2024 PROJECT PEER REVIEW
U.S. DEPARTMENT OF ENERGY
BUILDING TECHNOLOGIES OFFICE

Low-GWP Refrigerant Leakage Detection Sensor Development

PNNL

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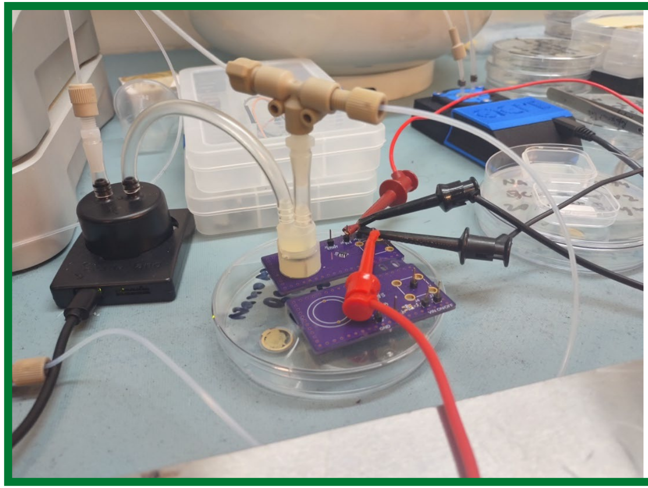

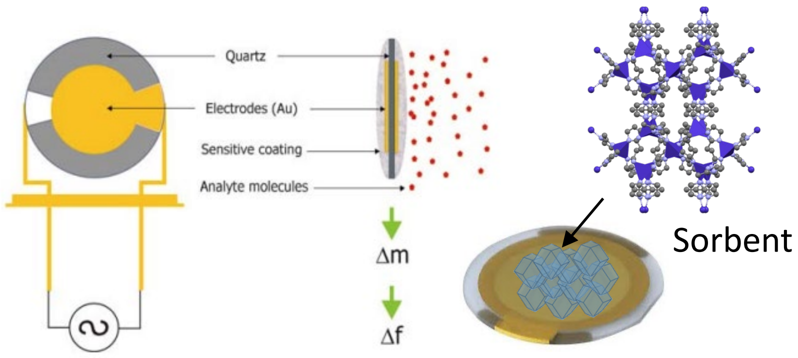

Performing Organization: Pacific Northwest National Laboratory

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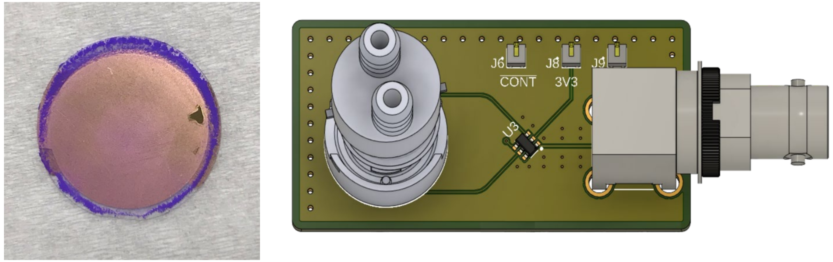
WBS#: 3.2.2.72

Project Summary

OBJECTIVE, OUTCOME, & IMPACT

The project aims to develop a reliable, low-cost A2L refrigerant sensor. This will enable the safe deployment of low-GWP heat pumps, reduce fugitive refrigerant emissions (about 5% of building sector GHG), and maintain optimal refrigerant charge levels for improved equipment efficiency.



Coated QCM Sensor and Prototype Signal Extractor

TEAM & PARTNERS

PNNL team consists of multi-discipline engineers with extensive experience in sensor development.

