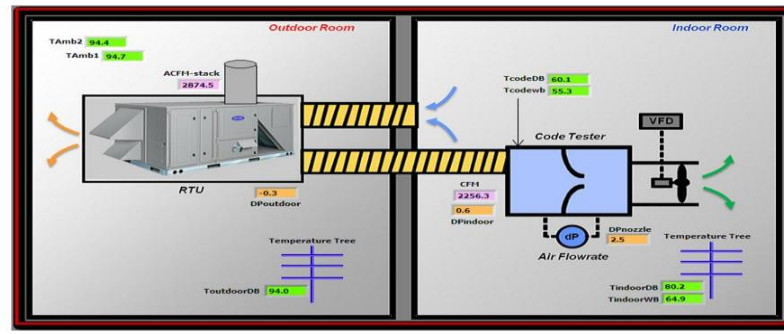
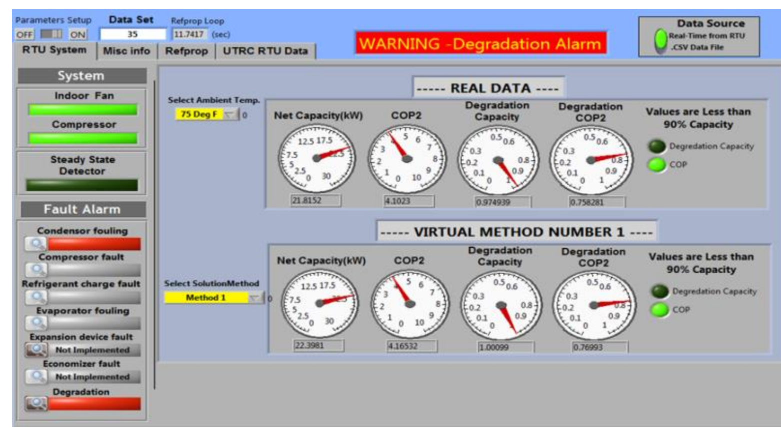
CBEI - Fault Detection and Diagnostics (FDD) for Advanced RTUs

2015 Building Technologies Office Peer Review





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CBEI/United Technologies Research Center

Project Summary

Timeline:

Start date: May 1, 2014

Planned end date: April 30, 2016

Key Milestones

1. Review and evaluate RTU FDD with respect to commercialization readiness for Advanced RTU: (1/14)
2. Workshop "Going from R&D to commercialization for RTU FDD"(07/14)
3. Complete instrumentation and implementation of fault emulation for Advanced RTU installed in the laboratory (10/14)
4. Overall evaluation of FDD performance and economic assessment (4/15)

Budget:

Total DOE $ to date: $0.55M (through 4/2015)

Total future DOE $: $0.385M (5/2015-4/2016)

Key Partners:

CBEI-URTC	CBEI-Purdue

Project Goal:

For advanced RTUs (RTUs meeting *DOE RTU Challenge*) implement and assess low-cost, embeddable fault detection and diagnostics (FDD) that achieve: ≥ 90% diagnosis rate of ≥ 10% performance degradation, < 1% false alarms and ≤ 3 year payback period

Target Market/Audience:

Market: small commercial buildings utilizing RTUs

Audience: RTU manufacturers; RTU monitoring and service companies

CONSORTIUM for BUILDING ENERGY INNOVATION

Vision:

By 2030, deep energy retrofits that reduce energy use by 50% in existing SMSCB, which are less than 250,000 sq ft

Mission:

Develop, demonstrate and deploy technology systems and market pathways that permit early progress (20-30% energy use reductions) in Small and Medium Sized Commercial Buildings

Our Goals:

- **Enable deep energy retrofits** in small to medium sized commercial buildings
- **Demonstrate energy efficient systems** tailored for SMSCBs in occupied buildings – living labs
- **Develop effective market pathways** for energy efficiency with utilities and other commercial stakeholders: brokers, finance, service providers.
- **Provide analytical tools** to link state and local policies with utility efficiency programs

CBEI Partners

Bayer MaterialScience
United Technologies Research Center

Industry

DVIRC
PIDC
Ben Franklin Technology PArtners

Economic Development Organizations

PennState
NJIT
Penn University of Pennsylvania
Drexel University
Carnegie Mellon University
VirginiaTech Invent the Future
Purdue University
Morgan State University
Rutgers

Universities

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This page contains no technical data subject to the EAR or the ITAR.

