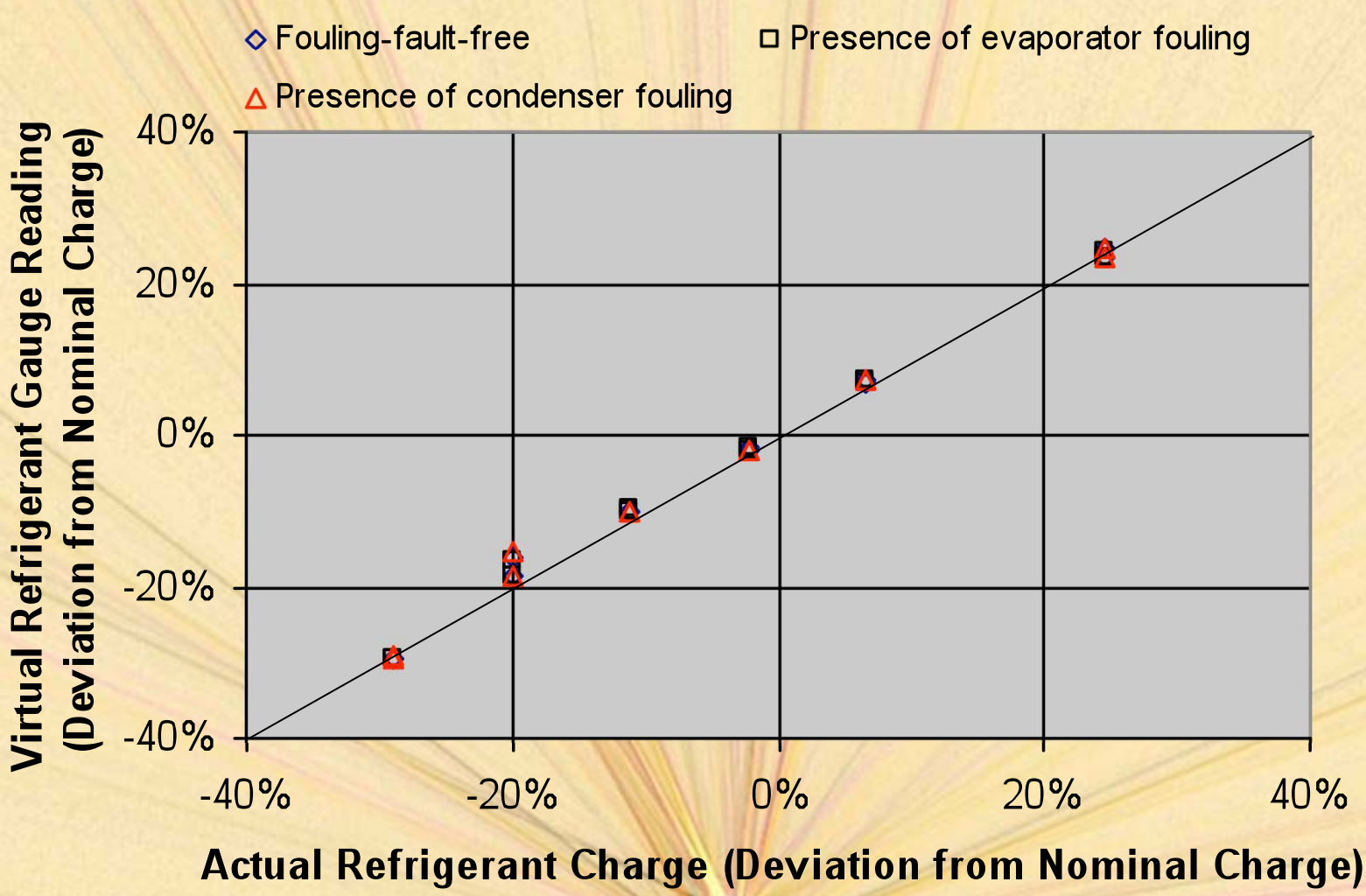
Example Handle-Held Diagnostic Tool – Virtual Refrigerant Charge Gauge



