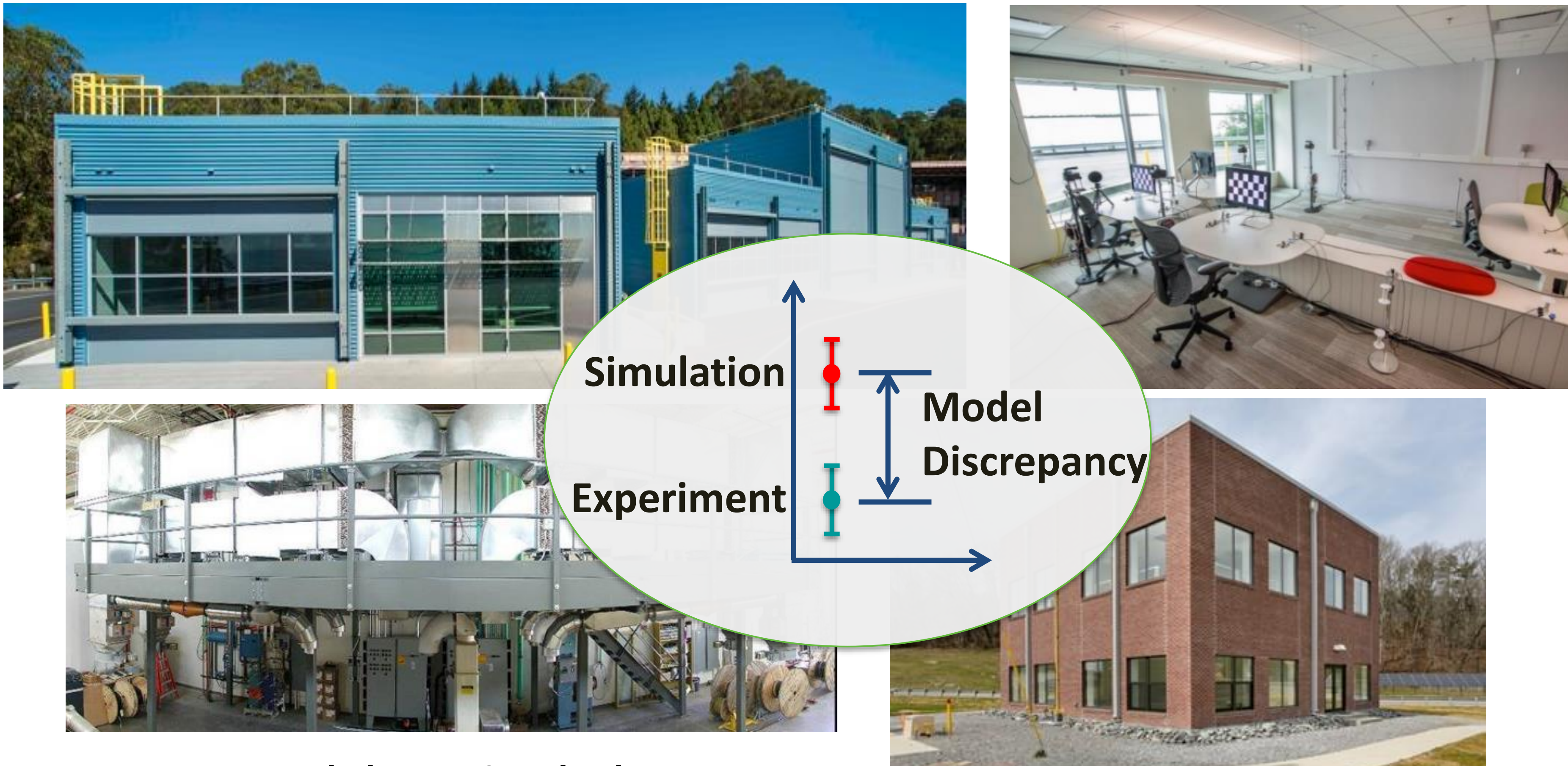
Validation and Uncertainty Characterization for Energy Simulation



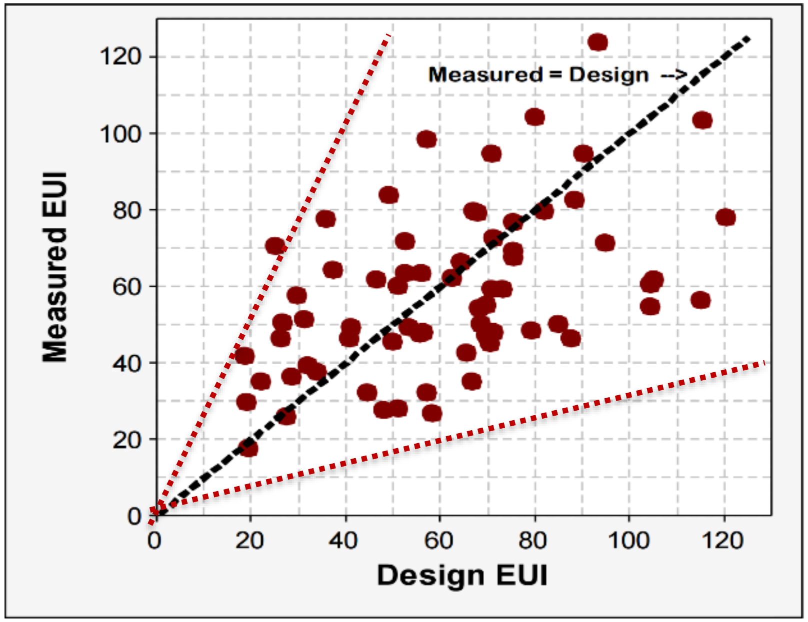
Lawrence Berkeley National Lab,

Argonne National Lab, National Renewable Energy Lab, Oak Ridge National Lab

The Problem

- Building Energy Modeling (BEM) supports EE decision making but is underutilized
  - Reputation for “inaccuracy” or “poor predictive capability”
- Reality: EUI prediction is hard (weather, occupancy) & often besides the point
- Perception: if you can’t predict EUI, how can you do anything at all?

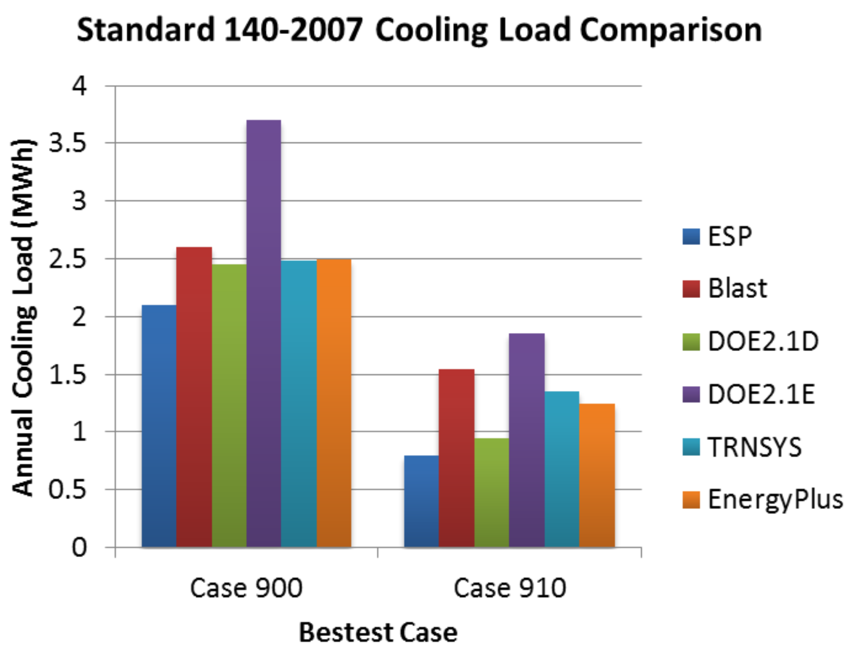
Reality



Perception

The "Solution"

- ASHRAE Standard 140 “Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs”
  - Analytical and comparative tests for a number of configurations
  + Improves consistency among BEM engines
  + Identifies areas in need of further investigation
  – Lack of “ground truth” empirical data feeds perception of inaccuracy



The Solution

LBNL FLEXLAB

ORNL FRP

- Use highly instrumented test facilities to develop empirical data sets for 140
- Expected impact
  - Make definitive quantitative statements about BEM engine accuracy
  - Improve BEM engine accuracy
  - Increase confidence in and use of BEM

Project Summary

Timeline:

Start date: 10/1/2015

Planned end date: 9/30/2019

Key Milestones

First SSPC 140 V&U Subcommittee Meeting; 5/25/2018

Second SSPC 140 V&U Subcommittee Meeting; 1/13/2019

Budget:

Total Project $ to Date:

- DOE: $4,136,000
- Cost Share: $260,000

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Key Partners:

ASHRAE SSPC 140
Southern California Edison

Project Outcome:

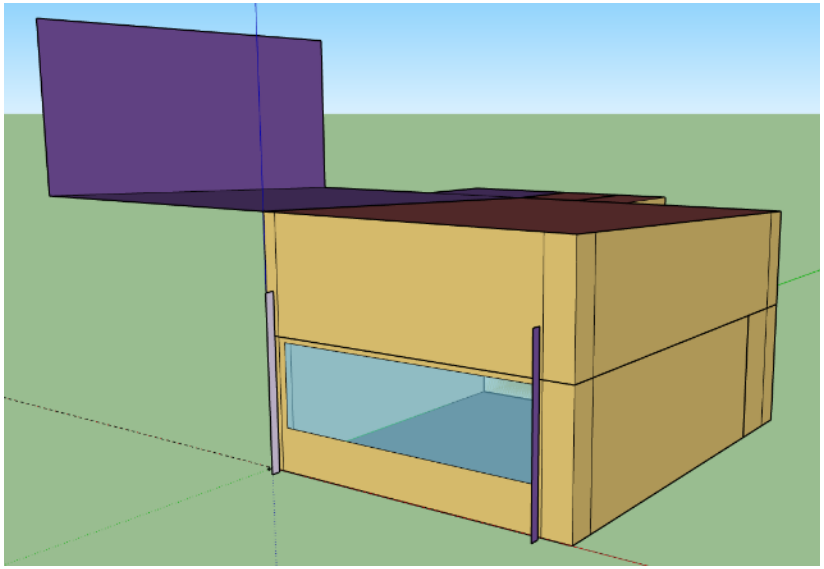
- Empirical data for ASHRAE Standard 140
- Methods/and procedures for identifying model discrepancies and reducing model uncertainty
- Improved understanding of experimental means for future empirical validation experiments

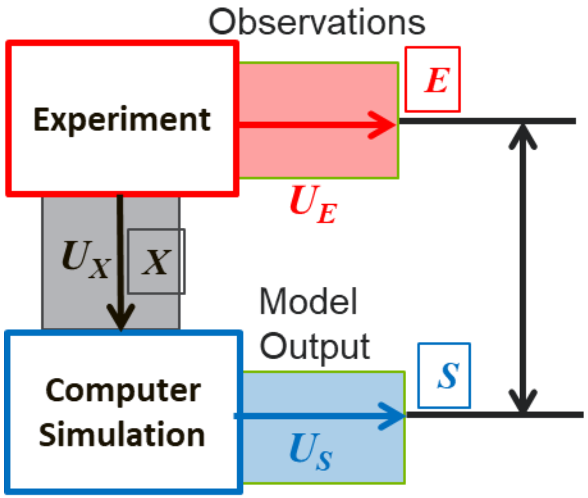
Team and Tasks

- **LBNL**: space cooling and heating load experiments
- **ORNL**: multi-zone VAV system experiments
- **NREL**: indoor/outdoor apartment module experiments
- **ANL**: uncertainty characterization for experiments and models

- **TAG**: vendors, practitioners and researchers: review plans and results – one to two meetings per year
- **ASHRAE** Standing Standard Project Committee 140 -- review of submissions for inclusion in Standard 140

