PHMSA
Pipeline and Hazardous Materials
Safety Administration

PHMSA CAAP: Innovative Sensor Network for Subsurface Emissions - InSENSE (DOT-PHMSA #693JK32050005CAAP)

August 16th, 2023

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Collaborative Effort:

PHMSA
Pipeline and Hazardous Materials Safety Administration

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METECH4
Colorado State University

- UTA Co-I – Suyun Ham
- UTA Post Doc – Younki Cho
- CSU UG Students (partial support)
  - Chandler Horst
  - Luke Addana
- UTA UG Students (UTA funded)
  - Nate Steadman
  - Ashley Nguyenminh

- Industry partners
  - SoCal Gas
  - Con Edison
  - Dominion
  - PG&E
  - XCEL
- PHMSA CAAP PM & Research Managers
  - Zhongquan Zhou (ZZ)
  - Nusnin Akter

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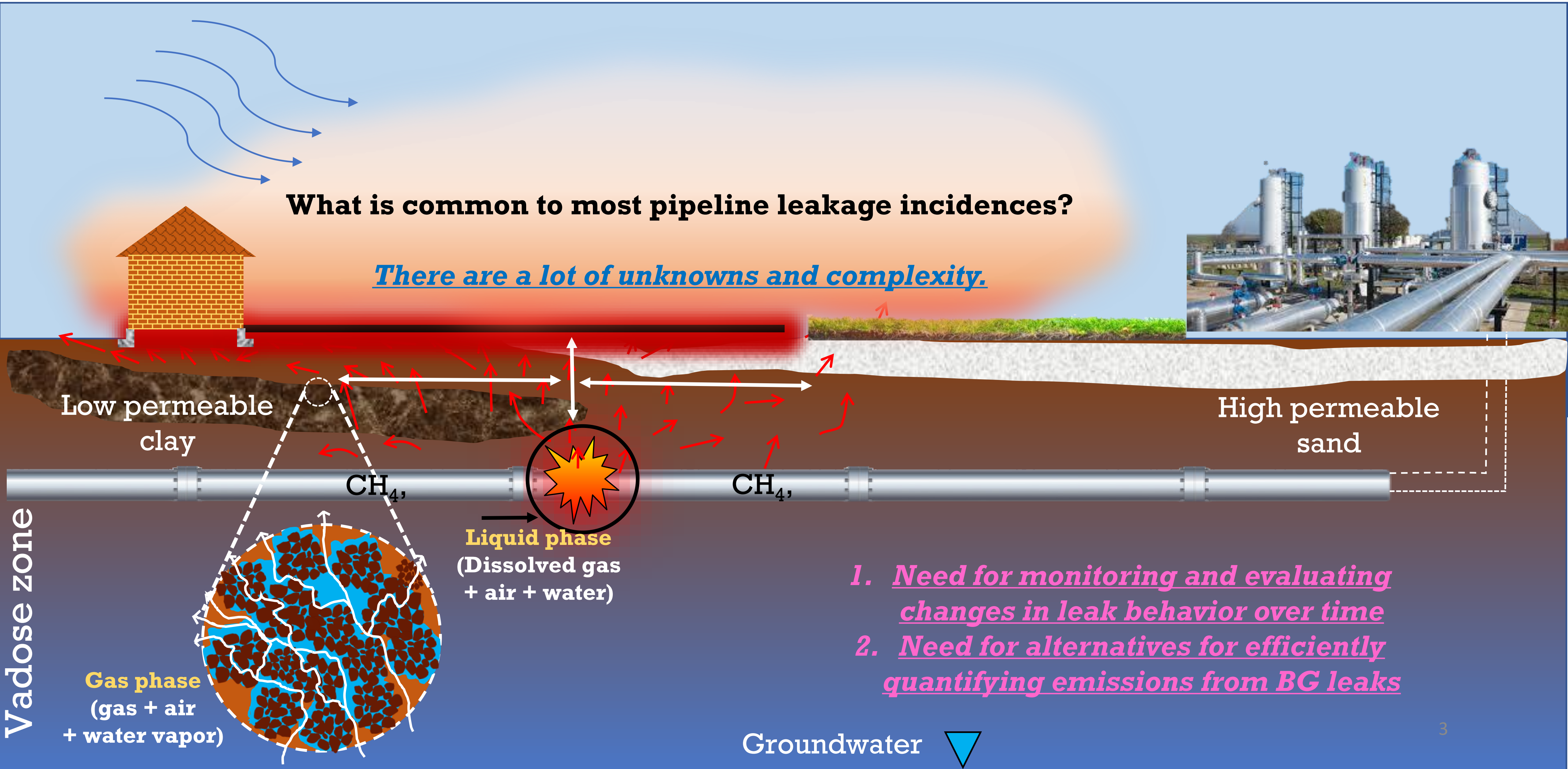
Statement of Problem/Challenge

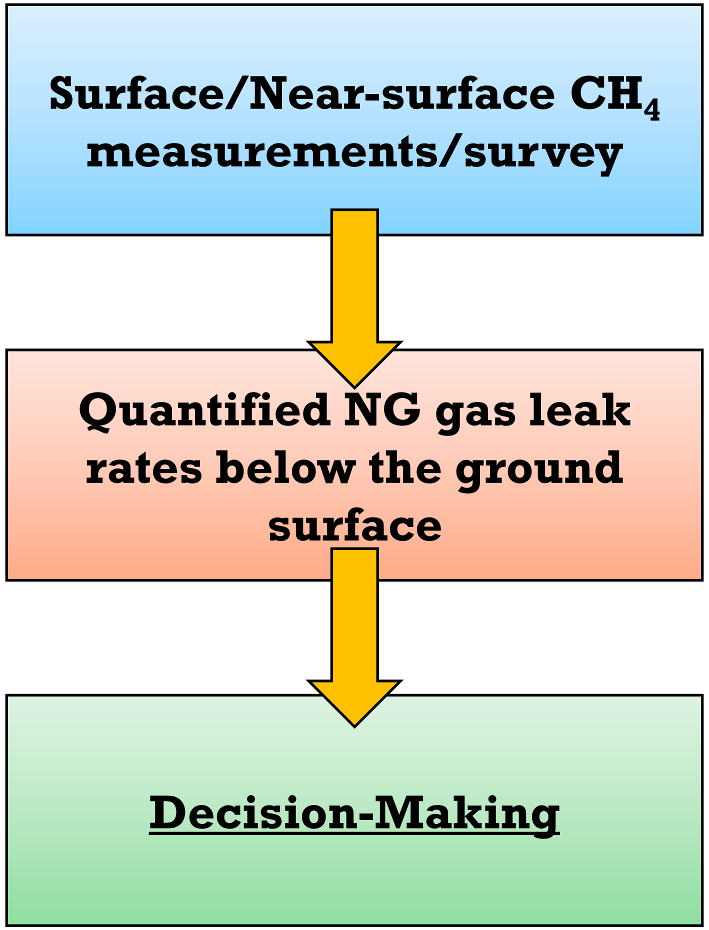


Limitations of Existing Approaches

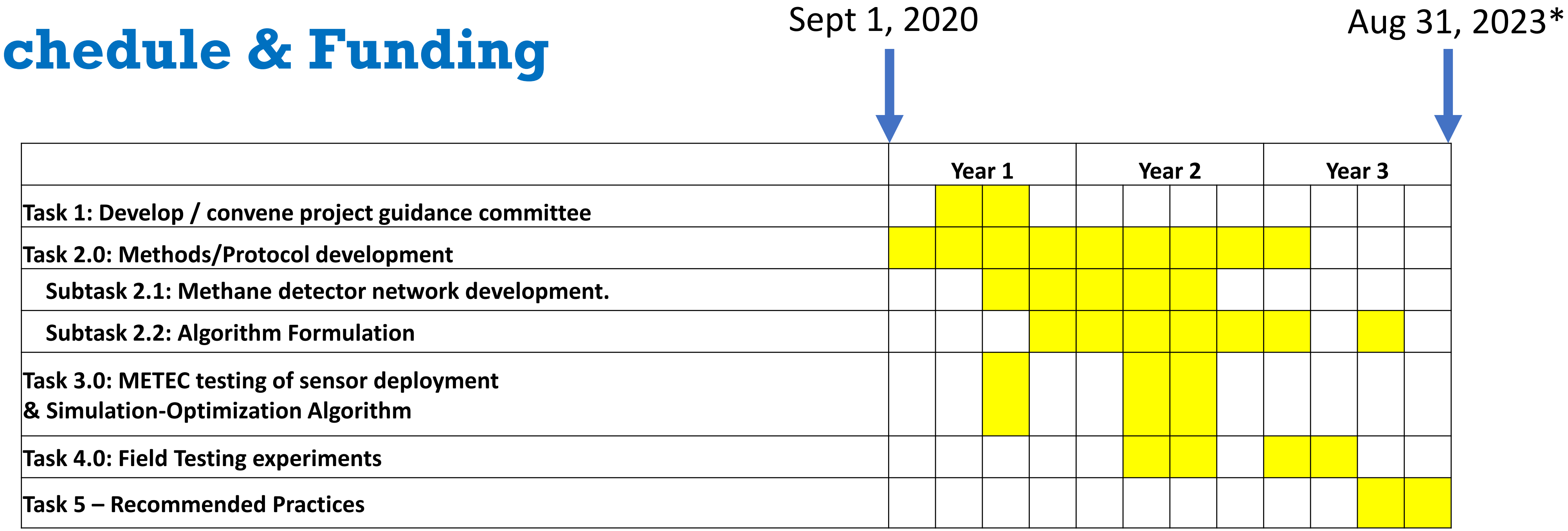
- Applicable to aboveground infrastructure, large emitters
- Current solutions mainly focus on sensor technology
- Available point source sensors mostly for indoor threshold detection (not quantification)
- Outdoor point source sensors traditionally implemented for outdoor air quality monitoring
- No previous study to integrate knowledge of gas migration and sensor networking specifically to address pipeline leakage incidents

Project Objective

- **To date, there is no standardized protocol available for considering these factors and how to account for such variables in data analysis.**
    - Develop a **near real-time methane detector network** to connect the methane monitoring system and a modified gas migration model to **quantify the underground non-steady natural gas leakage from the pipeline** by surface measurements and environmental conditions.
    - Establish a **recommended practice** that incorporates understanding of belowground gas behavior, specifically addressing how to improve the efficiency of understanding change in leak behavior.
    - Advance the **decision-making tool** and the science of leak detection and measurement methods for underground gas leakage from pipelines.



