PHMSA: Response Protocol for Large Underground Methane Emissions - RPLUME (DOT-PHMSA #693JK32010011POTA)

May 6, 2024

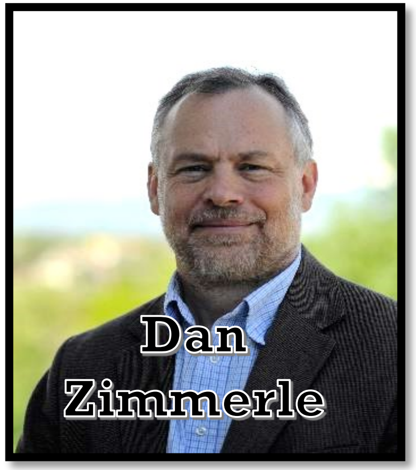
Dan Zimmerle

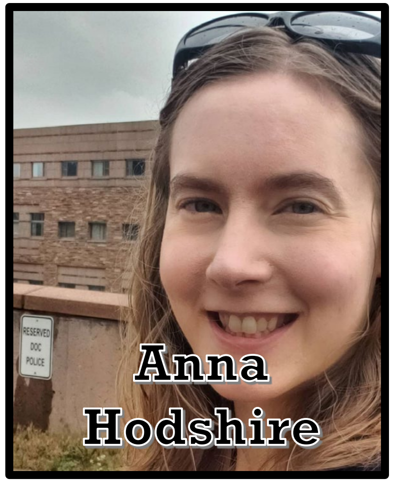
Director, Methane Emissions Program, Energy Institute
Director of METEC
Colorado State University

Kate Smits, PhD, P.E.

Solomon Professor for Global Development
Chair, Civil & Environmental Engineering
Southern Methodist University

Collaborative Effort:





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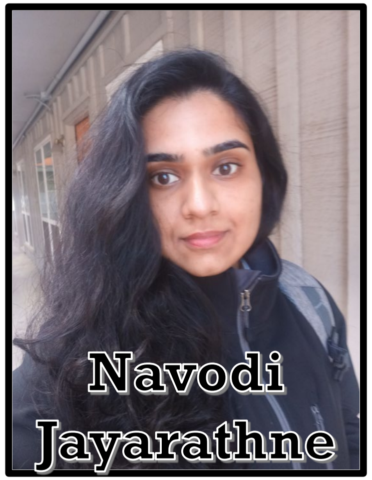
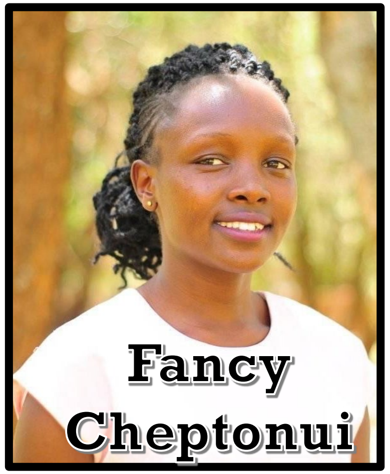




Collaborative Effort:

Post Doctoral Researchers
- Younki Cho
- Venkat Rao

PHD students
- Navodi Jayarathne
- Joelle Uribe
- Rayson Lo

Masters Students
- Richard S Kolodziej
- Mercy Mbua
- Fancy Cheptonui

CSU UG Students (partial support)
- Conor Cunningham
- Peter Ronney
- Chandler Horst
- Conner Mikesell

UTA UG Students (UTA funded)
- Nate Steadman
- Ashley Nguyenminh

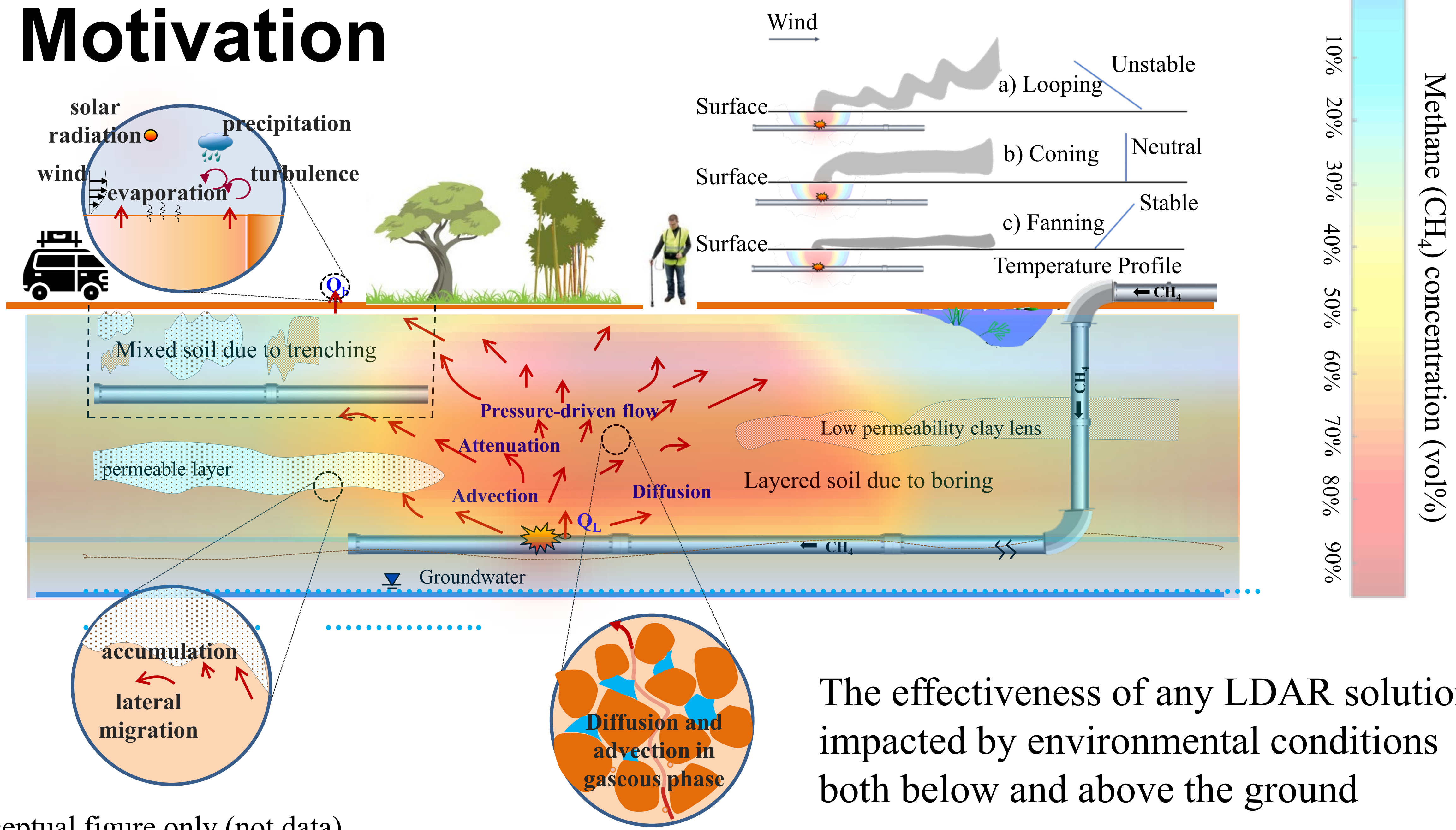
SMU UG Students (SMU funded)
- Aaron Chapman

Industry/Advisory partners
- SoCal Gas
- Con Edison
- Dominion
- PG&E
- XCEL
- DCP Midstream
- Western Midstream
- The Railroad Commission of Texas
- Colorado Energy and Carbon Management Commission (ECMC)
- Colorado Public Utility Commission

First Responders
- Poudre Fire Authority
- White Plains Fire Authority
- West Metro Fire Authority

PHMSA PM & Research Managers
- Andrea Ceartin
- Chris McLaren

Motivation



The effectiveness of any LDAR solution is impacted by environmental conditions both below and above the ground

Conceptual figure only (not data)

Project Objective

1. Characterize gas migration behavior at the surface and in the subsurface, under a range of environmental conditions
2. Develop methods to use readily-obtained gas concentration measurements & environmental observations to estimate extent and speed of gas migration
3. **Extend measurements using modeling for additional scenarios**
4. **Link understanding with <u>first responder and leak detection protocols</u>**

1. Belowground CH_4 measurements in a range of complex conditions

2. Determine maximum extent and rate of gas migration

3. Extend modeling of complex conditions belowground CH_4

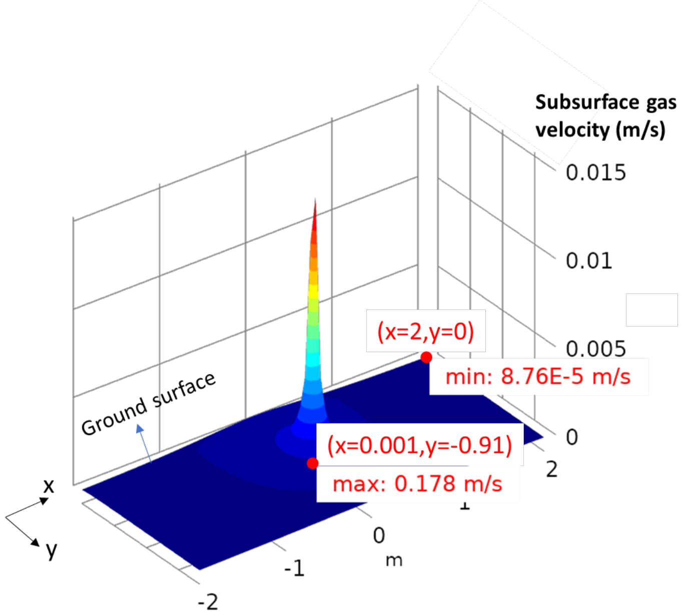
4. Connect to operator and first responder practice