Uncertainty Characterization and Evaluation Metrics



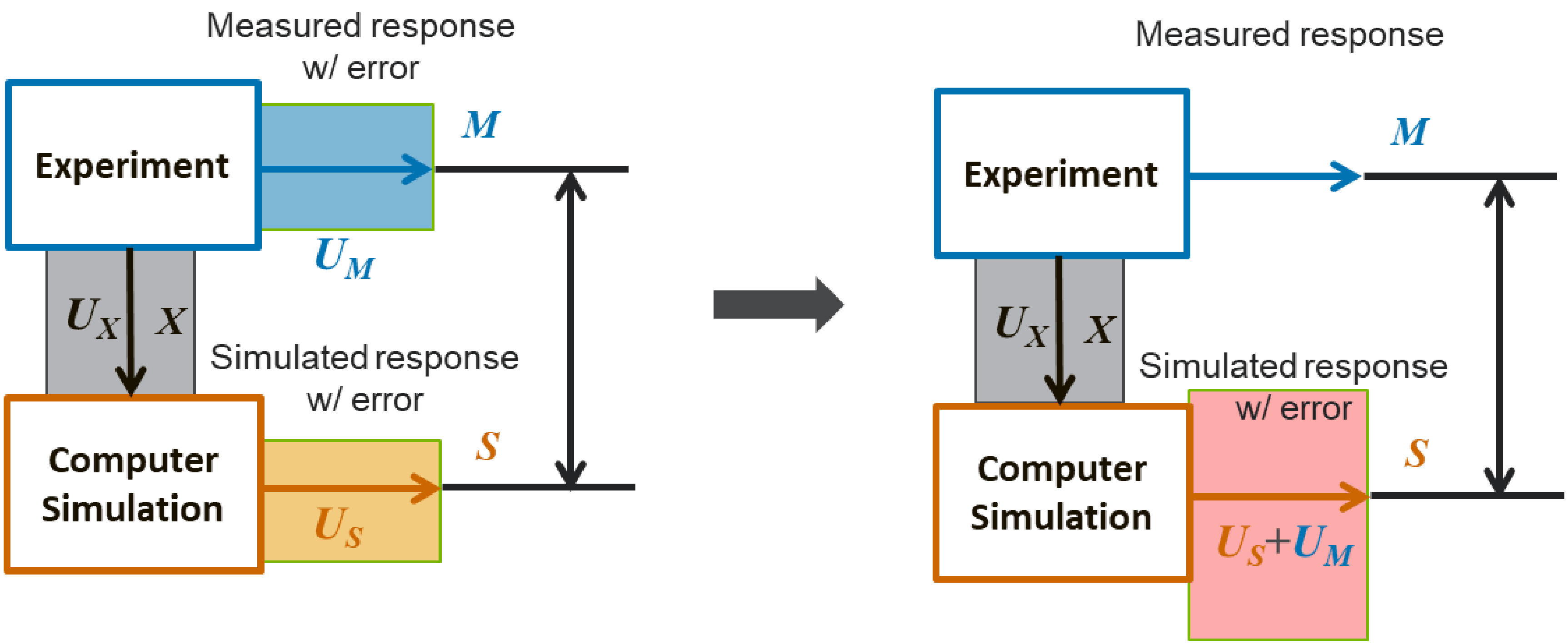


Argonne National Laboratory – Ralph Muehleisen – rmuehleisen@anl.gov

Qi Li

Uncertainty Propagation

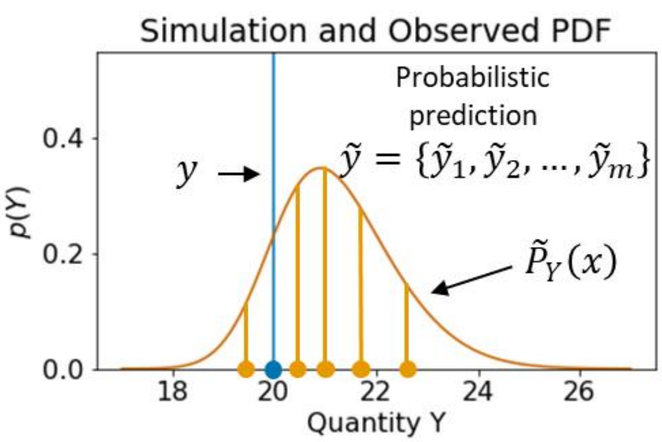
- Developed method for combining modeling and measurement uncertainties into one set of uncertainties in model
  - Key to creating a comparison metric that includes uncertainty …
  - Is statistically valid …
  - And simple to understand

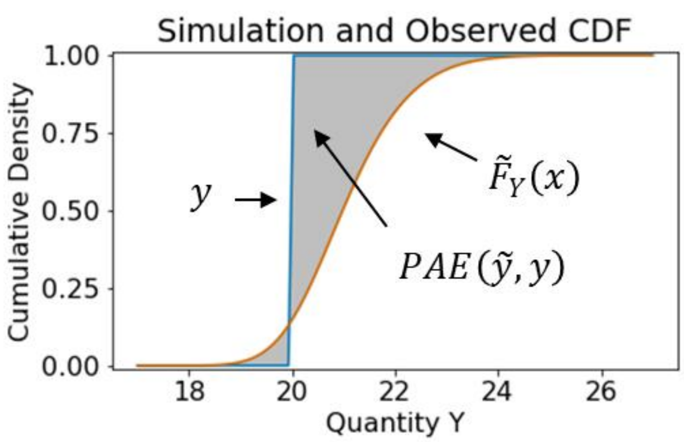


Metric Development

- Developed Probabilistic Absolute Error (PAE) Metric
  - Difference between Cumulative Distribution Functions (CDF) of simulation and measurement (both including uncertainty)
  - Collapses to normal Absolute Error when no uncertainty

$$PAE(\tilde{y}, y) = \int_{-\infty}^{\infty} \left(\tilde{F}_Y(x) - H(x - y)\right)^2 dx$$





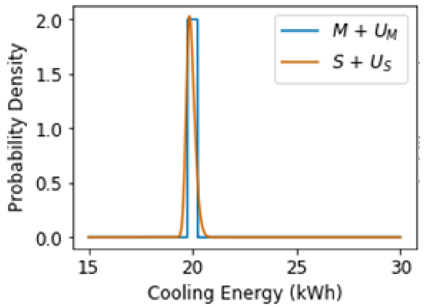
Why a new metric?

- In previous work people used uncertainty ratio (UR)

$$UR = \frac{\delta_m}{\sigma_M + \sigma_S}$$

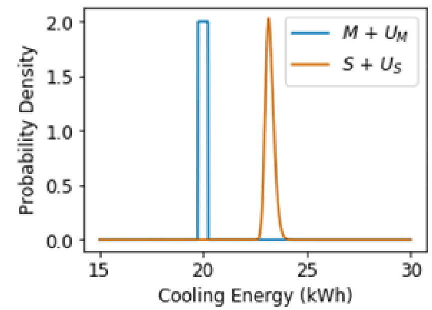
- UR doesn't work when uncertainty in either simulation or measurement is large

Small Bias, Small Uncertainty



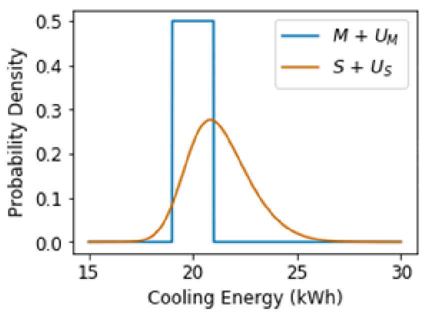
UR = 0.875
NPAE = 0.005

Large Bias, Small Uncertainty



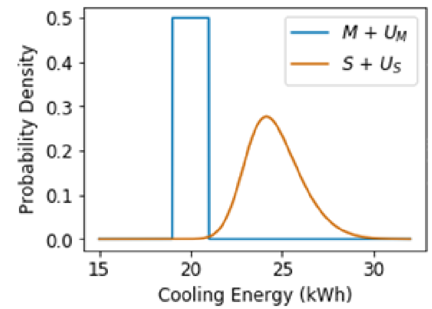
UR = 5.00
NPAE = 0.167

Small Bias, Large Uncertainty



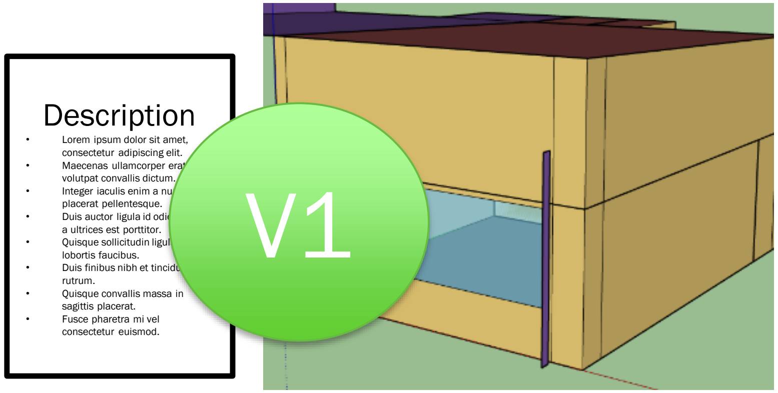
UR = 0.167
NPAE = 0.048

Large Bias, Large Uncertainty

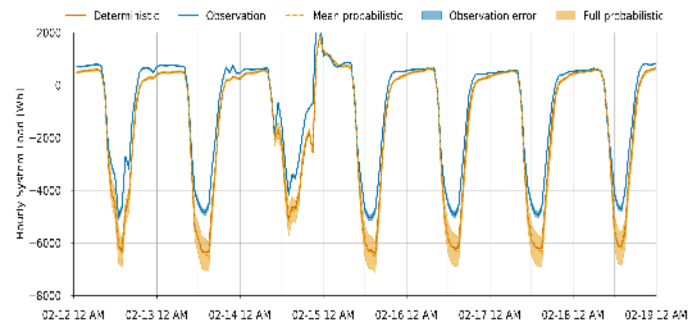


UR = 0.198
NPAE = 0.952

Feedback Process for Experiments

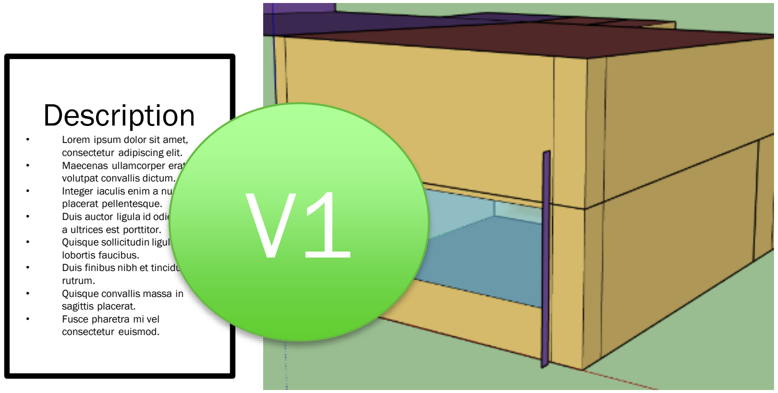


Create independent model from experiment description



Find discrepancies and inputs causing high uncertainty

Feedback Process for Experiments



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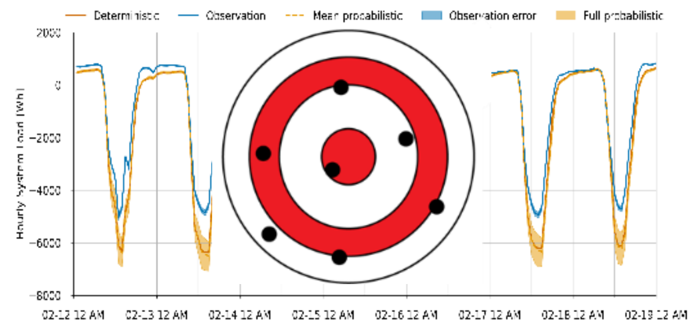

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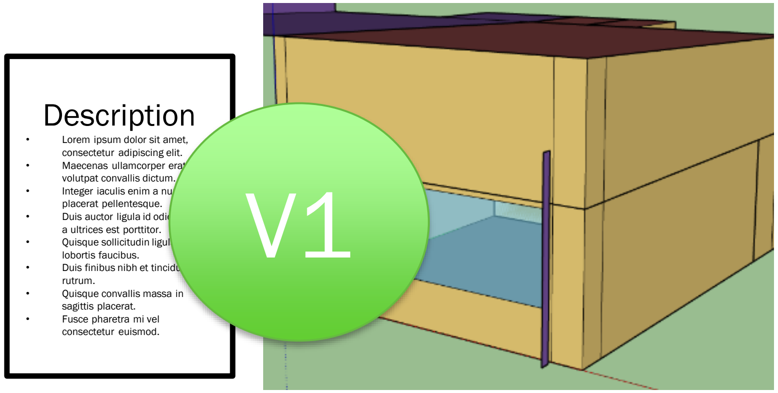