Purpose and Objectives

Problem Statement: Performance degradation of RTUs due to presence of operational faults leads to 10-15% HVAC energy waste during cooling season in buildings that employ RTUs.

Target Market and Audience: This technology targets RTU based HVAC systems for cooling of small and medium commercial buildings . RTUs serve 60% of commercial floor space and account for about 150 TWh of annual electrical usage (~ 1.56 Quads of primary energy) and about $15B in electric bills as well as estimated $2.5B sales in the US. Initial adoption is expected for high-end advanced RTUs with further extension for more standard RTUs
Audience: RTU manufacturers; HVAC monitoring, and service companies.

Impact of Project: Provide a proof-point of commercial viability through demonstration of **cost-effective FDD solution**:

1. Near-term: demonstration FDD for advanced RTU with 3 year payback
2. Intermediate-term: accelerated commercialization of technology
3. Long-term: Wide-spread deployment of FDD with potential for 68 TBtu/year HVAC energy usage reduction (BTO assessment)

Approach

Approach: Implement and assess low-cost, embeddable FDD for advanced RTU satisfying advanced RTU requirements. Use virtual sensors to reduce cost and determine FDD product cost for 3-year payback period. Achieve at least 90% diagnosis rate for performance degradation of 10% or more and a false alarm rate <1%. Develop low-cost methods for fault impact evaluation and service recommendations.

Key Issues: Diagnosis accuracy; Cost-effective, scalable deployment in field applications.

Distinctive Characteristics: Develop continuous FDD methods that can be integrated (embedded) within equipment controllers and on-board measurements in the factory. Emphasis on overall RTU performance degradation as detection of faulty behavior. Develop and demonstrate solutions for high end RTUs, e. g. Carrier LC RTU or Daiken Rebel, and later expand to standard units.

Approach

Detection

- Earlier awareness of faults (RTU performance degradation, e.g. 10% COP or capacity)
- Maintenance only when needed

Diagnosis

- Deeper understanding of root cause
- Fault(s) intensity evaluation with **virtual sensors**
- Less time needed for troubleshooting

Evaluation

- Identify implications of fault persisting
- Makes optimal service decisions possible

Energy

Equipment Life

Comfort

Progress and Accomplishments

Lessons Learned:

1) Lack of reliable data on fault types and frequency (prevalence) in the field complicates cost-benefit analysis
2) Performance degradation assessment alone brings significant benefit to the market
3) Compressor COP is a good proxy of RTU COP for fault impact analysis

Accomplishments:

- Demonstrated required accuracy and false alarm rate through lab testing
- Demonstrated feasibility of 3 year payback period
- Developed methods for fault impact evaluation and service recommendations

Market Impact: Secured commitment of OEM and national account customer to support field demonstration of AFFD. Collecting fault prevalence data, energy and equipment life benefits in field conditions will accelerate FDD market adoption.

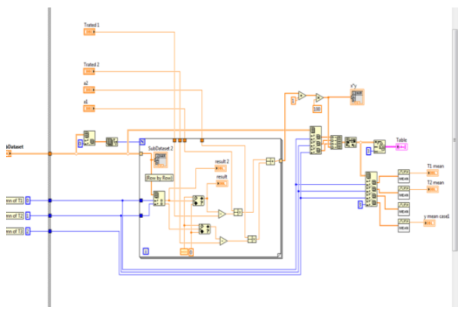
Awards/Recognition: None

Accomplishments: Performance Assessment Algorithm

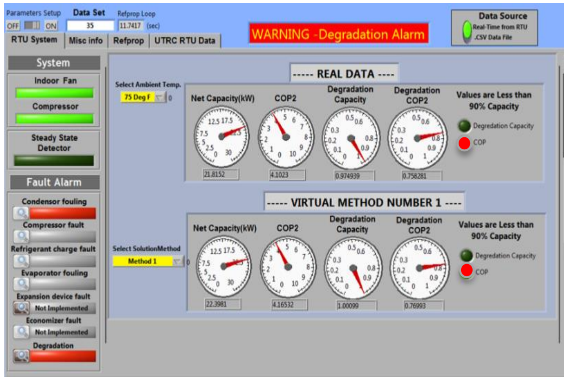
Manufacturer or field testing data on rating conditions