Approach

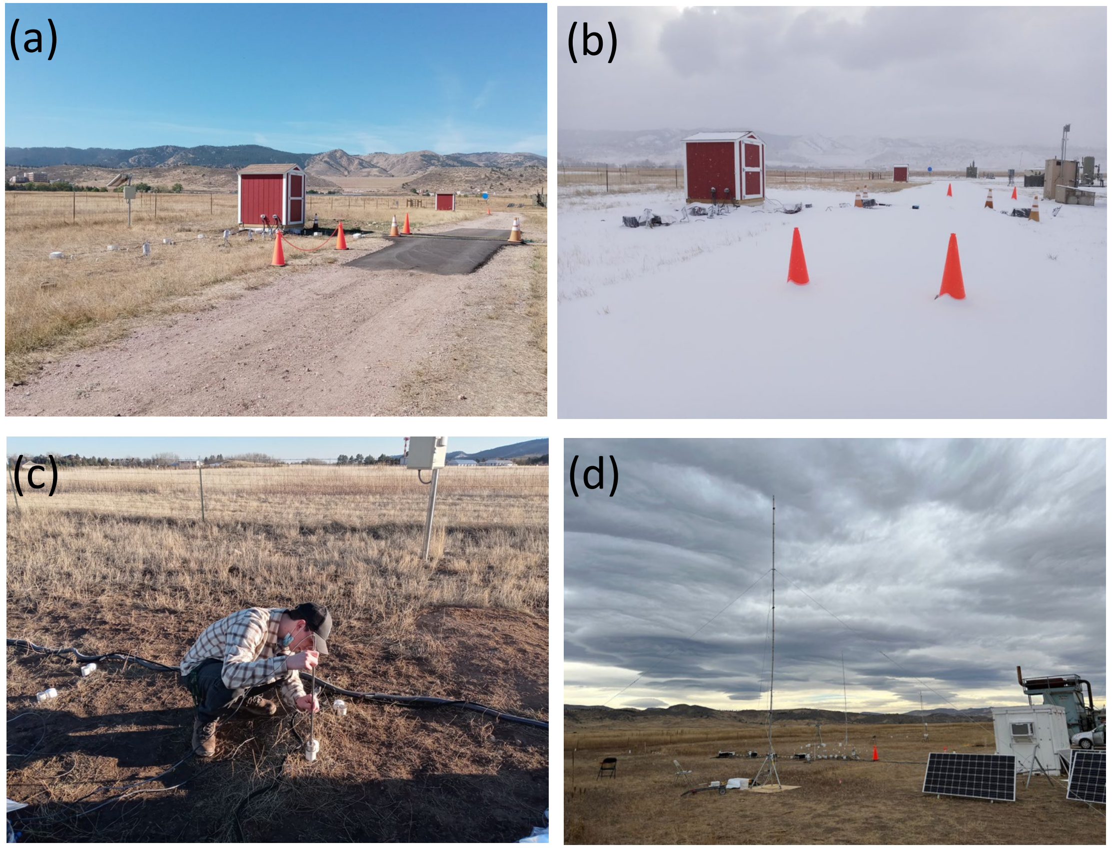
Goal: Identify what conditions are at most risk for <u>fast</u> and <u>far</u> gas migration → Improve leak detection performance and monitoring

Science & Modeling

1500+ model runs



150 Controlled Experiments at METEC



Operator Participation

<u>Worked with 1st responders, distribution, up and midstream companies</u>

- Survey operational practice
- Experimental design
- Scenario prioritization
- Recommended practices

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How R-PLUME project informs recommended practices

Focus

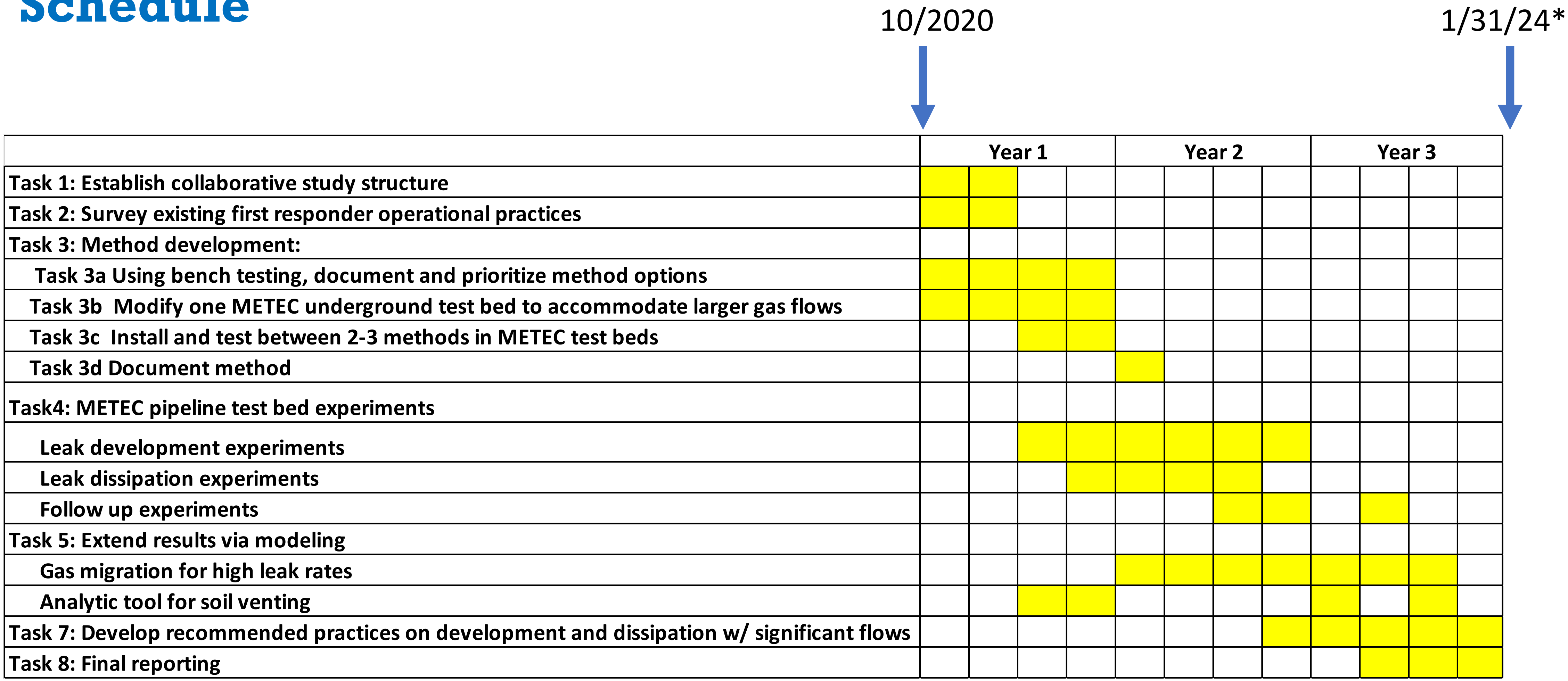
- Mid to large leak scenarios (20 + scfh)
- High resolution field tests by using belowground sensors to characterize gas migration speed and distance at high leak rates and concentrations above explosive limits

Set of experiments to investigate how gas movement is affected by:

- Size of leak
- Depth of leak
- Gas composition
- Surface above the leak - concrete, grass, no cover, frost
- Complexity of subsurface – presence of pipes, open conduits
- Environmental/weather condition – soil type, soil moisture, precipitation, snow, temperature, wind speed
- Combination of factors

Additional understanding to help determine subsurface concentrations <u>after leak termination</u>

Schedule



*AO granted a 4mo (due to COVID) & 6mo NCE

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Funding

TOTALS:

RPLUME	Year 1	Year 2	Year 3	**Total**
Request	$427,594	$395,735	$311,317	**$1,134,646**
Cost-Share	159,000	$103,473	$22,458	**$ 284,931**
TOTAL	**$586,594**	**$499,208**	**$333,775**	**$1,419,577**

Task Summary

- Task 1 – Establish a collaborative study structure ✓
  - Met with industry advisers quarterly ✓
  - Integration into tasks 2-7 ✓
- Task 2 – Survey existing first responder operational practices ✓
  - 1st responder and PHMSA emergency planning and guidelines review ✓
- Task 3 – Methods Development ✓
  - Task 3.1: Sensor Testing
  - Task 3.2: Installation of Test Sensors at METEC
  - Task 3.3: Document Method
  - Developed/validated belowground sensor system ✓
  - Constructed rural and urban pipeline testbeds capable of large (20 SCFH +) leaks ✓
- Task 4: METEC Experiments ✓
  - 150 experiments at METEC✓
  - Varied leak rate (10-200 slpm), weather, soil conditions (moisture, competing utilities), surface conditions (grass, snow/frost, pavement) ✓
- Task 5: Extend Results via Modeling ✓
  - Model validation✓
  - Conditions not available in the field ✓
  - Sensitivity study (1500 + model runs) ✓
- Task 7: Develop recommended practices on development and dissipation of leaks with significant flow rates ✓
  - Present findings that may inform practice and documentation ✓
    - Scenarios of deployment ✓
    - Surface concentration measurements ✓
    - Scientific understanding ✓
- Task 8: Final Reporting ✓

Summary of Project Deliverables/ Technology Transfer (Task 8)

- Controlled experimental data sets from METEC experiments publicly available on the Texas Data Repository and Dryad Data Repository
- Documented methods for measuring transient gas migration
- 12 Technical Advisory meetings
- Presentations of results to: industry, first responders, PHMSA safety groups, Pipeline Research Council International, American Gas Association, CSU/GTI CH_4 Connections Conferences, academic conferences (e.g. AGU/EGU)
- Undergraduate/graduate student/workforce training
- Guidance for improving RPs for large leak rates and transient gas migration events - - incorporation in training materials

- **12 peer reviewed papers (8 published, 4 in review)**
- **5 published data sets**
- **5 media articles**
- **23 conference presentations**

RPLUME Project - Outputs

Peer Reviewed Publications

1. Jayarathne, J. R. R. N., Kolodziej, R. S., Riddick, S. N., Zimmerle, D. J., & Smits, K. M. (2024). Flow and Transport of Methane from Leaking Underground Pipelines: Effects of Soil Surface Conditions and Implications for Natural Gas Leak Classification. **Environmental Science and Technology Letters**, ***Accepted***
2. Jayarathne, J. R. R. N., Kolodziej, R. S., Riddick, S. N., Zimmerle, D. J., & Smits, K. M. (2023). Influence of soil-gas diffusivity on expansion of leaked underground natural gas plumes and application on simulation efforts. *Journal of Hydrology*, *625*(PB), 130049. https://doi.org/10.1016/j.jhydrol.2023.130049
3. Mbua, M., Riddick, S. N., Tian, S., Cheptonui, F., Houlihan, C., Smits, K. M., & Zimmerle, D. J. (2023). Using controlled subsurface releases to investigate the effect of leak variation on above-ground natural gas detection. *Gas Science and Engineering*, *120*(July), 205153. https://doi.org/10.1016/j.jgsce.2023.205153
4. Cheptonui, F., Riddick, S. N., Hodshire, A. L., Mbua, M., Smits, K. M., & Zimmerle, D. J. (2023). Estimating the Below-Ground Leak Rate of a Natural Gas Pipeline Using Above-Ground Downwind Measurements: The ESCAPE-1 Model. *Sensors (Basel, Switzerland)*, *23*(20). https://doi.org/10.3390/s23208417
5. Lo, J., K.M. Smits, Y. Cho, G.P. Duggan, S.N. Riddick. 2023. Quantifying Non-steady State Natural Gas Leakage from the Pipelines Using an Innovative Sensor Network and Model for Subsurface Emissions -InSENSE, Environmental Pollution. *ENPO 122810.* https://doi.org/10.1016/j.envpol.2023.122810
6. Tian, S., S.N. Riddick, Y. Cho*, C.S. Bell, D.J. Zimmerle, K.M Smits. 2022. Investigating detection probability of mobile survey solutions for natural gas pipeline leaks under different atmospheric conditions. **Environmental Pollution**. https://doi.org/10.1016/j.envpol.2022.120027
7. Tian, S., K.M. Smits, Y. Cho*, S.N. Riddick, D.J. Zimmerle, A. Duggan. 2022. Estimating methane emissions from underground natural gas pipelines using an atmospheric dispersion-based method. **Elem Sci Anthr.** https://doi.org/10.1525/elementa.2022.00045
8. Riddick, S. N., Bell C., Duggan, A., Vaughn, T. L., Smits, K. M., Cho, Y., Bennett, K. E. and Zimmerle, D. J. (2021) Modelling temporal variability in the surface expression above a methane leak: The ESCAPE model. **Journal of Natural Gas Science and Engineering**. https://doi.org/10.1016/j.jngse.2021.104275
9. Cho, Y.*, K.M. Smits, N.L. Steadman, B.A.Ulrich*, C.S.Bell, D.J. Zimmerle, 2022, A closer look at underground natural gas pipeline leaks across the United States, **Elementa: Science of the Anthropocene**, https://doi.org/10.1525/elementa.2021.00095
10. Tian, S., S.N. Riddick, M. Mbua, Y. Cho*, D.J. Zimmerle, K.M. Smits. 2022. Improving the efficacy of leak survey methods using 3D plume measurements. ***In review***
11. Riddick, S. N., Cheptonui, F., Tian, S., Jayarathne, J. R. R. N., Mbua, M., Smits, K. M. and Zimmerle, D. J. Reconciling above and below ground methane concentration measurements for subsurface emissions of wet and dry natural gas. ***In preparation***
12. Jayarathne, J. R. R. N., Kolodziej, R. S., Riddick, S. N., Zimmerle, D. J., & Smits, K. M. (2024). Differential Subsurface Methane Migrations Influenced by Surface and Subsurface Structural Complexities. ***In preparation***