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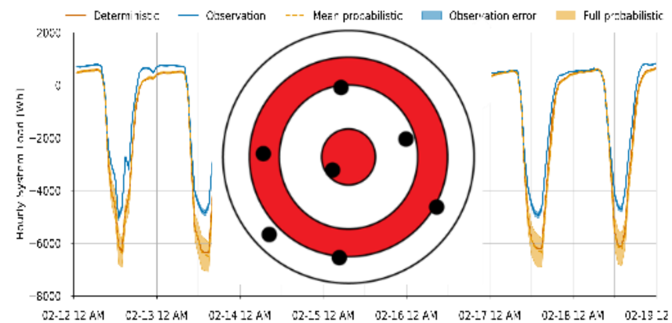

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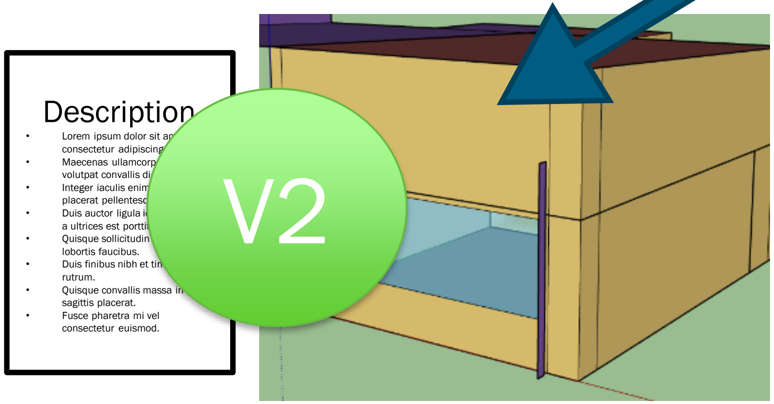
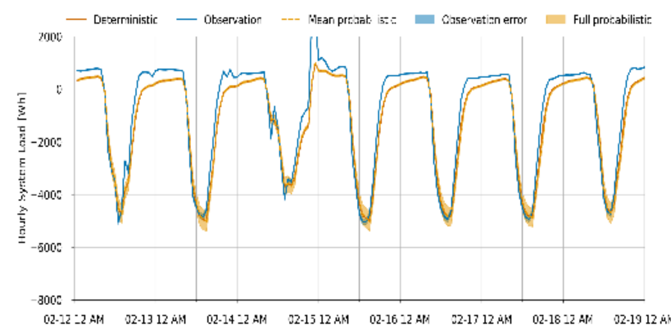
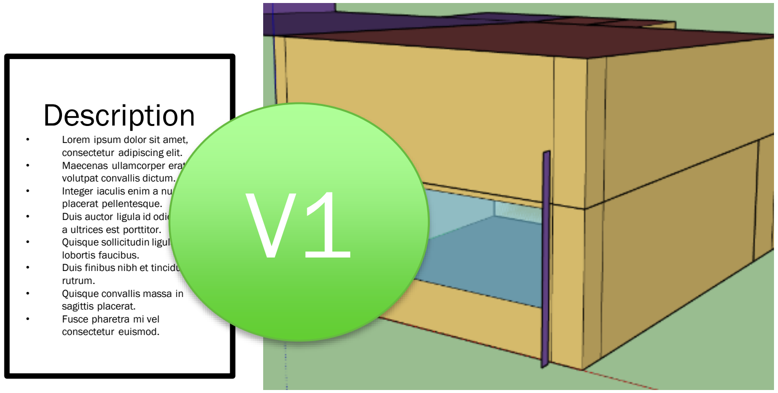


Update description and/or experiment



Reduced discrepancies and uncertainty

Feedback Process for Experiments



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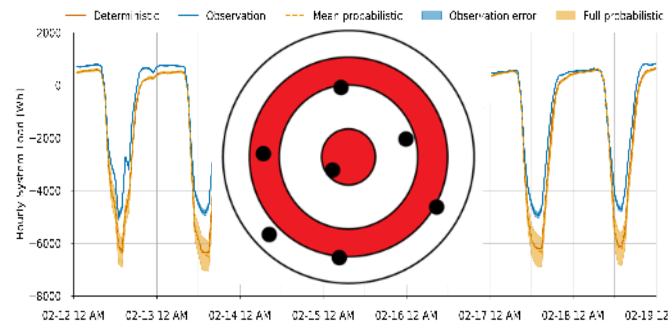

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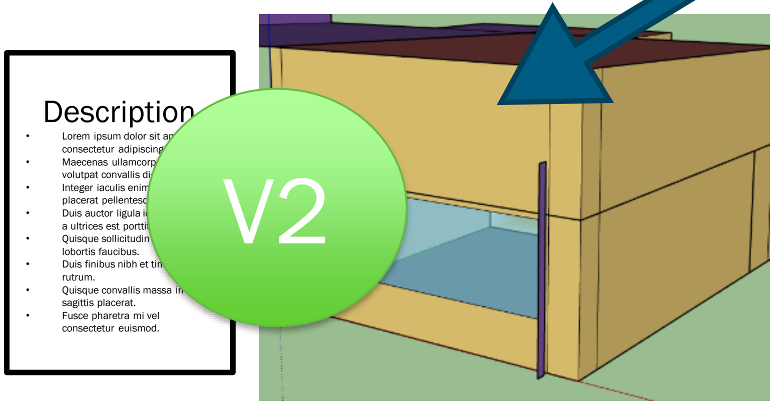

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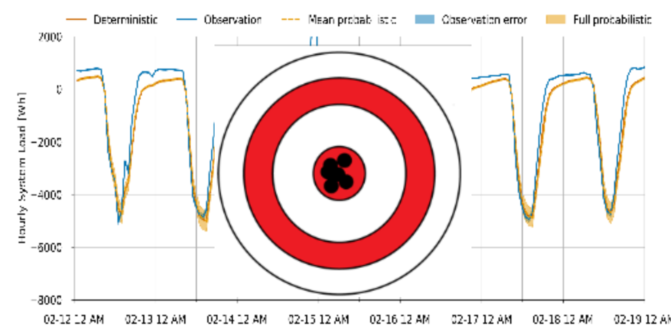
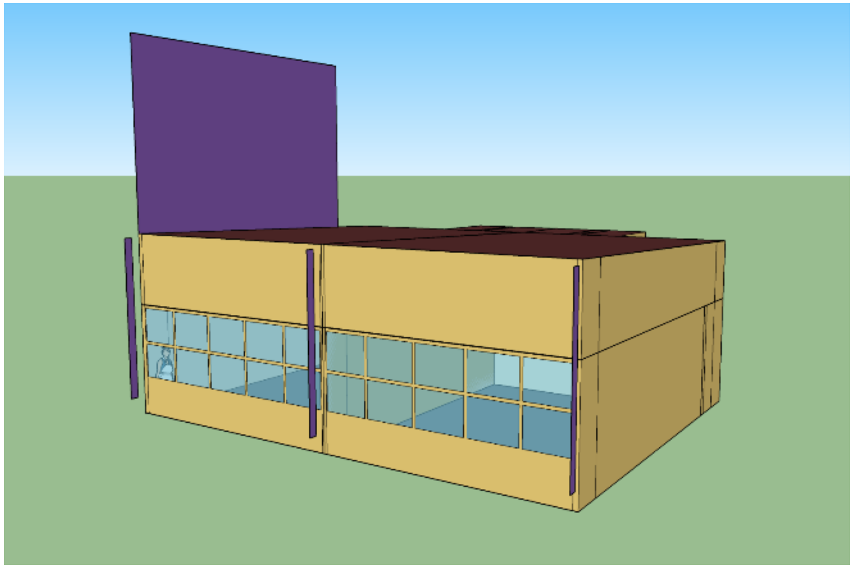


Reduced discrepancies and uncertainty

Zone Heating and Cooling Loads



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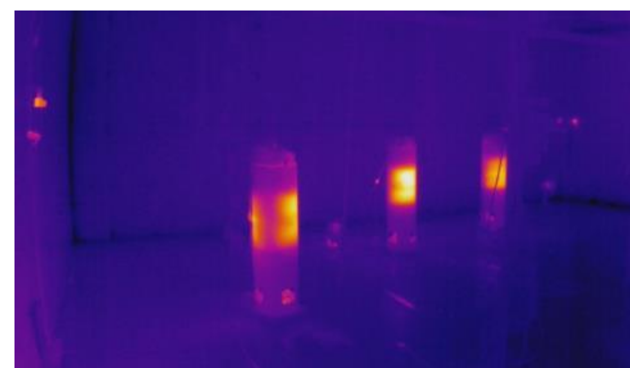
Philip Haves
Baptiste Ravache
Handi Chandra Putra
Ronnen Levinson
Darryl Dickeroff

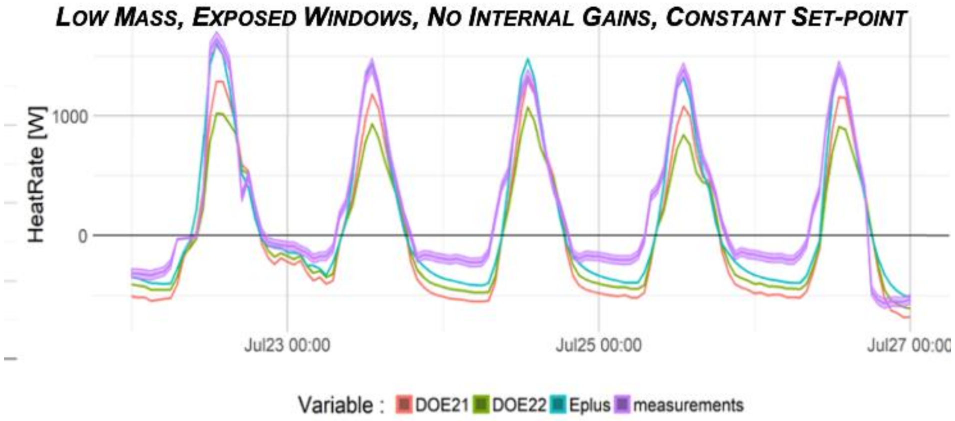
Background

- What is unique about FLEXLAB?
  - Single zone, configurable as south facing exterior zone or as an interior zone
  - Control volume is the room (excluded air handler, ducts etc)
  - Well instrumented hydronic heating and cooling system
- What calculations are we trying to validate?
  - Sensible heating and cooling load

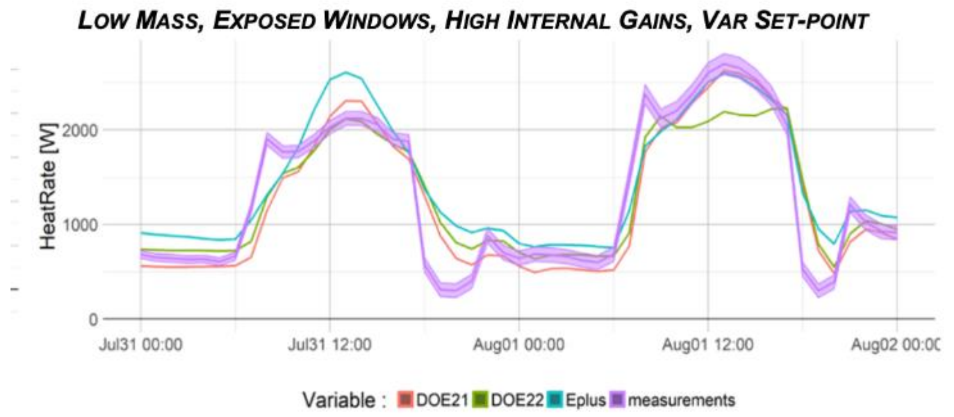


Previous activities

- Previous experiments (FY16-18)
  - 15 different experiments
    - High and low thermal mass
    - Covered and exposed windows
    - Constant setpoint and setbacks
    - Variable internal gains
    - Floating co-heating experiment
- Southern California Edison Project
  - Compared measurements to DOE-2 and EnergyPlus
  - Some disagreement between measurements and simulations were noted