Normal operation performance data module

Detection & Alarm



Compare



Operation real time data collection and processing

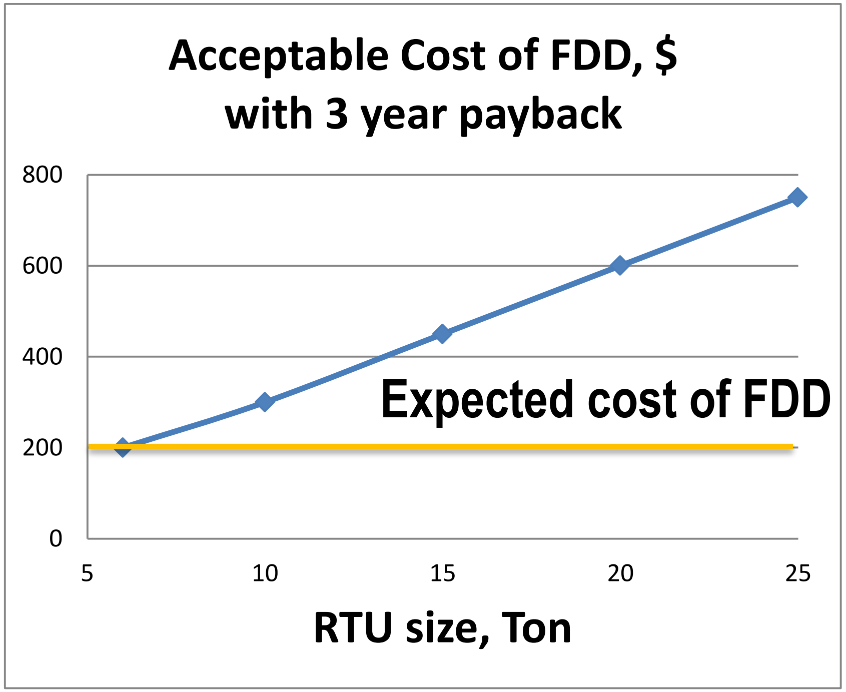
Real time performance estimation with virtual sensors module

Diagnostics, Service Suggestion & Report

RTU performance assessment algorithms developed to address market need priority

Progress and Accomplishments: Payback Assessment

Use existing UTRC RTU energy consumption analysis by climate region and building type to determine payback of various RTU diagnostics packages. Package costs and benefits to be based on sensor cost and fault impact analysis.



Even for 6 ton RTU FDD can achieve 3 year payback based on cost estimates

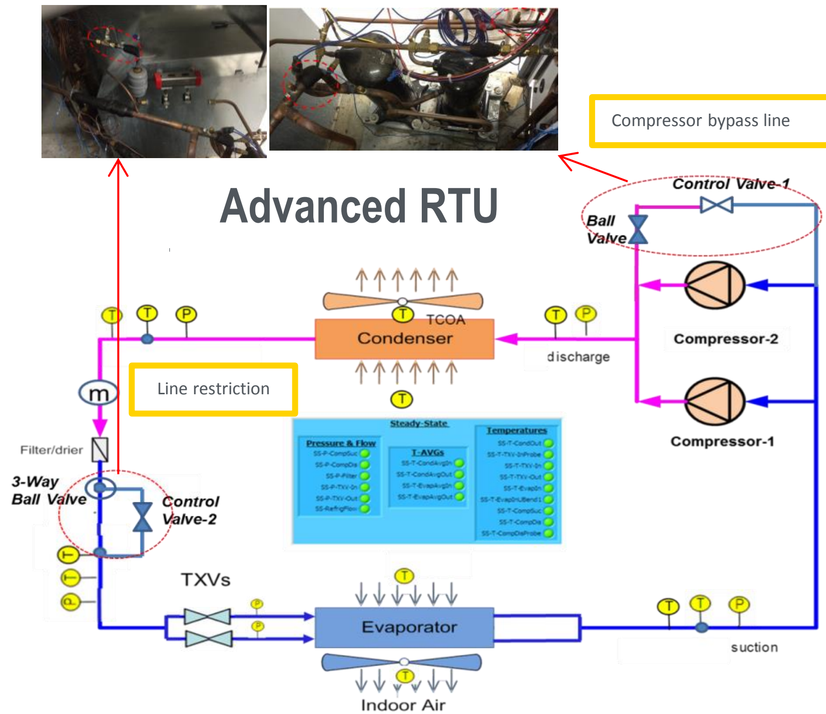
Accomplishments: FDD Lab Test Setup

RTU installation in UTRC for testing

Ability to inject common refrigeration cycle faults leading to RTU performance degradation :

