Locating and Measuring Air Leakage Using Refractive Fluid Flow Imaging

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Project Summary

Objective

- Real-time visualization of air leaks through building envelopes without a blower door
- Flow rate measurement with ±20% accuracy

Outcomes

Quicker, easier, and less intrusive air leakage reduction in residential and commercial buildings to decrease energy consumption by 1.91 Quads and CO_2 emission by 97 Mt per year.

Team and Partners

Oak Ridge National Laboratory

Stats

Performance Period: 10/1/20 – 9/30/24

DOE budget: $1.4M, Cost Share: $0k

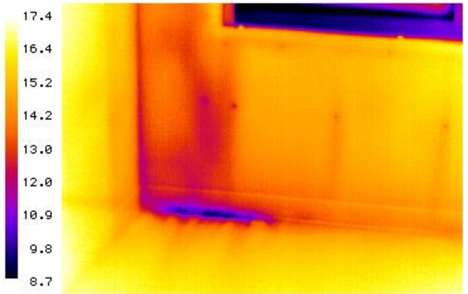
Milestone 1 (FY22): Visualize air from leakage site

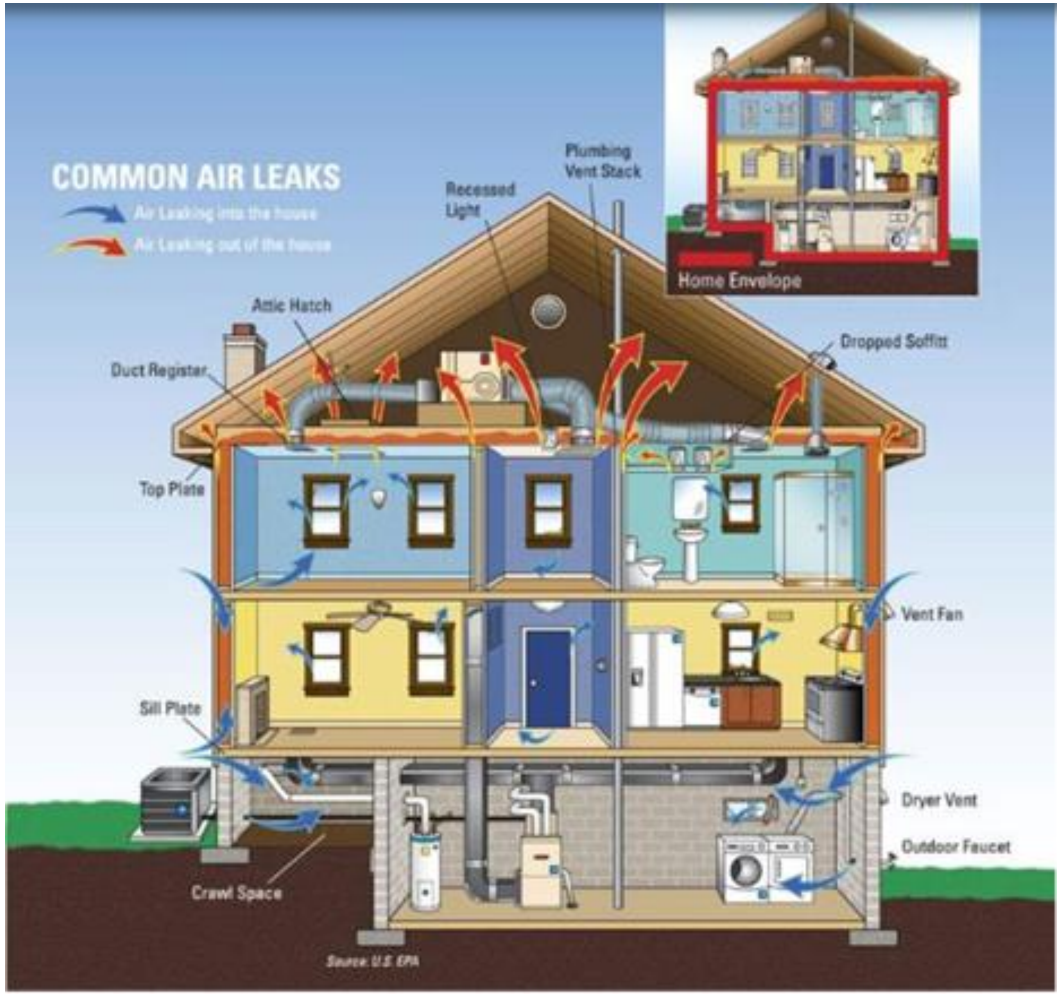
Milestone 2 (FY23): Measure flow from leakage site

Milestone 3 (FY24): Measure leakage on whole building and compare results to state of the art (blower door + IR imaging)

Air Leakage in buildings is a big problem

- Unwanted air leakage in residential and commercial buildings
  - Wastes 3.3 Quads of energy
  - Contributes 165 Mt of CO_2 emissions
- Air leakage can negatively impact occupant health, comfort, and envelope durability
- Current methods for measuring and locating leaks
  - *Time consuming*
  - *Can be disruptive to occupants*
  - *Cannot measure flow rate of individual sites*

