Workshop on AFDD for RTUs
Moving from R&D to Commercialization
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Introduction

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CONSORTIUM for BUILDING ENERGY INNOVATION

Workshop Goals and Organization

- Moving RTU AFDD (**<u>automated fault detection and diagnostics</u>**) from R&D to Commercialization
  - Where are we?
  - How do we get there?
- Workshop Organization
  - Diagnostic Technology Developments
  - Policy
  - Business Opportunities

Workshop Participants

Participant Type	Number
University/Government Researchers	13
Industry Developers	9
Utility & Policy	5
Customers	4

Introduction to FDD for RTUs

- What is AFDD?
- Importance of low cost implementations
- Why RTUs?
- Types of implementations
- Important faults
- Some R&D history
- AFDD Methods
- What R&D is still needed?
- How to accelerate commercialization?

AFDD

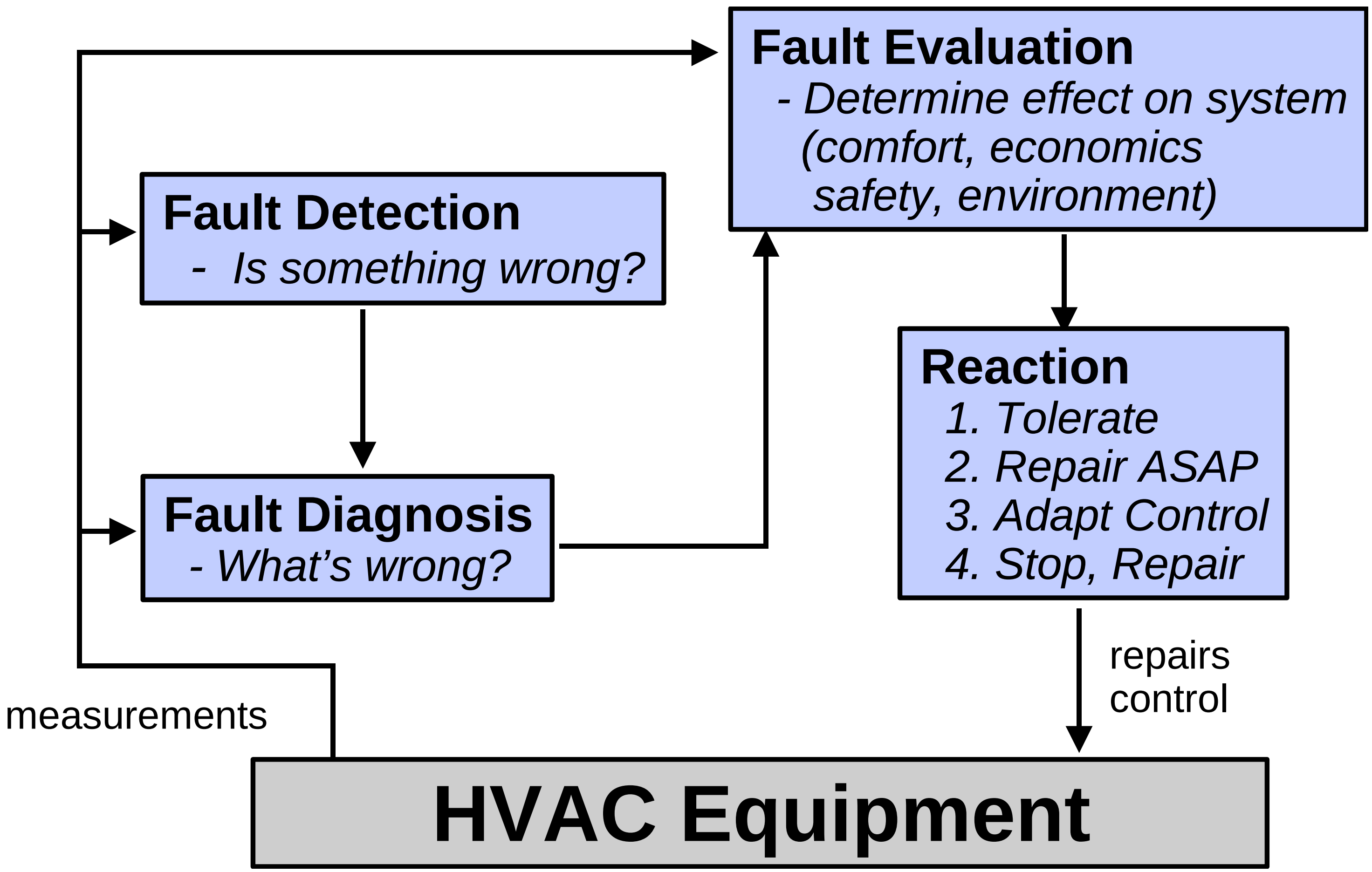
Definition

- Identification of maintenance or repair needs using measurements and software intelligence

Potential Benefits

- Improved comfort and indoor air quality
- Reduced maintenance costs
- Reduced energy costs
- Longer equipment life

AFDD Process



The Need for Low Cost Solutions

Increasing Benefits

Benefits	Applications
Safety	Nuclear Power Air Craft
Reduced Product Costs	Chemical Process Plants Manufacturing Plants
Lower End-Use Operating Costs (Maintenance & Energy)	Automotive HVAC