Schedule & Funding



*AO granted 3 yr performance periods for all CAAP FY 2020 awards

TOTALS:

	Year 1	Year 2	Year 3	**Total**
Request	$96,313	$91,317	$62,370	**$250,000**
Cost-Share		$30,788	$31,712	**$62,500**
GRAND TOTAL	**$96,113**	**$125,105**	**$94,082**	**$312,500**

Task Summary

- **Task 1** – Establish a collaborative study structure with InSeNSE advisors ✓
  - Met with 4-5 industry advisers quarterly
  - Integration into task 4- 5 field testing and practice
- **Task 2** – Methods/Protocol Development ✓
  - Task 2.1 Methane detector network development ✓
  - Task 2.2 Algorithm/approach to understanding non-steady state gas leakage using near real time data ✓
  - Developed network & tested approach✓
  - New algorithm based on resistance-based approach✓
  - Verification study ✓
- **Task 3** – METEC testing of detector network & algorithm ✓
  - 3 sets of 5 day experiments at METEC✓
  - Varied leak rate (2-7 SCFH), weather, soil conditions (moisture, competing utilities), surface conditions (grass, surface cap) ✓
- **Task 4** – Field testing of the approach with industry partners ✓
  - Tested@ 7 leak locations✓
- **Task 5** – Recommended practices ✓
  - Simple way to estimate possible gas migration/emissions✓
    - Scenarios of deployment ✓
    - Surface concentration measurements ✓
    - Scientific understanding ✓

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Project Outputs

- 2 peer reviewed papers (1 published, 1 in review)
- Published data set
- 3 'in the news' articles
- 13 conference presentations

Publications

1. Cho, Y., Smits, K. M., Riddick, S. N., & Zimmerle, D. J. (2022). Calibration and field deployment of low-cost sensor network to monitor underground pipeline leakage. Sensors and Actuators B: Chemical, 355, 131276., https://doi.org/10.1016/j.snb.2021.131276

2. J. Lo*, K.M. Smits, Y. Cho, J. Duggan, S. Riddick, Quantifying Non-steady State Natural Gas Leakage from the Pipelines Using An Innovative Sensor Network and Model for Subsurface missions – InSENSE (*Submitted to Journal of Environmental Pollutions – Under review)*

Data

Jui-Hsiang Lo; Kathleen M Smits; Younki Cho; Gerald P. Duggan; Stuart Riddick, 2023, "Replication Data for: Quantifying Non-steady State Natural Gas Leakage from the Pipelines Using an Innovative Sensor Network and Model for Subsurface Emissions - InSENSE", https://doi.org/10.18738/T8/SPE8QJ, Texas Data Repository

Media

1. Agor, J., 2020. "Monitoring gas leaks UTA civil engineering working to develop data network to monitor, quantify gas leaks." https://www.uta.edu/news/news-releases/2020/10/05/smits- gas-leaks Published on 5 October, 2020.

2. Agor, J., 2021, "UTA civil engineering professor earns grants to study, develop methods to assess and respond to large gas leaks," Jan 2021, https://www.uta.edu/news/news- releases/2021.

3. Rumende, Thevnin. "Civil engineering professor receives two grants to study natural gas leak detection methods," The Shorthorn, Published on February 11, 2021, https://www.theshorthorn.com/news/civil-engineering-professor-receives-two-grants-to-study- natural-gas-leak-detection-methods/article_9d943c92-6cd2-11eb-96be-832c69a5f352.html

Deliverables 6 – Project Output

Conference Presentations and Proceedings

1. Cho, Y.*, J. H. Lee , J. Lo , J. Duggan , K. M. Smits, and D. Zimmerle. "Natural gas fugitive leak detection and quantification using a continuous methane emission monitoring system and a simplified model" AGU 2022 Fall meeting (Poster)
2. Cho, Y., K.M. Smits, S. Riddick, D. Zimmerle, Methane detector network calibration and deployment for monitoring natural gas leaks from buried pipelines, American Geophysical Union Fall Meeting, Dec 2021 (Poster)
3. Cho, Y.*, J. H. Lee , J. Lo , J. Duggan , K. M. Smits, and D. Zimmerle. "Natural gas fugitive leak detection and quantification using a continuous methane emission monitoring system and a simplified model" American Geophysical Union (AGU) Fall Meeting, 12 - 16 December 2022, Chicago, Illinois. (Poster)
4. K. M. Smits, Cho, Y., J. Duggan, and J. Lo. Improving pipeline safety during gas leakage events using near real-time data networks and decision-making tools" PRCI Pipeline Research Council International REX 2023 conference Submitted (Presentation)
5. Lo, J *, K.M. Smits, Y. Cho, J. Duggan, S. Riddick, Utilizing the Near Real-Time Methane Detector Network to Study and Quantify Underground Natural Gas Leakage from the Pipeline, CH4 Connections conference, Oct 20-21, 2022 (Poster)
6. Lo, J *, K.M. Smits, Y. Cho, J. Duggan, S. Riddick, Utilizing the Near Real-Time Methane Detector Network to Study and Quantify Underground Natural Gas Leakage from the Pipeline, American Geophysical Union Fall Meeting, Dec 2022 (Poster)
7. Lo, J, K.M. Smits, Cho, Y., J. Duggan, C. Horst, L. Aldana, Development and Application of Remote, Near Real-Time Methane Detector Network for Belowground Pipeline Leaks, Energy Institute Publications
8. Lo, J.*, K.M. Smits, Cho, Y., J. Duggan, S. Riddick, Utilizing the Near Real-Time Methane Detector Network to Study and Quantify Underground Natural Gas Leakage from the Pipeline, GTI/CSU CH4 Connections conference, Oct 20-21, 2022 (Poster)
9. Lo, J., K.M. Smits, Cho, Y., J. Duggan, C. Horst, L. Aldana, Development and Application of Remote, Near Real-Time Methane Detector Network for Belowground Pipeline Leaks, Energy Institute Student Research Poster Session at Powerhouse, Colorado State University, May 10, 2022 (Poster).
10. Smits, K.M. Quantification of anthropogenic methane source`s through measurement studies: Finding targets for mitigation, SMU Earth Science Seminar Series, Jan 27, 2023 (Invited Presentation).
11. Smits, K.M. Unraveling the Influence of Environmental Conditions on Natural Gas Pipeline Leak Behavior, Center for Energy and Environmental Resources (CEER), The University of Texas at Austin, March 7, 2022 (Invited Presentation).
12. Smits, K.M., D. Zimmerle, Y. Cho, S. Riddick, B. Gao and S. Tian, Unraveling the influence of environmental parameters on methane behavior from belowground leaks, American Geophysical Union Fall Meeting, Dec 2021 (Presentation).
13. Smits, K.M., Tools for Predicting Underground Natural Gas Migration and Mitigating its Occurrence/Consequence, School of Global Environmental Sustainability, Colorado State University, Dec 6, 2021 (Invited Presentation).

Project Deliverables/ Tech Transfer (con't)

- METEC experimental data sets (3) publicly available
- Gas detector network (Cho et al., 2022, Sensors and Actuators)
- Method to estimate gas emissions from underground pipelines (Lo et al., in review, J. Env. Pollution)
- 8 industry advisory meetings
- Presentations of results to industry, AGU, PRCI, CH4 Connections Conference
- Final report
- Undergraduate/ graduate student/ workforce training
- Follow-on efforts