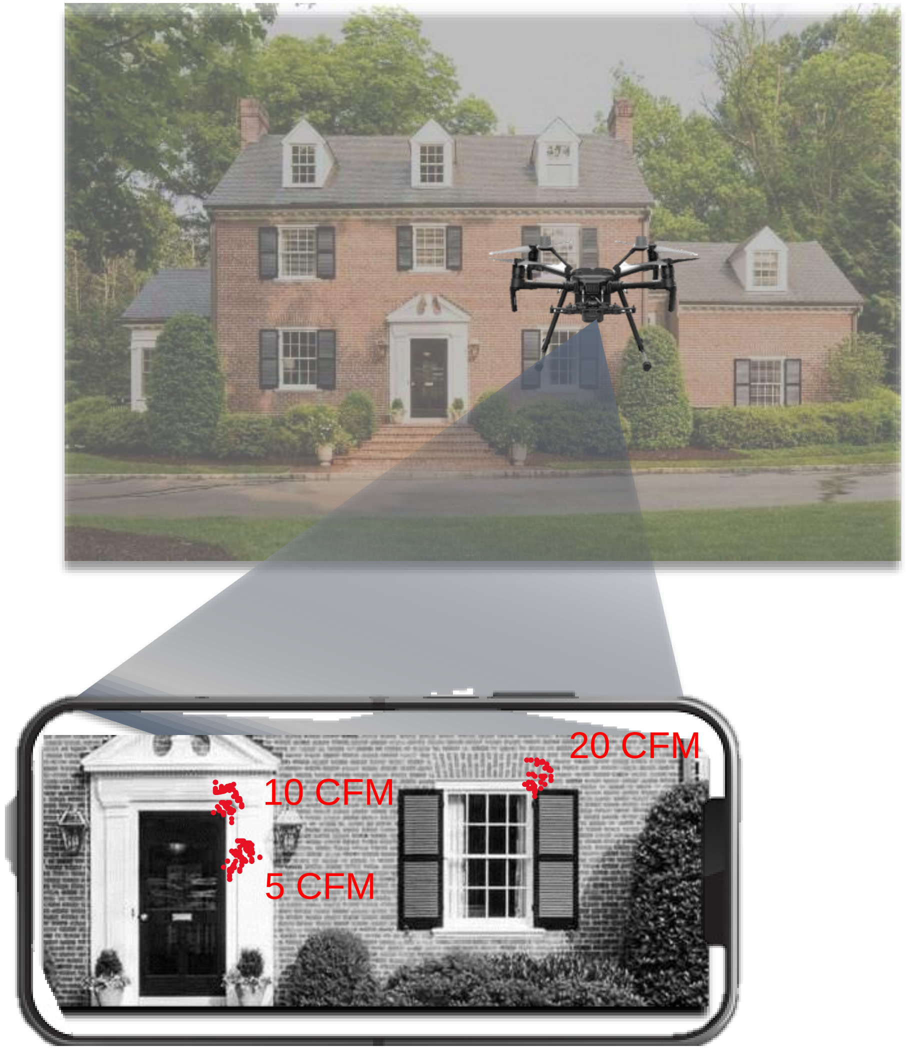




Credit: U.S. Environmental Protection Agency

Goals for a novel air leak detector

- Develop a real-time building air leak detector
  - Visualize air leakage through envelope without the need for a blower door
  - Measure flow rate of individual leaks to prioritize sealing efforts
  - Faster than state-of-the-art methods. Save time by:
    - Not setting up blower door
  - Detect problems before mold and rot and related health and structural problems occur
- Enable air leakage reduction in buildings
  - Reduce energy use and costs and CO_2 emissions
  - Increase building durability
  - Increase occupant health and comfort



Alignment and Impact

Air leak detector (ALD) use case.

License ALD to sensing manufacturer (FLIR, FLUKE) that will commercialize product.

ALD Users:
- Building Energy Inspector/Auditor
- Retrofit Contractor/Firm

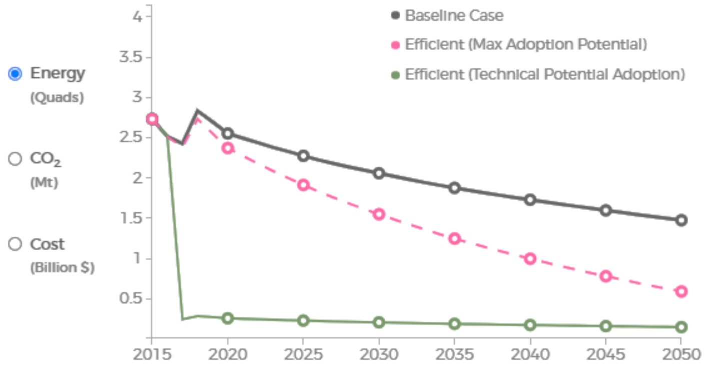
Fast, non-invasive, economical method to find and measure air leaks

Report leakage findings to:
- Home/Building Owner
- Facility Manager
- Builder
- Retrofit Contractor

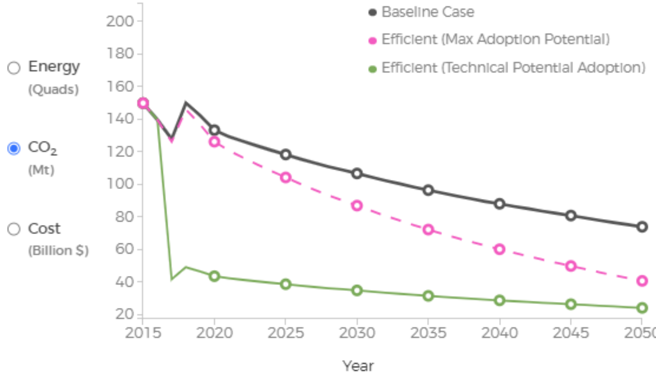
Seal leakage sites using prioritized list and remeasure total leakage
- Builder/Retrofit contractor
- Inspector

Contribution to EERE/BTO Goals

Enable increased building energy efficiency by 2050 – Save 1.91 Quads/yr*



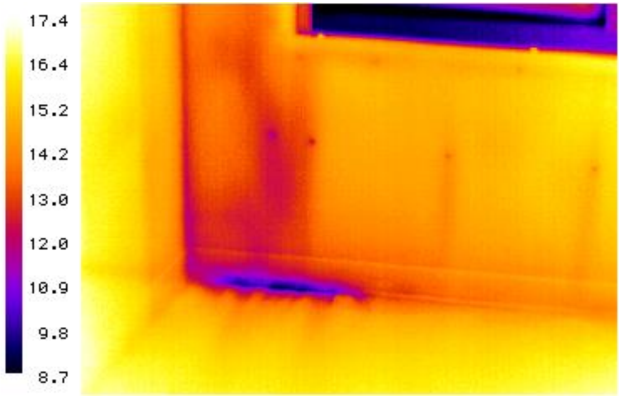
Greenhouse gas emissions reductions - 97.3 Mt of CO_2 reduction/year by 2050*