Allowable Costs

Measurement Costs vs. Benefits

Increasing Costs

Measurements	Application
Vibration	Predict Mechanical Failures
Energy Use	Performance Impact Evaluation
Pressures/Temperatures	Detect and Diagnose Thermal System Problems

Increasing Benefits

Decreasing Cost-to-Benefit Ratio

- Lower hardware costs (sensors & micro-processors)
- Development of analytical approaches that utilize "virtual" sensors
- Emergence of *"Information Technology"* in the service business (scheduling, parts tracking, etc.)
- Consolidation of service and facility management companies

Why RTUs?

- Significant part of the commercial building market
  - space conditioning for over 60% of the commercial floor space
  - over 50% of commercial cooling requirements
- Tend not be well maintained
  - highly distributed nature of installations
  - Not typically part of building control system

Types of AFDD Implementations

- Hand Tools
  - » used by service technicians during maintenance checks
  - » costs spread over many systems
    - – allows more expensive measurements
  - » generic (e.g., rule-based) approaches
    - – reduced diagnostic sensitivity

- Integrated Diagnostics
  - » additional sensors permanently mounted on unit
    - – requires low-cost sensors
  - » integrate diagnostics within unit controller or on a remote server (e.g., cloud-based solution)
  - » enables equipment specific diagnostics
    - – improved diagnostic sensitivity