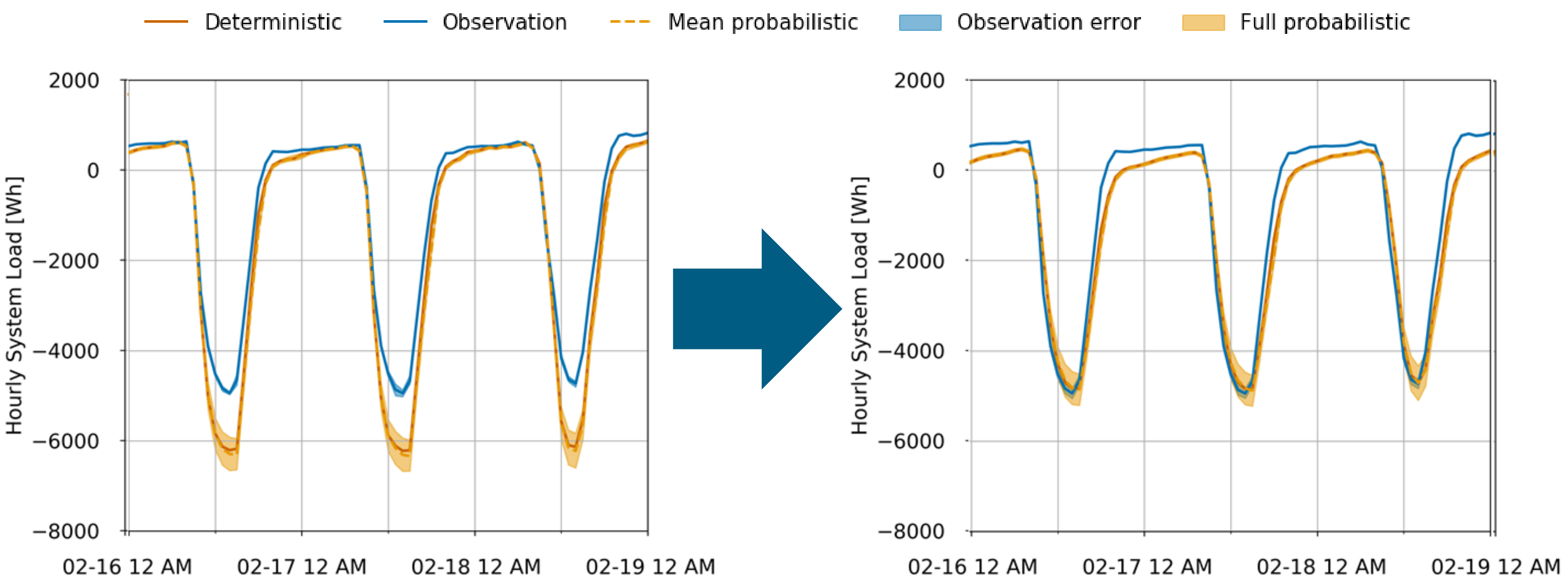
FY18: nighttime mismatch



FY18: Setback mismatch

Model/Uncertainty Framework Feedback

- Uncertainty added to 200+ model inputs
- Improved description of experiments
- Measured specific heat of drywall and slab
- Changed interior surface coefficients from “Ceiling Diffuser” to TARP
- Starting simplified heat transfer experiments



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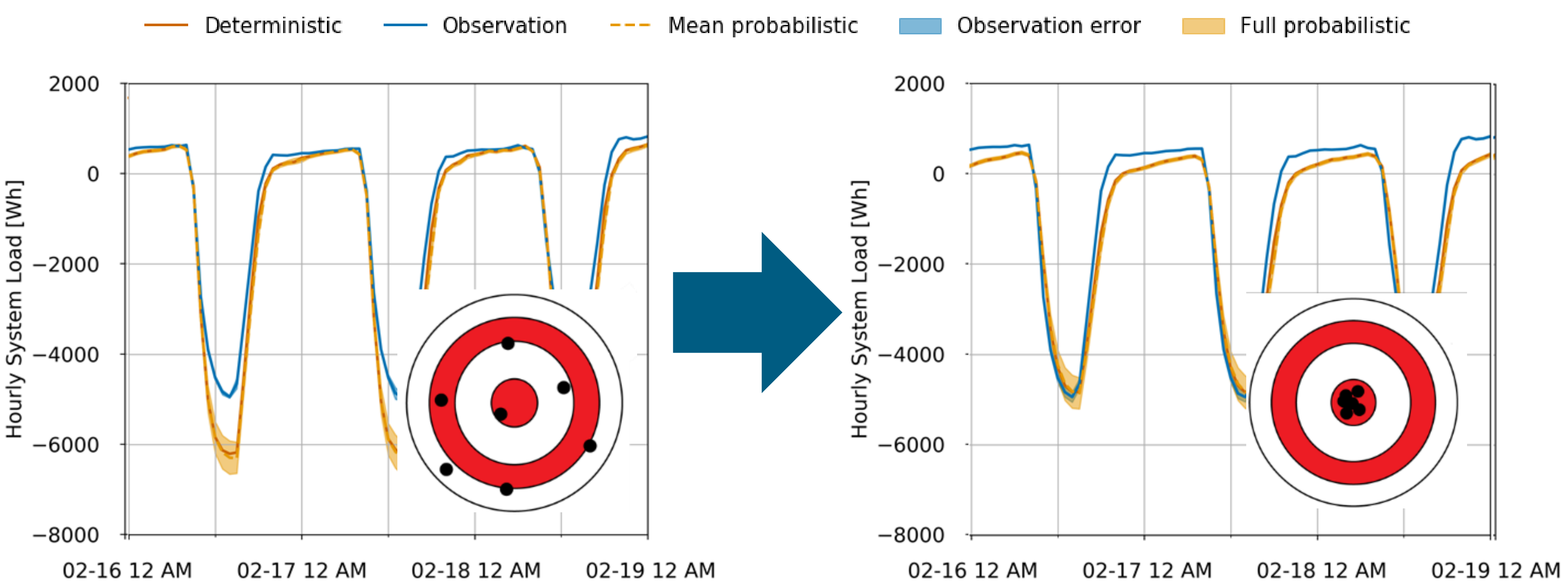
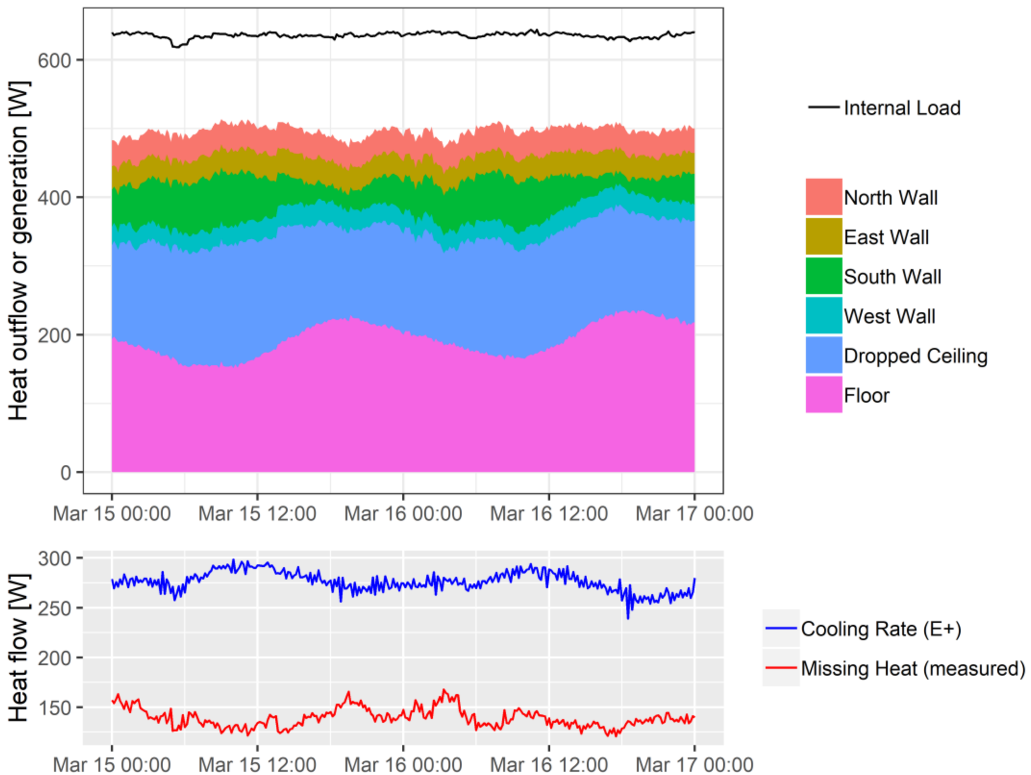


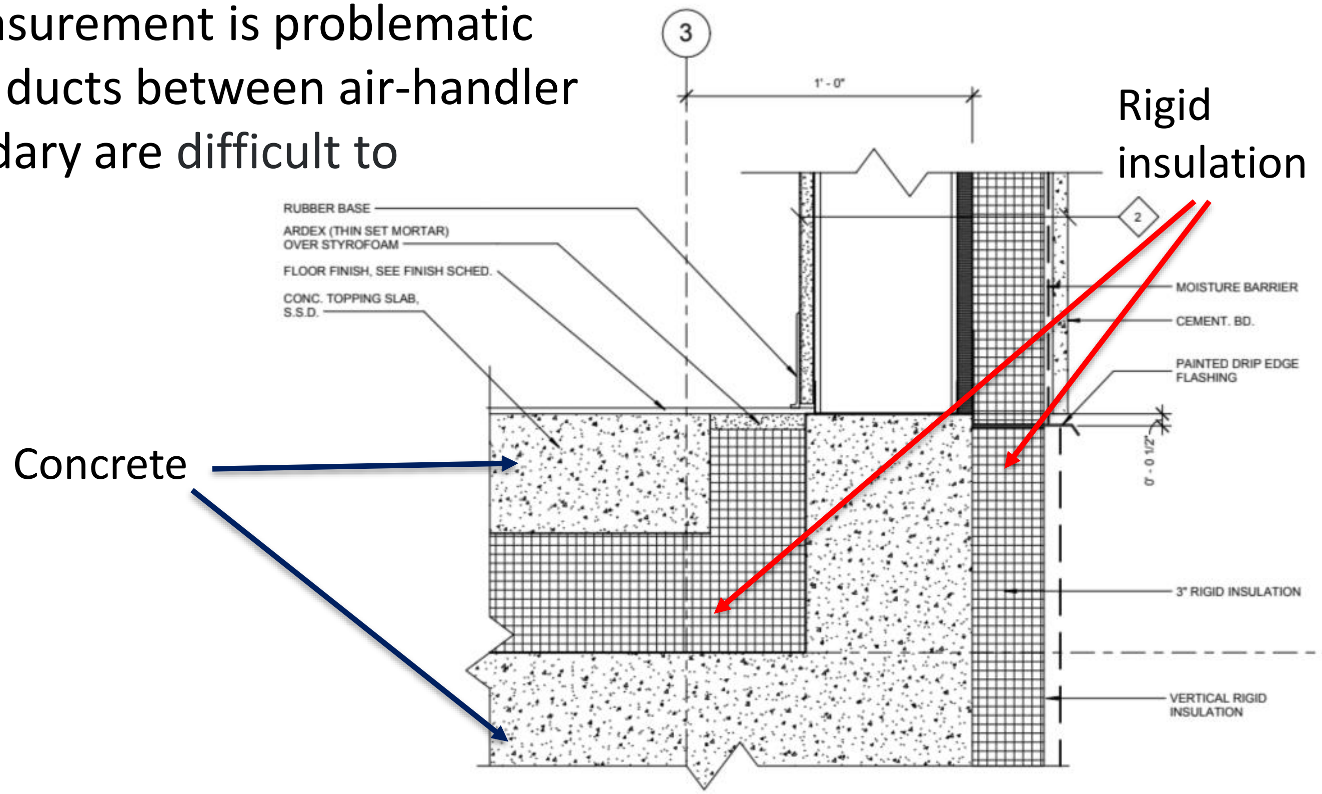
FY19 activities to date

- Established metrics to quantify consistency of the measurements, starting with zone heat balance
- Installed additional heat flux sensors
- Ran 54 days of experiments
- Determined that slab edge effects prevented us from getting sufficient closure on zone heat balance