*DOE Scout tool

Current state of the art

- If a building does not meet local code for max leakage rate, leaks must be located and sealed
- ASTM E1186 outlines 5 ways to locate leakage sites for a whole building – 3 of which are commonly used:



Common methods require the use of a blower door, and none measure flow of individual leakage sites:

- Infrared scanning
  - Requires ΔT ≥ 5-10C
  - Thermal anomalies can be interpreted as air leakage
- Smoke
  - Requires proximity to leakage site
- Theatrical fog
  - Intrusive to occupants

Improvements to state of the art

- Less intrusive: no smoke, no blower door
- Faster: no blower door setup required
- Direct detection of leakage (unlike thermography) requires less interpretation
  - No false leakage detection due to thermal anomalies in building envelope
- Measuring individual leaks enables sealing prioritization – seal big leaks first
  - Save time and money knowing the reduction in leakage when sealing each leak
- Real-time assessment!

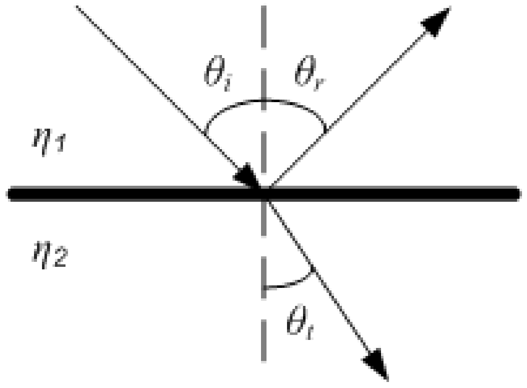
Can background oriented schlieren (BOS) photography be applied to visualizing and quantifying building leakage?

What is BOS?

It can detect refracted light described by Snell's Law:

$$\frac{n_2}{n_1} = \frac{\sin \theta_i}{\sin \theta_t}$$

n = refractive index
θ_i = angle of incidence
θ_t = angle of transmission



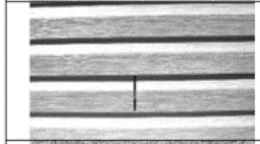
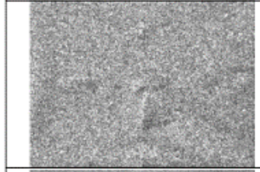
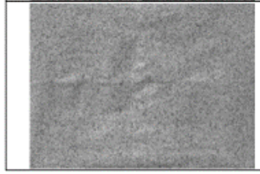
Used by permission, Copyright – Joseph Orman

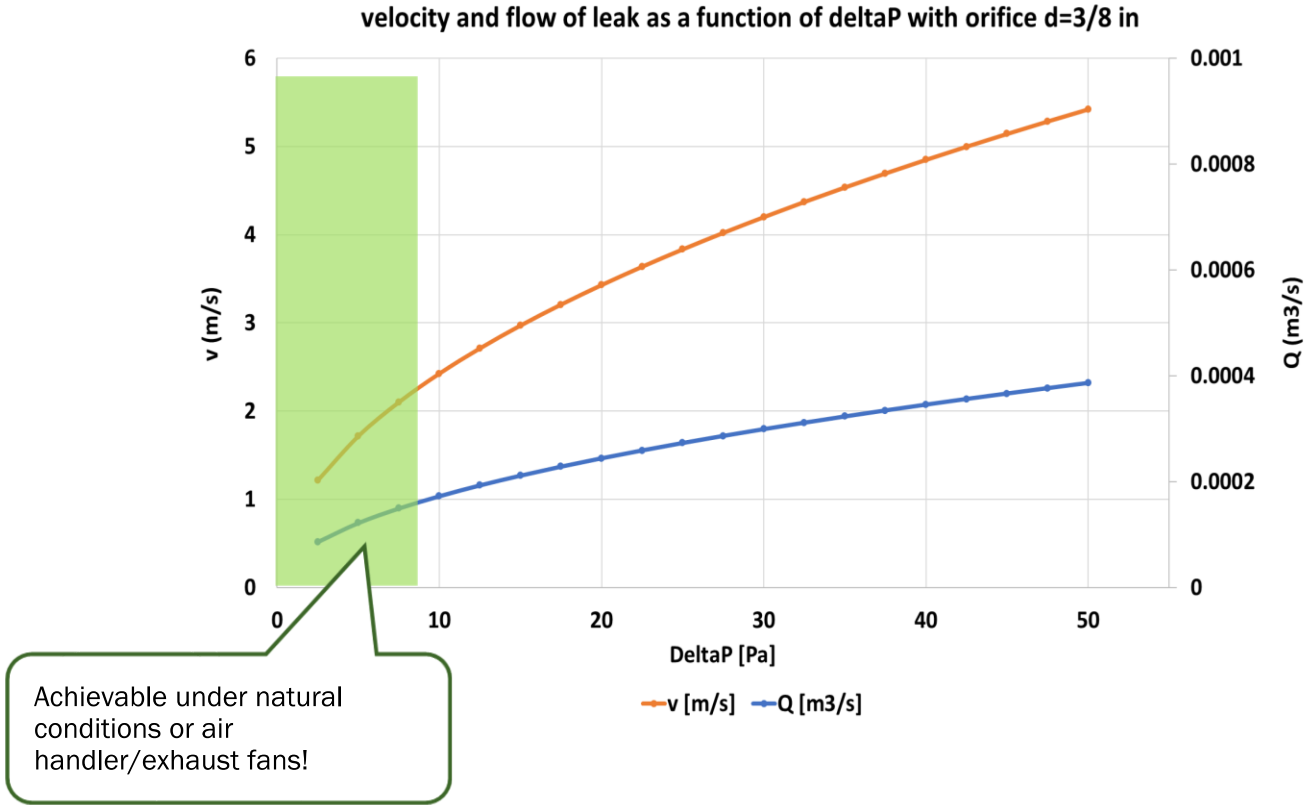
BOS in a nutshell:

- Can visualize and measure invisible fluids (leakage) that have a different refractive index from the ambient fluid (indoor or outdoor air)
- It does this by detecting small displacements in the background imaged by a camera
- Heat haze/mirage is a common example of BOS that we all experience!