- Inappropriate refrigerant charge fault
- **Compressor efficiency degradation**
- **Liquid line restriction**
- Stuck TXV
- Non-condensable gases in refrigerant
- **Condenser fouling**
- **Evaporator fouling**

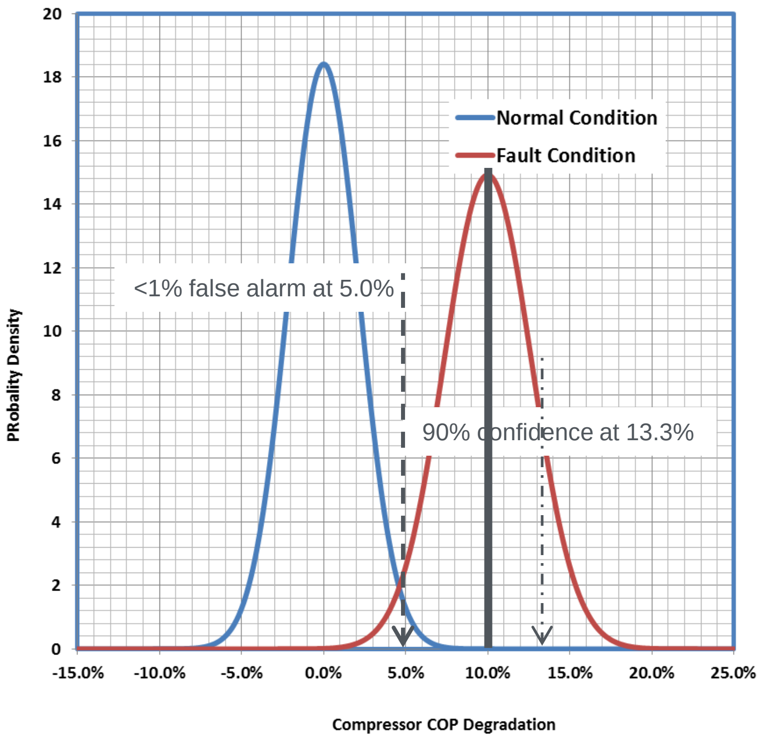
Modifications on advanced RTU for fault injections

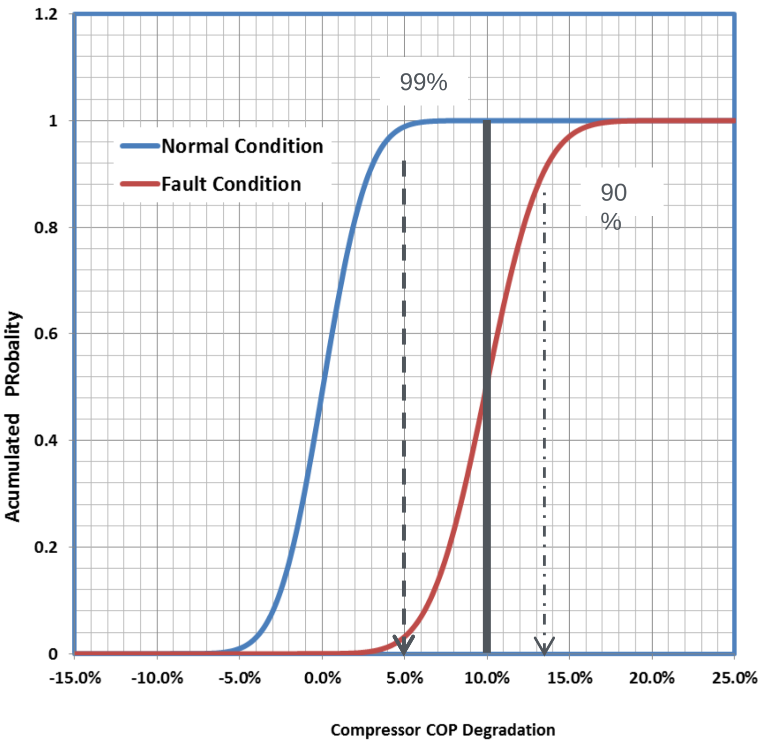


Ability to inject faults and keep good energy balance (air vs refrigerant side).