ENVIRONMENTAL Science & Technology LETTERS

pubs.acs.org/journal/estlcu Letter

Flow and Transport of Methane from Leaking Underground Pipelines: Effects of Soil Surface Conditions and Implications for Natural Gas Leak Classification

Navodi Jayarathne,* Daniel Zimmerle, Richard S Kolodziej, Stuart Riddick, and Kathleen M Smits

Cite This: https://doi.org/10.1021/acs.estlett.4c00039 Read Online

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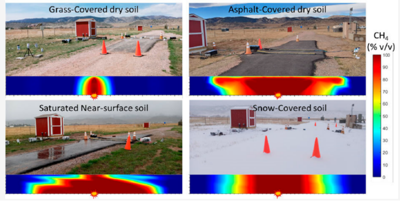

Journal of Hydrology 625 (2023) 130049

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

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Research papers

Influence of soil-gas diffusivity on expansion of leaked underground natural gas plumes and application on simulation efforts

J.R.R. Navodi Jayarathne [a,*], Richard S. Kolodziej [a], Stuart N. Riddick [b], Daniel J. Zimmerle [b,c], Kathleen M. Smits [a]

Environmental Pollution 312 (2022) 120027

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

ELSEVIER

Investigating detection probability of mobile survey solutions for natural gas pipeline leaks under different atmospheric conditions☆

Shanru Tian [a], Stuart N. Riddick [b], Younki Cho [b], Clay S. Bell [b], Daniel J. Zimmerle [b,c], Kathleen M. Smits [d,*]

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Task 2: Survey existing first responder operational practices

Objectives:

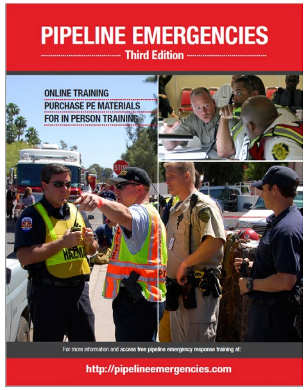
- Understand how environmental variability is accounted for in first responder's protocols and guidance documents
- Analyze existing protocols to build the team's understanding of leak response procedures
- Guide project execution
- Assist in incorporating study results into future RP guidance

Activities:

- Reviewed emergency response guidelines, fire authority operational directives on hazardous material operations, HazMat modeling documents, fire department emergency planning guides, PHMSA reports (8 main & 10 secondary source documents)
- Analysis of PHMSA Pipeline Incident Flagged Files over past 10 years
- Discussions with first responders/industry on operational practice

Task 2: First Responder Document Review – current understanding

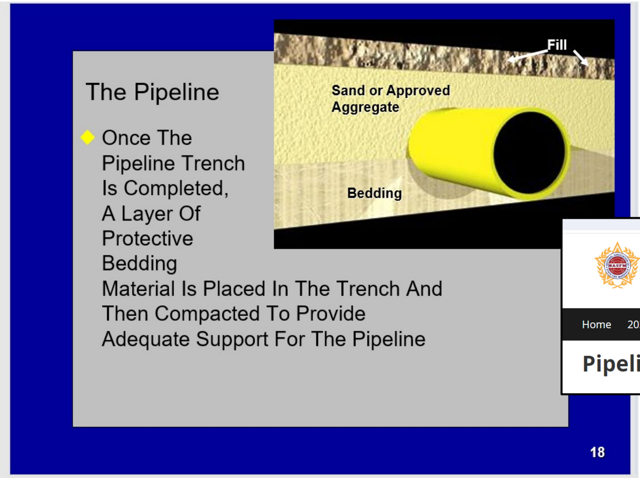
Statements & figures acknowledging impact of <u>belowground gas behavior</u>, <u>weather and gas type</u> limited



Street Smart Tips

Always remember these street smart tips when dealing with a natural gas pipeline incident:

1. Natural gas is lighter than air and will rise.
2. Natural gas can be trapped under asphalt, concrete, or frozen ground and move laterally from its source in underground conduits, casings, and right-of-ways.
3. Underground leaks of natural gas will follow the path of least resistance. Soil that has been disturbed by excavation will allow for the easier passage of natural gas. In addition, certain soils may cause the mercaptan odorants to be "scrubbed" from the natural gas.



Pipeline Emergencies 101
Internet Training v10

Example statements:

"Natural gas can be trapped under asphalt, concrete, or frozen ground and move laterally from its source in underground conduits, casings, and rights of ways". (Blankinship et al., 2008, *National Association of State Fire Marshals*)

"Natural gas leaks can produce a situation where product may filter through soil, follow storm drains, sewers, water lines, or other utilities and then emerge some distance from the actual leak site." (NVFC and USDOT PHMSA (2018), ICS-204)

"One concern is the ability of gas leaks to migrate through the soil, follow water and sewer lines, or collect in storm drains." (NVFC and USDOT PHMSA (2018), ICS 215A)

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Task 2: First Responder Document Review – current understanding

- **The first priority is to protect the public, which is achieved by shutting down the gas, establishing safe zone and methodically checking houses, confined & open spaces for explosive concentrations of methane**
- **With a better understanding of how environmental factors include gas spread, responders could improve evacuation zone estimates**

Zoning

- Confined space = 10% LEL
- Open space = 20% LEL

POUDRE FIRE AUTHORITY OPERATIONAL DIRECTIVE

HAZARDOUS MATERIALS OPERATIONS

HOT ZONE

7. The Hot Zone is the area most affected by the hazardous materials release and also the beginning point of the contamination reduction corridor. When available, the use of Threshold Limit Values (TLV) should be used to determine the boundaries of the Hot Zone.

8. The Hot Zone should be distinguished by the use of red fire line/Hot Zone barrier tape or other recognizable material. The location of the safe refuge area should be located near the entrance to the decontamination (decon) corridor and **shall** be monitored to ensure that further contamination of citizens and responders is not occurring.

9. Hot Zone guidelines

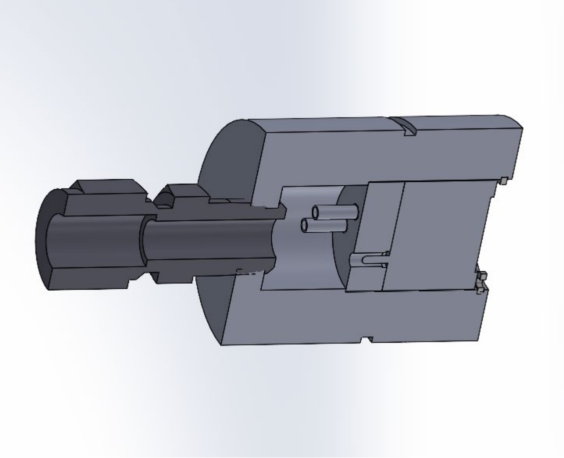
   - Toxicity - Readings greater than the TLV/TWA (Time Weighted Average) or PEL (Permissible Exposure Limits) exposure values.
   - Flammability - If dealing with a confined space or indoor release, the zone determination level is 10 percent of the lower explosive limit. If dealing with an open-air release, the zone determination level is 20 percent of the lower explosive limit.
   - Oxygen – Oxygen-deficient atmospheres are those with readings of 19.5 percent oxygen or less. Oxygen-enriched atmospheres are those with readings of 23.5 percent oxygen or higher. In evaluating oxygen-deficient atmospheres, consider that the available oxygen may be influenced by the contaminants present.

Task 3.1: Measuring methane concentration in the soil

- Measures between 100 ppm and 100% methane by volume
- Operating conditions
  - Temperatures between -40 °C and 75 °C
  - Relative humidity between 0 and 99%
- Low power 32 mA
- Small volume 5 cm^3
- Sensors installed into testbed in a bespoke aluminum holder
- Sensor inserted into the soil to measure methane concentration at different depths

Sensortech SGX INIR-ME100 sensors

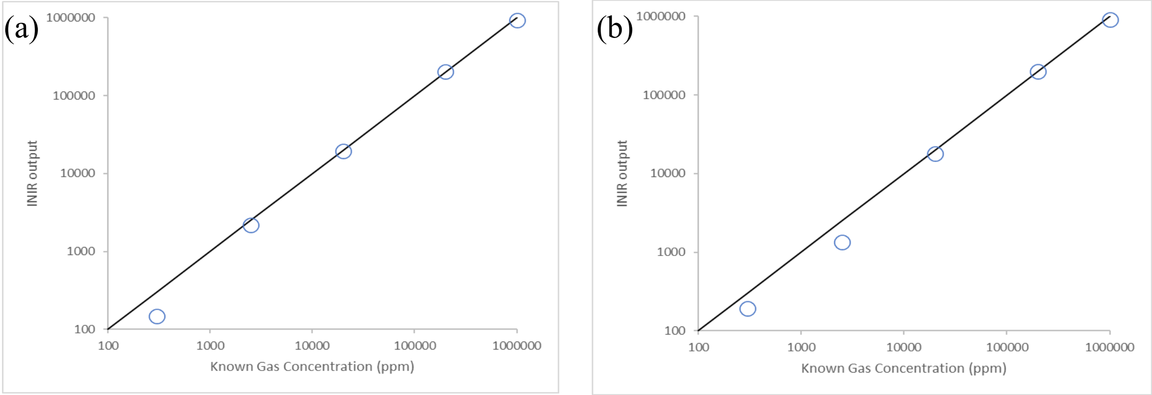
Sensor casing design



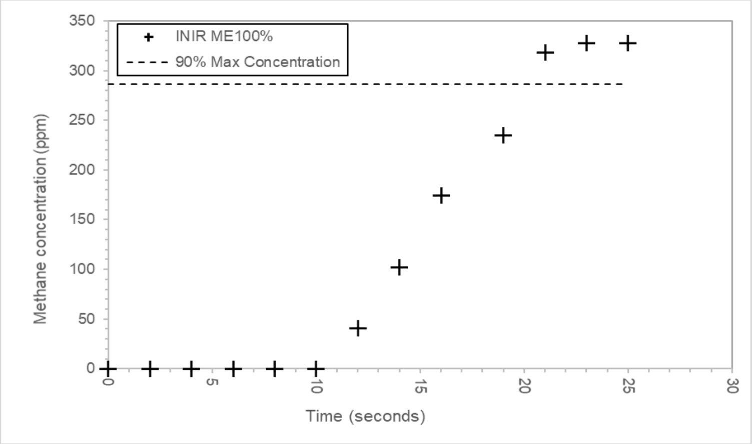
Task 3.1: Measuring methane concentration in the soil

