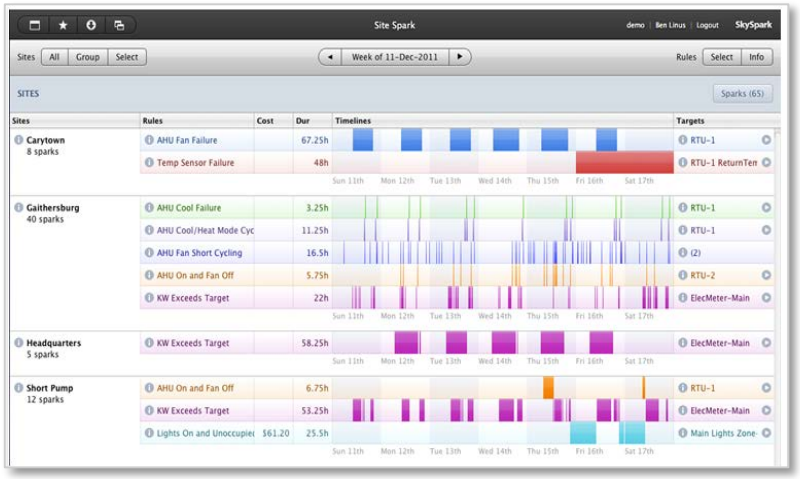
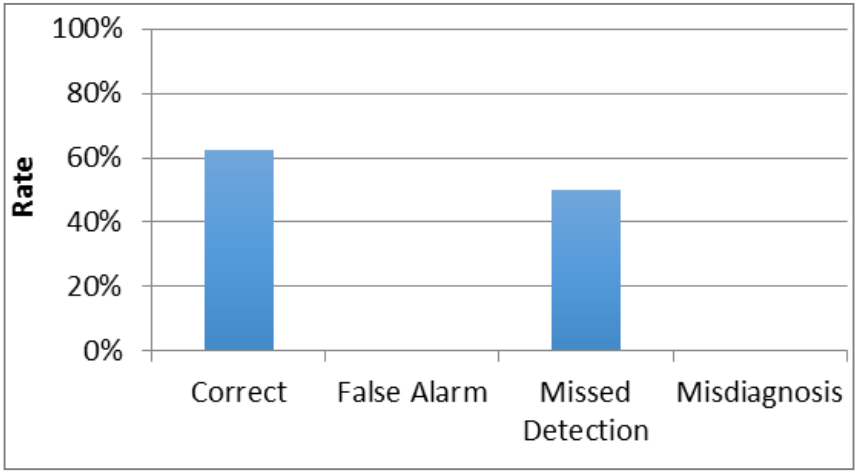
U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Automated Fault Detection and Diagnostics (AFDD) Performance Testing





Lawrence Berkeley National Laboratory

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Project Summary

Timeline

Start date: October 1, 2016

Planned end date: Sept 30, 2020

Key Milestones

1. Initial FLEXLAB data acquisition tests; FY17
2. AFDD performance testing procedure; FY18
3. Example performance tests, benchmarks FY18

Budget

Total Project $ to Date:

- DOE: $600K
- Cost Share: $0K

Total Project $:

- DOE: $1200K
- Cost Share: $TBD

Key Partners

National Renewable Energy Laboratory
Pacific Northwest National Laboratory
Oak Ridge National Laboratory
Industry Technical Advisory Group, 17 Orgs