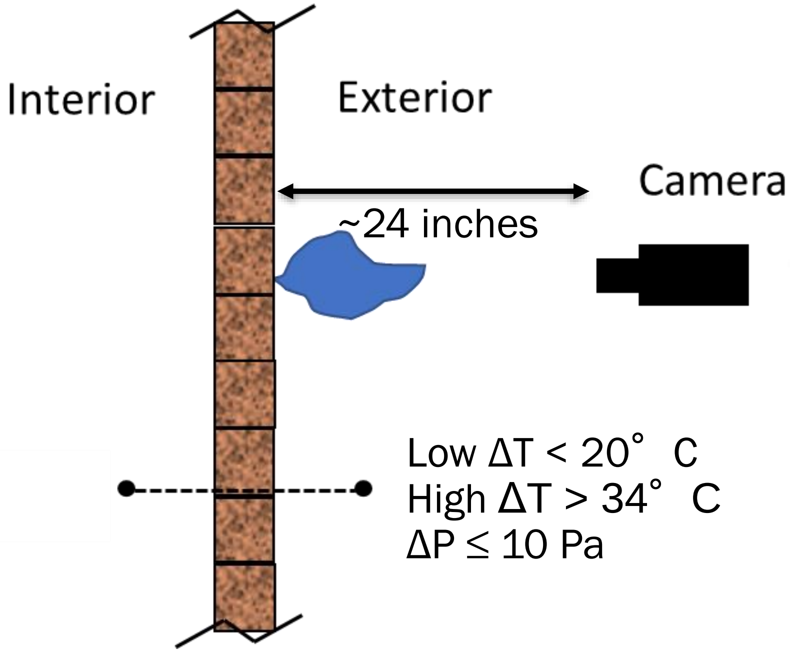
Building leakage can satisfy BOS requirements

- Density difference (BOS can measure ΔT as small as 5°C)
- Textured background (can be determined using local contrast measurement)
- Pressure differential

Background image	Background material	Contrast
	CMU	Horizontal - 2,378.25 Vertical - 2,697.93
	Brick	Horizontal - 820.39 Vertical - 1,650.98
	Vinyl	Horizontal - 192.19 Vertical - 943.57
	10,000 1 mm diameter dots, randomly distributed	Horizontal - 4,949.87 Vertical - 5,075.18
	5,000 1 mm diameter dots, randomly distributed	Horizontal - 1,390.13 Vertical - 1,463.52