Accomplishments: Performance Degradation Assessment

- *RTU compressor COP 10% degradation diagnostics accuracy is evaluated*
- *False alarm rate is less than 1% if COP degradation is more than 5.0%*
- *More than 90% confidence rate when COP degradation is above 13.3%*





Developed FDD meets key requirements

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Accomplishments: Fault Impact Evaluation

- *Isolate individual fault impacts in presence of multiple simultaneous faults.*
- *Use only virtual sensor for inputs.*
- *Generally applicable to multiple types of systems.*

Capacity Impact

$$r_{cool} = \frac{\dot{Q}_{cool,virtual}}{\dot{Q}_{cool,normal}}$$

Sensible Heat Ratio Impact

$$r_{SHR} = \frac{SHR_{virtual}}{SHR_{normal}}$$

Efficiency Impact

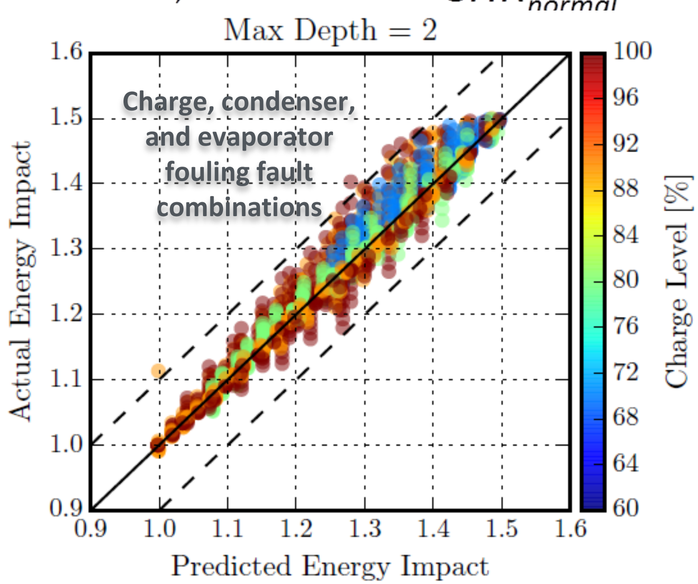
$$r_{COP} = \frac{COP_{virtual}}{COP_{normal}}$$

Run-time Impact

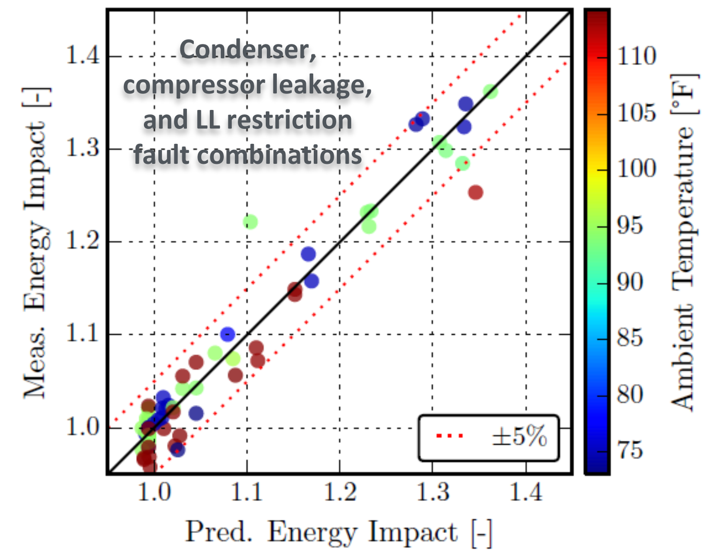
$$r_{run} = \frac{1}{r_{SHR} r_{cool}}$$

Energy Impact

$$r_W = \frac{r_{cool}}{r_{COP}} r_{run}$$



Ensemble decision tree regression model trained and tested on **simulated** data.



Polynomial regression model trained and tested on **experimental** data.

Model for fault energy impact evaluation developed

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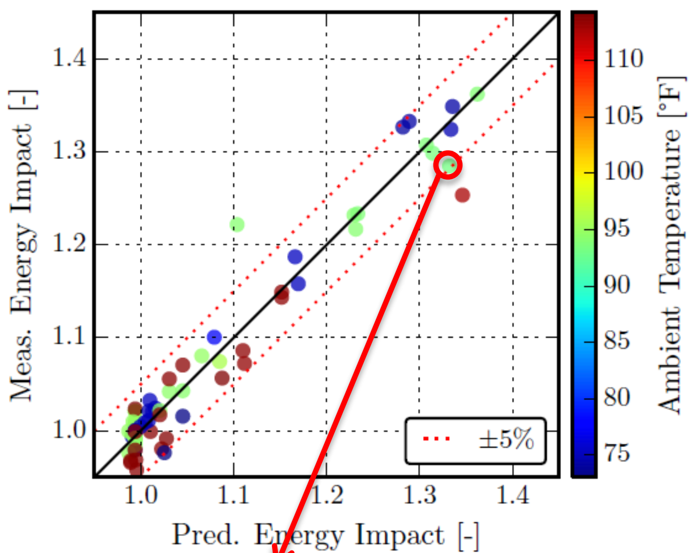
Accomplishments: Maintenance Decision Making