Task 1: Project Management and Planning

Objective : Establish collaborative study structure

- 5 Industry Partners
- Collaborative structure
- Quarterly meetings

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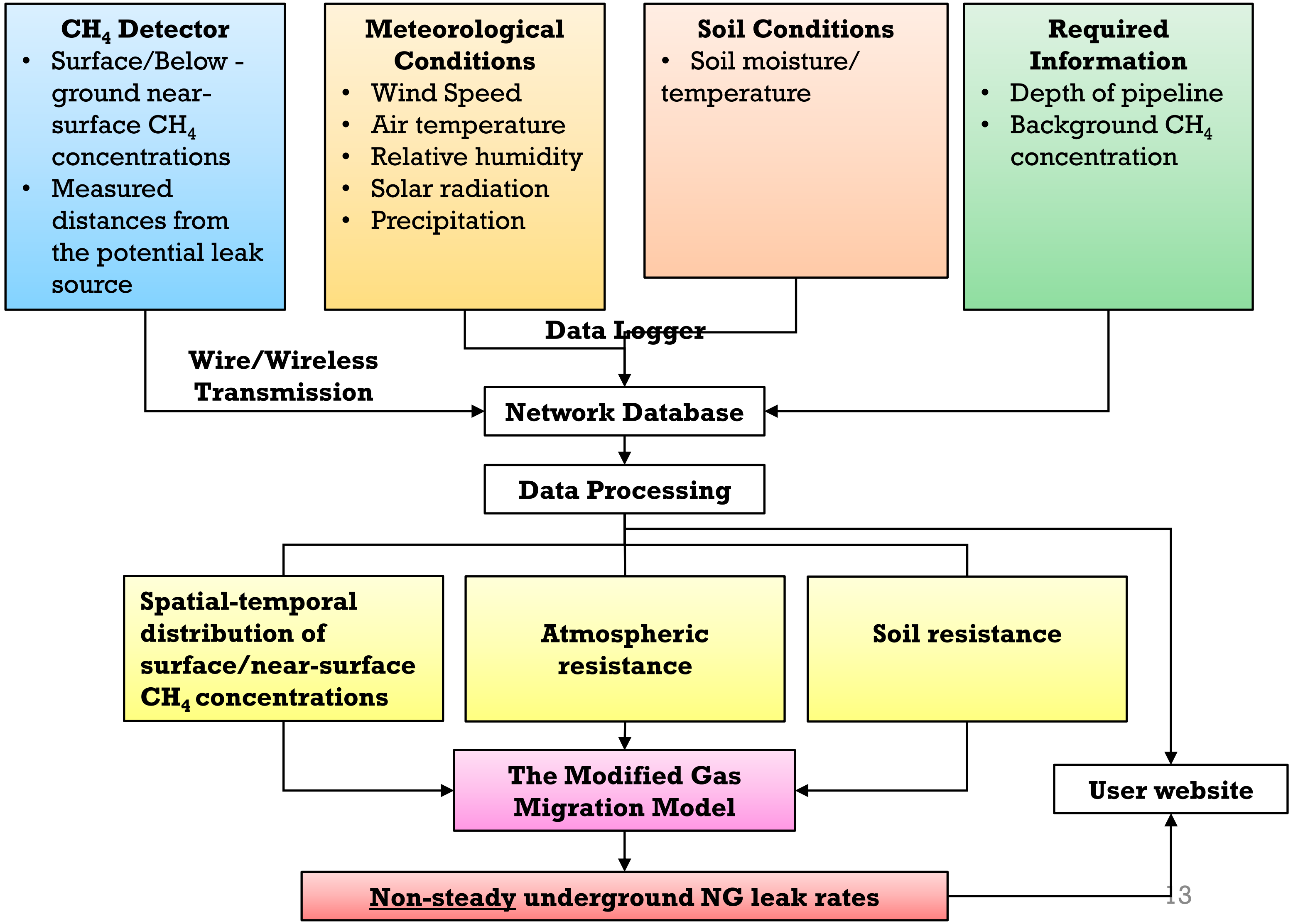
Task 2 – Methods/Protocol Development

- Task 2.1 – Methane detector network development
  - Objective : Develop a low-cost near real-time CH_4 detector network that linked multiple sensors to a simulation model.

- Task 2.2 – Algorithm/approach to understanding non-steady state gas leakage using near real time data
  - Objective: Develop the algorithm based on resistance-based approach to estimate non-steady state underground gas leakage using near real-time measurements

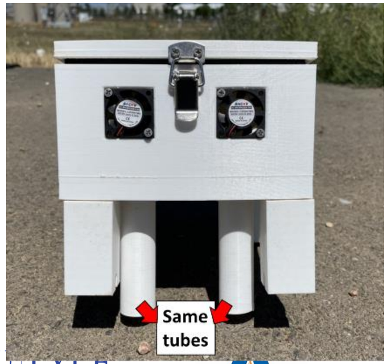
Low-cost, Near-real-time, Wireless CH_4 Detector Network

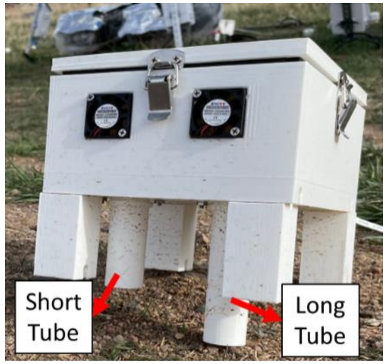
- Collect near-real-time data
  - Surface and belowground near-surface (BNS) CH_4 concentrations
  - Meteorological conditions
  - Soil moisture and temperature
- Process data to provide required inputs for the modified gas migration model.
- Estimate non-steady underground NG leak rates

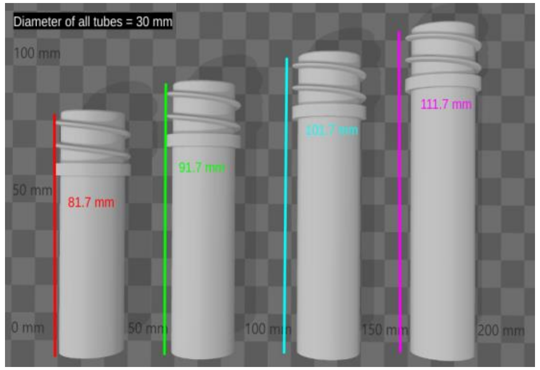


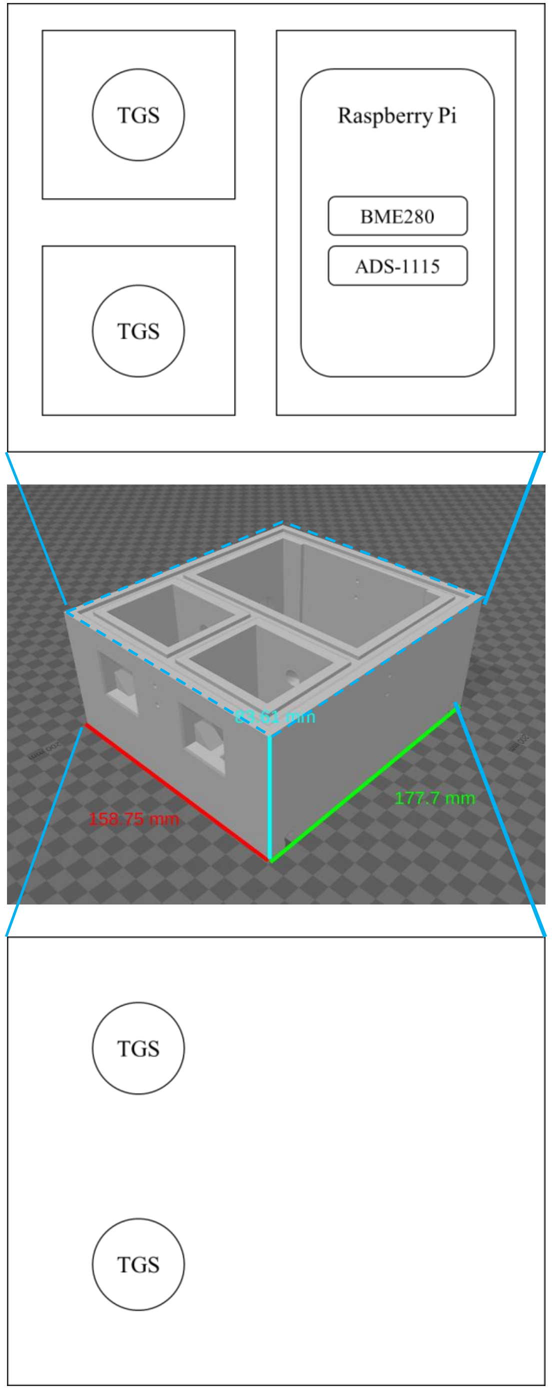
Low-cost Near-real-time CH_4 Detector

- The low-cost near-real-time CH4 detector was modified based on low-cost CH4 sensor (Cho et al., 2022).
- Detector consists of
  - Two metal oxide semiconductor (MOS) sensors (TGS2611-E00, Figaro USA Inc.),
  - An environmental condition sensor (BME280, Bosch Sensortec Inc.)
  - A 16-bit analog-to-digital converter (ADS-1115)
- Two tubes at the bottom of detector
  - Allow the surface and belowground near-surface CH4 to meet MOS sensors
  - Can be changed to measure at different depths as needed.