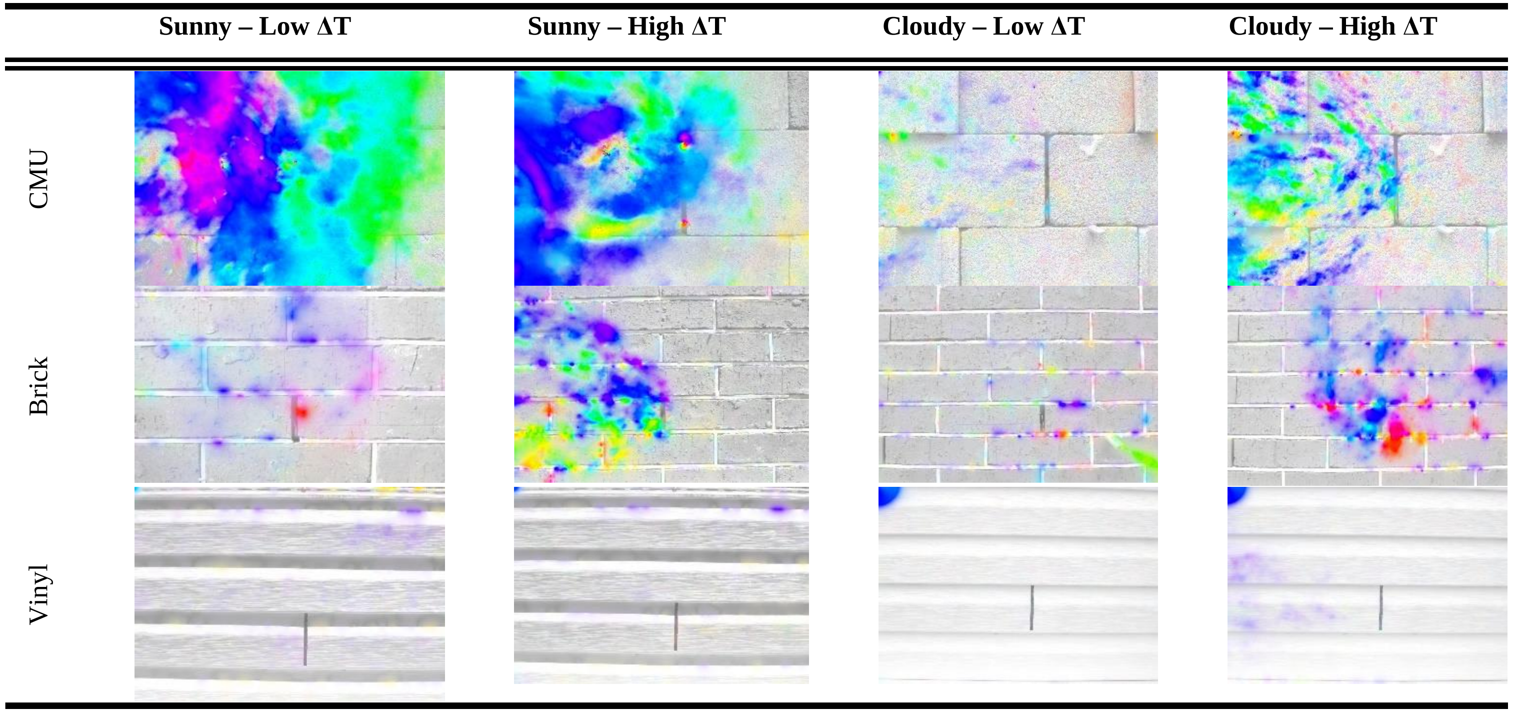


Progress: Leakage Visualization with post processing



mono machine vision camera
12mm focal length lens
30 frames per second
2.3 megapixels

Team visualized exfiltration in ambient environment!

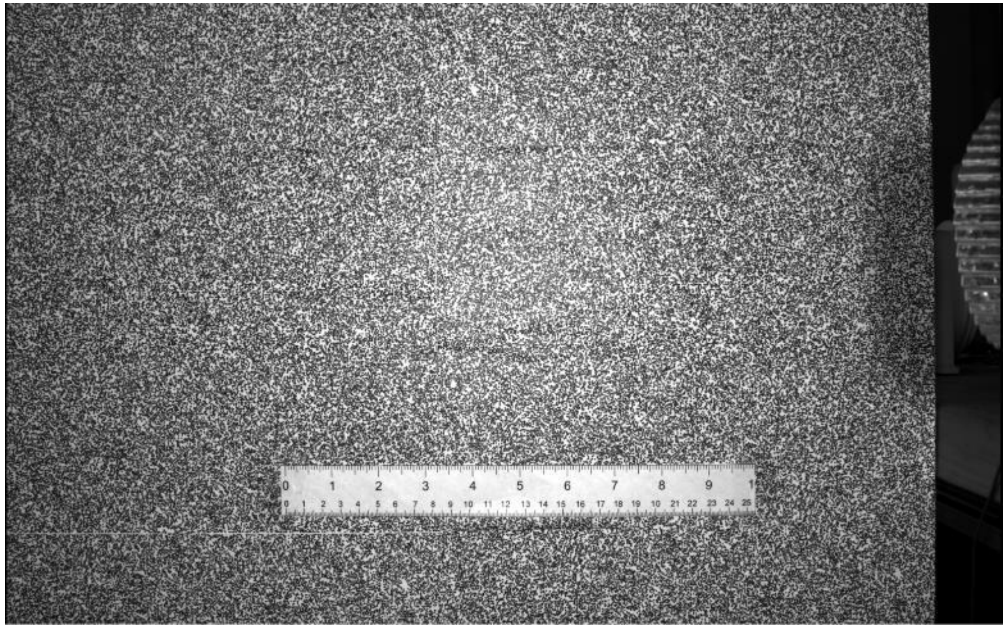


Optical flow-based analysis.

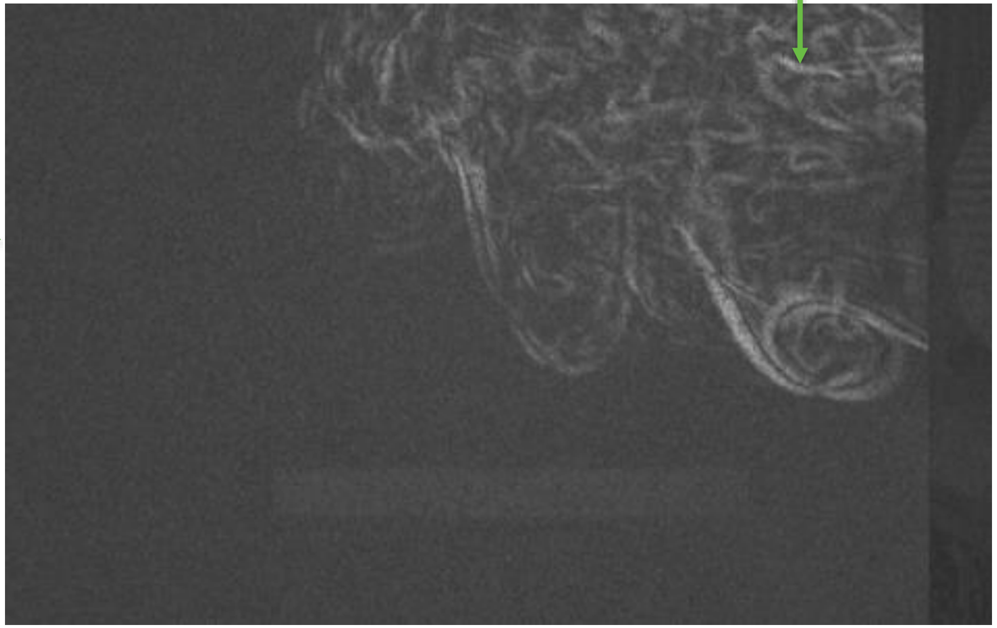
Progress: Real-time Leakage Visualization

ORNL developed software that uses difference imaging to see air.