Lab Testing of INIR-ME 100% sensor

Six-point calibration of the SGX INIR-ME 100% sensor in (a)air and (b) dry soil

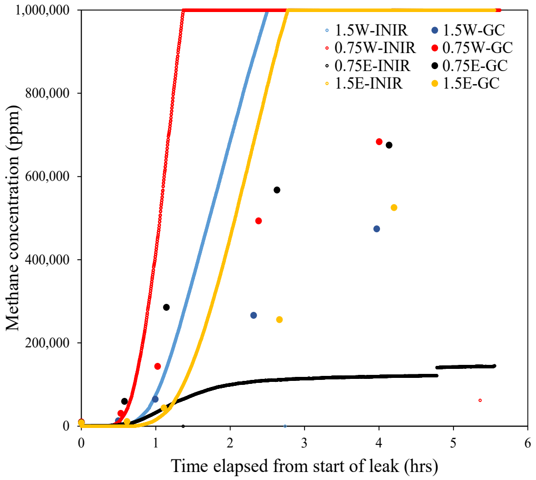


Response rate of the INIR ME100% sensor between 0 and 300 ppm



Field Testing of INIR-ME 100% sensor

Methane concentration by INIR sensors and Gas Chromatography at different measuring locations



Data Acquisition (DAQ) Unit placed at the testbed during experiment.

Jayarathne et al., 2022, *PRCI Proceedings*

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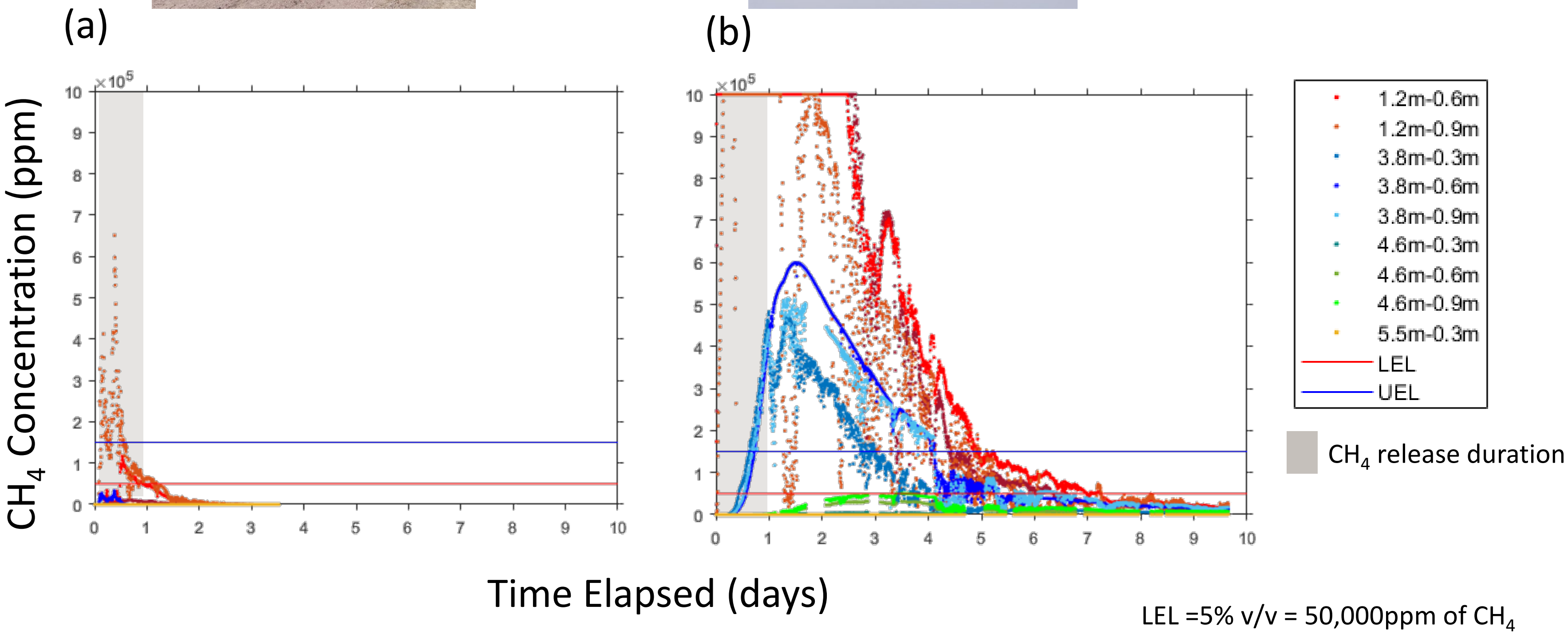
Sample subsurface data (effect of surface cover)

Grass/ Dry topsoil
1 day release @ 11 SLPM (23 SCFH)

Snow/Frozen topsoil
1 day release @ 11 SLPM (23 SCFH)



LEL =5% v/v = 50,000ppm of CH_4
UEL = 15% v/v = 150,000ppm of CH_4

Snow/ice surface conditions

- NG spreading up to 5 times farther than dry grass covered conditions in similar time frames
- CH_4 concentrations exceeded LEL over 3.2 m (10.5 ft) from the leak location within 6 hours of the leak initiating
- CH_4 continued to migrate away from leak point after the leak was stopped at concentrations exceeding LEL
- LEL levels persisted 8 days after the leak was stopped

Jayarathne et al., 2022, *METEC Research Alert*
Zimmerle et al., 2022, *METEC Research Alert*
Jayarathne et al., 2024, *Env. Sci. Tech.*

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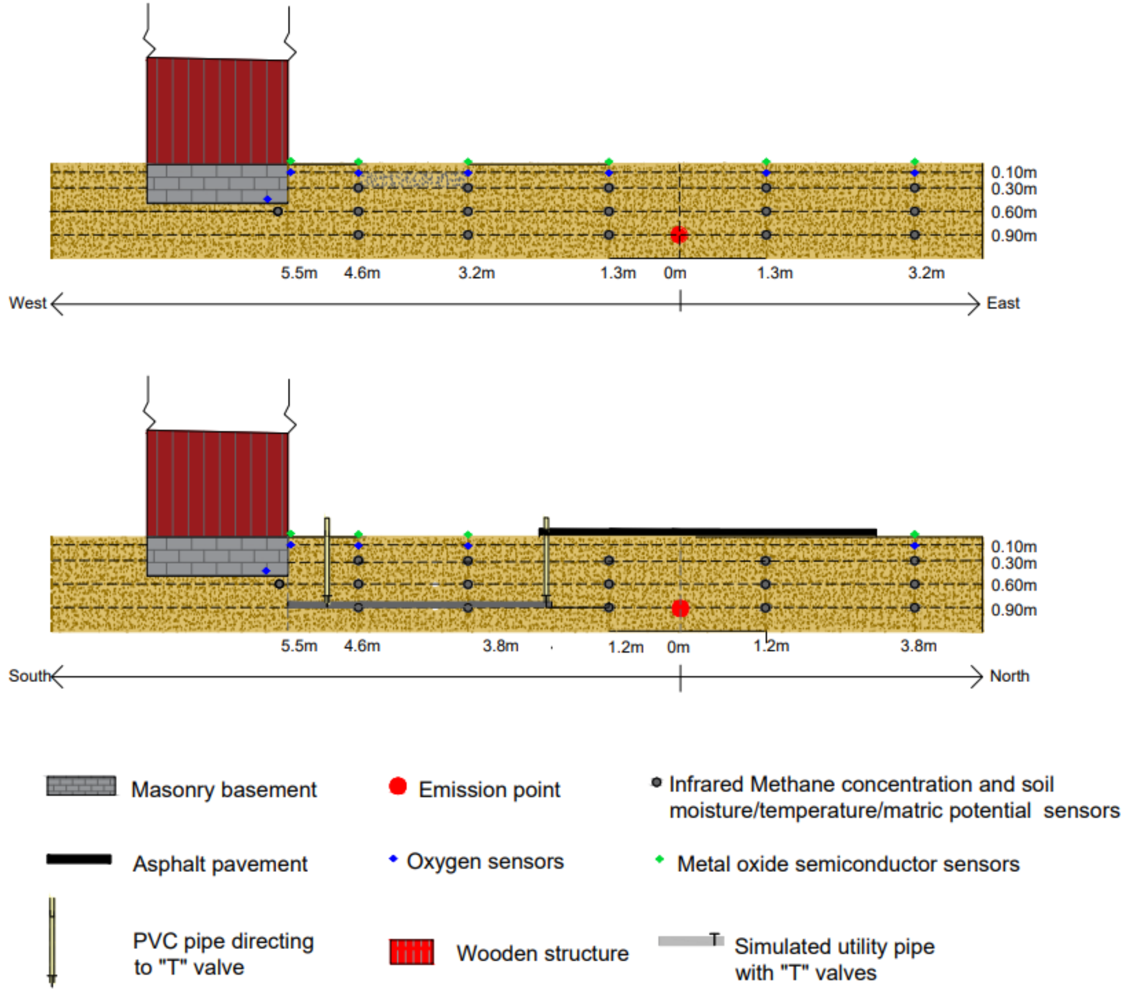
Task 3.2 Urban testbed design and construction

METEC urban testbed, Ft Collins, CO



- Custom designed testbed simulating urban/suburban and rural environments
- Controlled leak rates from 10 – 200 slpm
- Continuous monitoring for surface and subsurface CH_4 and environmental parameters