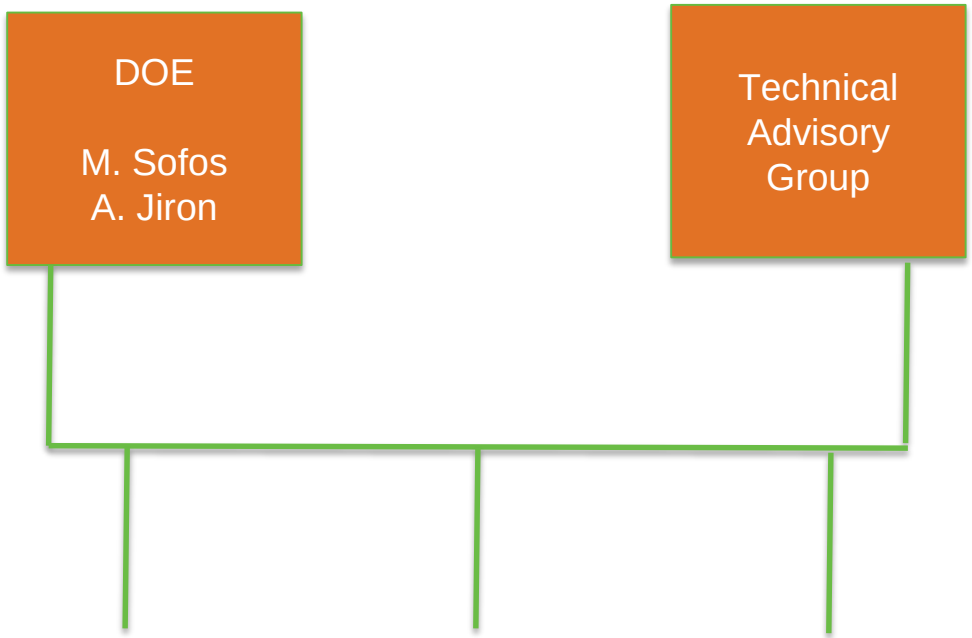
Project Outcome

Test procedures and public data sets to evaluate performance of automated fault detection and diagnostic (AFDD) solutions from industry and research community

Develop benchmark for R&D and innovation in AFDD to enable BTO's goals for advanced controls, including MYPP

Relevant to MYPP goal for self-commissioning controls to optimize building performance; Strategy 2, self-aware, self-calibrating controls