“Wiggles” due to refractive index difference of entrained ambient air, causing turbulent flow



$$\Delta I_{x,y} = I_{x,y}^{Fi} - I_{x,y}^{Fi-1}$$

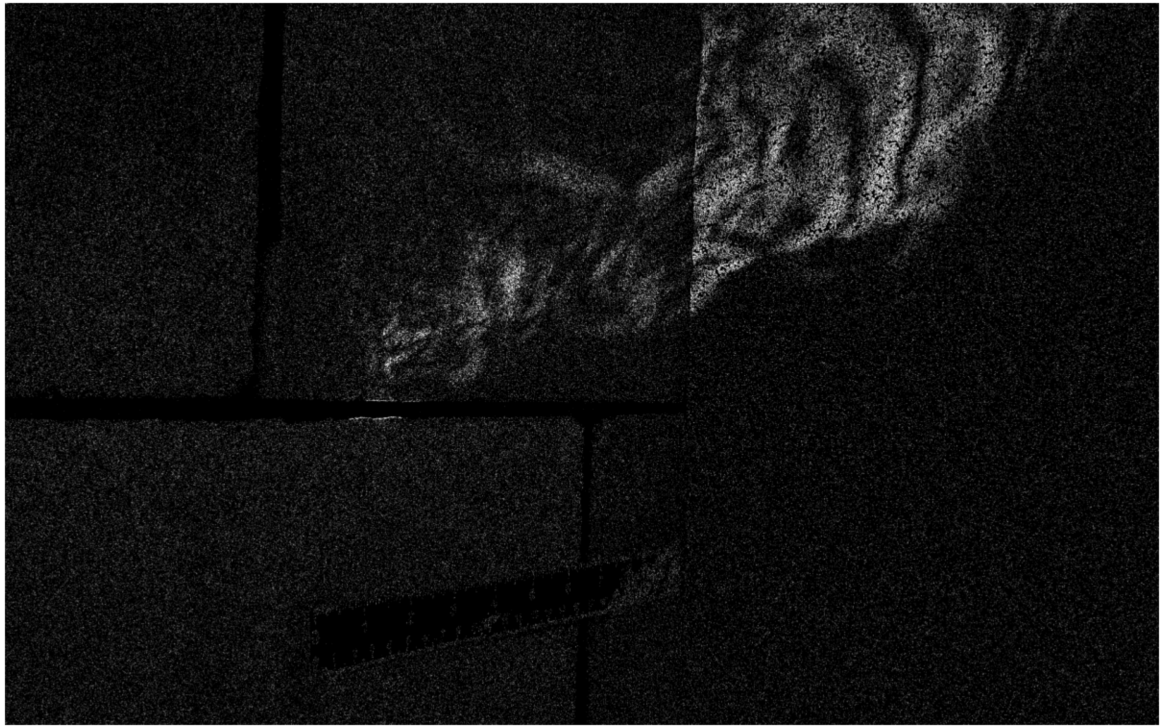


Faster computation than optical flow based analysis– enables real time visualization!

Progress: Real-time Leakage Visualization

Accomplished using difference imaging

Background – Concrete Masonry Unit wall and random dots
$\Delta T = 20^{\circ}$ C
$v < 0.5$ m/s
30 frames per second



Example difference image that can be computed in real time

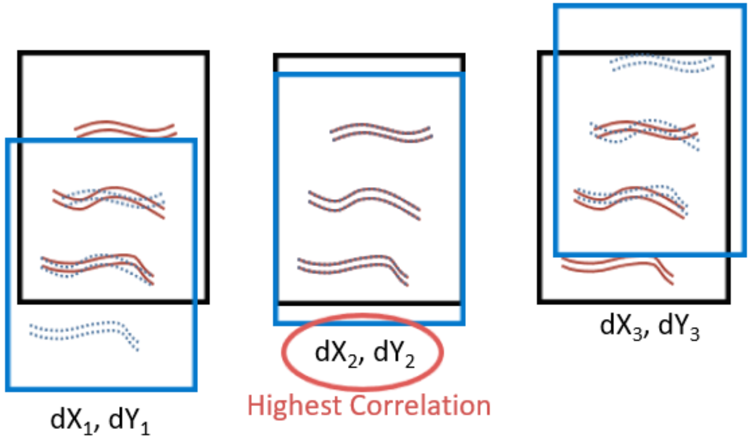
Exfiltration through CMU was visualized in real-time

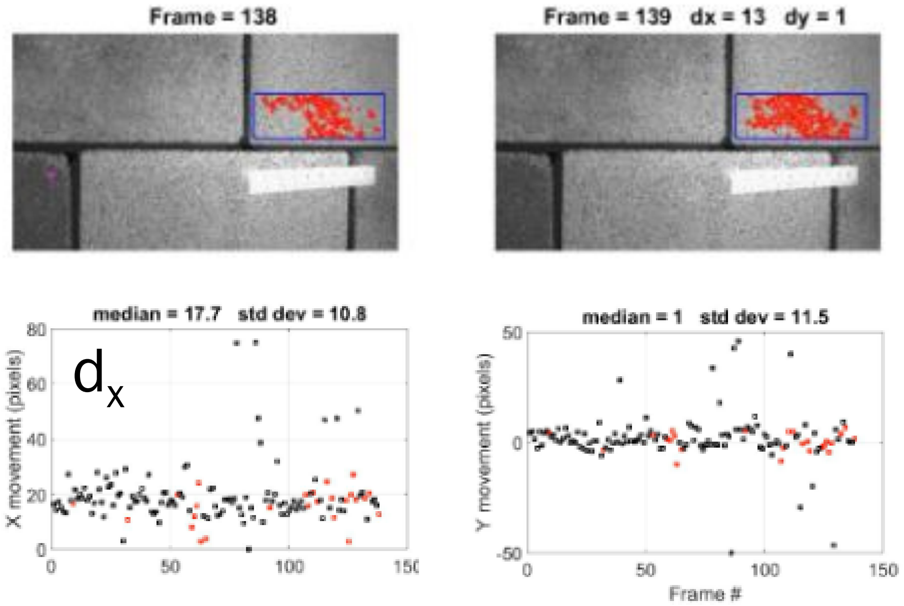
Progress: Leakage Flow measurement

Flow measurement is a two-step process

1. Measure velocity of leakage
2. Measure cross-sectional area of leakage ⟶ flow = area * velocity

To measure velocity, cross-correlation of a region of interest in two consecutive frames in used, and wiggle motion is tracked.