Technical Advisory Group

AHRI Air-Conditioning, Heating, & Refrigeration Institute · U.S. Department of Defense · NIST National Institute of Standards and Technology · Oak Ridge National Laboratory · Guidehouse · NREL National Renewable Energy Laboratory · Pacific Northwest National Laboratory

STATS

Performance Period: FY23 Q3 – FY26 Q2

DOE Budget: $1,350K

- Establish technical advisory group, determine sensor specs (12/31/23)
- Optimize sensor film (7/30/24)
- **Go/No-Go:** Approval to move to sensor assembly (8/15/24)

Problem

- With the current transition to mildly flammable A2L refrigerants, and a probable transition to highly flammable A3 refrigerants, safety becomes a critical concern for residential and commercial building occupants.
- Several A2L sensors are available on the market, however low-cost options that meet all requirements of the relevant safety standards (UL 60335-2-40, ASHRAE 15 &15.2) are limited. Key stakeholders in the DOE Refrigerants R&D Working Group have also identified support of better, faster, cheaper, and more selective A2L and A3 leak detection sensors as a priority.
- Outside of safety concerns, refrigerant leakage also accounts for roughly 5% of building sector GHG emissions and is expected to increase by roughly 60% over 2021 levels due to increased electrification.[1]
- Refrigerant leakage not only leads to direct GHG emissions, but also indicates a loss of refrigerant charge which results in decreased reliability and performance of the HVAC system.
- This project aims to develop a sensor that will address these concerns, increasing safe deployment of heat pumps, reducing direct emissions from refrigerant leakage, and maintaining operational efficiency of HVAC systems.

1. DOE. 2024. “Decarbonizing the U.S. Economy by 2050”

Alignment and Impact

Goal

- Develop fast, reliable, and low-cost A2L refrigerant sensor

Impact

- Fugitive emissions from leaking refrigerants account for around 5% of total building GHGs
- Reliable refrigerant leak detection sensor will enable safe and wide-scale deployment of low-GWP HVAC equipment

Accelerate onsite emissions reductions

Increase building energy efficiency

Early identification and repair of refrigerant leaks:

- Eliminate fugitive refrigerant gas emissions
- Maintain efficiency through optimal system refrigerant charge

Approach: Need For Faster, Lower-Cost, and More Selective Refrigerant Leak Sensors

- Several A2L sensors available on the market, but limited options meet all requirements of relevant safety standards (UL 60335-2-40, ASHRAE 15 &15.2)
- The DOE R&D Refrigerant Working Group has also identified improved sensors as a need
- Existing products use a variety of sensing technologies, each with advantages and disadvantages
  - Infrared, electrochemical cell, metal oxide semiconductor, catalytic type, micro machined membrane, speed of sound
- Research question: Can better, faster, lower-cost, and more selective sensors be developed?

Approach: Collect Industry Feedback to Inform Research Approach and Outcome

- Established a technical advisory group for feedback and guidance
  - Feedback on refrigerants of interest, sensor applications, and key criteria
  - Review project progress and testing results
- Attended 2024 AHR Expo
  - Spoke with OEMs to understand their sensor needs
  - Learned about commercially available refrigerant leak detection products

Technical Advisory Group

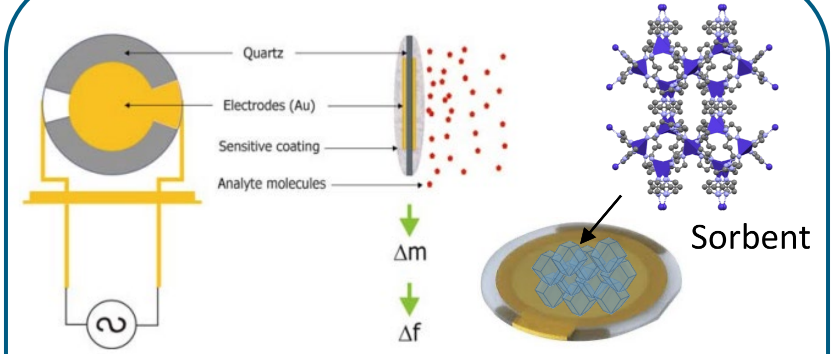
Approach: Commercially Available Sensors