Integrated Diagnostics

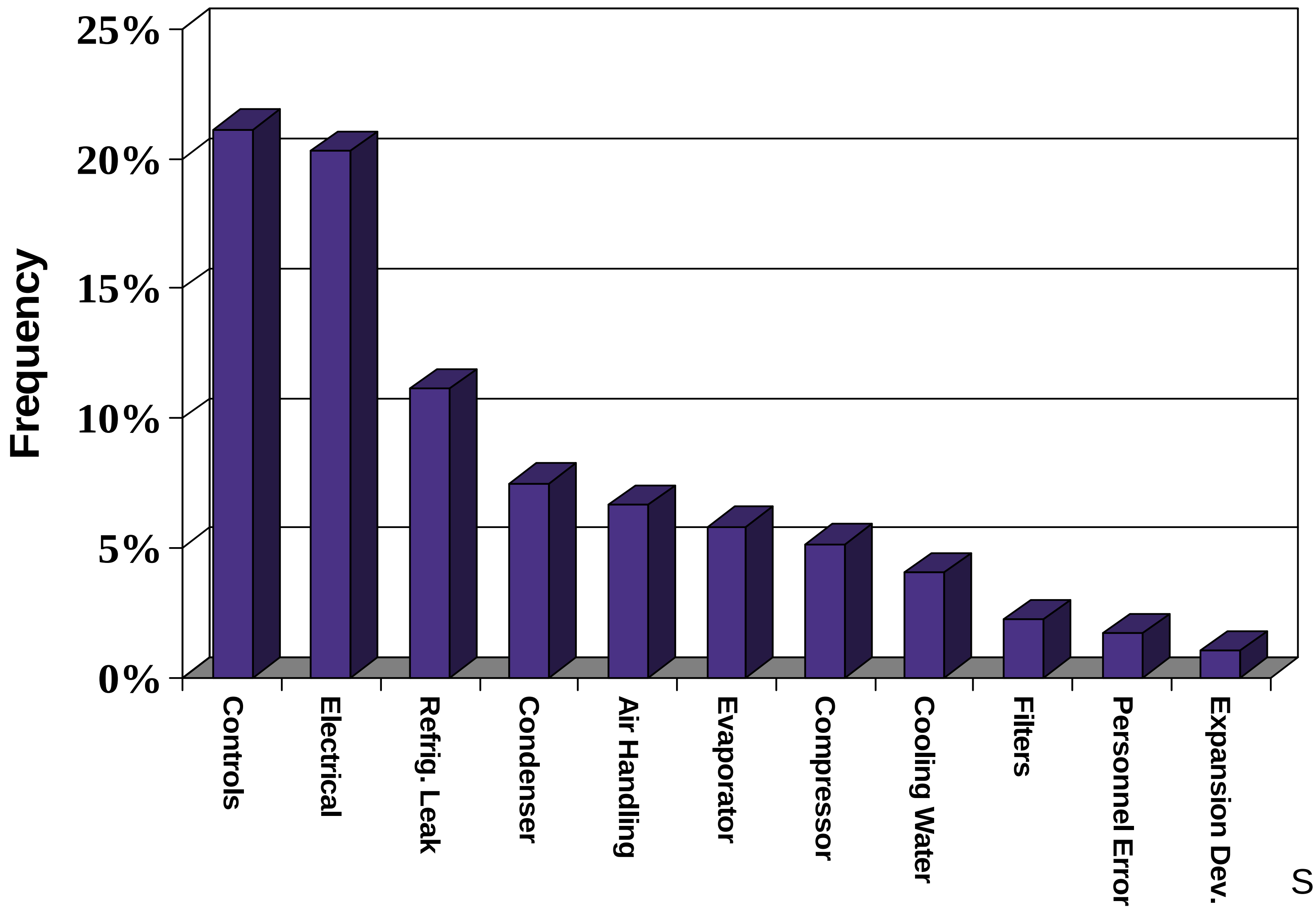
Important Faults

- Component failures
  - » controls
  - » economizer
  - » ….
- Degradation faults that lead to premature failures, loss of comfort, or excessive energy consumption
  - » refrigerant leakage
  - » evaporator air flow (e.g., fouled filter)
  - » condenser fouling
  - » liquid-line restriction
  - » compressor valve leakage
  - » non-condensable gas in refrigerant