$v_x = d_x$ [pixels/frame]* f [FPS] *c [m/pixel]

Best measured accuracy is 5% from actual velocity. Current work to improve accuracy for through leaks.

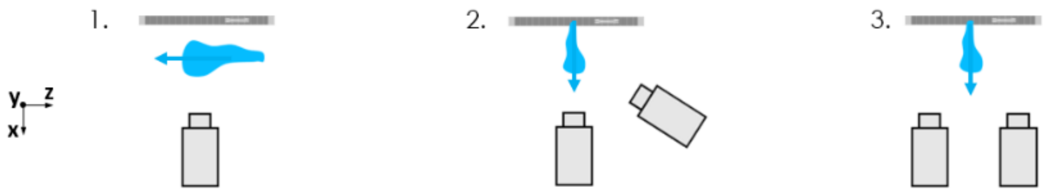
Current/Future Work: Leakage Flow measurement

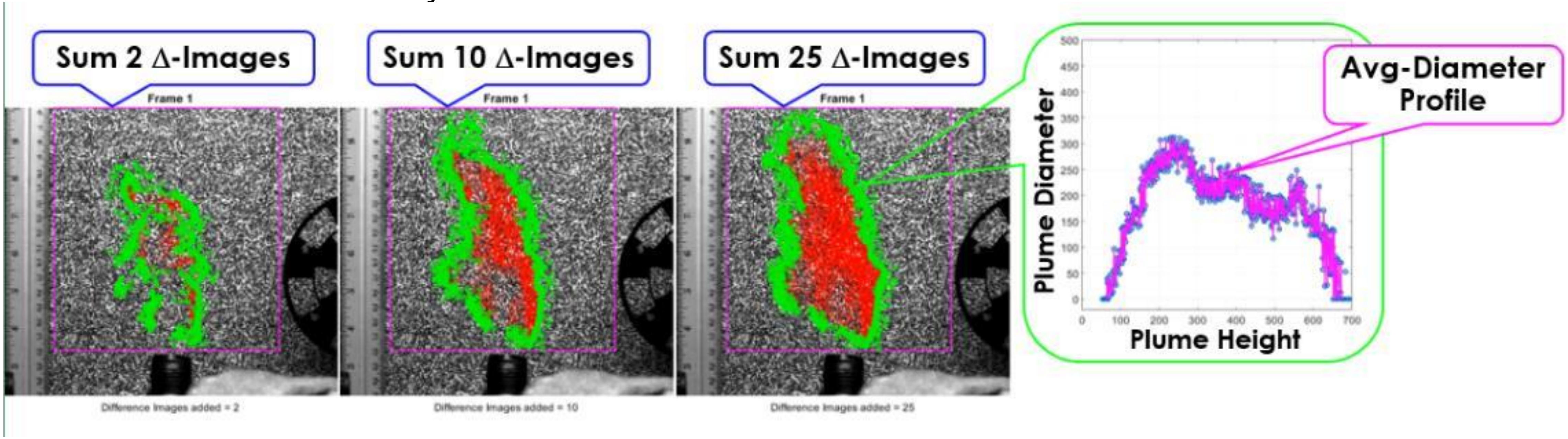
Flow measurement is a two-step process

1. Measure velocity of leakage (*v*)
2. Measure cross-sectional area of leakage – Q = A * *v*

   - *Will investigate different approaches*

   – *Two cameras could yield more accurate flow measurement*





Calculating flow rate based on this method is still in the early stages; results to come.

Future Work/Next Steps: Leakage Flow measurement

- Flow rate measurement
  - Improve accuracy
  - Investigate two camera methods for cross section and depth measurements of leak for improved flow measurement accuracy
  - Improve speed to enable real time measurement
    - Calculating velocity currently takes ~ 1 minute to analyze 150 frames of video
- Develop laser speckle projection system for building surfaces with little or no texture
- Move from lab to field measurements
  - Measure flow of real building leaks for priority sealing

Challenges, Risks, Commercialization

Challenges and Risks

- Measuring flow rate accurately enough to rank leaks
  - Optimize lens and focus, hardware, and acquisition parameters (frame rate, aperture) for building leaks
- Dealing with building materials that do not have the required texture
  - Investigate projecting texture on to low contrast materials like drywall or siding

Commercialization

- Participated in IMPEL+ (pitching school) to better understand market and how leak detector could benefit industry

Publications and Intellectual Property

- Publications and Presentations
  - Boudreaux, P., Venkatakrishnan, S., Iffa, E., and Hun, D. 2022. "*Application of reference-free natural background oriented schlieren photography for visualizing leakage sites in building walls*." Building and Environment 223, 109529.
  - Boudreaux, P., Iffa, E., Venkatakrishnan, S., and Hun, D. "*What does it take to see air leakage through a building envelope?*" ASHRAE 2022 Buildings XV Conference. December 5, 2022. Clearwater Beach, FL. (<u>Won Best Paper Award – second place</u>)
  - Boudreaux, P., Venkatakrishnan, S., Iffa, E., and Hun, D. 2022. "*Application of refractive fluid flow imaging techniques for visualizing building exfiltration*." Residential Building Design & Construction Conference (RBDCC). Pennsylvania Housing Research Center. Online. May 11-12, 2022.

- Intellectual property
  - *Building Leakage Detector Using Reference-Free Background Oriented Schlieren Photography.* Provisional patent application #63/452741.