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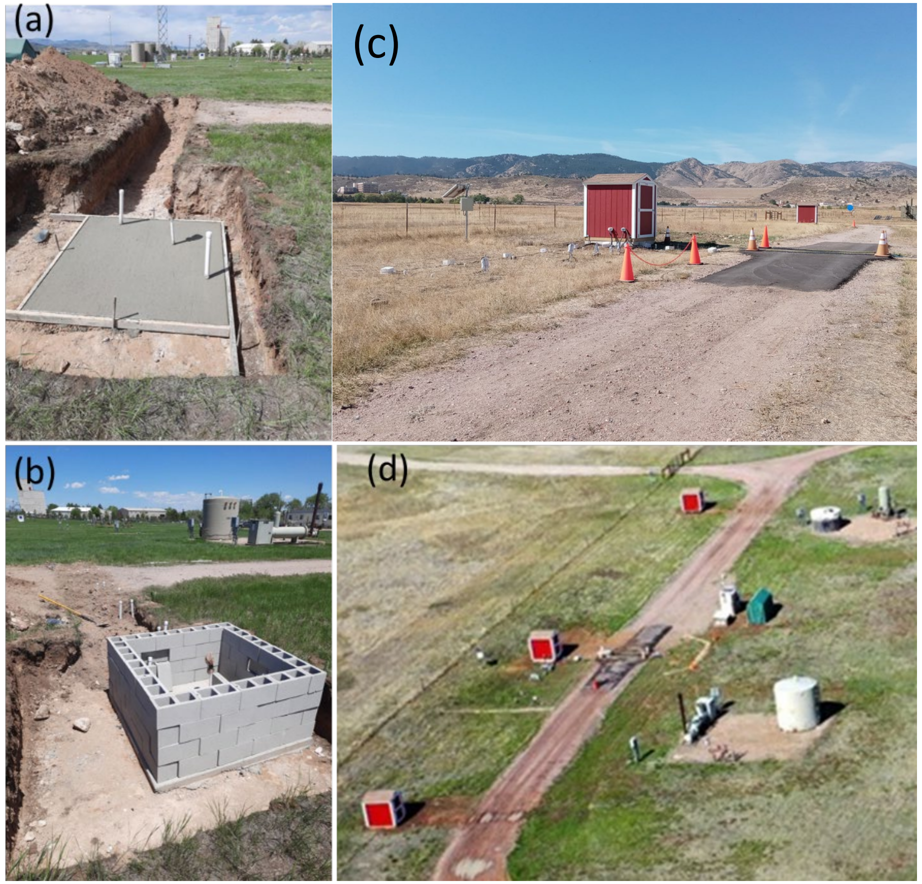
Jayarathne et al., 2022, ***PRCI Proceedings***

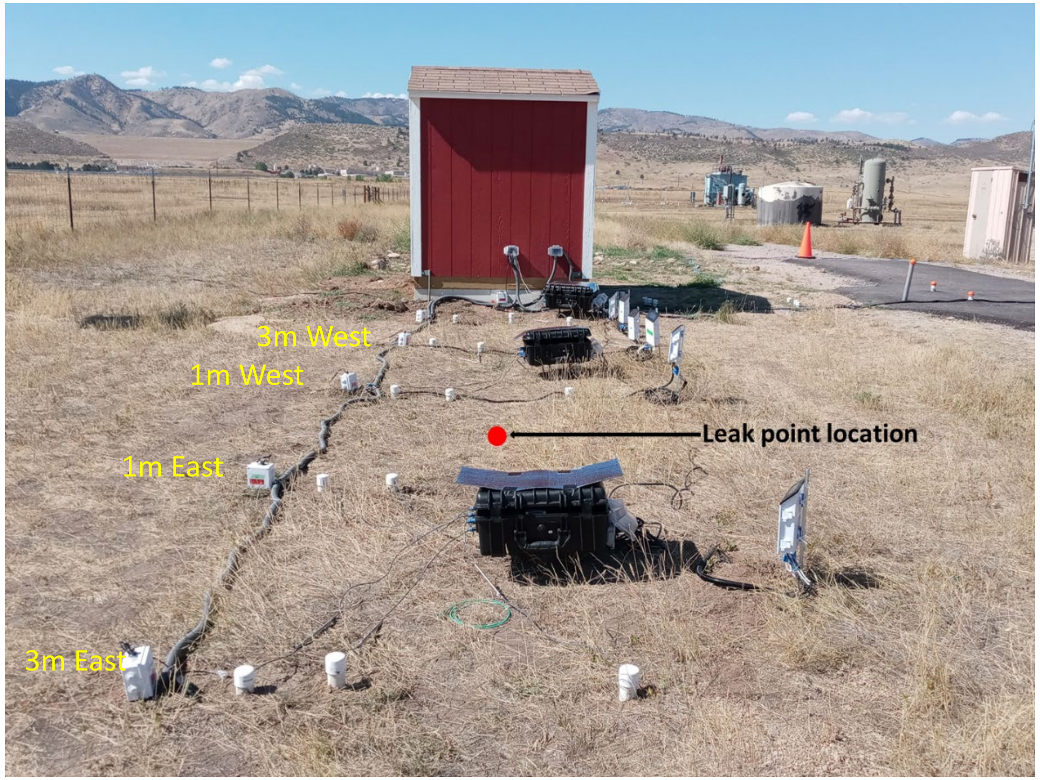
Task 3.2 Urban testbed design and construction

METEC urban testbed, Ft Collins, CO



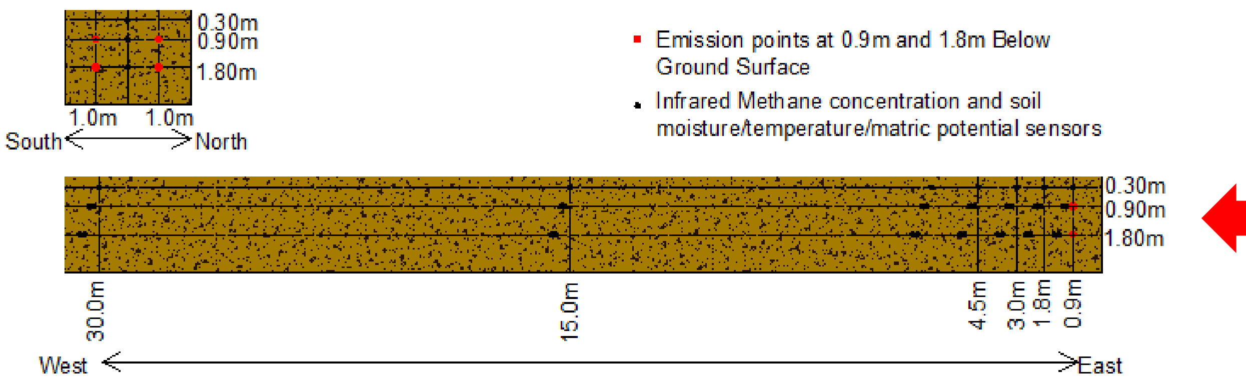
(a) Concrete slab construction
(b) Basement construction
(c) Asphalt road
(d) 3 Sheds representing – concrete slab, basement, and a crawlspace foundations

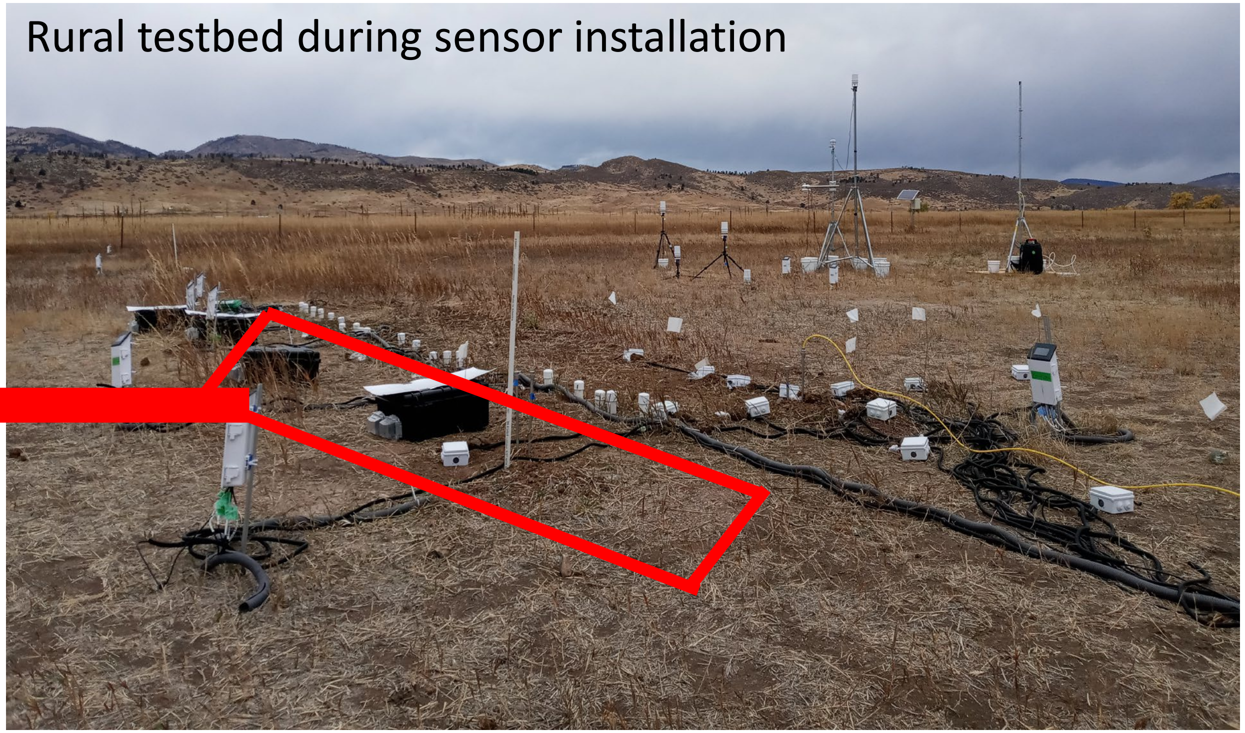
Sensor layout



Task 3.2 Rural testbed – Subsurface layout and sensors

METEC urban testbed, Ft Collins, CO





- Environmental sensors (0.3 m, 0.6m, 1.8 m)
- INIR sensor (0.3 m)
- INIR sensor (0.9 m)
- INIR sensor (1.8 m)
- Leak point (0.9 m , 1.8 m)

Sensor name	Description
Environmental sensors	Soil moisture-TEROS 10 Metric potential-TEROS11 Soil temperature-TEROS21
INIR sensor	SGX Integrated Infrared (INIR) Sensor

Jayarathne et al., 2022, *PRCI Proceedings*

Task 4 – Controlled Field Experiments

- Conducted 24-month experimental series at METEC to cover diverse weather conditions, surface, and subsurface scenarios
- Industry support and feedback throughout experiments
- Total of 150 experiments with leak rates from 10 – 200 slpm (20 – 400 scfh).

a) Placement of CH_4 concentration sensors
b) Opening the belowground valve to simulate an open pipe running towards house
c) Placement of AM2 mattings to create a surface cover
d) Testbed preparation for snow experiments
e) Poudre Fire Department support for testbed watering (Heavy rainfall experiments)

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Task 4 – Controlled Field Experiments