Team



NREL: S Frank, simulation-based FDD

ORNL: P Im, experimental building science

LBNL: J Granderson, analytics technology use & development

PNNL: D Vrabie, controls modeling & optimization

NREL NATIONAL RENEWABLE ENERGY LABORATORY

OAK RIDGE National Laboratory

BERKELEY LAB

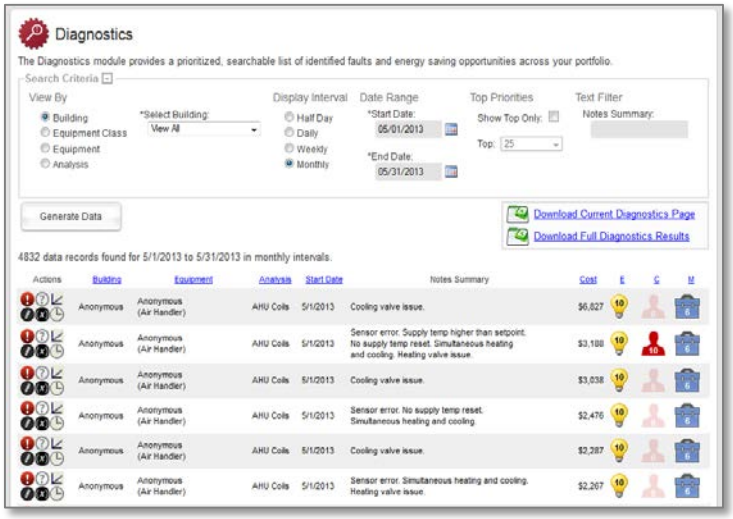
Pacific Northwest

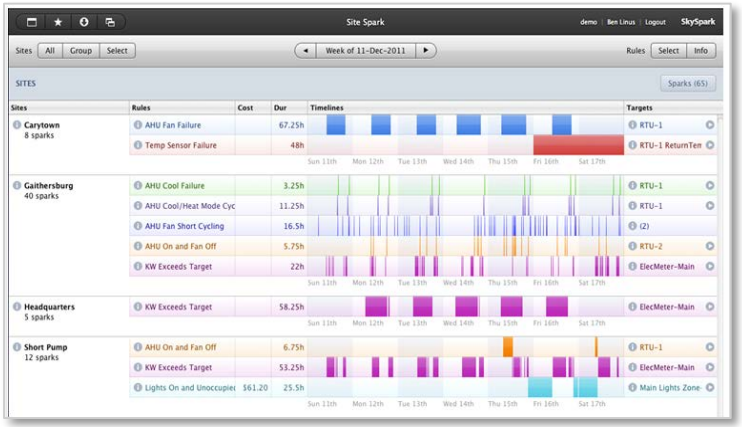
Multi-lab collaborative work

Challenge

Context

- As ‘big’ data and data science comes to buildings, explosion of interest in development adv. analytics approaches
- Software-based analytics represent one of fastest growing markets in technologies for bldg. operations - $0.8B in 2015
- AFDD in particular holds great potential and large target market, 15% savings, in buildings with BAS, 556 Tbtu potential
  - AFDD use building operational data to identify system or equipment level faults, and isolate their causes





Above: Screen shots from KGS Clock Works and SkyFoundry’s SkySpark

Challenge

- Users are bewildered about what the market offers, how offerings are different, and scope of capabilities of today's AFDD software tools

- New AFDD algorithms continuously developed

- No way for users, research community to compare/contrast, benchmark performance
  - How do we know what's good?
  - How do we know if we are improving?
  - How do we know where to focus further development effort?