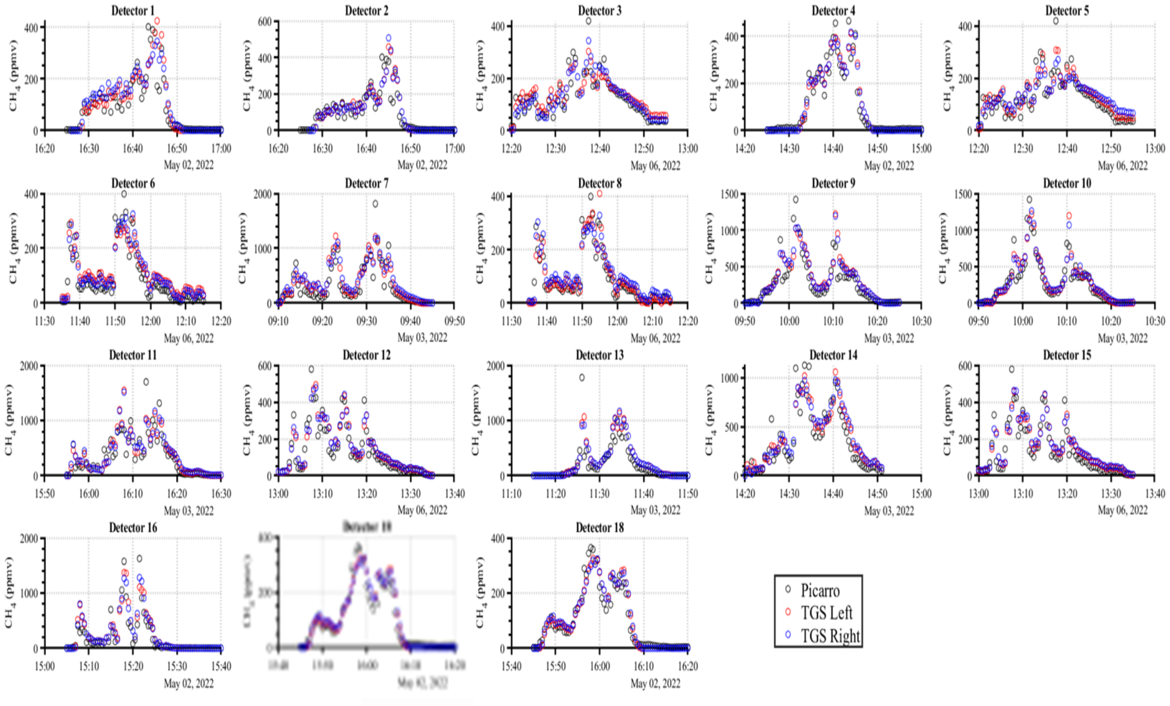


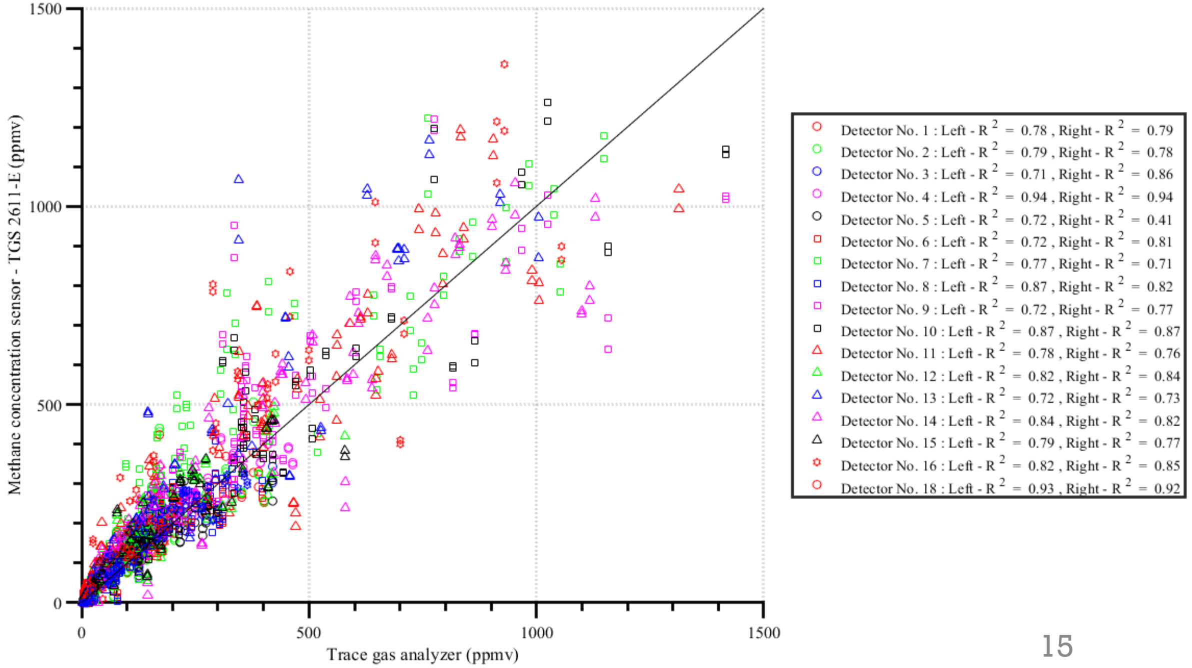




Calibration of Low-cost Near-real-time CH4 Detector

- Calibration of detectors was conducted in a laboratory by comparing gas concentrations measured from a cavity ring-down spectrometry analyzer (G4302 GasScouter, Picarro, Inc.)
- Correlation coefficient (R^2) was generally greater than 0.7 ($R^2 > 0.7$).





The inversion algorithm for quantifying underground gas leakage using near real-time data (Modified ESCAPE model)

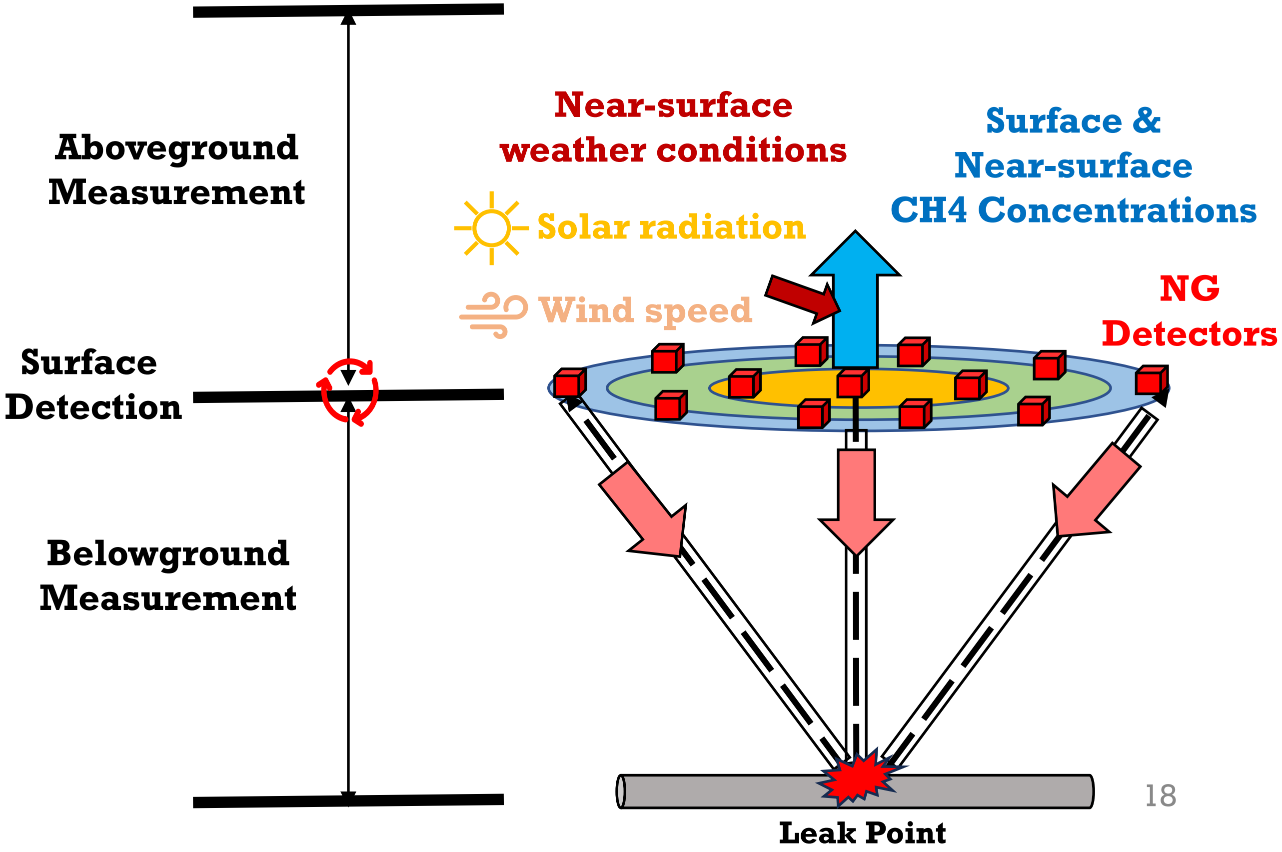
- Modifying the ESCAPE model [Riddick et al., 2021] using **surface** and **below-ground near-surface** CH_4 measurements, aboveground weather conditions, and belowground soil properties to **quantify the non-steady NG leak rates** from the pipeline **without the impermeable surface covers**.

Input

- Wind speed and solar radiation
- Surface and subsurface CH_4 concentrations
- Soil moisture and temperature
- Known leak location and depth

Output

- Estimated non-steady underground NG leak rates (a single point source)



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Algorithm for Quantifying Underground Non-steady Gas leakage – Modified ESCAPE Model

- Modifying the ESCAPE model [Riddick et al., 2021] using **surface** and **below-ground near-surface** CH_4 measurements, aboveground weather conditions, and belowground soil properties to **quantify the non-steady NG leak rates** from the pipeline **without the impermeable surface covers**.

Non-steady NG leak rates — *Steady-state NG leak rate* — *Transient change*

$$Q_L(t) = \overline{Q_L} + Q_{LT}(x, C_s, C_{sub}, \mathbf{R_s}, \mathbf{R_{at}}, t)$$

where,

$Q_L(t)$ is the non-steady changes in underground NG leak rates (cfh)

$\overline{Q_L}$ is steady belowground NG leak rate estimated by the original ESCAPE model (cfh)

Q_{LT} is the transient change in the NG leak rate(cfh)

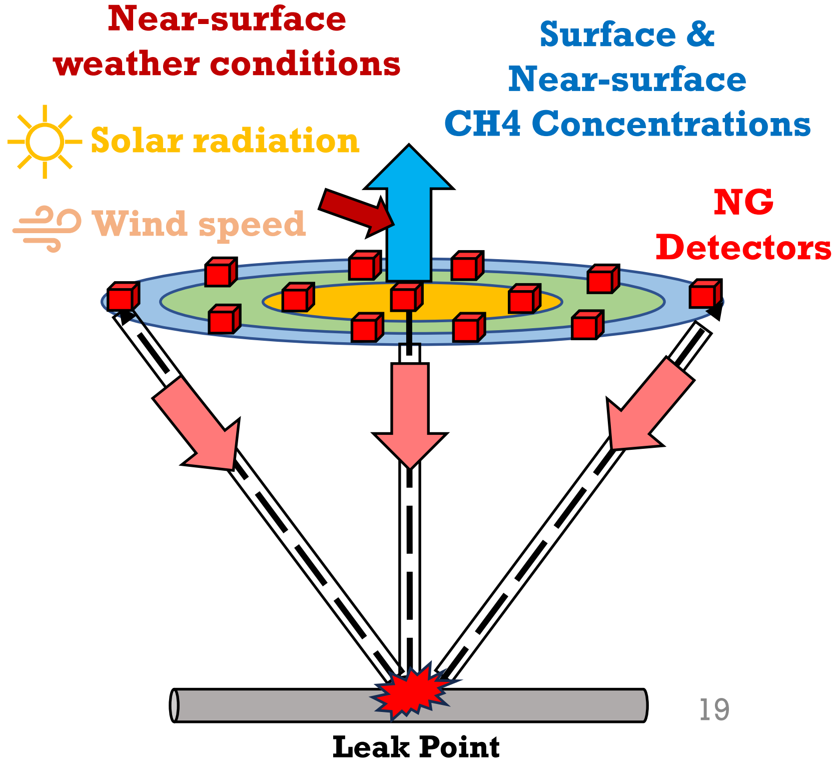
x is the distance from the leak point to measured location (ft)