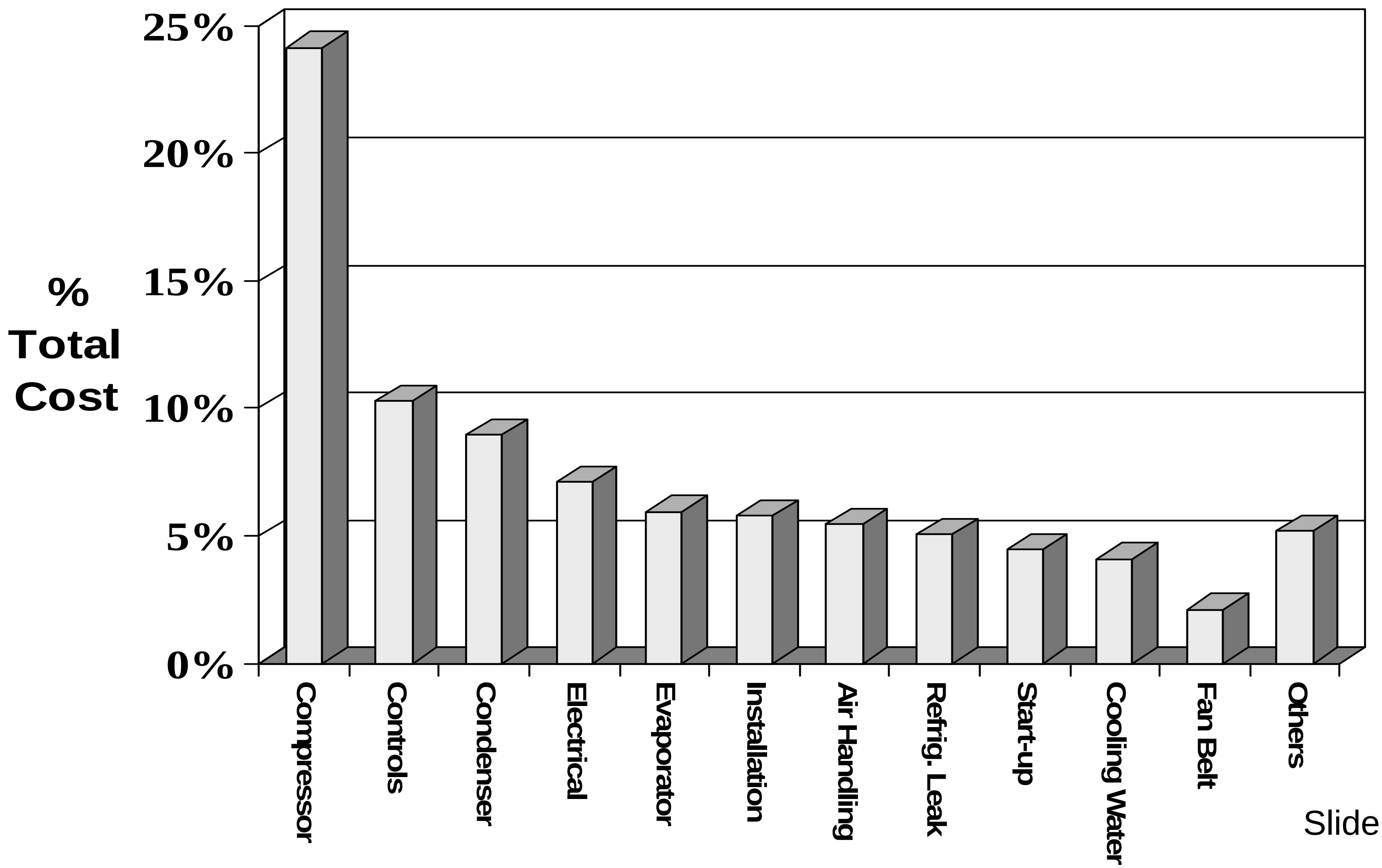
Jacobs (2003) – Commercial AC

- 63% of economizers were malfunctioning.
- 46% had incorrect refrigerant charge.
- 39% had low airflow.
- There were numerous control related problems causing fans, heating and cooling to operate incorrectly.