		PIR & NDIR	EC	MOS	Catalytic-type
Cost Range	Stationary	$1,000-12,000	$250-1,600	$500-1,300	$700-1,500
	Sensing Element	N/A	$100-200	$3-100	$50-100
T90 Response Time		5-30s	<90s	15-90s	20-30s
Lifetime		10-15 years	1-3 years	3-5 years	2-5 years

- Summarized from AHRTI-9009 (Published 2017)
- Other sensors (e.g., micro machined membrane, speed of sound) have come to market and been tested but pricing is not transparent

Approach: Novel Sensing Technologies

- Leverage previous work on proof-of-concept Surface Acoustic Wave (SAW) and Quartz Crystal Microbalance (QCM) sensors
- Refrigerant gas is collected in a sorbent layer on the QCM or SAW sensor
- SAW sensor uses acoustic waves and measures shift in wave phase which is associated with uptake of refrigerant gas
- QCM sensor vibrates at a specific frequency which is associated with uptake of refrigerant gas



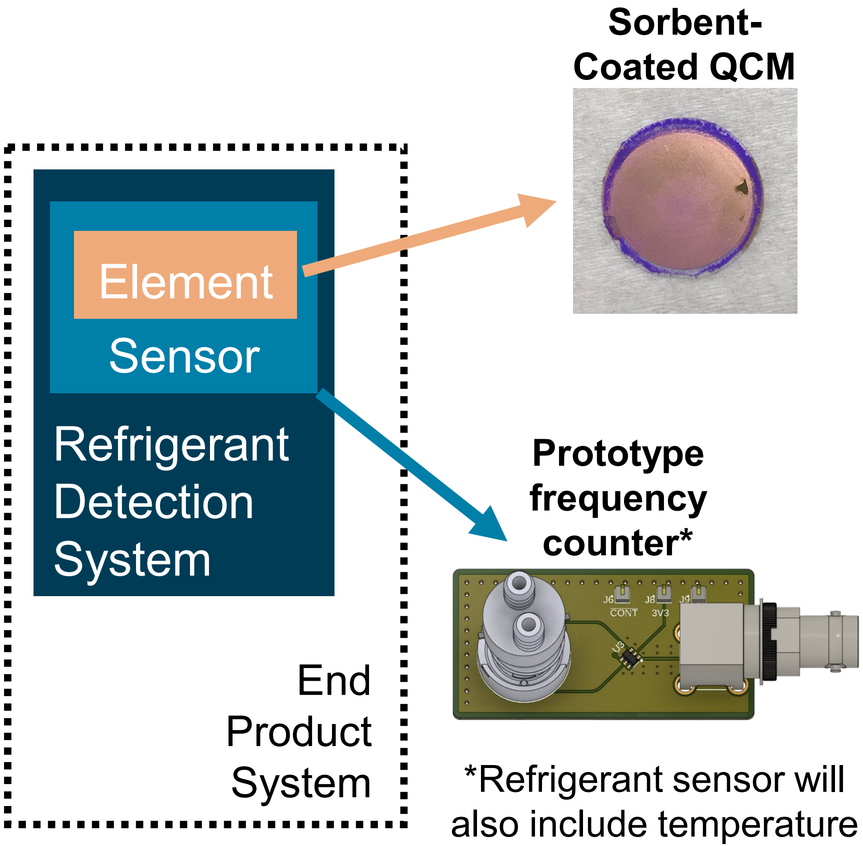
QCM Sensor

Why is this technology promising?
Fast response, low cost, and low power requirements

QCM image from: Yuwono, A. and Schulze Lammers, P., 2004. Odor pollution in the environment and the detection instrumentation.