C_s is the surface CH_4 concentrations (ppm)

C_{sub} is the subsurface CH_4 concentrations (ppm)

R_s is the soil resistance (s/ft) [van de Griend and Owe, 1994]

R_{at} is the atmospheric resistance (s/ft) [Riddick et al., 2021]



Task 3 – METEC Testing of Detector Network & Algorithm

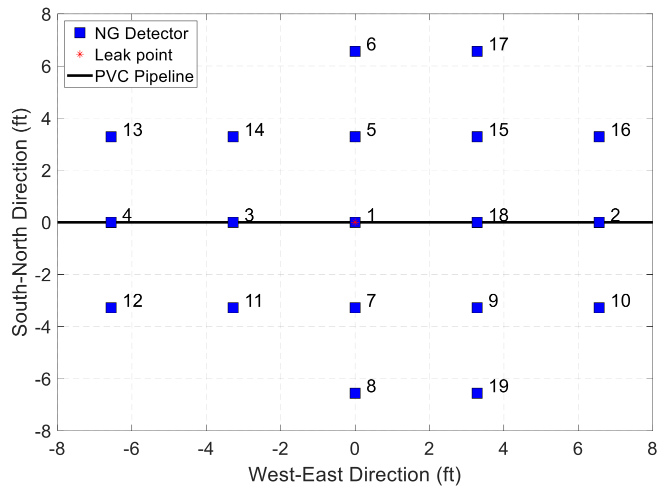
Objective : Conduct multiple controlled NG testing at METEC in various scenarios to evaluate performances of the low-cost near-real-time CH_4 detector network and the inversion algorithm on detection and quantification of underground NG leakage.

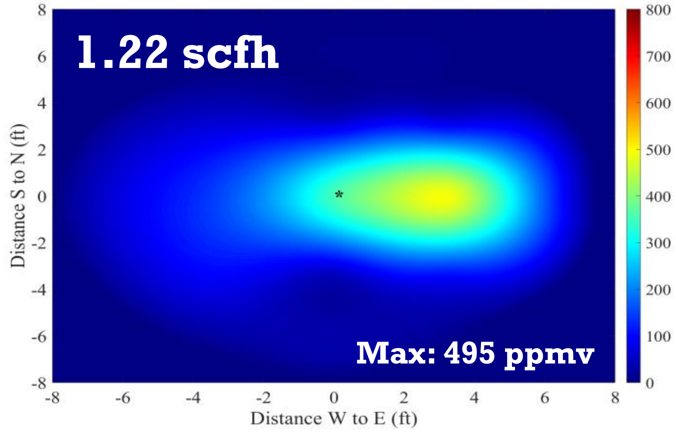
- 3 sets of 5-day controlled gas release experiments at METEC
  - Experiments #1 and #2 : 5 days, rural scenario (open surface), and steady-state gas leak rates (1) 1.22 ± 0.3 (cfh) and (2) 4.54 ± 0.5 (cfh)
  - Experiments #3 : 5 days, rural scenario (open surface), and non-steady gas leak rates
    1) **Level 1: 1.99 ± 0.26 (cfh) for 2 days.**
    2) **Level 2: 4.77 ± 0.36 (cfh) for 1.5 days.**
    3) **Level 3: 6.50 ± 0.24 (cfh) for 1.5 days.**

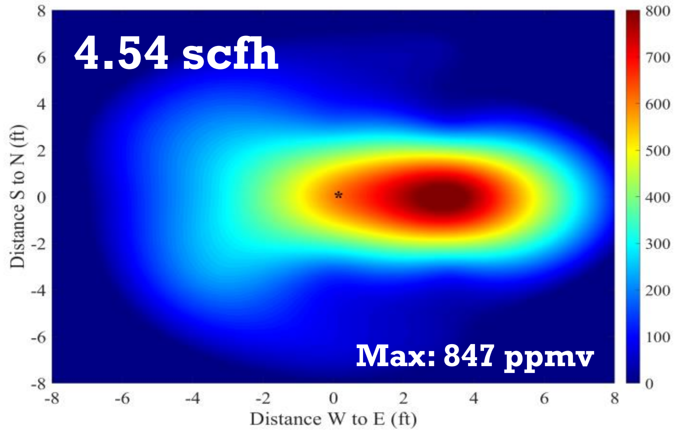
- Estimation of underground non-steady NG leak rates using near-real-time measurements of environmental conditions and gas concentrations

Controlled NG Release Experiments at METEC – Exp. #1 & #2

- **Controlled gas leak rates**
  - Open surface scenario
  - Leak depth = 3 ft.
  - **Steady-state leak rates** (1) 1.2 ± 0.3 (cfh) (2) 4.5 ± 0.5 (cfh)
- As expected, increase leak rate, increase the maximum CH_4 concentration **increased from 495 ppmv to 847 ppmv (71%)**
- The plume area of the surface CH_4 at a leak rate of 4.54 ± 0.5 (cfh) **extended approximately 1.25 times** farther than that of the surface CH_4 at the average leak rate of 1.22 ± 0.3 (cfh).







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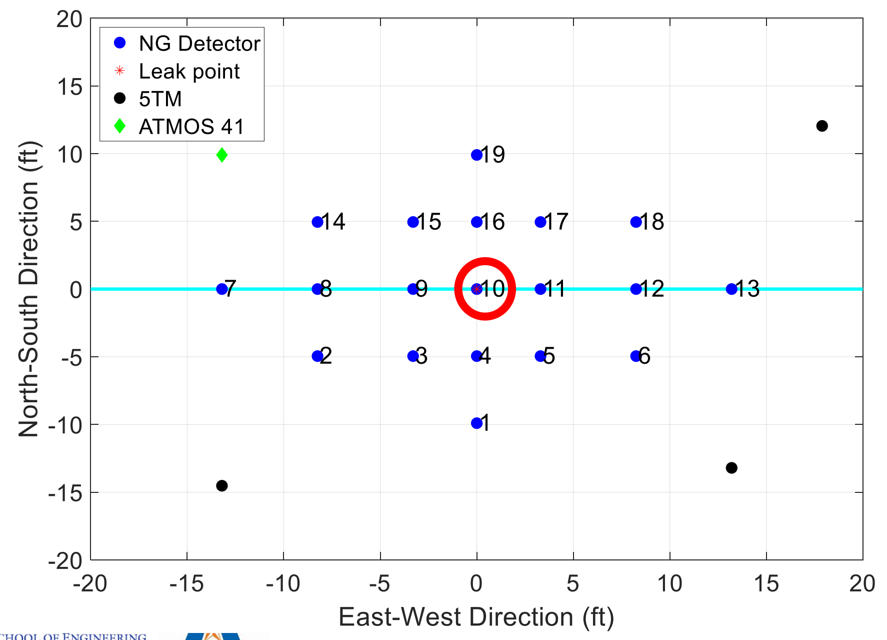
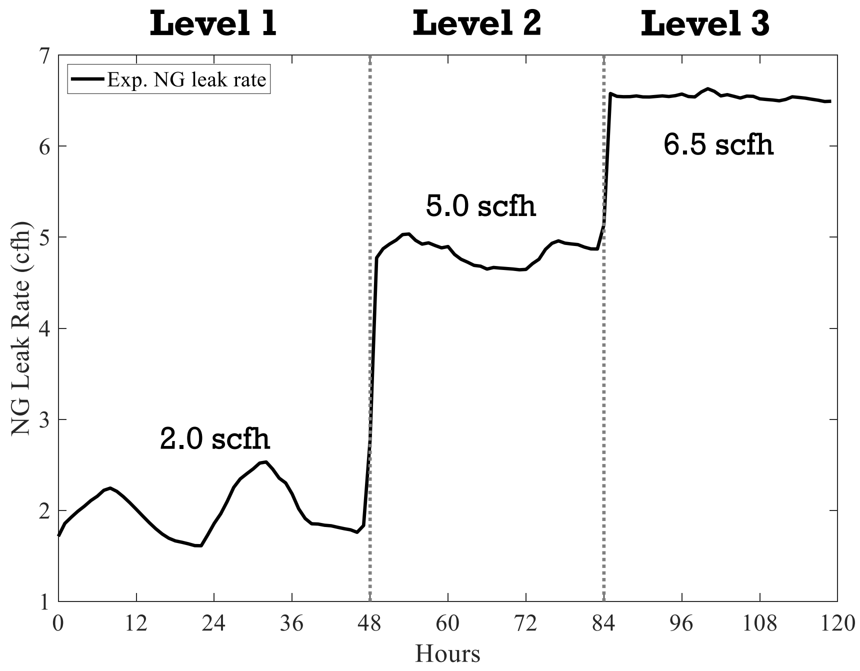
Controlled NG Release Experiments at METEC – Exp. #3

- **The detector network**
  - 18 NG detectors (Blue point) to detect surface & belowground near-surface (BNS) (depth is 1.2 cm/0.47 in) CH_4 concentration
  - 3 soil moisture/temperature (Black point)
  - Portable MET sensor (Green diamond) above ground surface