Challenges

- Slab heat transfer is not uniform because of edge effects – in spite of insulation below slab and on perimeter
- Direct solar gain (sun patches) on the slab create additional non-uniformity
- Water-side load measurement is problematic because losses from ducts between air-handler coil and space boundary are difficult to quantify accurately



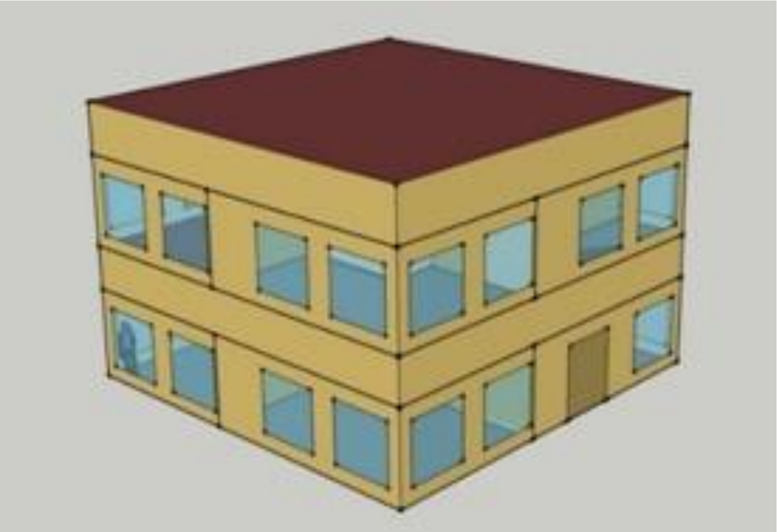
Current and future activities

- Current experiments
  - Electrical co-heating experiment (constant, accurately determined heat load)

- Implementation of next experiments
  - Decouple from slab and ground, esp. perimeter
    - Low mass cases: add 4” of Polyiso on top
    - High-mass cases: add thermal mass above new insulation
  - Exposed and covered windows
  - Accurate cooling load determination: water side heat balance on “co-cooling” source in the space

- Demonstrate heat balance with blocked and exposed windows and high and low mass decoupled from slab

Multizone HVAC System Validation using ORNL's Flexible Research Platform



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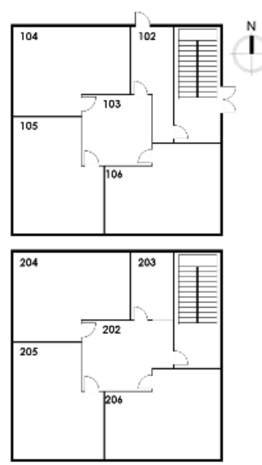
Joshua New **Jaewan Joe**
Yeonjin Bae **Anthony Gehl**

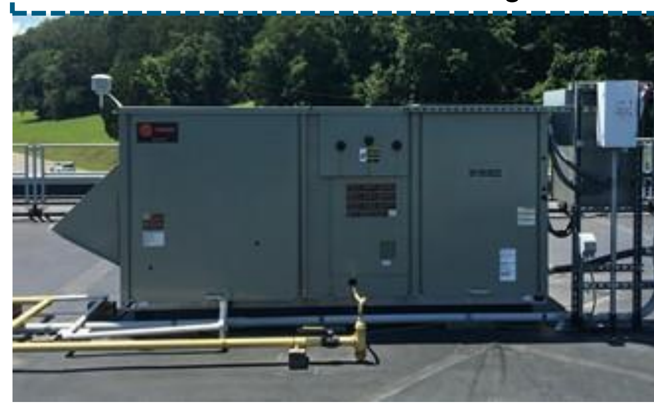
Validation of Multizone HVAC System Model

- **Purpose**
  - Create an empirical validation datasets from a multizone small office building, which has limited input uncertainty compared to real buildings.
- **Test Facility: Flexible Research Platform (FRP)**
  - Multi-zone building with VAV system setup resembling small/medium offices
  - Limited uncertainty with
    - Occupancy emulation
    - Onsite weather station
    - More than 500 sensors for HVAC, envelope, and thermal zones.

Flexible Research Platform (FRP)



Multi-zone HVAC
- RTU with VAV Reheating



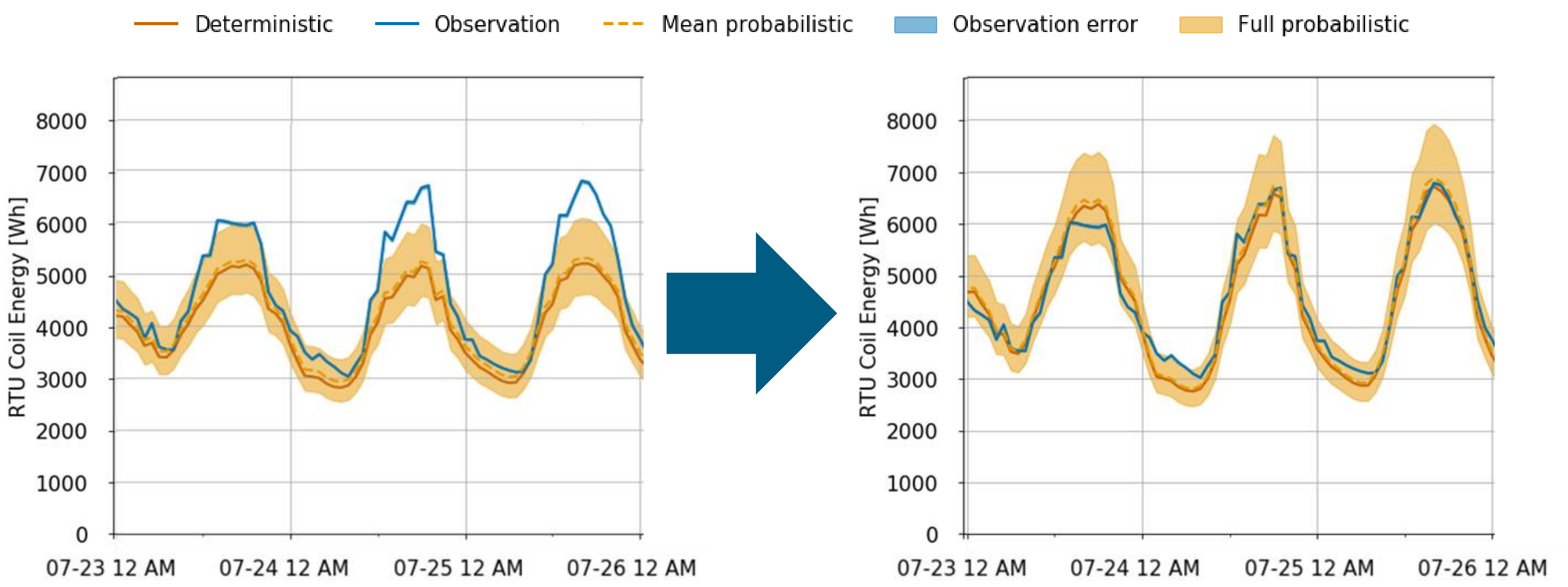
Previous Activities

- **FY16-FY18**
  - Development of Multiyear Test Plan per SSPC140 feedback
  - 2 Cooling season tests & 2 Heating season tests
  - Model input specification & Detailed EnergyPlus models
  - Data sets:
    - Test data sets: 1 min and 60 min resolution per test
    - Weather data: 1min resolution
  - Draft SSPC140 Submission Package
- **Issues/Challenges**
  - EPlus model uses a generic RTU model, which cannot characterize the real system performance
  - There was no zone level air flow rate measurement, and only total RTU air flow has been measured.
  - Blower door test results cannot verify zonal infiltration rates in different outdoor conditions.

Needed to be addressed in FY19

Model/Uncertainty Feedback

- Uncertainty in 120+ model inputs
- Measured HVAC performance maps
- Measured duct leakage
- Measured infiltration (to be updated in Q3)



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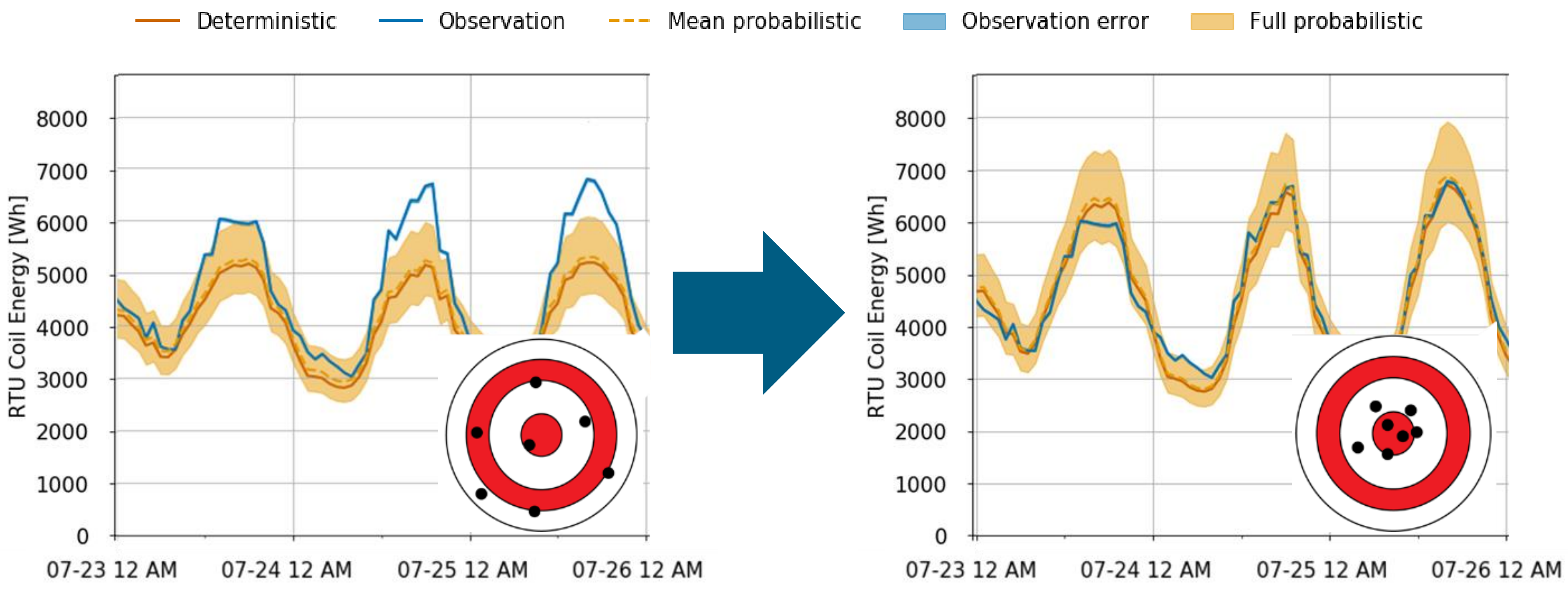
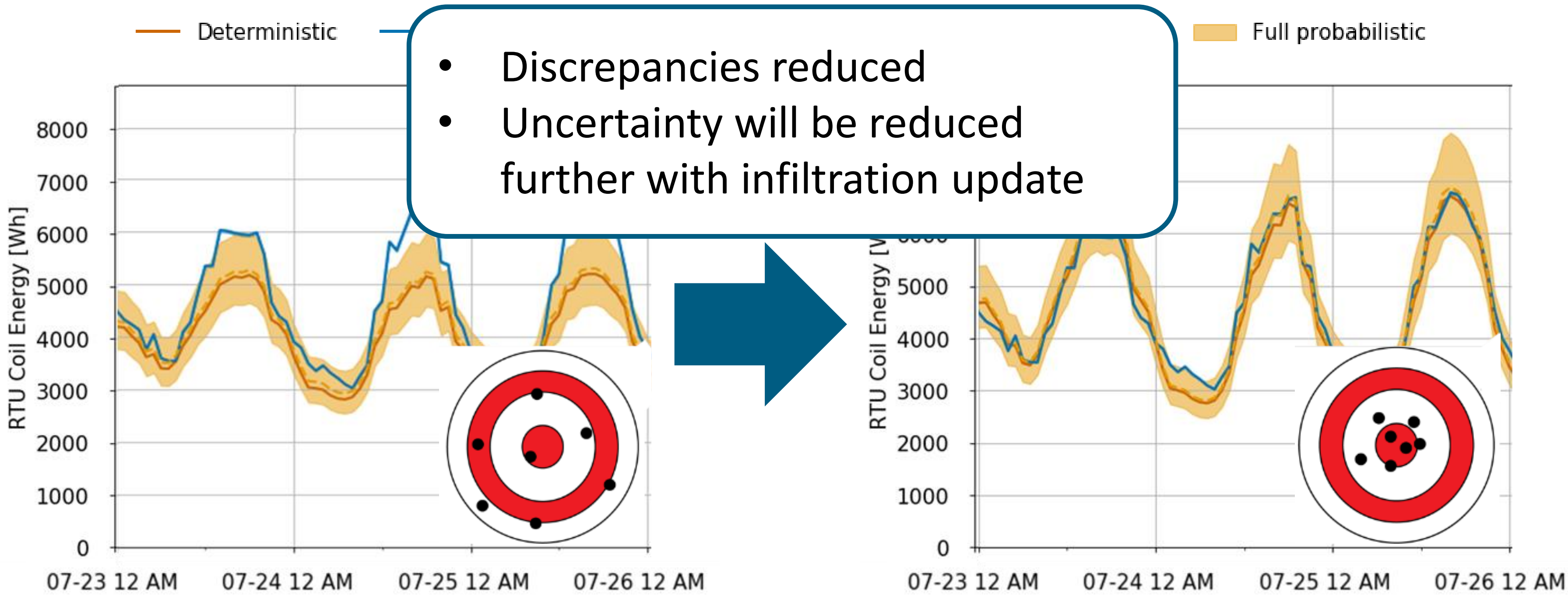