Approach: Scope of Work

- Development and optimization of sensing element
- Assembly and testing of the refrigerant sensor, including housing, circuit board, and sensors for humidity & temperature compensation
- Future scope of work includes working with an industry partner to develop full refrigerant detection and end product system



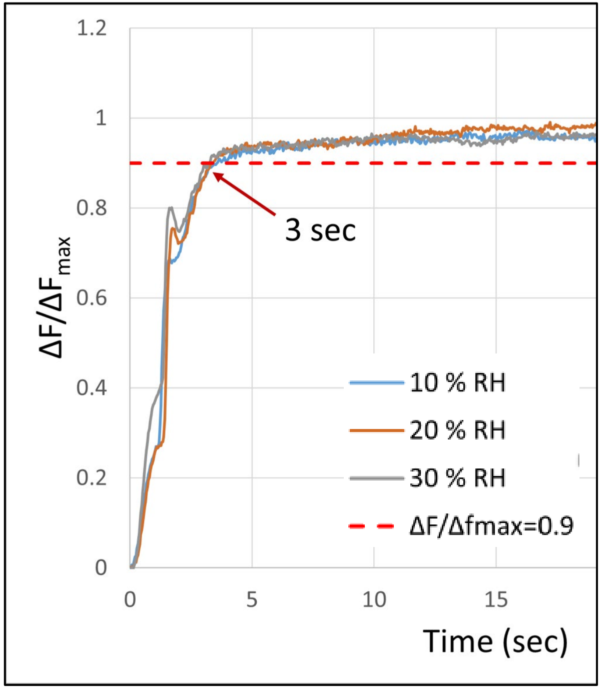
*Refrigerant sensor will also include temperature and humidity sensors

Approach: Risks, Challenges, & Mitigation Strategies

Project Risk or Challenge	Description	Mitigation Strategy
Ability to meet safety standards	• Requirements governed by UL 60335-2-40, ASHRAE 15, & 15.2. • Status unknown until testing is completed	• Materials improvements or adjustments • Include Go/No-Go decisions at various points following testing
Market competitiveness	• OEM <> sensor manufacturer-negotiated price points are unknown. This makes it challenging to determine a specific cost target.	• Competitive analysis and continued feedback from industry • Consider transition of project scope (or addition) to develop sensor for A3 refrigerants

Progress: Major Milestones and Progress

- Convened technical advisory group twice for project feedback
  - Key refrigerants of interest (R-32, R-454B, R-290) – optimizing for R-32 first
  - Key sensor criteria: cost, lifetime, response time, and poisoning/interfering chemicals
  - TAG also provided feedback on Go/No-Go Milestone after initial sensor optimization testing
- Screened several candidate sorbents and optimized selection for R-32
- After testing, found QCM sensors to be more promising than SAW sensors



T90 Sensor Response
(R-32 @ 25% LFL)