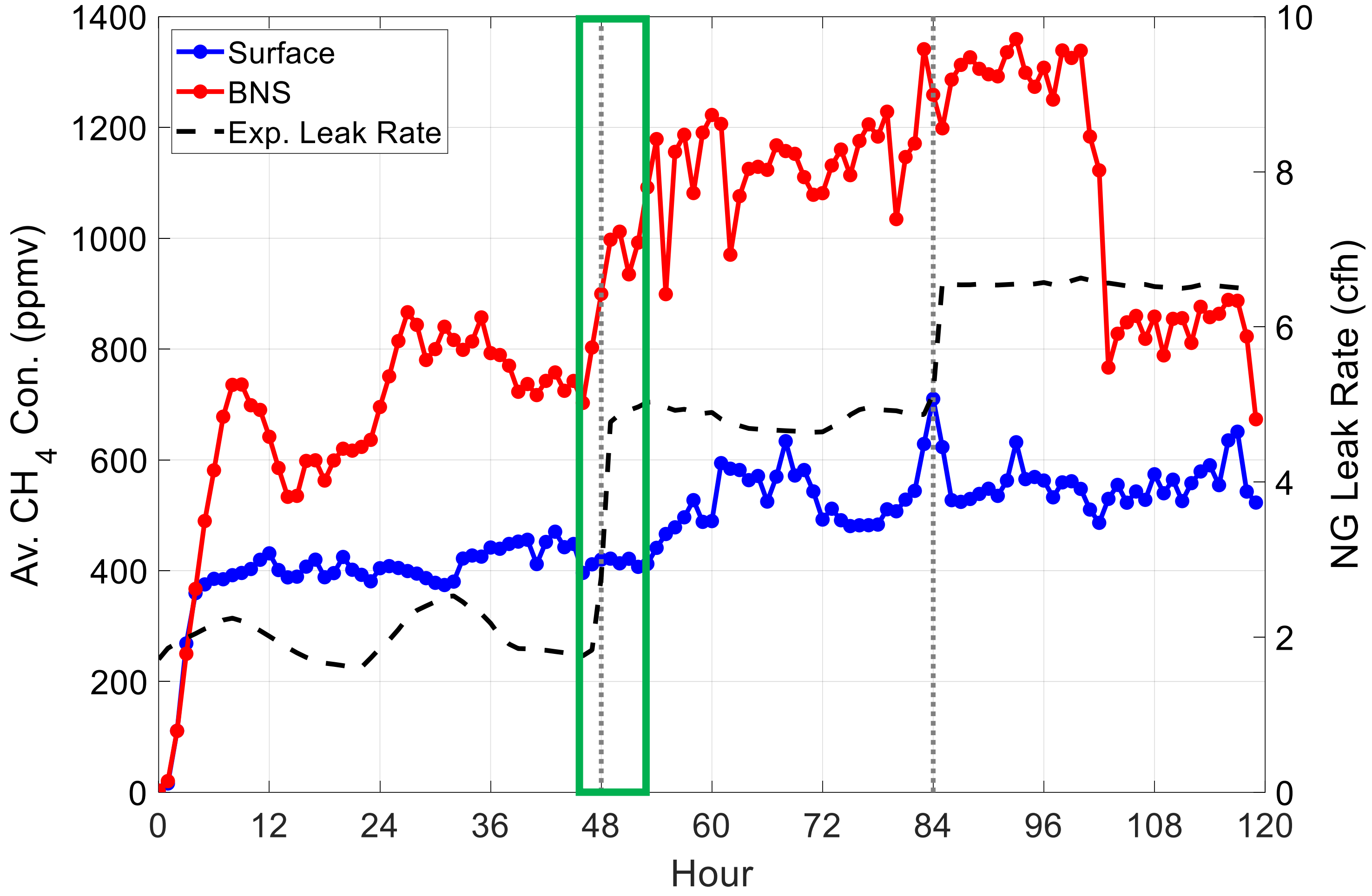
- **Controlled gas leak rates**
  - Depth of leak point/pipeline was **3 ft / 0.91 m** directly below Detector 10.

1) Level 1: 2.0 ± 0.26 (cfh) for 2 days.
2) Level 2: 5.0 ± 0.36 (cfh) for 1.5 days.
3) Level 3: 6.5 ± 0.24 (cfh) for 1.5 days.



Belowground concentrations higher long before surface concentrations

- As the leak rate increased from 2 to 5 scfh (37 to 84 g/h), an increased in the **BNS CH_4** concentration increase was observed **within 3 hours**.
- However, the increase in surface concentrations was not observed in this period.
- **Changes in surface CH_4 concentration alone do not reflect changes in a belowground leak rate (2 to 6.5 scfh tested) (understood by industry but not previously quantified)**



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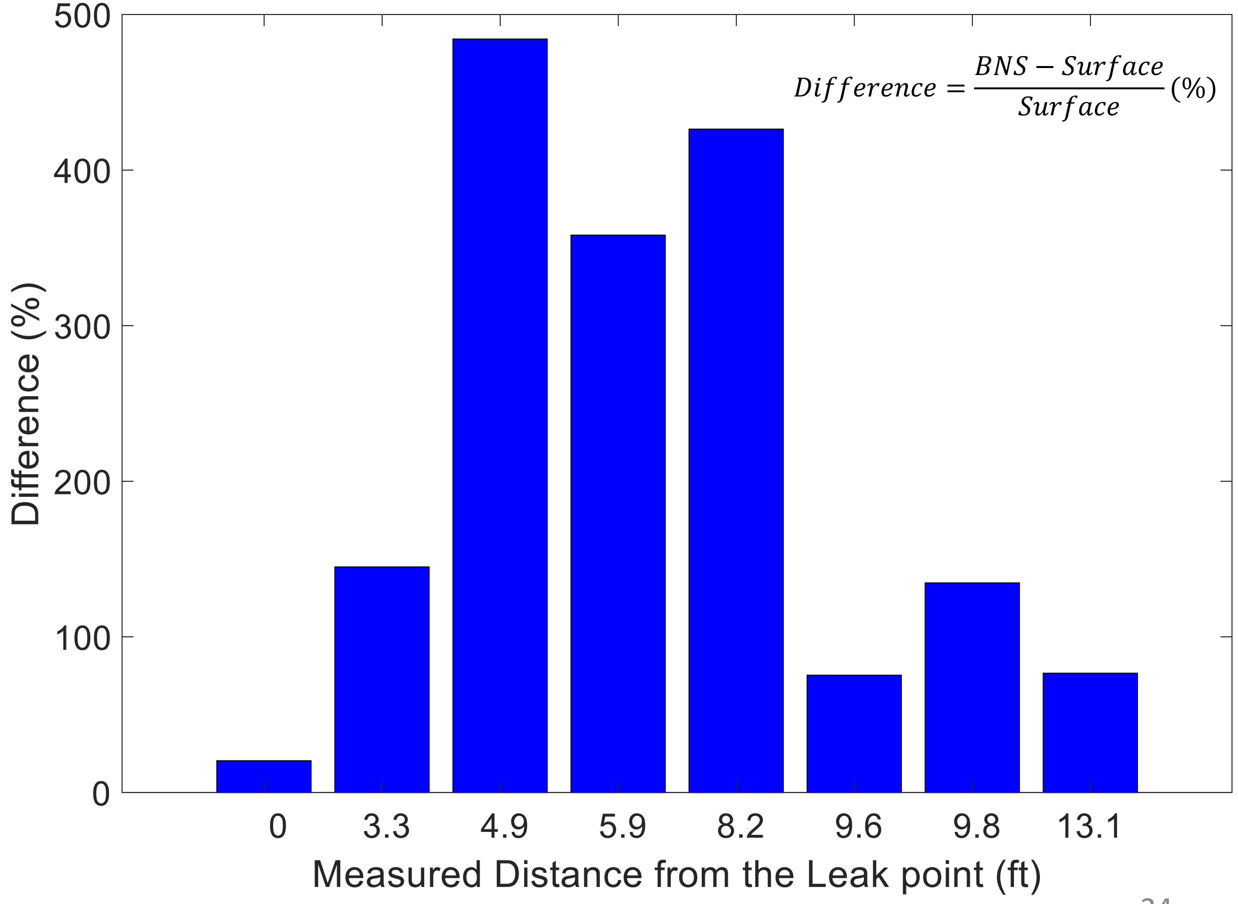
Average belowground concentrations significantly higher than surface concentrations

- On average, belowground (1.2 cm below the surface) CH_4 concentrations between 20 - 500% higher than the average surface concentrations
- Variation a function of distance from the leak point



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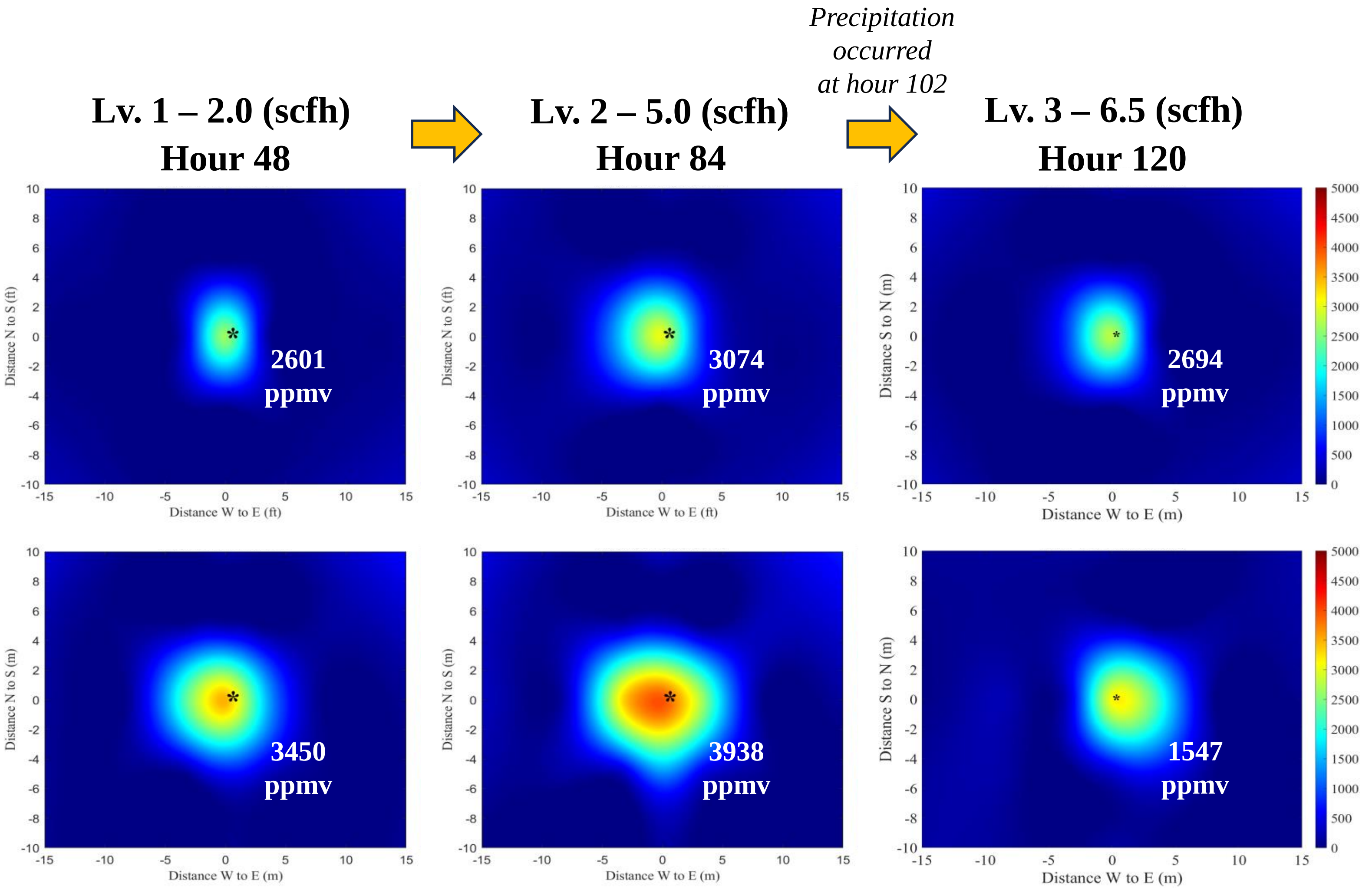
Belowground plume extends farther and faster than observable surface plume during non-steady state conditions