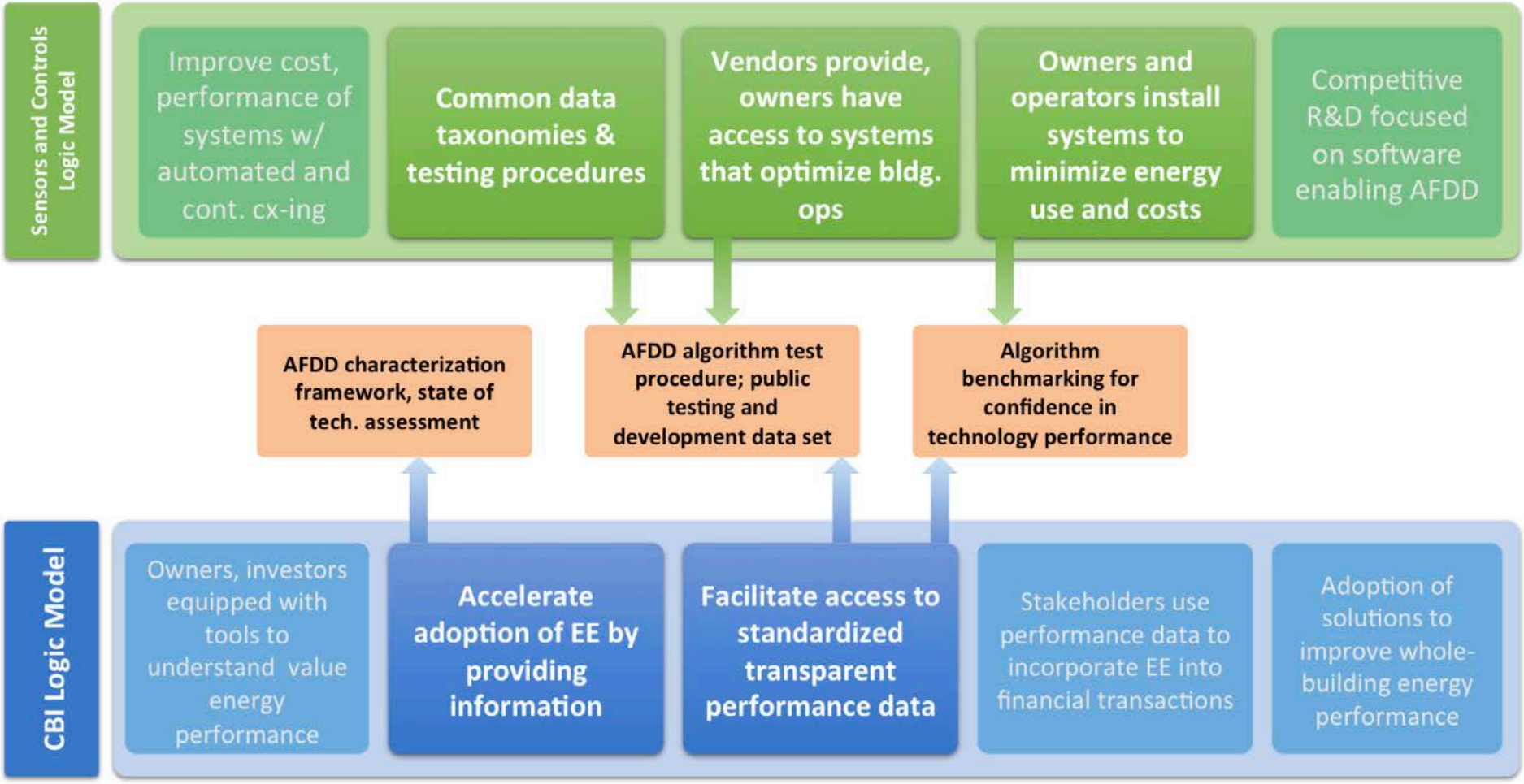
Approach

- Conduct R&D to define AFDD characterization framework, assess state of technology
- Develop public procedure and data sets to performance test AFDD algorithms
  - Apply to benchmark AFDD solutions from industry and research
  - Make available to public for replication and ongoing use (longer-term)
- Leverage TAG to engage stakeholders, inform and guide the work

Right: TAG representing AFDD providers, technical experts, market users

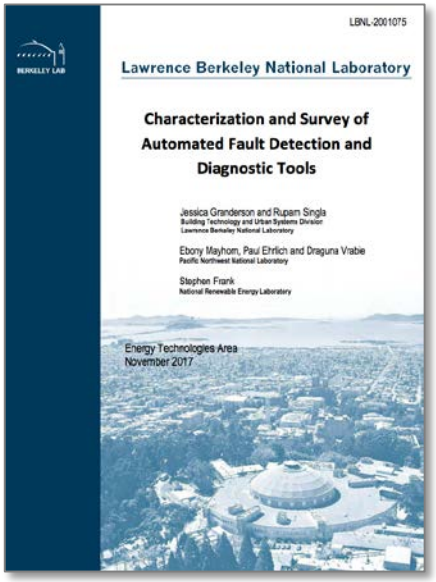
Impact

- Project connects ET and CBI goals in AFDD technologies
  - Provides tests, benchmarks to guide R&D innovation and evaluate achievement in consistent uniform manner