Multi-Fault Scenario

~25% Condenser Airflow Reduction

~12% Compressor Ref. Leakage

0% Liquid Line Restriction

Energy Impact Isolation Results:

Total Impact:	+30.7%
Cond. Fouling:	+20.5%
Comp. Leakage:	+10.2%
LL Restriction:	0.0%

Use virtual sensors and fault impact isolation model to determine best time to do service

Operating Costs

Utility Costs

Equipment Costs

Service Costs

$$\Delta\overrightarrow{OC} = \left(\Delta\overrightarrow{UC} + \Delta\overrightarrow{EC}\right) \boxed{\vec{\omega}} \quad \Delta\overrightarrow{SC}$$

Set of Service Tasks

Result:

Automated methodology to suggest maintenance for any combination of faults

Methodology for fault ranking and service decision making developed

Project Integration and Collaboration

Project Integration: Engaged industry OEM (Carrier) and National Account Customer (7-Eleven Convenience Stores) to review technical approach and market requirements. The need for performance degradation assessment is emphasized by OEM and National Account customer. The need for root cause highlighted by National Account customer.

Partners, Subcontractors, and Collaborators: This work is undertaken as part of the Penn State Consortium for Building Energy Innovation (CBEI). Overall team under this consortium includes UTRC and Purdue University.

Communications: Work was presented at Workshop on FDD for RTUs "Moving from R&D to Commercialization", 2014, Purdue University

Next Steps and Future Plans

1. In collaboration with OEM and National Account customer select representative field demonstration sites

2. Overall evaluation of field FDD performance and economic assessment

   - Performance degradation assessment
   - Fault isolation and impact evaluation
   - Maintenance decision making

3. Implement and evaluate VOLTTRON application through testing within a laboratory environment

REFERENCE SLIDES

Project Budget

Project Budget: Annually funded as part of CBEI. Total DOE budget $935M.
Variances: No project budget variances to date.
Cost to Date: $527K of DOE funds expended to date

Budget History					
CBEI BP3 (past) 2/1/2013 – 4/30/2014		CBEI BP4 (current) 5/1/2014 – 4/30/2015		CBEI BP5 (planned) 5/1/2015 – 4/30/2016	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$0K	$0K	$550K	$110K	$385K	$77K

CBEI – Consortium for Building Energy Innovation (formerly EEB Hub)
BP – Budget Period

Project Plan and Schedule

- Go/No-Go completed on October 20th, 2014

Project Schedule												
Project Start: **5/1/2014**		Completed Work										
Projected End: **4/30/2016**		Active Task (in progress work)										
	◆	Milestone/Deliverable (Originally Planned) use for missed										
	◆	Milestone/Deliverable (Actual) use when met on time										
	BP3 (2013-14)				BP4 (2014-15)				CBEI BP5 (2015-16)			
Task	Q1 (Feb-Apr)	Q2 (May-Jul)	Q3 (Aug-Oct)	Q4 (Nov-Apr)	Q1 (May-Jul)	Q2 (Aug-Oct)	Q3 (Nov-Jan)	Q4 (Feb-Apr)	Q1 (May-Jul)	Q2 (Aug-Oct)	Q3 (Nov-Jan)	Q4 (Feb-Apr)
Past Work												
Provide summary report describing RTU FDD readiness					◆							
Workshop materials and summary of outcomes						◆						
Progress report describing FDD evaluation						◆						
Report describing algorithms submitted							◆					
Overall evaluation of FDD performance and economic assessment								◆				
Current/Future Work												
Field FDD installation									◆			
Develop VOLTTRON application										◆		
Evaluate VOLTTRON application through lab testing											◆	
Overall evaluation of field FDD performance												◆

BP – Budget Period for Consortium for Building Energy Innovation (formerly EEB Hub)