Model/Uncertainty Feedback

- Uncertainty in 120+ model inputs
- Measured HVAC performance maps
- Measured duct leakage
- Measured infiltration (to be updated in Q3)

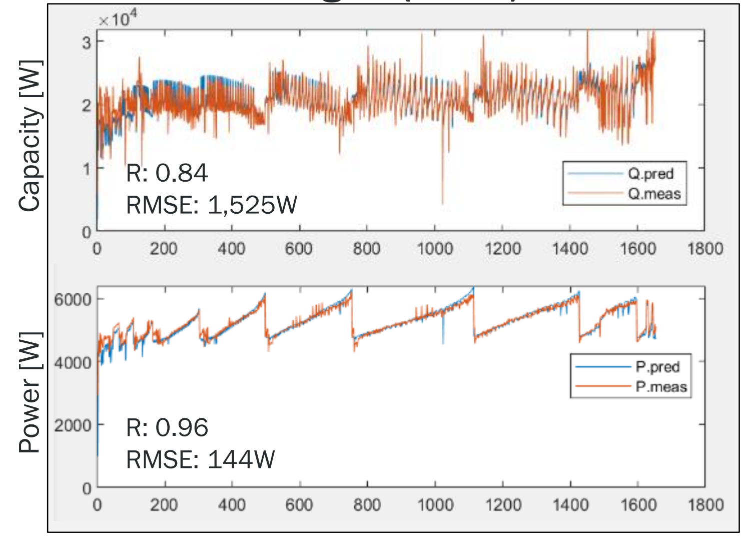
- Discrepancies reduced
- Uncertainty will be reduced further with infiltration update

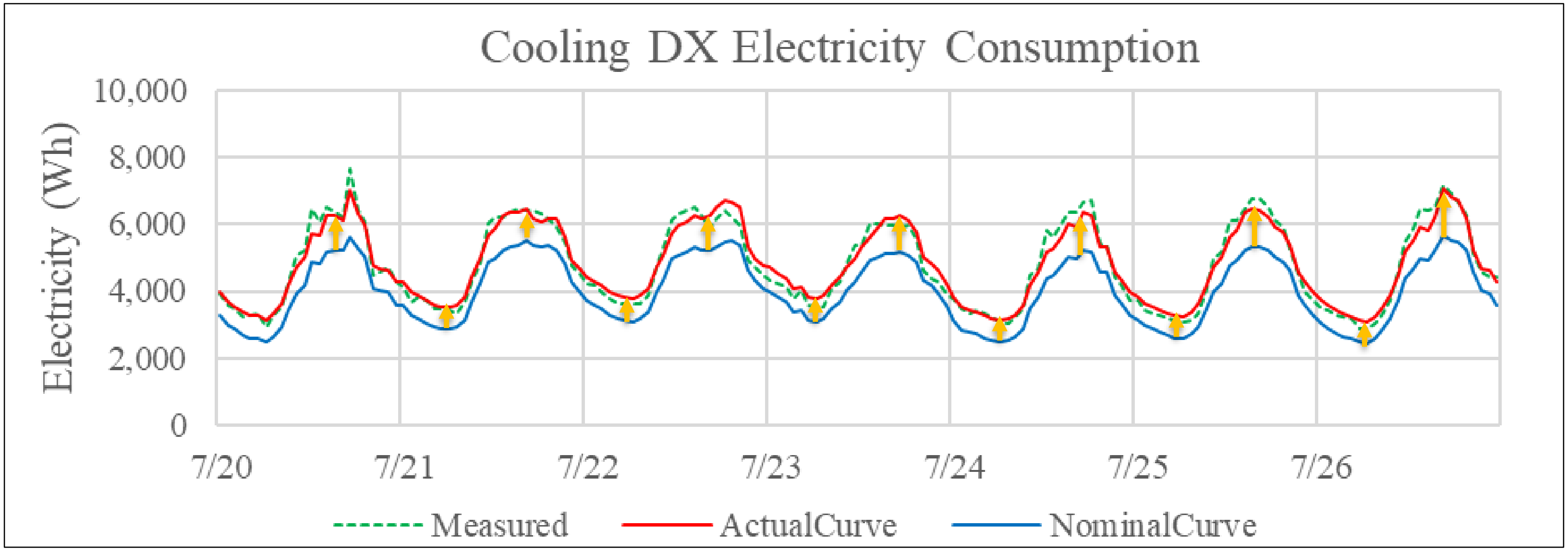


FY19 Progress – RTU performance curve

- Issue – initial model used a generic RTU model, which cannot characterize the real system
- A real RTU performance curve was generated based on historical data.
- Demonstration in EnergyPlus
  - Improved NMBE & CV(RMSE)
    - 16.3% & 17.8% → −0.3% & 5.23%

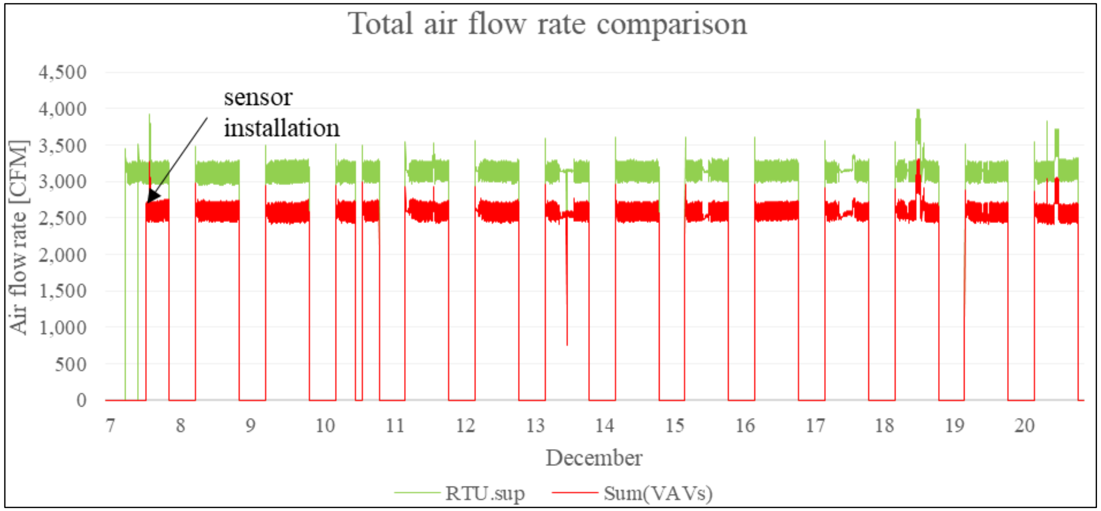
Stage1 (coil 1)

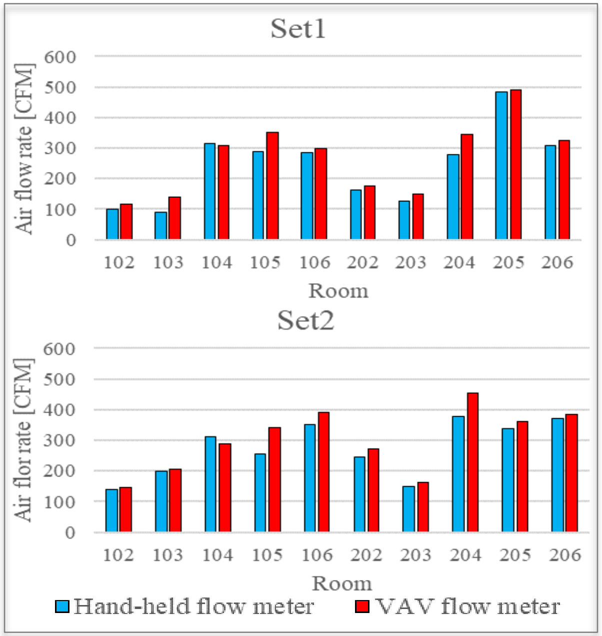




FY19 Progress – VAV airflow measurement

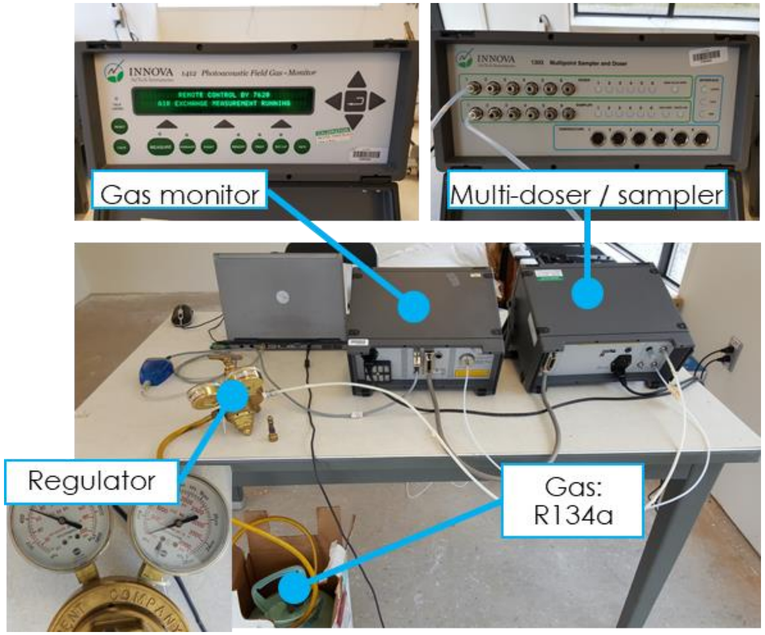
- Issue -- no zone level air flow rate measurement, and only total RTU air flow has been measured.
- New VAV airflow meters were installed
  - Total RTU airflow measurement ≥ Sum of VAVs air flow measurements
  - Upstream duct leakage identified
  - Duct leakage integrated into EnergyPlus model