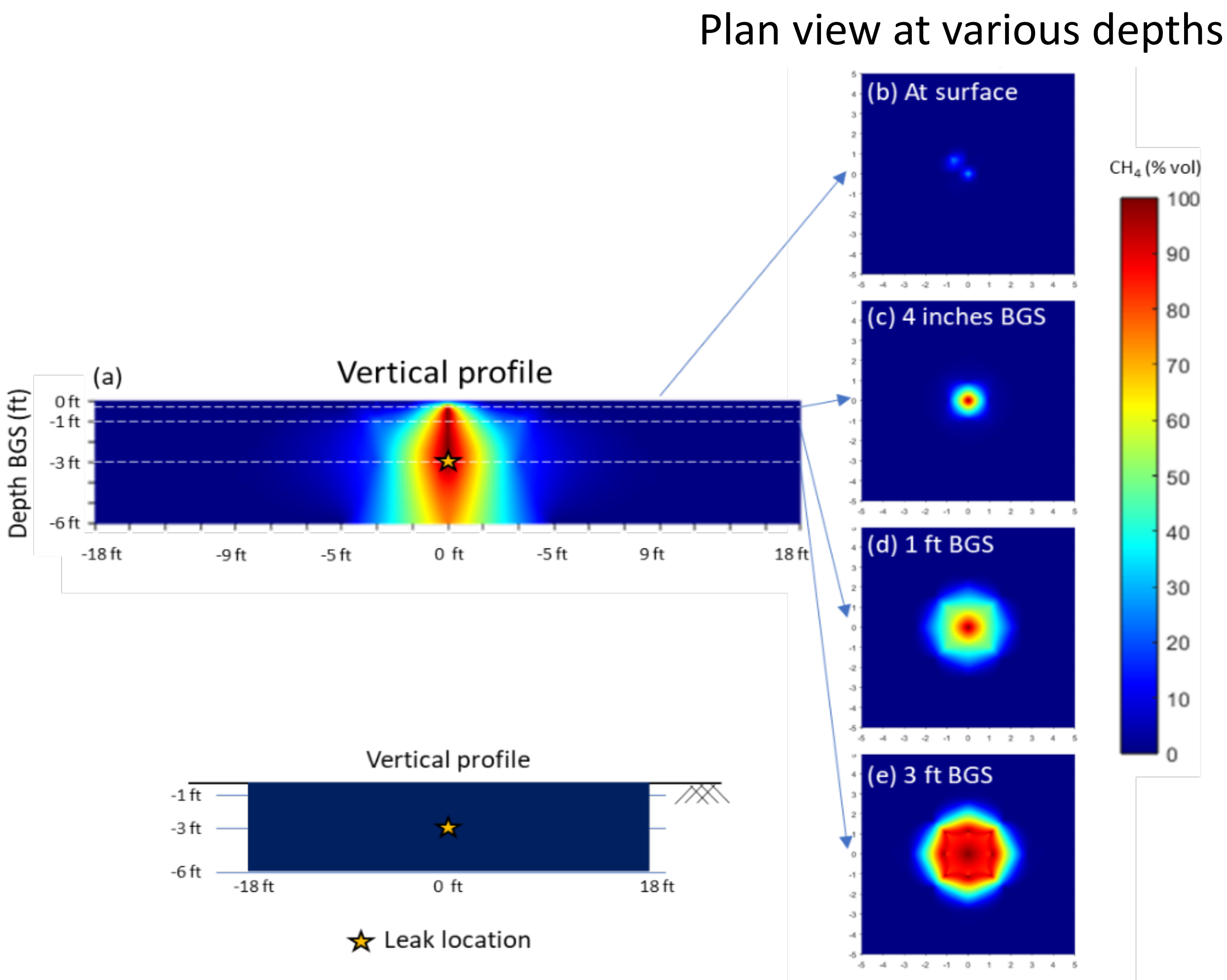
Experimental Variables

Parameters	Range tested
NG Leak rate	10 slpm (21scf) – Base case characteristic
	35 slpm (71 scfh)
	50 slpm (102 scfh)
	100 slpm (212 scfh)
	200 slpm (424 scfh)
Soil moisture	25% by volume – Base case characteristic
	40% by volume
Surface conditions	Uncovered – Base case characteristic (Dry-Grass)
	Asphalt cover (Asphalt-Dry)
	Moisture cap (Grass-Moist)
	Snow cover (Grass-Snow)
	Asphalt surrounded by moisture cap (Asphalt-Moist)
	Asphalt covered with snow (Asphalt-Snow)
Subsurface complexity	Undisturbed dry soil – Base case characteristic
	Disturbed dry soil with a buried Pipe (Trench-Pipe)
	Disturbed moist soil (Trench-Moist)
	Disturbed moist soil with a buried Pipe (Trench-Pipe)

- More than 150 field-scale experiments
- Continuous measurements for 24 months (August 2021 – August 2023)
- Industry support and feedback
- Base case – 10 slpm (20 scfh) leak under unpaved undisturbed dry loam soil conditions
- Comparisons relative to the base case

Sample subsurface results & analysis

Vertical profile & plan views of CH_4 for a 20 scfh NG leak under dry soil conditions



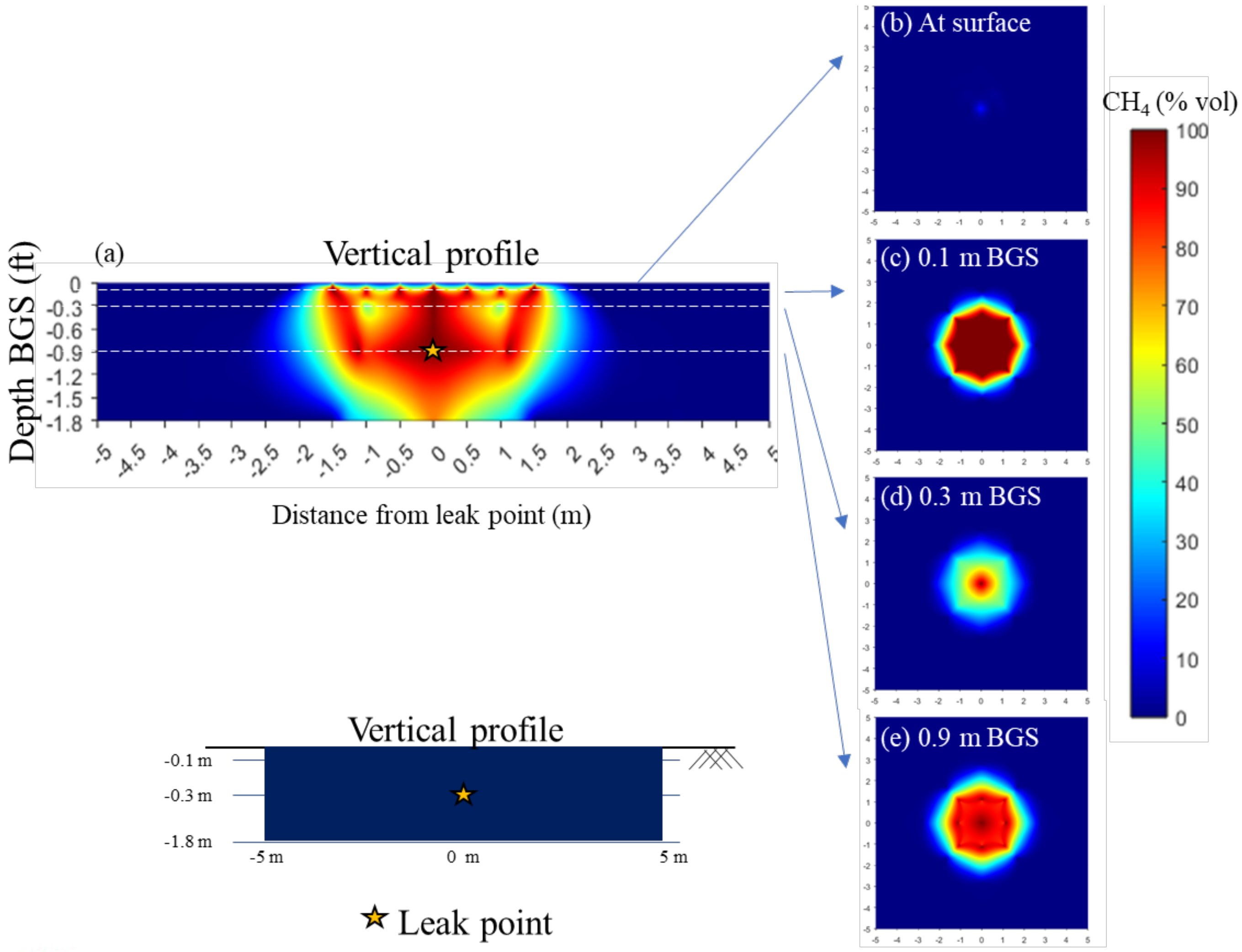
What is detected at the surface using CGI is not representative of what is present belowground

Plume radius @ leak depth > 4 x's surface radius

Sample subsurface results & analysis

Vertical profile & plan views of CH_4 for a 20 scfh NG leak under <u>wet</u> soil after a heavy rain event

Plan view at various depths



Surface concentrations as observed using a CGI

Very poor indication from the surface

0.1 m (4 inch)

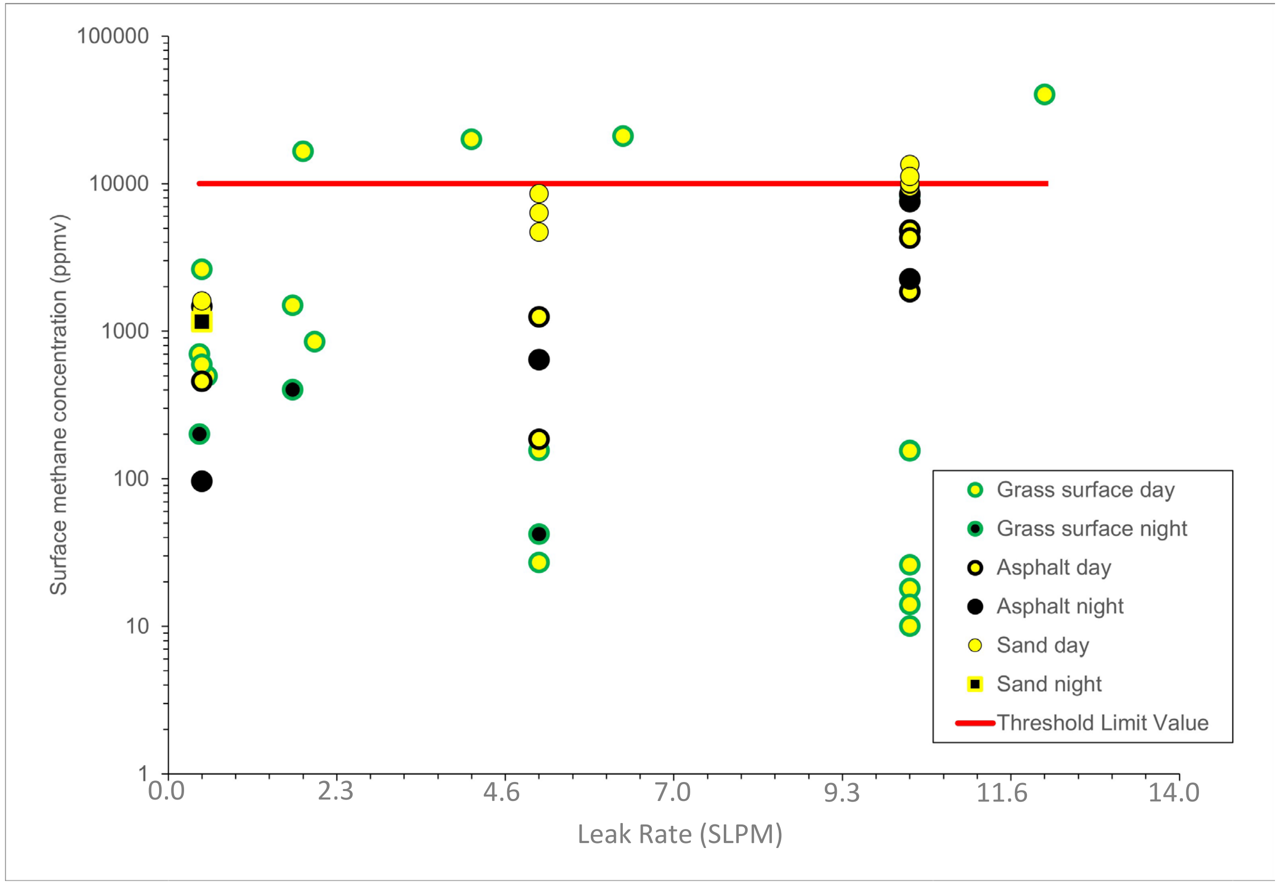
but a lot of gas at 4” depth

0.3 m (1 ft)