Breuker (1997) – Rooftop Unit Loss of AC



Breuker (1997) - Service Costs for Rooftops



Causes of Early Compressor Failure

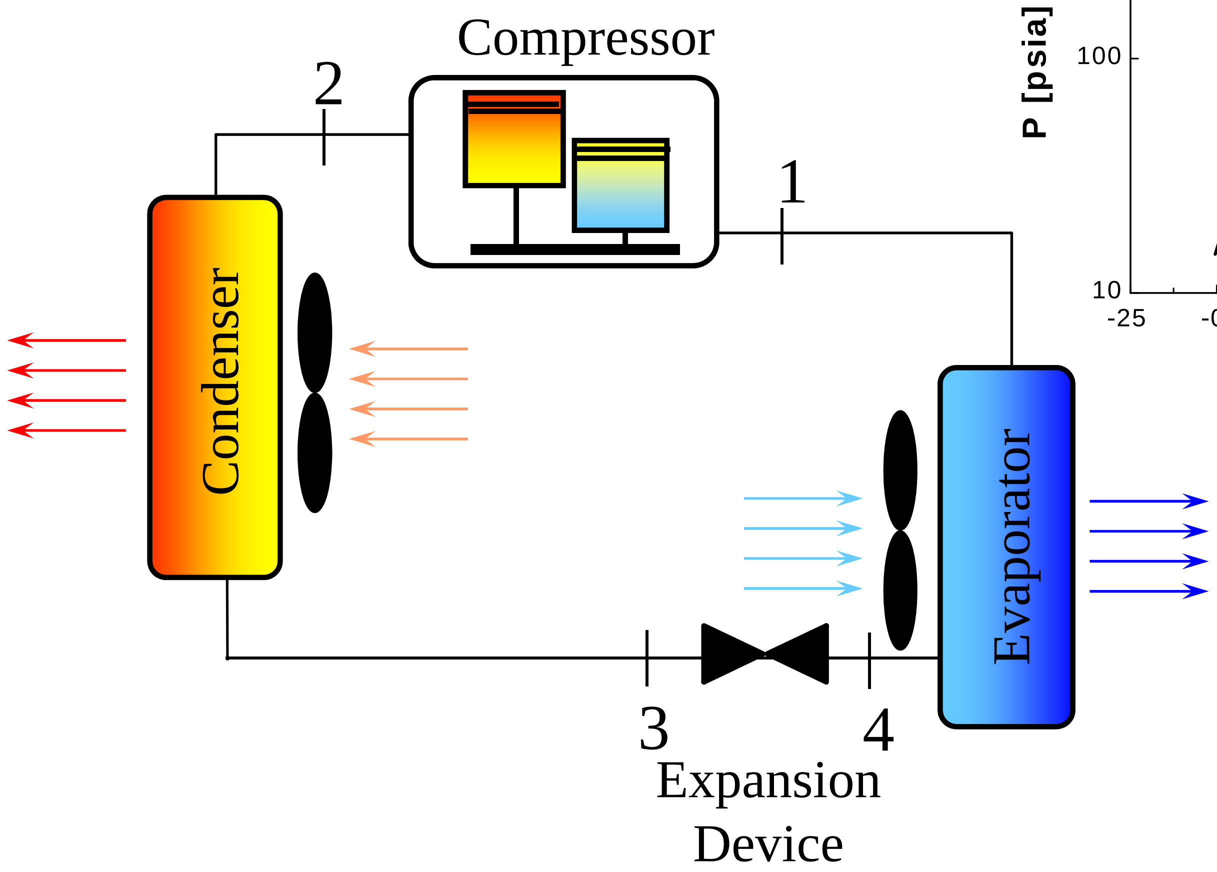
- 70% due to motor failures
- Motor failures often caused by thermal system faults
  - » Liquid floodback
    - – loss of evaporator load
    - – fouled evaporator or condenser coils
    - – refrigerant overcharge
    - – faulty thermal expansion valve (TXV)
  - » High compressor temperatures
    - – low refrigerant charge (leakage)
    - – liquid line restriction