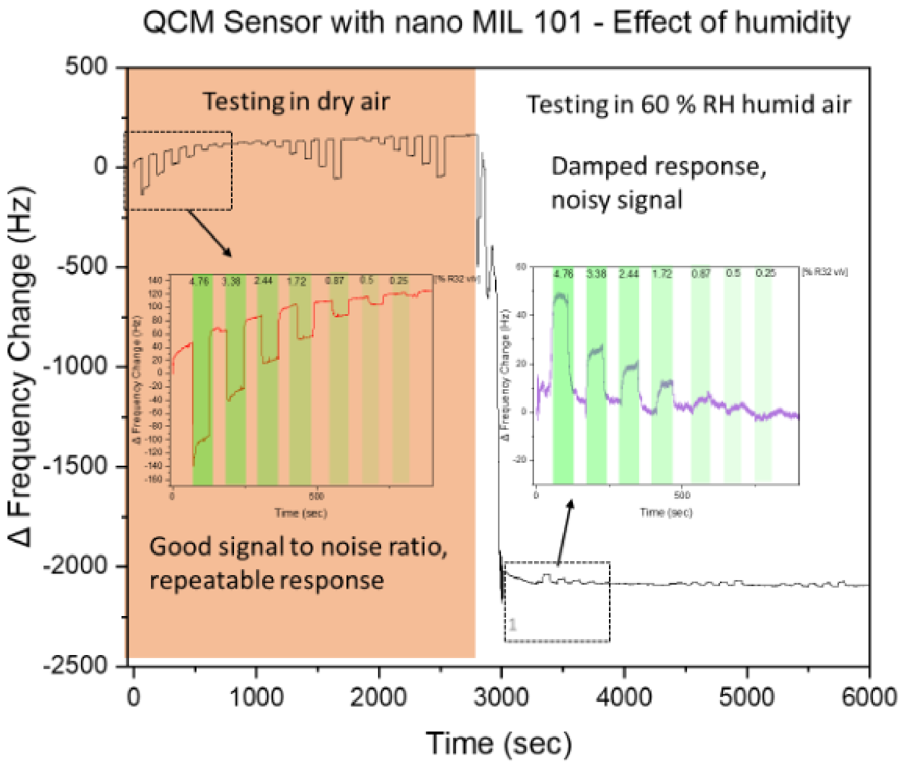
Progress: Key Findings

Features	
Cost range	$25/piece, sensing element $10-15
Size	<20 g
Power	<0.25 W
Refrigerant type	R32
Limitations	
Measurement range	5,000-1,000,000 ppm
Response time	T90 ~3 seconds
Operating temperature	10-45 °C, requires further testing to expand range
Humidity	0-60% RH, requires further testing to expand range
Lifetime	Requires further testing

Sensor Strengths

- Fast response
- Low cost
- Low power
- Regenerates in ambient air

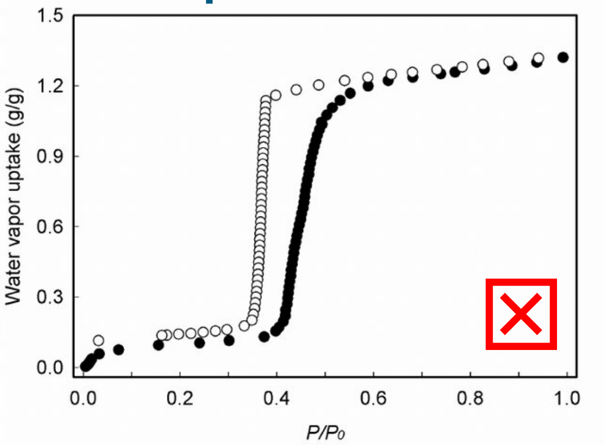
Progress: Unexpected Issues – Humidity



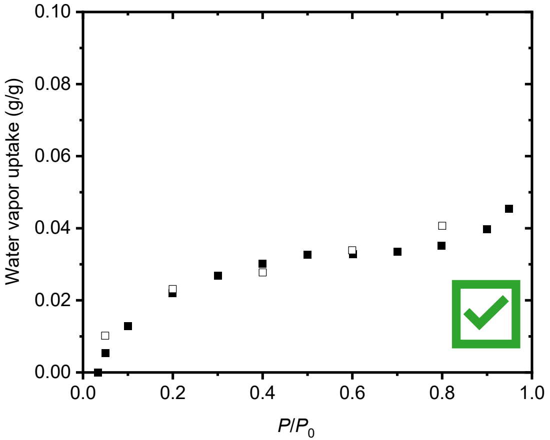
- Testing in humid air yielded a damped response and noisy signal
- Several humidity mitigation strategies were tested, including:
  - Carbonization of MOFs
  - Two types of hydrophobic polymer coatings
  - Hydrophobic sorbent selection
- Ultimately, we selected a new hydrophobic sorbent