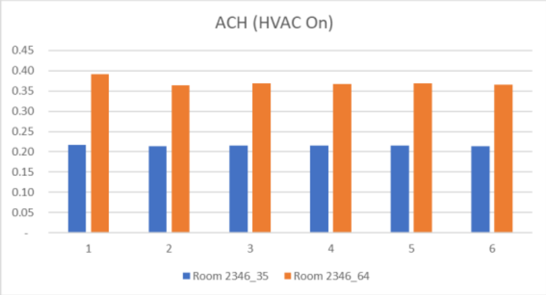


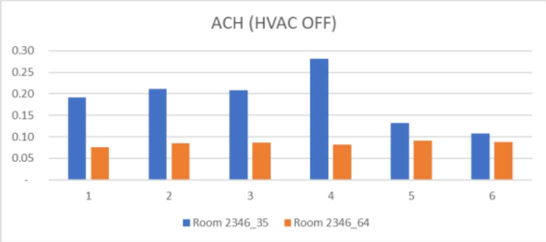
FY19 Progress – Improving infiltration model

- Issue – blower door tests cannot verify zonal infiltration rates under different outdoor conditions
- Tracer gas tests performed using multi-point doser & sampler
  - Measured gas concentration in multi-zones
  - HVAC On and Off modes
  - Estimate the infiltration rate per ASTM standard (E741)



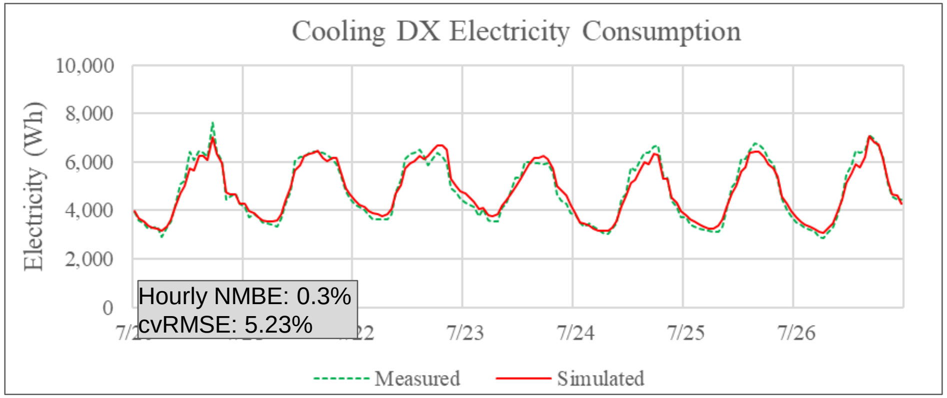
- Preliminary results
  - Different ACH (Air Change/Hour): On > Off
  - Homogeneous ACH at On for each room and time
  - In EnergyPlus model, higher deviation in larger temperature difference

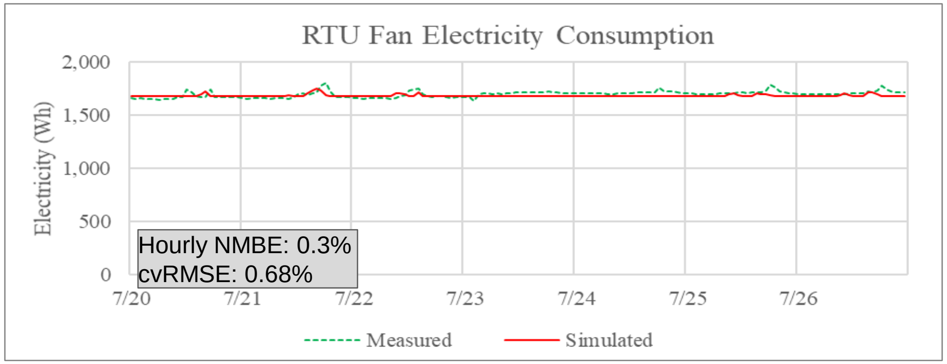


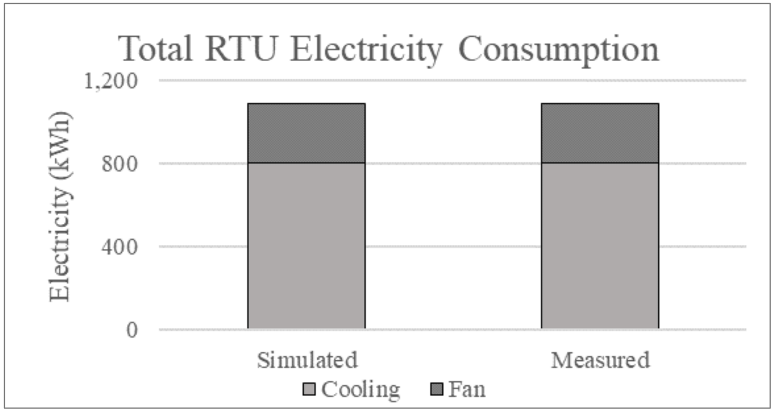


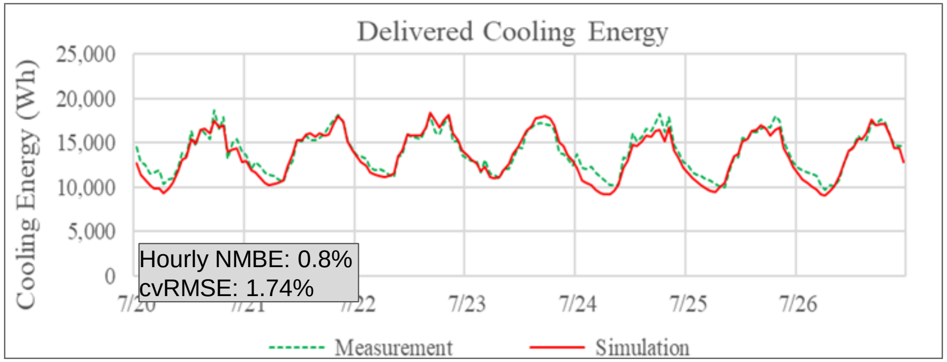
FY19 Progress – Sample result

- Test 1: Cooling Baseline
  - No occupancy emulation
  - All internal lights are turned off; no internal loads
  - Fixed discharge temperature of 55°F and no Outdoor air ventilation or exhaust air
  - No humidity control and no heating (including no reheating)
  - Fixed zone set point temp of 72°F









Less than 1% difference

Current & Future work in FY19

- Improving Infiltration model
  - Tracer gas tests for various outdoor conditions to generalize infiltration model
  - Blower door tests
- Additional cooling/heating season tests and model validation
  - Heating season tests were completed in Dec/Jan 2019
- Update duct leakage model
  - Up & down stream leakage
- Update model input specification document
- Work with ANL for uncertainty quantification
- Finalize the SSPC140 submission with data sets

U.S. DEPARTMENT OF ENERGY
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

NREL Indoor-Outdoor Modular Test Building

National Renewable Energy Lab - Ron Judkoff <ron.judkoff@nrel.gov>

Indoor/Outdoor Modular Apartment

Indoor/outdoor 380 ft^2 modular apartment test building allows key thermal input parameters to be directly measured via calorimetry and other test methods not possible outdoors. After completion of the indoor tests the building was moved outdoors (3/9/19) to create data sets against which simulation programs can be tested.

Input Determination Tests: (indoor)

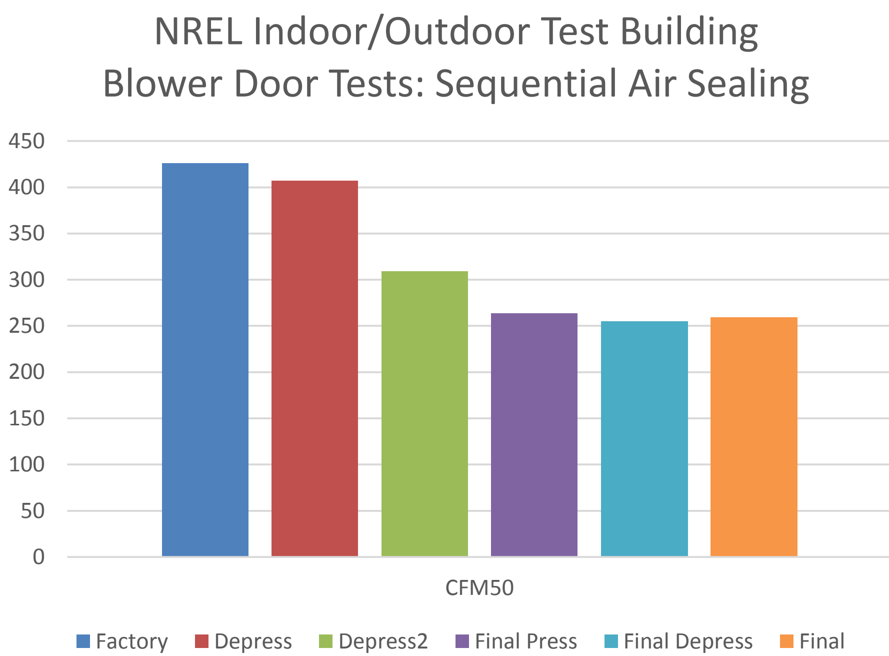
- UA_0
- Tracer gas infiltration
- Blower door
- Duct blaster
- Heat capacitance
- In-situ HVAC COP map

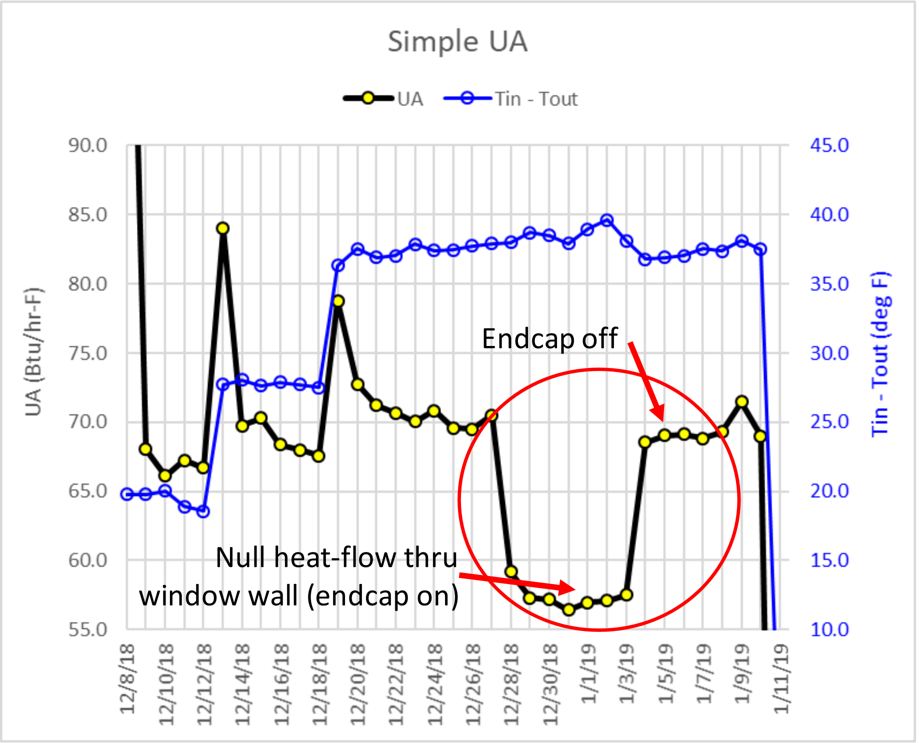
Environmental endcap off module

Modeled vs Measured Tests: (outdoor)

- Heating energy consumption at varying time intervals from sub hourly to > monthly
- Cooling energy consumption at varying time intervals from sub hourly to > monthly
- Temperatures
- Test the tests with TRNSYS and EnergyPlus