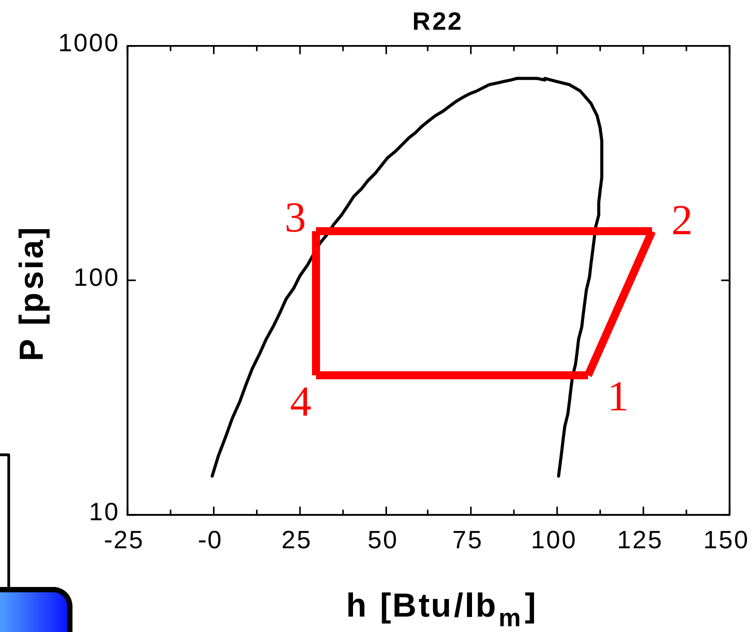
Overview of Diagnostic Approaches

- Thermodynamic Impact
  - associate specific faults with changes in thermodynamic (e.g., temperature) measurements
  - requires models for “expectations” under normal conditions
  - does not handle multiple-simultaneous faults

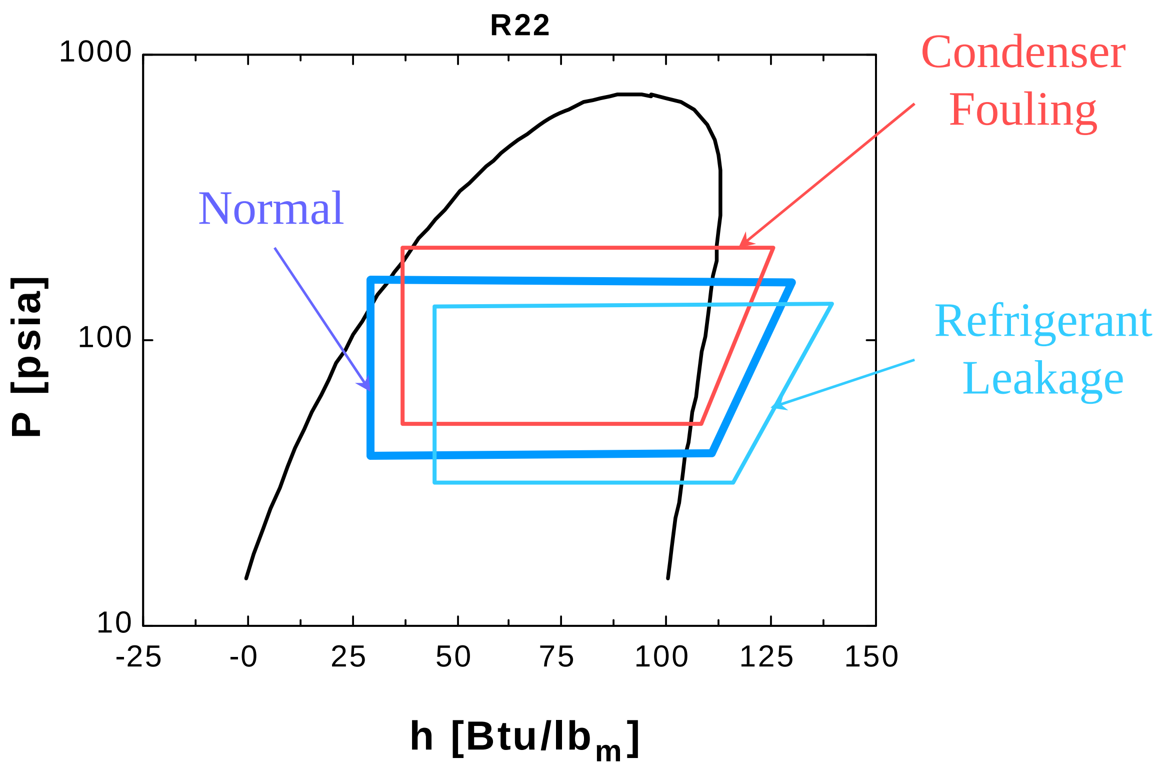
- Decoupling Features
  - identify quantities that uniquely depend on individual faults (e.g., air flow)
  - can handle multiple-simultaneous faults
  - utilize “virtual sensors” to eliminate expensive measurement requirements (e.g., flow rates)