0.9 m (3 ft)

Plume radius @ leak depth > 16 x’s surface radius

Variation of surface concentration with leak rate



- Comparison of 46 experiments that measured concentrations directly at the surface
- Methane concentration measured on the surface varies with daily changes in weather and surface condition (e.g. asphalt, grass)
- **Current practice:** Hot zone (300' for gas, 150' for liquids) should be established is CH_4 concentration measured in the air by a four-gas monitor
  - Threshold Limit value (TLV) of 10% LEL in enclosed spaces (5000 ppm)
  - TLV of 20% LEL in open spaces (10,000 ppm)

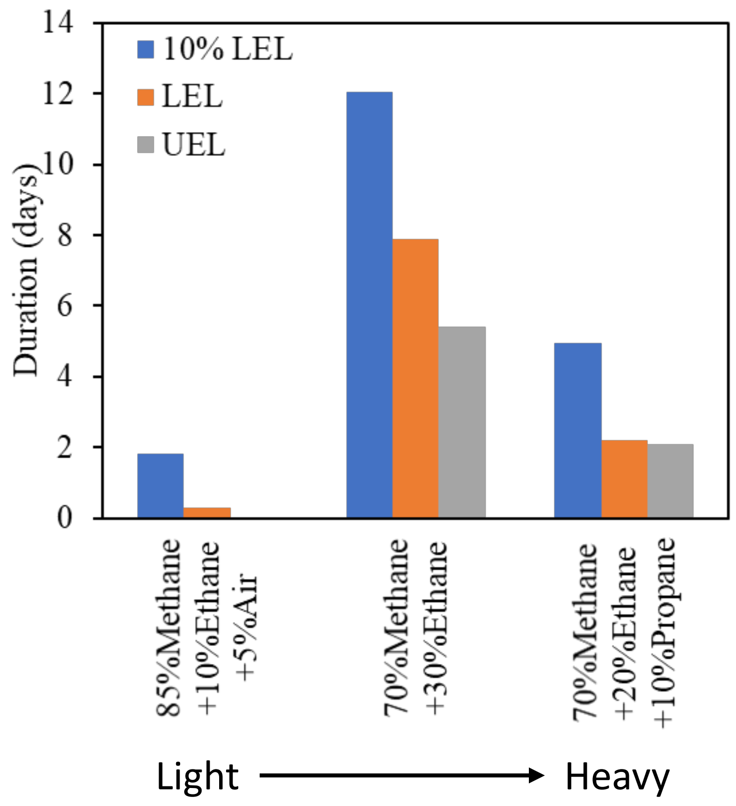
Recommended practice:

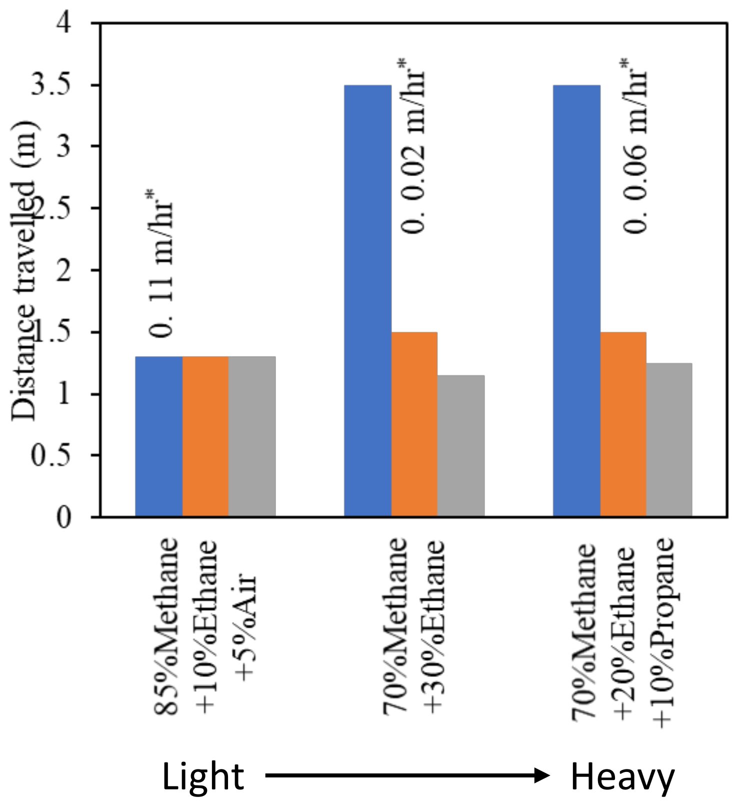
- Consider lower Threshold Limit values
- Consider establishing hot zone even if the TLV of 20% LEL has not been exceeded for the following cases
  - Water logged soil
  - Snow Cover
  - Ice
  - Asphalt
  - High winds
  - Nightime
  - Very sunny conditions
- Hot zone (300' for gas and liquids) should be established is CH_4 concentration measured in the air by a four-gas monitor.

Effect of Gas Composition

Higher ethane and propane increases migration distance by 3 times and retention duration by ~6 times

Explosive limit concentration duration and distance traveled for various gas compositions for a leak rate of 10 SLPM

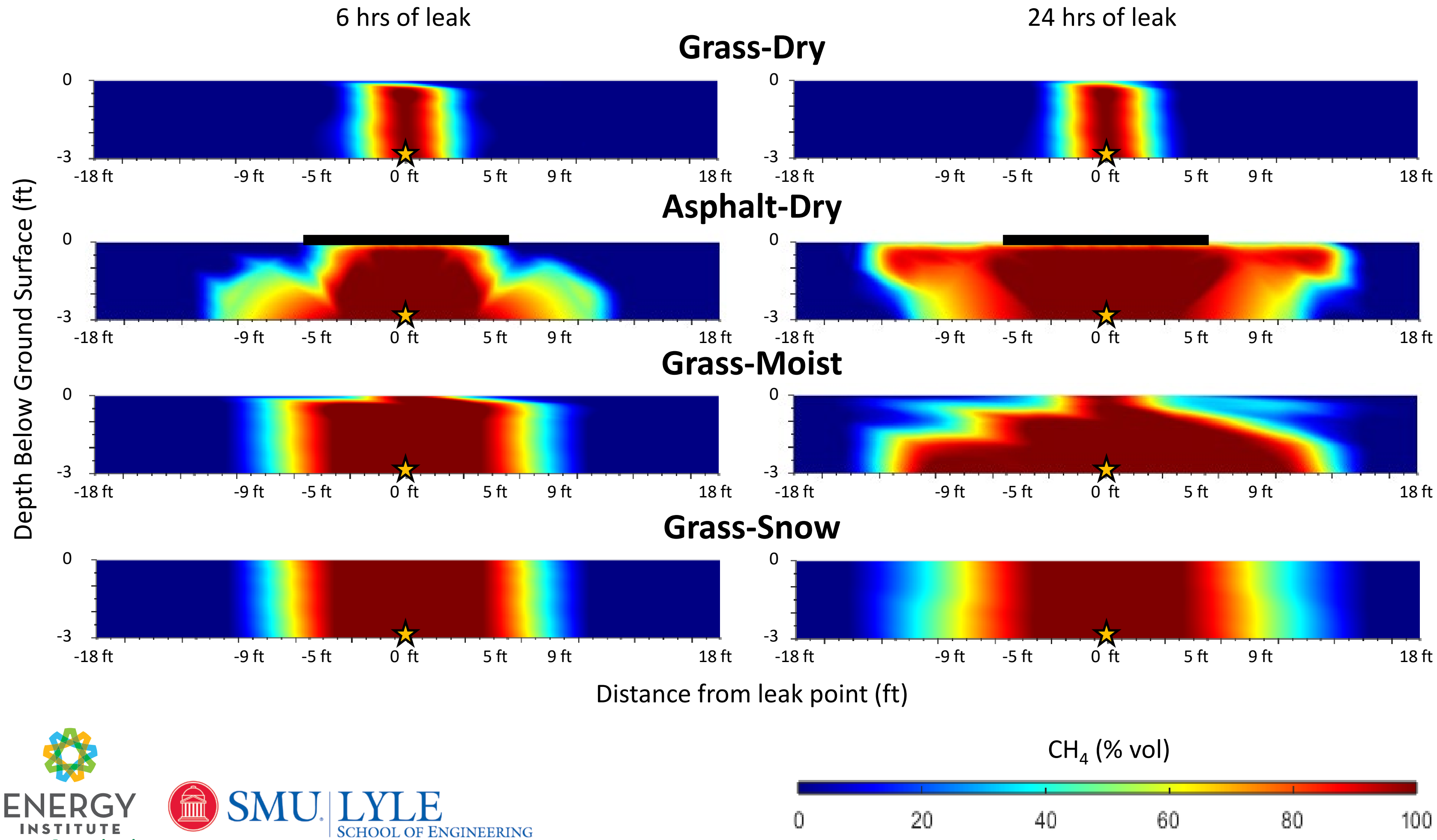




LEL = 50,000 ppm (5% CH_4 V/V)

UEL = 150,000 ppm (15% CH_4 V/V)

Surface cover – impact on migration distance and time



Max Migration Distance*	Time to Reach Max Distance
< 5ft	2.5hrs
3 x Grass-Dry	7 x Grass-Dry
4 x Grass-Dry	13 x Grass-Dry
4 x Grass-Dry	6 x Grass-Dry