Progress: Lessons Learned in Sorbent Selection

MIL-101 Water Vapor Isotherm



Water Vapor Isotherm of New Sorbent



○ Desorption
● Adsorption

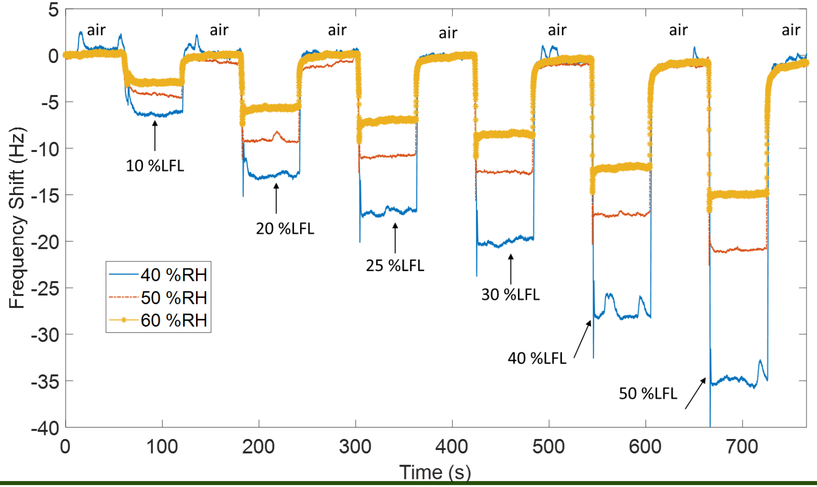
Important elements to consider:

- Reversible adsorption/desorption isotherms
- Low water capacity (notice scale of water vapor uptake)

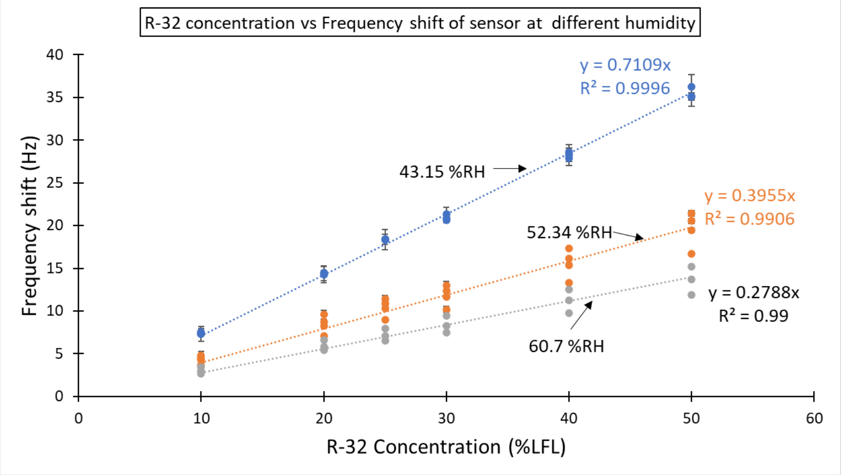
Progress: New Sorbent Enables Humidity Compensation

Raw Sensor Response

varied refrigerant concentrations & RH



Humidity Compensation Curves



- Selecting an optimal sorbent led to good sensor response
- Testing at varied humidities to construct RH compensation curves
- Test setup modifications required to perform tests for RH > 60%

Future Work: Near Term Actions

- Sensor benchtop testing
  - Increase temperature and humidity ranges
  - Other key tests listed in safety standards (e.g., selectivity/poisoning, pressure, etc.)
- Sensor placement testing
- Manufacturer and industry partnerships
- Other refrigerants to consider (R-290 [A3], R-454B [A2L])

Future Work: To Be Successful…

- Continued industry engagement and feedback
- Explore other applications of this sensor technology (e.g., multi-split, combination, VRF, Monobloc, commercial refrigeration, mechanical room, HPWH, etc.)
- Gain a better understanding of the market and the competitiveness of this sensor technology
- Monitor the status of safety standard updates and future transition to A3 refrigerants

Thank you

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Project Execution

	FY2023				FY2024				FY2025			
Planned budget	$100K				$560K				$690K			
Spent budget	$40K				$492K							
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Past Work												
Establish Advisory Committee												
Acquire Sensor Components												
Sensor Component Optimization												
Go/No-Go: Approval to Move to Sensor Assembly												
Assemble Sensor Components for Benchtop Testing												
Current/Future Work												
Benchtop Testing Summary												
Final Specifications and Integration												

Team

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