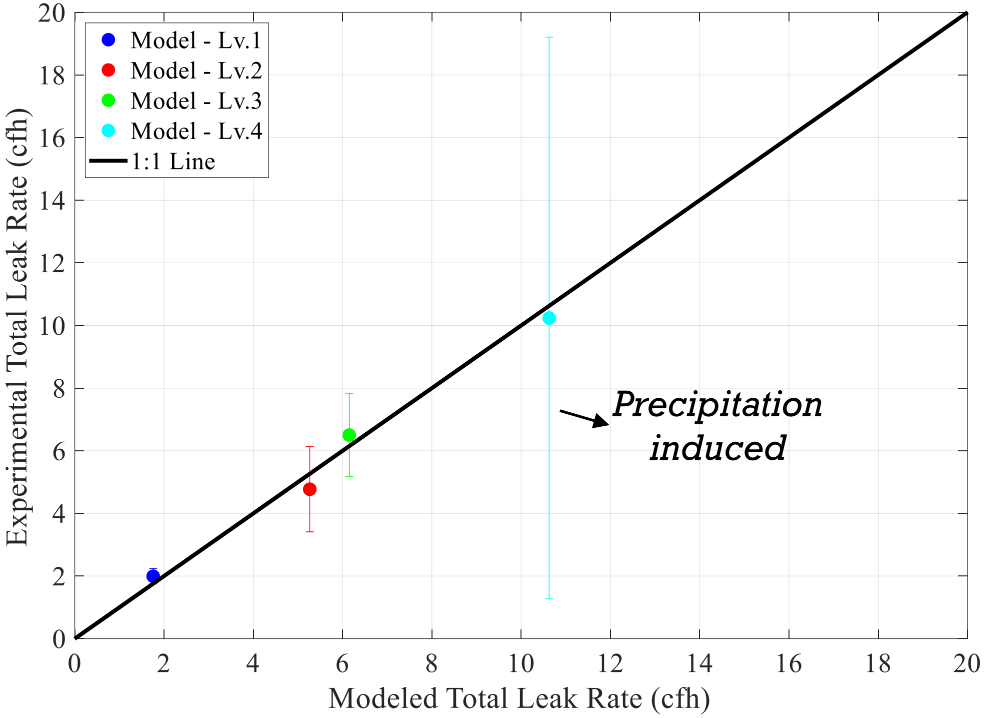
- Plume area belowground ~ **two times** farther than surface plume as the gas leak rate increased from 2.0 to 6.5 (scfh) (37 to 84 g/h).

- **Belowground (right under the surface) concentration is an important factor in leak rate estimates as the surface expression does not necessarily define the belowground plume extent**



Estimated Underground Non-steady NG Leak Rates (Exp. 3)

- Model used **the meteorological data**, **soil moisture/temperature**, and **surface/BNS CH_4 concentrations** to estimate the non-steady NG leak rate
- Estimates agree well with experiments (**m=0.99 and R^2=0.77**)
- Demonstrates importance of including select soil characteristics and belowground data in **estimates of non-steady NG leak rates for both low and moderate NG leak rate scenarios** (leaks from 2 to 5 scfh (37 to 84 g/h)



NG Release Rate Level		Experimental (cfh)	Modeled (cfh)	Standard deviation (cfh)	Difference (%)
Modified ESCAPE (Surface + BNS CH_4)	Lv. 1	1.99	1.76	0.01	-11.87
	Lv. 2	4.77	5.28	0.07	10.65
	Lv. 3	6.50	6.13	0.07	-5.71
	Lv. 4	10.24	10.63	8.97	3.80

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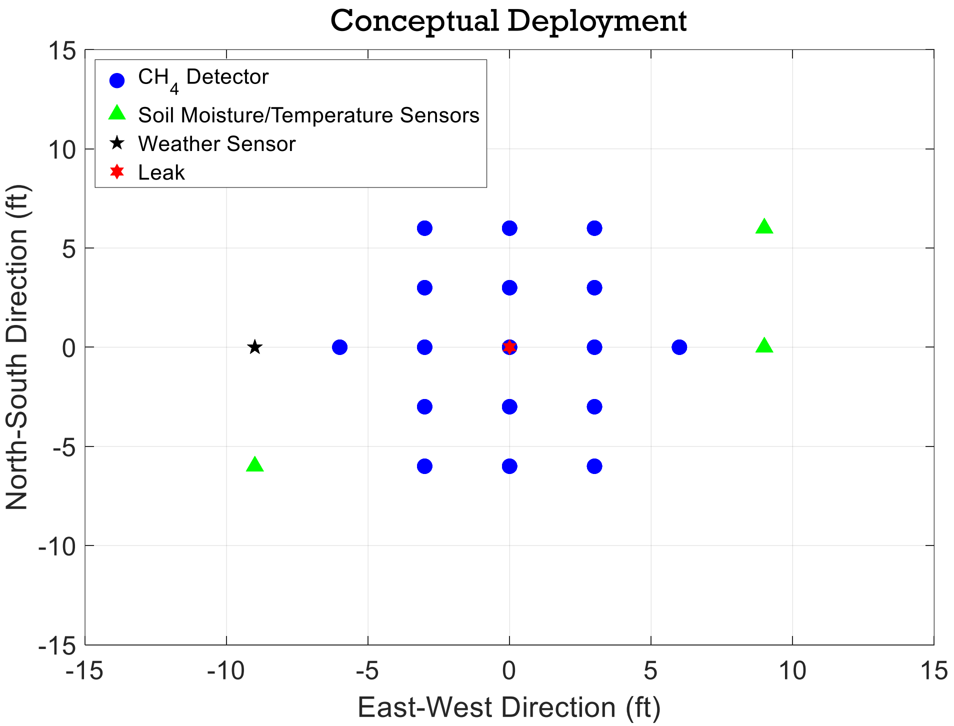
Task 4 – Field Testing experiments with Industry

Objective : Evaluate the capability of the low-cost near-real-time CH_4 detector network and the modified ESCAPE model for a wide range of field applications.

- Seven field experiments
- Leak rates determined by the modified ESCAPE model & compared with measurements from HI-FLOW and an industry-standard method (i.e., flux chamber approach).

Implementation of Field Experiments

- Conducted field experiments at 7 sites.
- At each test site,
  1. Located the potential leak point with the highest surface methane concentrations by **DP-IR +**.
  2. Deployed sensors and detectors to collect data over 2 hours
     - **NG detectors** to detect surface and subsurface (depth is 1.2 cm) methane emissions every 5s.
     - **Three soil moisture/temperature sensors** to monitor the soil moisture/temperature every 30s.
     - **A portable weather sensor** to record the local weather condition every 30s above the ground surface 20 inches (50 cm).
  3. **Hi-Flow** – Measured leak rates and methane concentrations in 2 to 3 surface scenarios.
- Process data and simulate the leak rates by the modified gas migration model



Site Number	Duration	Surface Condition
#1	3.5 hours	Soil, grass, and partial sidewalk
#2	3.5 hours	Soil, grass, and partial sidewalk
#3	2.5 hours	Soil, grass, and partial sidewalk
#4	2.5 hours	Soil, grass, and partial underground construction
#5	2 hours	Soil, grass, tree, and partial sidewalk
#6	2 hours	Soil, grass, tree, and partial sidewalk
#7	3 hours	Soil, grass, and partial road surface

Estimating Underground Natural Gas Leak Rates through Field Experiments

- The field application of the modified ESCAPE model was properly assessed for the leak rates between 0.5 cfh and 5 cfh (low to medium gas leakage) in collaboration (difference < ±10%).
- The very low leak rates (< 0.5 cfh) may not be able to be determined by the model, no ground truth of actual leak rate, not enough field sites to make conclusions – follow on effort needed

Location #	Av. NG leak rates by HI-FLOW (cfh)	Av. NG leak rates by the modified ESCAPE model (cfh)	Difference of total gas leak rates (%)	Category of gas leakage
1	0.84	0.89	6.56	Low
2	0.06	0.07	14.33	Very Low
3	0.35	0.07	-79.69	Very Low
4	0.07	0.40	469.57	Very Low
5	0.48	0.40	-15.65	Very Low
6	0.98	0.91	-7.46	Low
7	4.69	4.69	-0.09	Medium