FY19 Progress – Indoor Testing

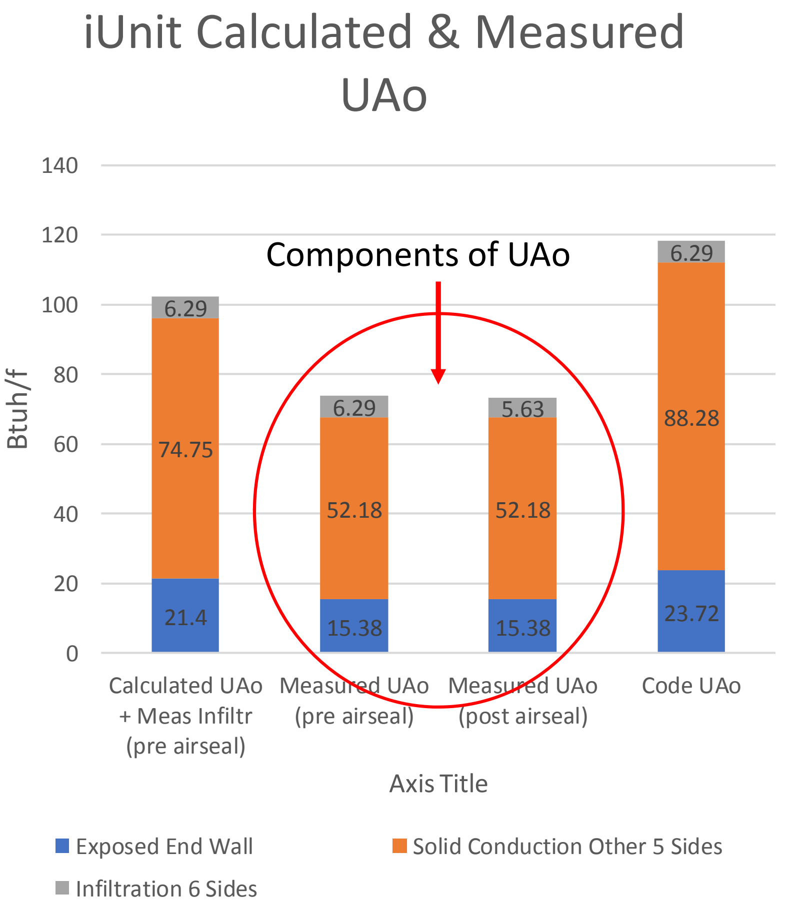


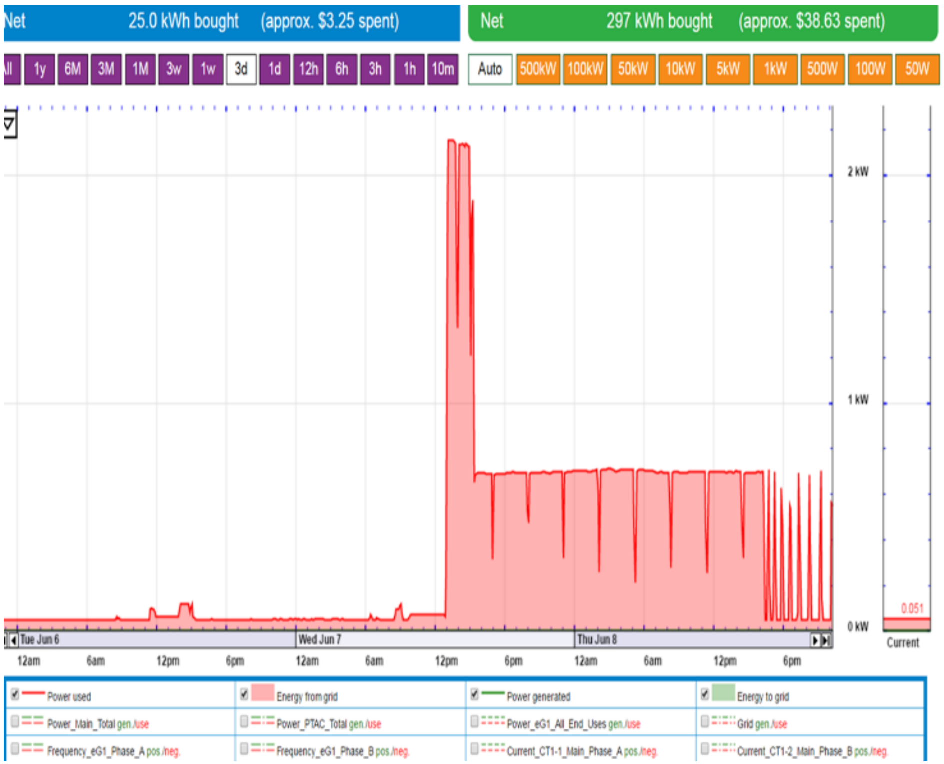


Series of blower door depressurization and pressurization tests to evaluate the air tightness of the building in CFM50

Overall heat transmission coefficient UA_0 with and without endcap - isolates UA of window wall by attaching an insulated box

FY19 Progress - Indoor Testing





UA_0 – Conduction (window wall and other walls) and Infiltration

Heat Pump PTAC power use after correction of default on-board thermostat settings

Stakeholder Engagement

Technical Advisory Group

- Combination of scientists, engineers, developers from labs, academia, & industry
- Provided project guidance and feedback
- Met semi-annually 2016-2018

ASHRAE SSPC 140

- Validation & Uncertainty (V&U) working group meets in person each ASHRAE meeting
  - Focus on steering V&U project and submissions to SSPC140 to help ensure project fits needs of ASHRAE 140
  - First meeting 1/14/19 in Atlanta
  - Second meeting planned for 6/24/19 in Kansas City
- Reports and discussions for 30 – 90 min at each SSPC140 meeting
- V&U Project and Submissions are planned to be topic of discussion in SSPC140 Stakeholder meetings planned for May and June 2019

Remaining Project Work

All

- Submit draft documentation of current tests to SSPC 140

LBNL

- Further set of experiments designed to reduce uncertainties, as defined by metrics:
  - Insulate slab and add additional mass above new insulation
  - Install water-cooled device in space

ORNL

- Improving infiltration model based on additional tracer gas tests
- Update model input specification document

NREL

- Collect Outdoor Summer and Winter data sets from apartment module
- Assist ANL as liaison to SSPC-140

ANL

- Iterate with LBNL and ORNL to understand and resolve model discrepancies
- Refine Validation Framework
- Take over role as formal liaison to SSPC-140

Full Project Summary

- Every year we have improved the quality of the experiments and characterization for modeling to the point we are confident that our most recent results will be approved by ASHRAE 140 as the basis of a new test suite by the January 2020 meeting.

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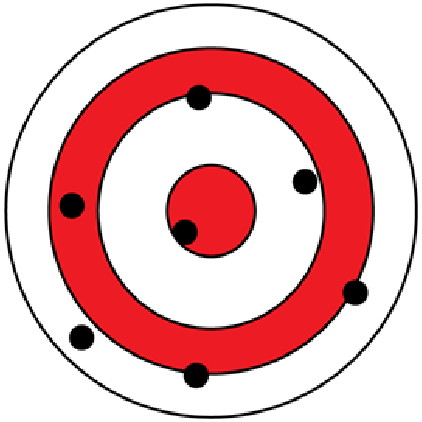

Year 2

Will this work at all?

Full Project Summary

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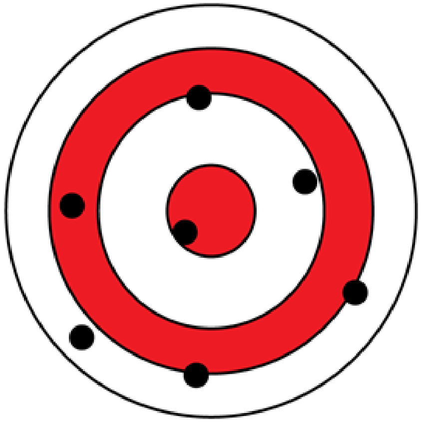
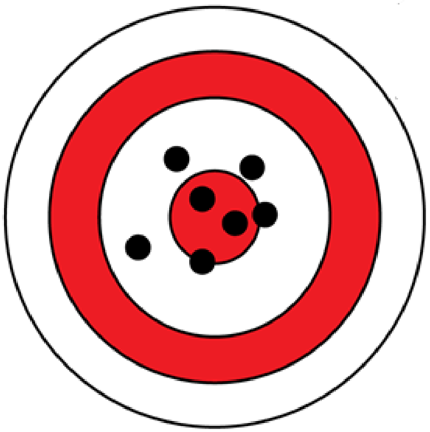


Year 2

Will this work at all?



Year 3

Is this good enough for 140 yet?

Full Project Summary

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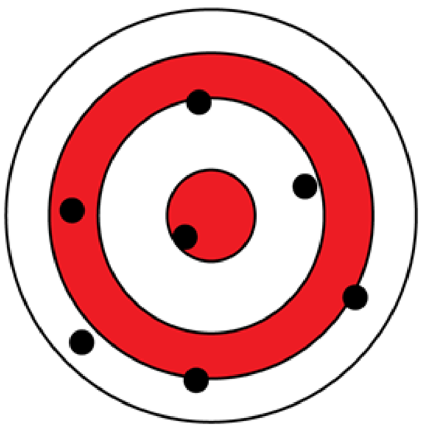

Year 2

Will this work at all?

Year 3

Is this good enough for 140 yet?

Year 4

YES! It's 140 Worthy!

Thank You

Argonne, Lawrence Berkeley, National Renewable and Oak Ridge National Laboratories
Christian Kohler
cjkohler@lbl.gov

REFERENCE SLIDES

Project Budget

Project Budget: Three year multi-lab project, $2,700k for first three years
Variances: Original three year project was extended with $1,436k for FY19
Cost to Date: $499k (ANL: $40k, LBNL:$254k, NREL: $73K, ORNL:$132K)
Additional Funding: Cost share in FY16-FY18 from Southern California Edison.

Budget History					
FY16– FY 2018 (past)		FY 2019 (current)		FY 2020 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$2,700k	$260k	$1,436k	—	—	—

Project Plan and Schedule (FY16-FY18)

Project Schedule												
Project Start: Oct 1, 2016	Completed Work											
Projected End: Sep 30, 2018	Active Task (in progress work)											
	Milestone/Deliverable (Originally Planned) use for missed											
	Milestone/Deliverable (Actual) use when met on time											
	FY2016				FY2017				FY2018			
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)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Draft project plan and experimental designs												
Completed Development of Validation Metric(s)												
First EnergyPlus validation with FRP data												
First EnergyPlus validation with FLEXLAB data												
Documented data for mixing ventilation (F/L)												
Completed Heating/Cooling Tests & Analyses(FRP)												
Complete Validation of FLEXLAB and FRP Experiments												
SEER 17 & IEER 23 mapped, data in TPEX, paper												

Project Plan and Schedule (FY19 - LBNL)

Project Schedule		
Project Start: 10/1/2018		Completed Work
Projected End: 9/30/2019		Active Task (in progress work)
		Milestone/Deliverable (Originally Planned) use for
		Milestone/Deliverable (Actual) use when met on time

	FY2019			
Task	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Past Work				
Q1 Milestone: Present plan to TAG/140				
Current/Future Work				
Q2 Milestone: Report of complete validation process (LBNL)				
Q3 Milestone: Documented Measured data for mixing ventilation (LBNL)				

Project Plan and Schedule (FY19 – ANL)

Project Schedule													
Project Start: 10/1/2018		Completed Work											
Projected End: 9/30/2019		Active Task (in progress work)											
		Milestone/Deliverable (Originally Planned) use for missed											
		Milestone/Deliverable (Actual) use when met on time											
	FY2019												
Task	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)									
Past Work													
Submit Flexlab Analysis report to SSPC140													
Submit FRP Analysis report to SSPC 140													
Current/Future Work													
Submit Paper to Building Sim on PAE													
Submit Journal Paper on PAE													

Project Plan and Schedule (FY19 – NREL)

Project Schedule		
Project Start: 10/1/2018		Completed Work
Projected End: 9/30/2019		Active Task (in progress work)
		Milestone/Deliverable (Originally Planned) use for missed
		Milestone/Deliverable (Actual) use when met on time

Task	FY2019 Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)								
Past Work												
Complete prep for final indoor tests												
Complete indoor testing move unit outside												
Current/Future Work												
Collect outdoor data for mixed & warm weather												
Collect outdoor data for hot weather												
Collect outdoor data for cold weather												

Project Plan and Schedule (FY19 – ORNL)

Project Schedule		
Project Start: 10/1/2018		Completed Work
Projected End: 9/30/2019		Active Task (in progress work)
		Milestone/Deliverable (Originally Planned) use for missed
		Milestone/Deliverable (Actual) use when met on time

Task	FY2019 Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Past Work				
Installation of airflow stations for 10 VAV boxes and verify the zonal air flow				
Creation of RTU performance curve from field test data				
Current/Future Work				
Update model input specifications and cooling/heating test results				
Infiltration test - Tracer gas test and/or blower door test				
Final Package to SSPC140				