Virtual Refrigerant Charge Gauge - Demo

Demonstration Results

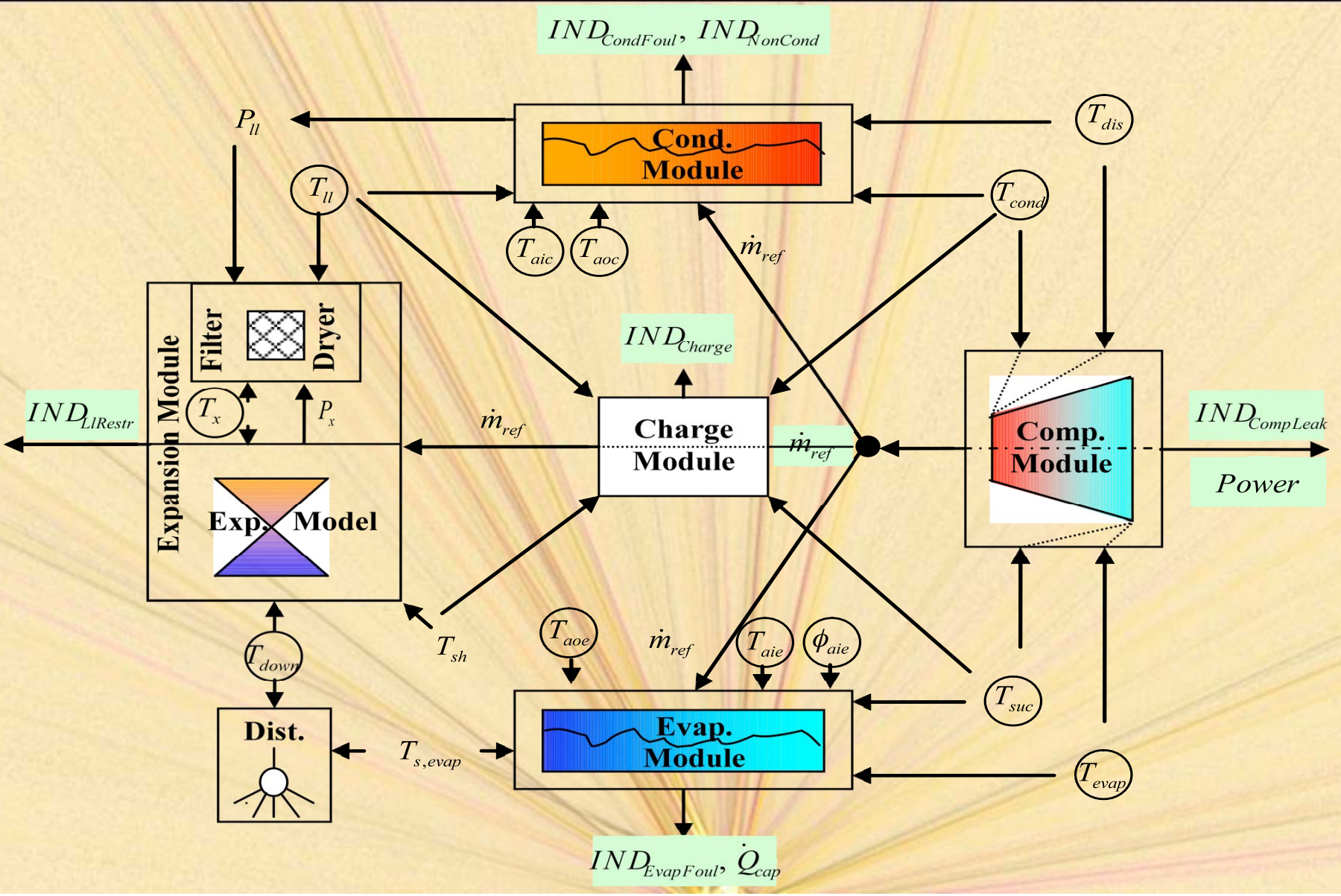
A 1.5 kW FXO Window Air-Conditioner Using R22 as a Refrigerant



Embedded Diagnostics for New Systems

- Approaches
  - Built-in Low-cost Measurements -temperature sensors only
  - Component Performance Data - compressor map & expansion device performance map
  - Virtual Sensing Algorithms
  - Virtual Calibration Algorithms
  - Decoupling-based Diagnosis Algorithms
- Advantages
  - Sophisticated algorithms
  - Integrated with controls
- Economically feasible for new systems, especially for high-end systems
  - <$5 for sensors
  - <$10 for data acquisition and microcontrollers leveraged by others
  - Negligible costs for installation (compared to retrofit)

Embedded Decoupling-Based Diagnostics for New Cooling Systems



This work is possible due to generous funding from Department of Energy (DOE), California Energy Commission (CEC), NCESR, SMI and Other Private Companies