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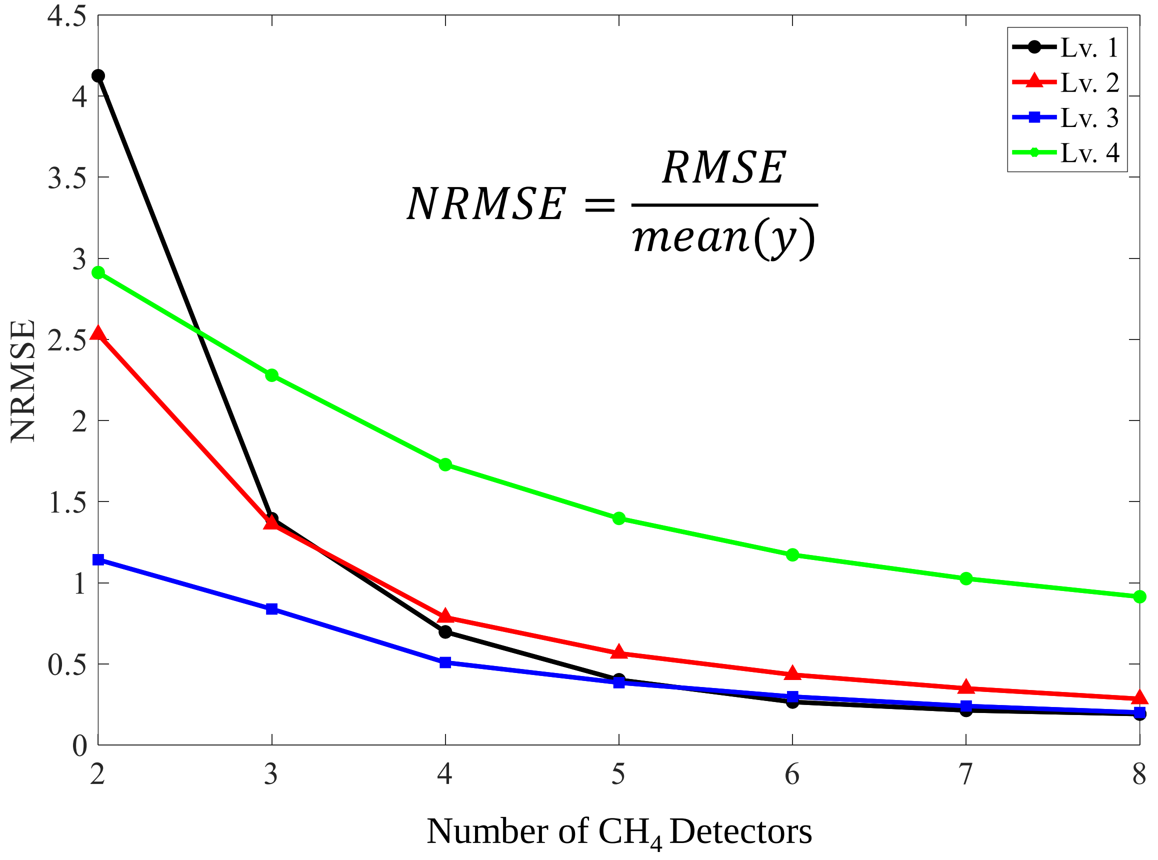
Task 5 – Recommended Practices

Objective : Use results from Tasks 2 to 4 to establish suggested practices

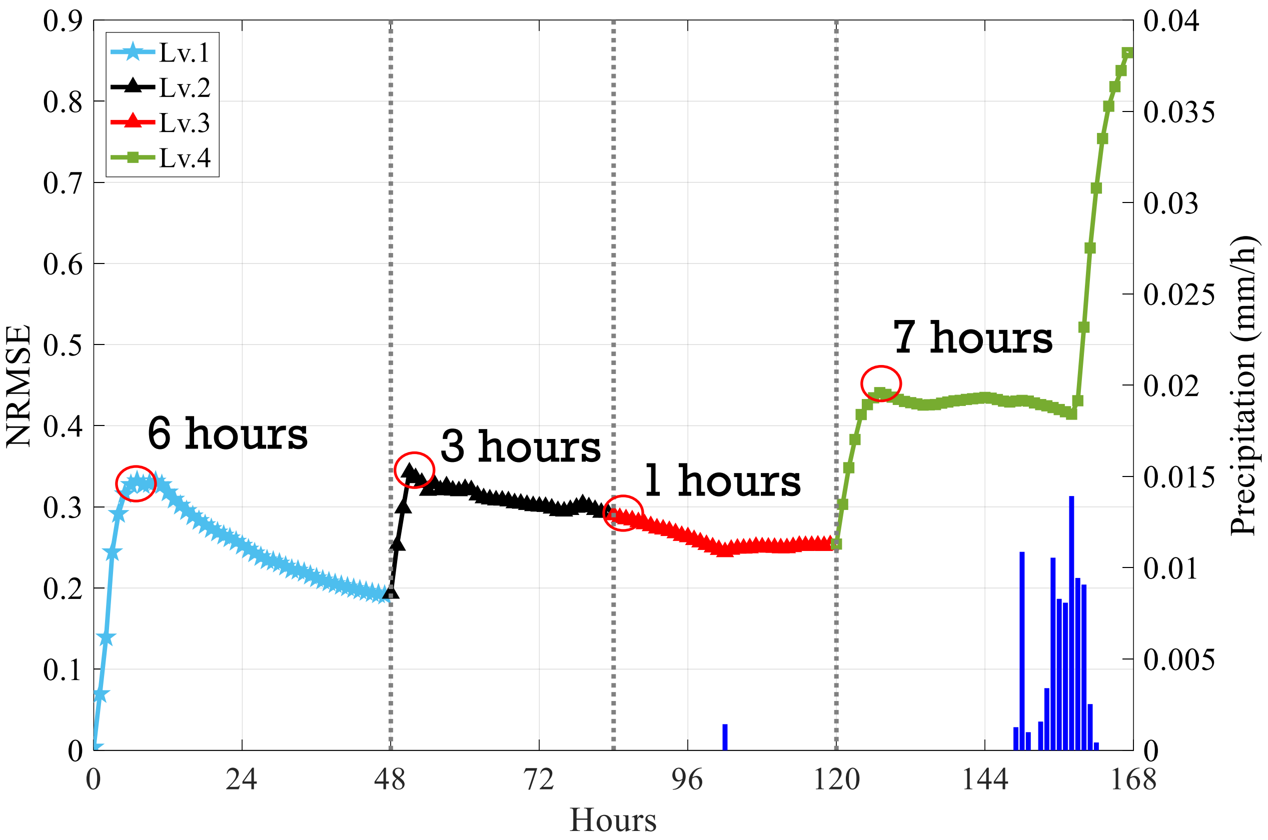
Number of Detectors (Exp. 3)

- Decrease error with an increase in detectors
- Minimum number of detectors : 3



Measured Time (Exp. 3)

- The time when the error decreased indicates the minimum time period of measurement by the detector network.
- The minimum time of measurement decreased as the underground NG leak rates increased.
- Precipitation increased the soil moisture and induced more lateral gas migration in the belowground near-surface. Thus, detector might need more measured time during or after precipitation (Lv. 4).



Underground NG Leak Rate	Time when NRMSE Decreased (Hours)
0 to 1.99 cfh (Lv.1)	6
1.99 cfh (Lv.1) to 4.77 cfh (Lv. 2)	3
4.77 cfh (Lv. 2) to 6.50 cfh (Lv. 3)	1
6.50 cfh (Lv. 3) to 10.24 cfh (Lv. 4)	7

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Recommended Scenarios of Deployment of CH4 Detectors

	Surface Soil & Grass	Surface Impermeable Covers (e.g., Pavement)
Subsurface No Underground Constructure	**At least 3 detectors** • 1 methane detector at the leak point • 1 methane detector at least on the boundary of plume • 1 methane detector at least at proposed measure distance	**At least 4 or 5 detectors** • 1 methane sensor at the leak point • 1 methane detector at least on the boundary of plume • 1 methane detector at least at proposed measure distance • **1 methane detectors at least on boundary of pavement** • **1 methane detector on the cracks (if cracks occur)**
Subsurface With Underground Obstructions	**At least 4 detectors** • 1 methane detector at the leak point • 1 methane detector at least on the boundary of plume • 1 methane detector at least at proposed measure distance • **1 methane detector at least in close to any underground structures**	**At least 5 or 6 detectors** • 1 methane detector at the leak point • 1 methane detectors at least on the boundary of plume • 1 methane detector at least at proposed measure distance • **1 methane detectors at least on boundary of pavement** • **1 methane detector at least should be placed close to the underground obstruction (if it is at the site)** • **1 methane sensor on the crack (if it is at the site)**

Conclusions

- Surface CH_4 measurements do not accurately reflect a change in subsurface leak behavior
- Belowground near surface CH_4 measurements should be considered in underground NG leak rate quantification
- Soil characteristics linked with belowground CH_4 measurements can advance estimations of non-steady NG leak rates for both low and moderate NG leak rate scenarios (leaks from 37 to 121 g/h)

Future Work

- **Conduct field experiments in various scenarios of deployments of detectors**
  - Urban scenarios (e.g., at the urban testbed) with pavement

- **Application to leak quantification**
  - Alternatives for efficiently estimating emissions from belowground pipeline leaks
  - Develop an efficient procedure to measure leak rate of underground pipeline leaks using widely available operator equipment
  - Develop the software to implement the procedure with compatibility to a hand-held device

Final Report and Presentation

The final report and presentation – "Innovative Sensor Network for Subsurface Emissions - InSENSE (DOT-PHMSA #693JK32050005CAAP)" are posted and available at:

https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=897

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QUESTIONS

Q & A

ANSWERS