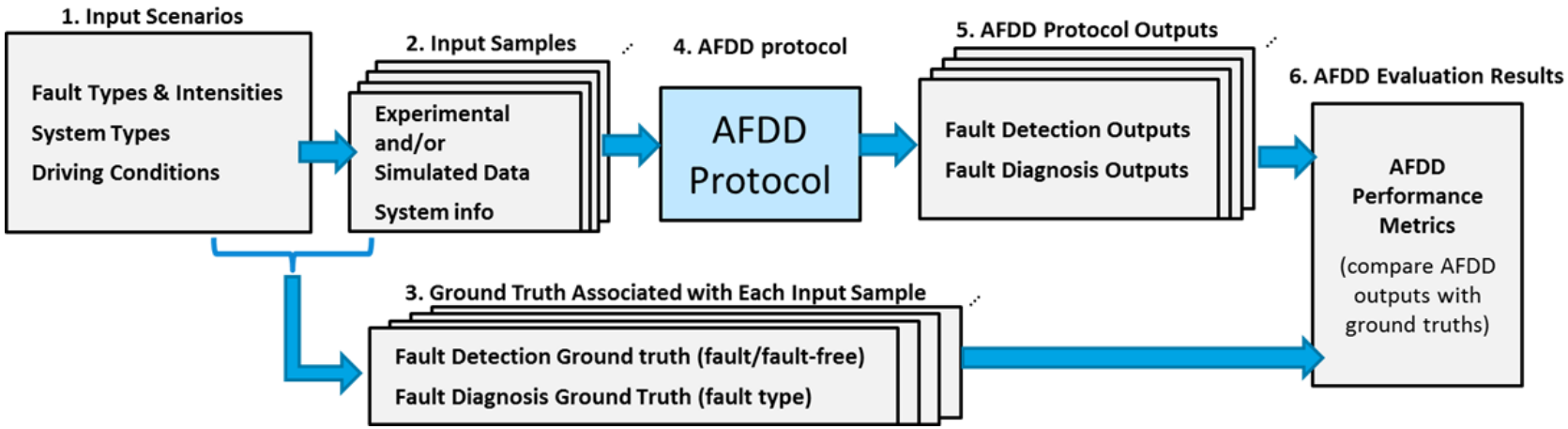
Progress: AFDD Tool Characterization

- Developed framework of capabilities spanning delivery to market, technical capabilities, additional features beyond FDD



- Selected key findings from application to 14 leading AFDD offerings
  - Software-as-a-service dominates, analysis-as-a-service is growing
  - Offerings distinguished by additional features, options in delivery models
  - Rule-based methodologies still heavily used, process history-based techniques emerging
  - While improving, IT and data integration represent one of the largest barriers to scale
  - Value proposition and implementation best practices are informational barriers

Progress: Performance Testing Procedure



Above: Generalized procedure adapted from Yuill & Braun 2013

- Literature review across multiple domains to determine options for defining input scenarios & ground truth, input samples, performance metrics
- Interviews with TAG SMEs for perspectives on building AFDD applications
- Nontrivial R&D challenge to extract simplicity from complexity, retain 'fairness': diversity in algorithm design, implementation for users, systems and 100s of faults, experimental design for robust ground truth
  - Impossible to satisfy all needs simultaneously, so clearly define options, implications, 80-20 pathways

Progress: Testing Procedure Options

- Presence/absence of a fault depends on whether definitions are condition-based, behavior-based, or outcome-based

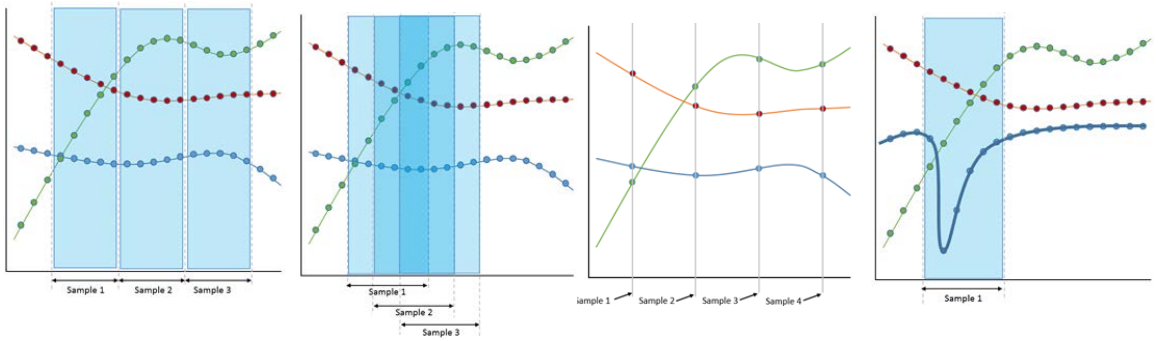
Example: Stuck Economizer Damper

Condition-Based	Behavior-Based	Outcome-Based
▪ Outside air damper is stuck at 72% open	▪ Outside air damper is stuck at 72% open	▪ Outside air damper is stuck at 72% open
▪ Outside air temp. is 63 °F	▪ Outside air temp. is 63 °F	▪ Outside air temp. is 63 °F
▪ AHU is calling for cooling	▪ AHU is calling for cooling	▪ AHU is calling for cooling
▪ AHU is economizing	▪ AHU is economizing	▪ AHU is economizing
▪ Cooling energy is 188% of predicted	▪ Cooling energy is 188% of predicted	▪ Cooling energy is 188% of predicted
Fault: Yes	**Fault:** No	**Fault:** Yes