Thank you

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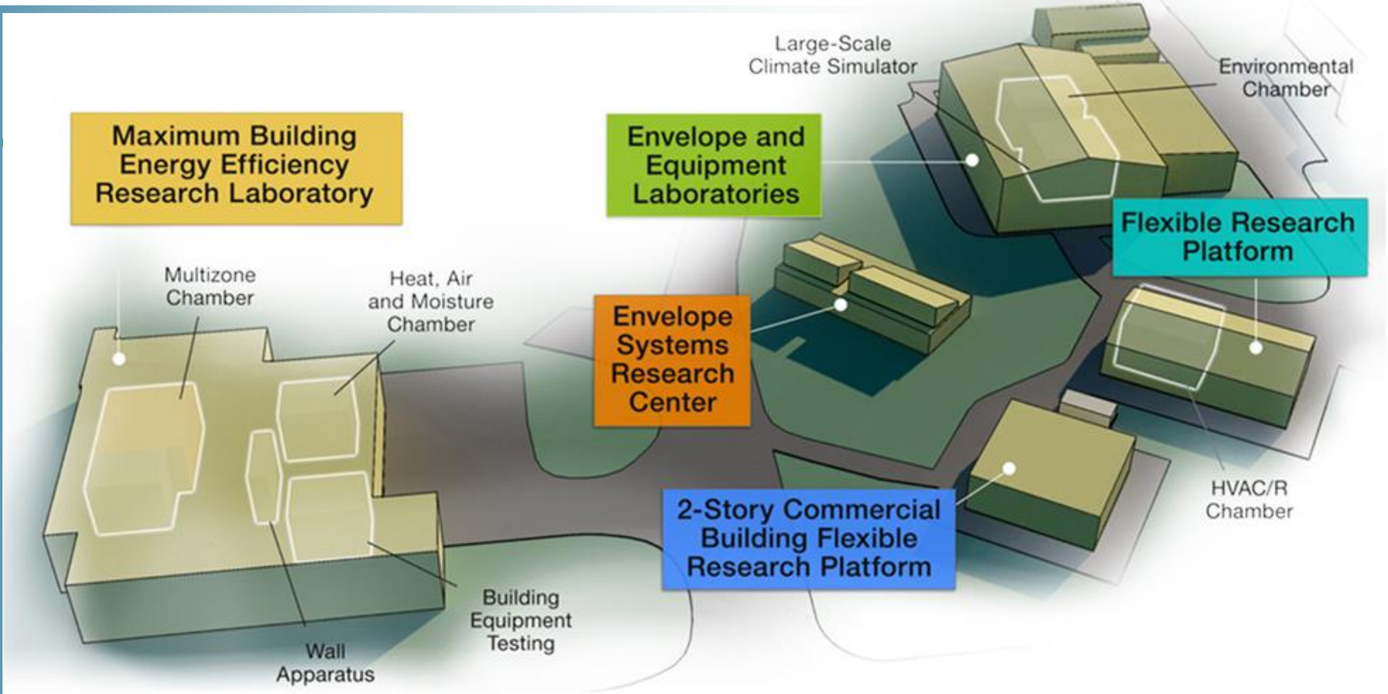

ORNL's Building Technologies Research and Integration Center (BTRIC) has supported DOE BTO since 1993. BTRIC is comprised of 60,000+ ft^2 of lab facilities conducting RD&D to support the DOE mission to equitably transition America to a carbon pollution-free electricity sector by 2035 and carbon free economy by 2050.

Scientific and Economic Results

236 publications in FY22
125 industry partners
54 university partners
13 R&D 100 awards
52 active CRADAs

BTRIC is a DOE-Designated National User Facility

REFERENCE SLIDES

Project Execution

	FY2021				FY2022				FY2023				FY2024			
Planned Budget	$300K				$350K				$400K				$350K			
Spent Budget	$247K				$345K				$190K				$---K			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Past Work																
M1.1: Set specifications for ALD																
M1.2: Detect leaks against concrete masonry unit																
M1.3: Detect leaks through high-contrast façade																
M1.4: Detect leaks through low-contrast façade																
M1.5: Determine metrics for leak detectability (texture of background, etc)																
D1.1: Form advisory group that provides feedback on benefits of ALD over current state of the art.																
D1.2: Demonstrated that the ALD can be used to convert the optical flow (pixel/frame) to spatial flow (distance/time) by measuring flow parallel to optimized speckle background (ideal for optical flow																
D1.3: Demonstrated that the ALD can measure flow when there is not sufficient background texture that is needed for indoor operation by measuring flow in front of low contrast materials (drywall)																
D1:4: Developed imaging system that visualized and measured the velocity of leaks within ±20% of an anemometer. Leak characteristics will vary by exfiltration and infiltration and in the type of background.																
Current/Future Work																
D4.1: Measure velocity of CMU-wall through leaks using the ALD with comparison to anemometer. The target ALD measured velocity is ± 20% of an anemometer.																
D4.3: Measure flow of CMU-wall through leaks using the ALD with comparison to flow hood or equivalent measurement technique. The target ALD measured flow is ± 40% of a standard measuring device.																
D4.3: Characterization of exfiltration sites through high-contrast façade at field location with leak-site location and flow measured using state-of-the-art methods.																
M4.4: Characterization of exfiltration sites through high-contrast façade at field location with leak-site location and flow measured using ALD.																
D6.1 Develop projection technique to enable flow measurement through low-contrast materials, such as drywall or other interior finishes, with flow measurement accuracy ≤ 40% of flow hood or equivalent.																
D6.2 Develop projection technique for outside applications to enable flow measurement through low-contrast cladding materials, such as vinyl siding, with measurement accuracy ≤ 40% of flow hood or equivalent.																
D6.3 Characterization of infiltration sites through drywall at field location with leakage-site location and flow measured using state-of-the-art methods.																
D6.4 Characterization of infiltration sites through drywall and exfiltration sites through low-contrast façade (vinyl) at field location with leakage-site location and flow measured using ALD. Results compared with Deliverable 4.3 and 5.3 with same leakage site ordering based on flow.																

◆ Regular
◆ Go/No Go

Team

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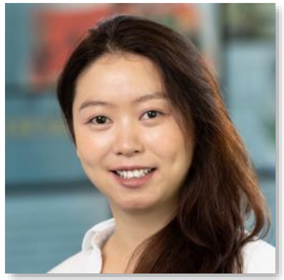

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