Thermodynamic Cycle





Themodynamic Impact



Example Diagnostic Rules

Fault	T_{evap}	T_{sh}	T_{cond}	T_{sc}	T_{hg}	ΔT_{ca}	ΔT_{ea}
Refrigerant Leak	↓	↑	↓	↓	↑	↓	↓
Comp. Valve Leak	↑	↓	↓	↓	↓	↓	↓
Liquid Restriction	↓	↑	↓	↑	↑	↓	↓
Condenser Fouling	↑	↓	↑	↓	↑	↑	↓
Evaporator Fouling	↓	↓	↓	↓	↓	↓	↑

T_{evap} - evaporation temperature
T_{sh} - suction superheat
T_{cond} - condensing temperature
T_{sc} - liquid line subcooling
T_{hg} - hot gas temperature leaving compressor
ΔT_{ca} - condenser air temperature difference
ΔT_{ea} - evaporator air temperature difference

Refrigerant Cycle AFDD Research History

- McKellar (1987), Stallard (1989), Grimmelius et al. (1995)
  - Demonstrated the concept of using thermodynamic impact for fault detection
- Rossi (1995)
  - Presented overall AFDD process for HVAC applications: detection, diagnosis, impact, decision
  - Statistical, rule-based fault detection and diagnostic methods based on thermodynamic impact
  - Simple algorithm for optimal heat exchanger cleaning
- Breuker (1997)
  - Survey of common faults
  - Extensive evaluation of Rossi AFDD method

Refrigerant Cycle AFDD Research History

- Li (2004)
  - Decoupling AFDD method to enable robust handling of multiple-simultaneous faults
  - Development and validation of virtual sensors, including refrigerant charge
  - Development of simple metric for capturing economic penalty associated with faults
- Kim (2013)
  - Extension and validation of virtual sensors
  - Demonstration and evaluation of integrated AFDD based on virtual sensors

Economizer AFDD Research History

- Brambley et al. (1998), Katipamula et al. (1999), House (2001), Schein et al. (2003, 2005, 2006), Seem et al. (2009)
  - Rule-based AFDD approaches that primarily utilize thermodynamic fault impacts
  - Use passive observations
- Fernandez et al. (2009)
  - Employs combination of passive & active testing approaches
- Wichman et al. (2007)
  - Self-calibrating, virtual mixed-air temperature sensor
- Hjortland et al. (2013, 2014)
  - Statistical rule-based approach using passive/active testing
  - Simple metric for capturing energy impacts of faults

AFDD Performance Evaluation

- Economizer Diagnostic Performance Evaluation
  - Wichman (2007): approach based on combination of testing and modeling

- Refrigerant Cycle Diagnostics
  - Breuker (1997): Data-driven approach for evaluating and improving AFDD methods
  - Cheung (2014): Mechanistic models for simulating the effect of faults on thermodynamic states and overall performance; parameters trained using data from a number of systems
  - Yuill (2014): developing AFDD tool evaluator that employs database of normal and faulty performance generated using Cheung's models

What R&D is still needed?

- Evaluate/reduce implementation costs
  - Minimize any training requirements associated with engineering AFDD approaches for individual equipment models
  - Simplify algorithm implementations
- Application to new equipment
  - Micro-channel heat exchangers
  - Tandem compressors
  - Variable-speed equipment
- Decision support that considers tradeoffs between operating and service costs
- Overall performance metrics for evaluating AFDD performance

Where are we?

- Diagnostic "hand tools" have been available for several years
  - still need to understand how well they work
  - still not part of the main stream
- Some integrated diagnostic features are available as add-ons to existing equipment
- Some factory integrated diagnostics are appearing for high-end equipment and in response to CA Title 24 for economizers
  - factory integration can reduce costs and takes advantage of manufacturer specific information

What's holding back commercialization?

- Industry Perspective:
  - Making a business case?
  - Risk of exposing product deficiencies?
  - ….
- Customer Perspective:
  - Does it work?
  - What are the benefits?
  - ….

What's needed to accelerate commercialization?

- Incentives?
- Government requirements/mandates?
- Large customer requirements?
- AFDD performance standards?
- More tools for developers?