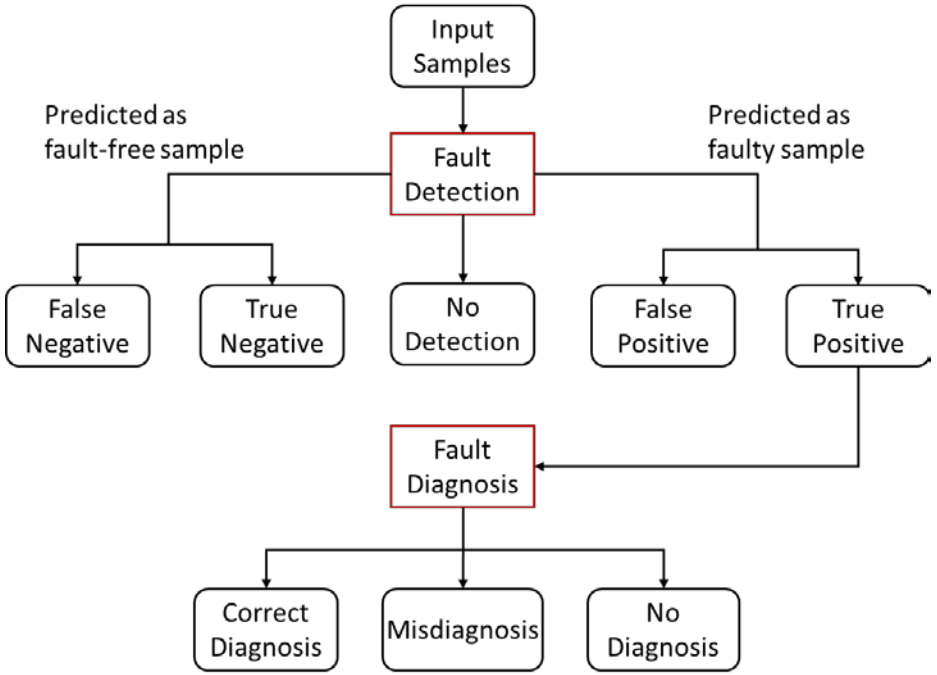
- Condition-based formulations are most common in literature, especially for buildings
- Commercial AFDD products may use a mix, mostly condition and behavior
- Experts suggested that condition based most common, most appropriate for diagnosis

Progress: Testing Procedure Options

- Input samples contain data for which AFDD output is compared to ground truth
- Literature review, SME input suggests regular slice of time, ~day in duration aligns with design and use of most AFDD tools
- Several options for metrics to compare AFDD outputs to ground truth
  - Foundational $\text{FPR} = \frac{\text{FP}}{\text{CP}}$ $\text{CDR}_{\text{total}} = \frac{\sum_{i=1}^{N} \text{CD}_i}{\text{TP}}$
  - More nuanced $\text{MCC} = \frac{\text{TP} \times \text{TN} - \text{FP} \times \text{FN}}{\sqrt{(\text{TP}+\text{FP})(\text{TP}+\text{FN})(\text{TN}+\text{FP})(\text{TN}+\text{FN})}}$
  - Unified, single score



A regular slice of time | Rolling time horizon | A single instant of time | Event

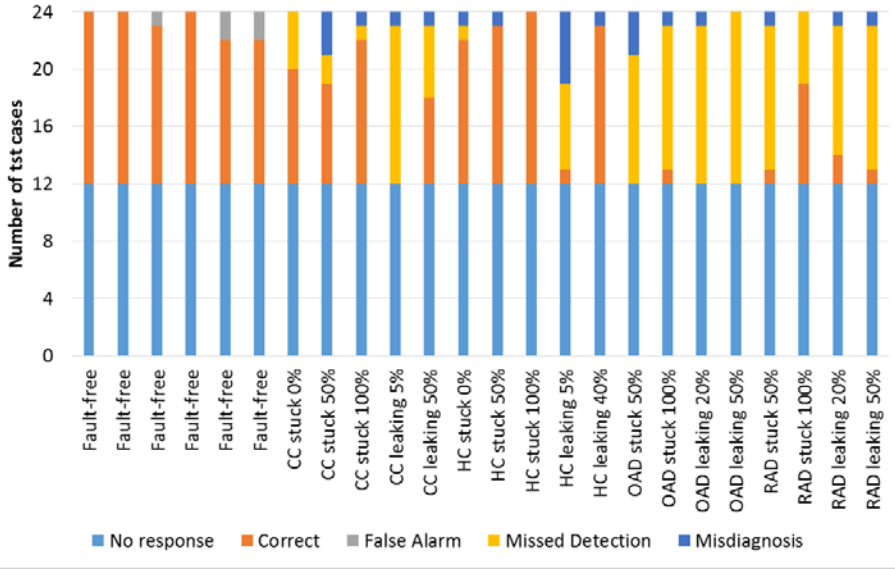


Progress: Initial Experimental Data Curation & Vetting in LBNL's FLEXLAB

- Single zone dedicated air handler with cooling coil, heating coil, VFD
- Chilled water plant and hot water plant

Above: FLEXLab experimental test facility

Fault (SZCAV & SZVAV)	Fault intensity	Method of Implementation
Cooling/heating coil valve		
Valve stuck	0%, 50%, & 100% open	Automated **override of control signal values** to force the valve to a given state
Valve leaking	5%, 50% of maximum coil valve flow	Open cooling coil **bypass valve** to 5% and 50% (cooling) or 40% (heating) of maximum coil valve flow
Outside/return air damper		
Damper stuck	Min position*, 50%, & 100% open	Automated **override of control signal values** to indicate that damper is stuck.
Damper leaking	20%, 50% of maximum damper flow	If control signal from algorithm drops below X%, then **fix control output** at X% [from damper characteristic curve]. **Otherwise damper controls normally**. (X= 2/10 at 20%/50% intensity)
Outside air, supply air, zone air, and mixed air temperature sensor		
Temperature sensor bias*	+3°F, -3°F offset*	Automated **override of control signal values** to indicate constant offset on sensor reading



Right: Data and process vetting using NIST FDD rules complemented with manual data verification

Stakeholder Engagement and Remaining Project Work

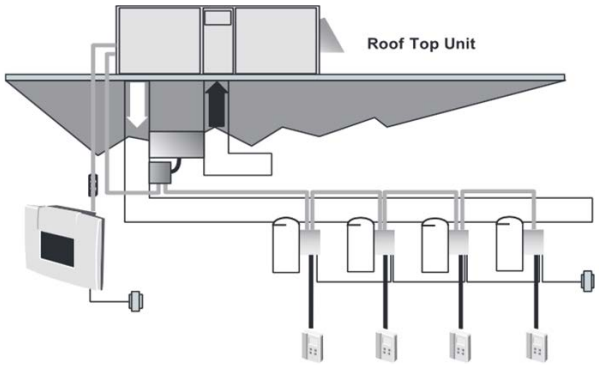
- Progress recap:
  - Characterization framework and assessment to understand capabilities of today's technology
  - AFDD performance testing procedure and detailed review of parameters necessary to define for execution
  - Initial creation of experimental and simulated test data sets for high-impact faults, systems
  - Engaged stakeholder TAG with deep subject matter expertise

- Summary of Remaining Work

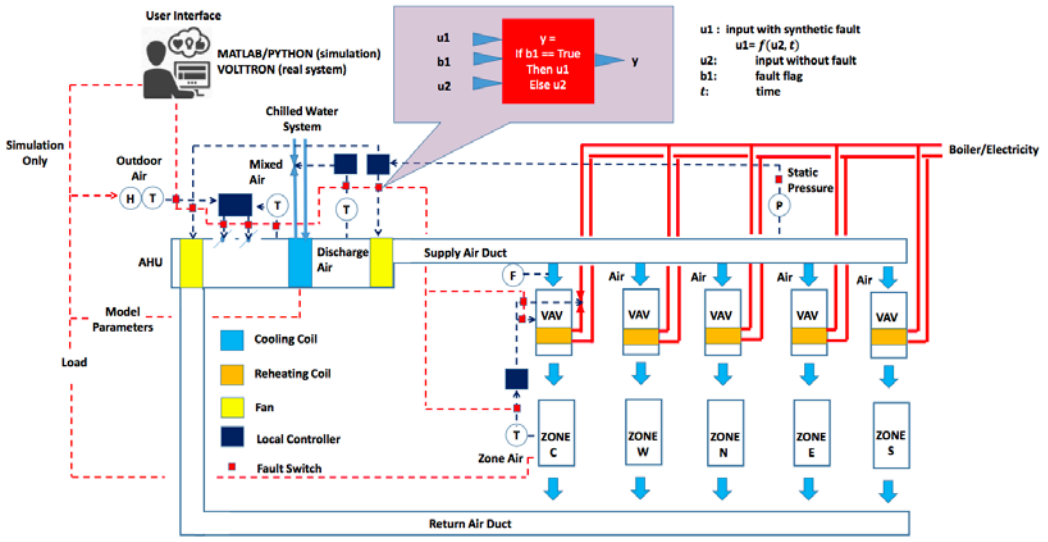
Synthesize existing data, expand data set → Document test procedure, share data set with public → Use data and procedure to evaluate AFDD algorithms → Disseminate, build awareness, ongoing use by others

Remaining Project Work: Test Data Creation

- NREL/ORNL experimental data set
  - RTU & whole-building faults
  - ORNL Flexible Research Platform



- PNNL simulated data set created for
  - Multi-zone AHU-VAV system with typical controls configuration



- Merge with LBNL data set to expand scope of coverage

- Further prioritized expansion of systems, faults covered – boilers, chillers, cooling plants …

Remaining Project Work: Public Availability

- Testing procedure discussion paper to establish
  - Common technical vocabulary
  - Contextualization for buildings applications
  - Pros/cons for parameter options and recommendations

- Rich collection of test data
  - Broad variety of system types and configurations, controls, operating conditions
  - Quality assurance to align with testing requirements
  - Standardization to provide consistent input samples

- Work with FDD developer community to test 2-3 algorithms; generate public case study examples of performance testing findings/insights

Remaining Project Work: Long-term Use

- Disseminate procedure & data for wide industry awareness and use

- Considerations:
  - Where is data set stored, how is it formatted, how is it accessed?
  - What infrastructure facilitate use and how is it maintained?
  - Potential/interest in standardization or certification? By who?
  - What is effect of test procedure options on evaluation outcomes?

Thank You

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REFERENCE SLIDES

Project Budget

Project Budget: $300K/yr FY17-FY18, expected flat through FY20

Variances: No variances from original planned budget

Cost to Date: Spending on track, $385K of $600K spent through February 2018

Additional Funding: Potential for out-year cost share TBD

Budget History					
FY 2017 (past)		FY 2018 (current)		FY 2019 – FY 2020 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$300K		$300K		$600K	TBD

Project Plan and Schedule

Project Schedule									
Project Start: October 1, 2016		Completed Work							
Project End: September 30, 2020		Active Task (in progress work)							
		Milestone/Deliverable (Originally Planned)							
		Milestone/Deliverable (Actual)							
	Status	FY 2017				FY 2018			
Task		Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Past work									
T1. Conduct initial overview of existing AFDD tools and define initial scope of AFDD test methodology (systems, faults, composition of test data set, test metrics, etc.)	Complete								
T2. Conduct Initial FLEXLAB investigation and data acquisition tests.	Complete								
T3. Evaluate data collection and test methodology for refinement.	Complete								
T4. AFDD Phase 1 documentation completed in partnership with NREL and PNNL	Complete								
Current Work									
T1. Acquisition plan completed for expanded test data set (physical and simulated), based on assessment of FY17 findings and direction from the TAG	Complete								
T2. Working definition of infrastructure; where data lives, how it is formatted and accessed, how data and/or testing methodology are made available to public, etc.	Ongoing								
T3. 2-3 FDD algorithms are tested on currently developed data set to provide public case studies, and testing outputs and insights	Ongoing								
T4. FY18 documentation completed in partnership with NREL, ORNL, and PNNL	Not started								