*Magnitudes are specific to METEC soil

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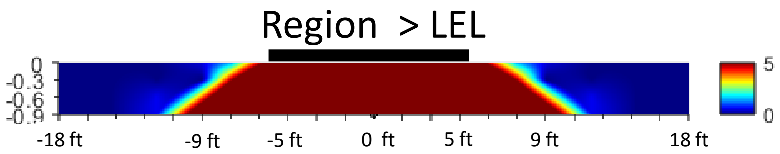
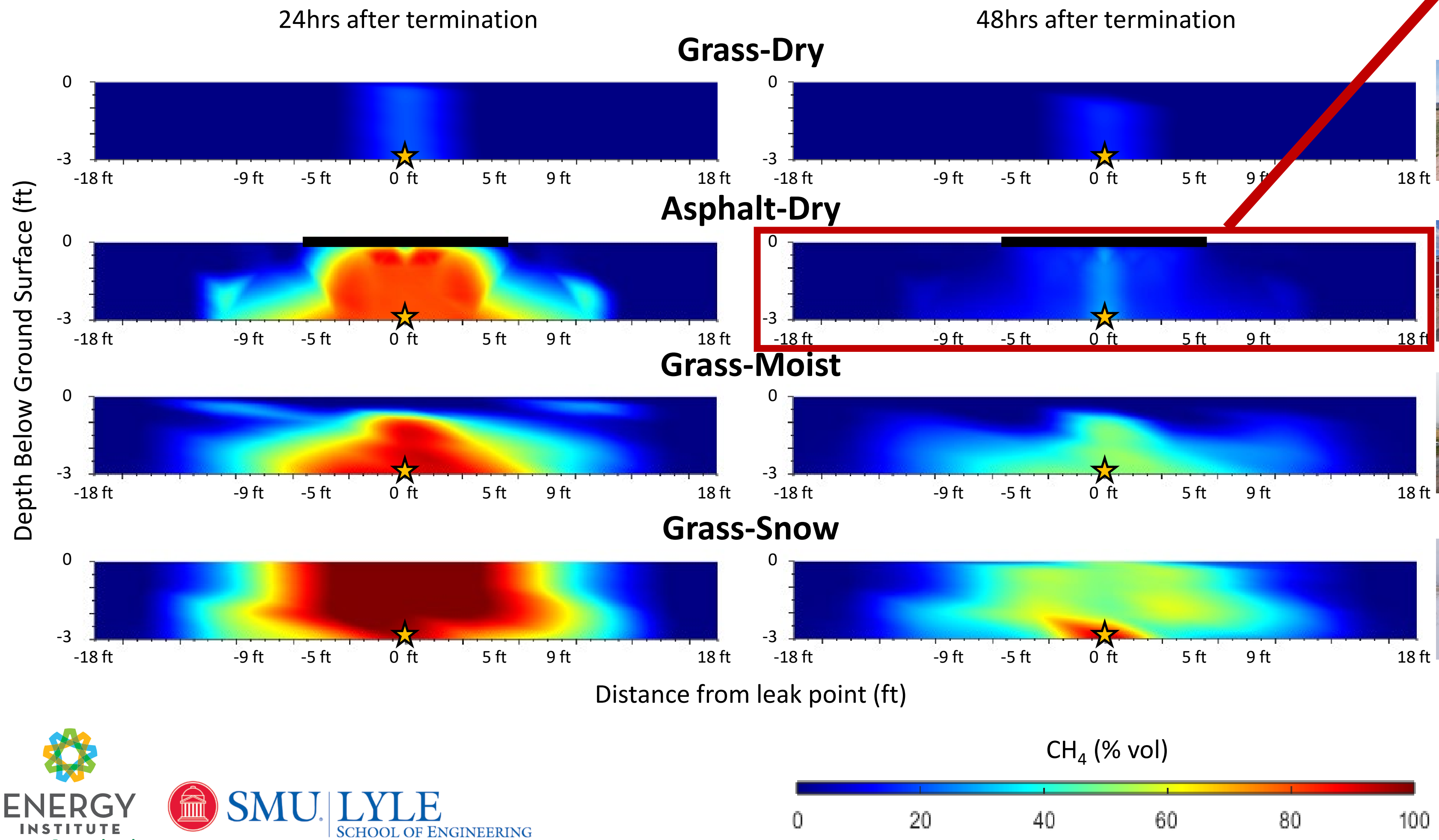
Jayarathne et al., 2024, *Env. Sci. Tech.*

Leak termination



- Gas retention time under no surface cover is ~1 day but increases when the surface complexity increases.
- Gas continues to migrate outwards (albeit slowly) after leak termination.



Max Migration Distance*	Duration to Vent
< 5ft	< 24hrs
3 x Grass-Dry	7 x Grass-Dry
4 x Grass-Dry	5 x Grass-Dry
4 x Grass-Dry	5 x Grass-Dry

*Magnitudes are specific to METEC soil

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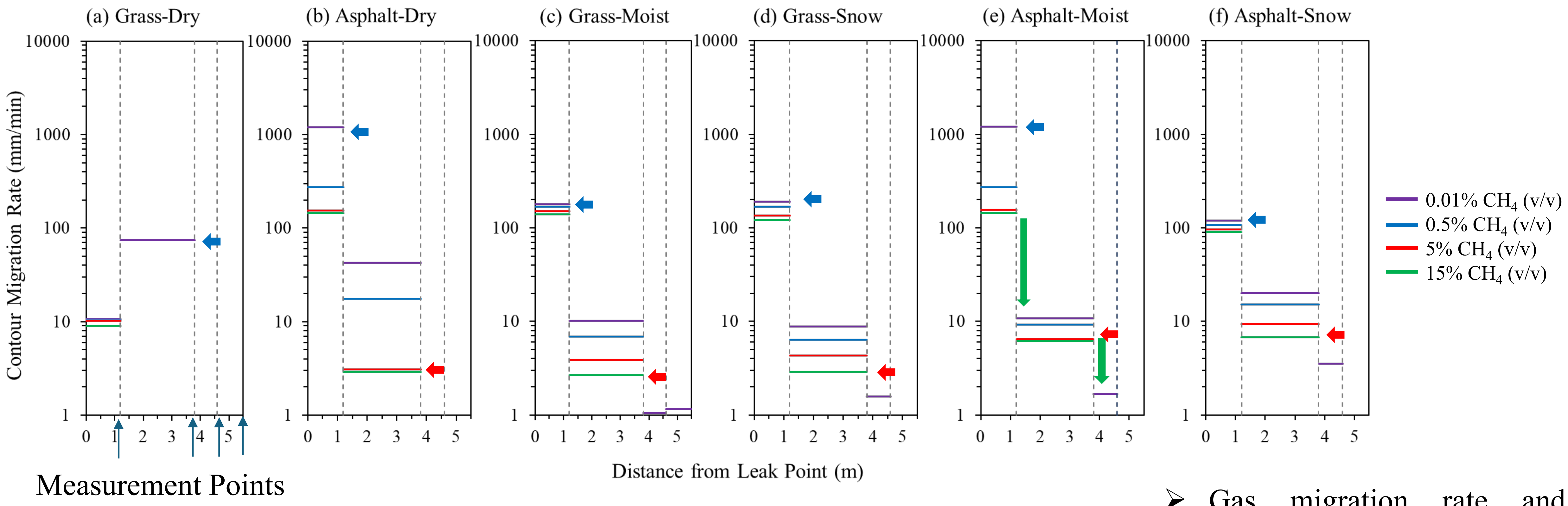
Migration rate varies based on the concentration of interest

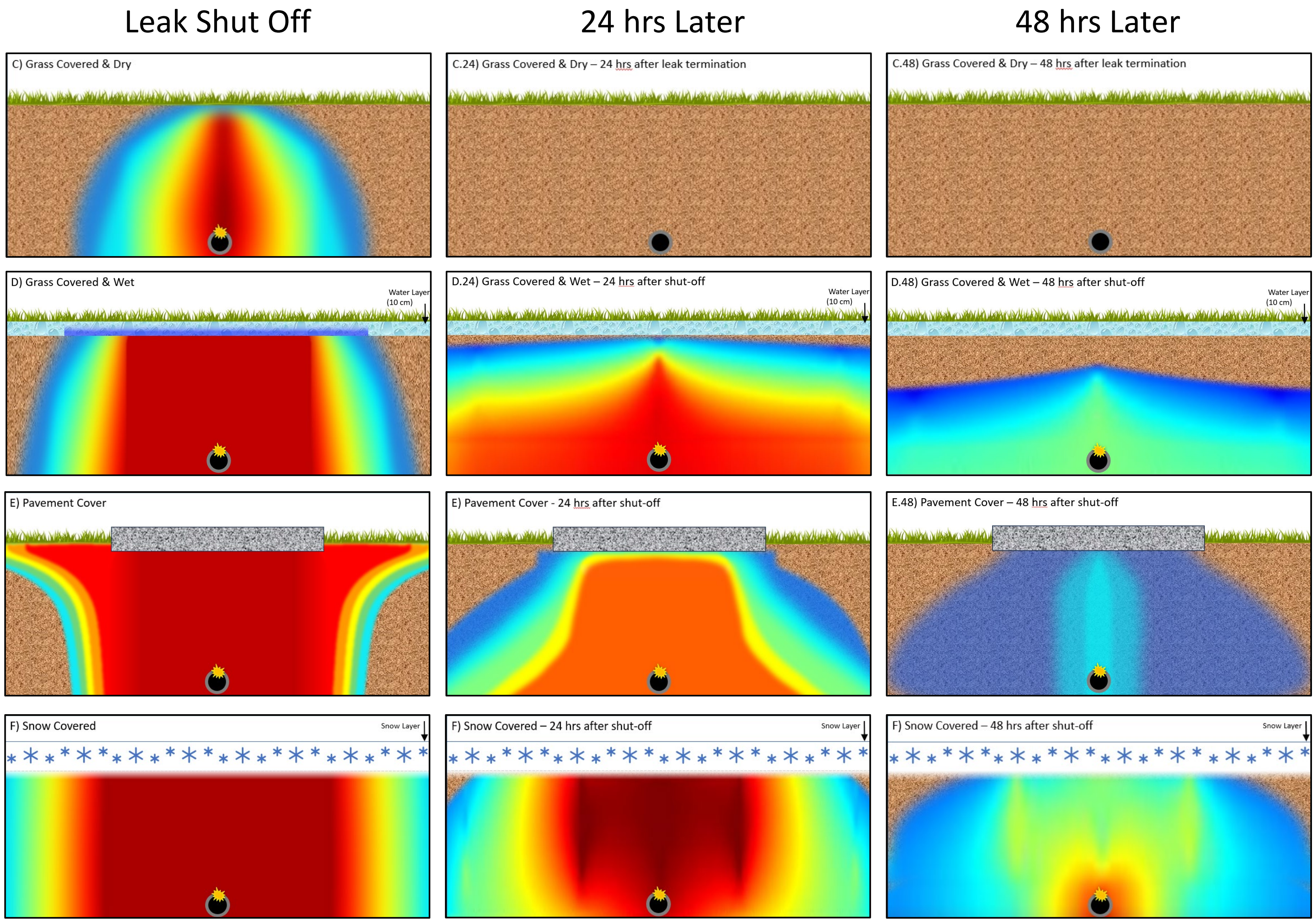


- ➢ Gas migration rate and extent vary based on the concentration profile of interest

- ➢ Migration rate diminishes as the distance from the location increases
- ➢ Large variation in 0.01% and 0.5% CH_4 (v/v) (small concentration) contour migration rates
- ➢ Small variation in 15% CH_4 (v/v) (high concentrations) contour migration rates

Example from the FR Report: Leak termination

- Even when the gas source is terminated (i.e. shut off or repaired), gas will remain in the soil below ground and continue to move outwards until enough time has passed for full dissipation.
- Surface cover, moisture, and temperature impact gas concentrations after leak shut-offs.



Cartoon figure (not real data)

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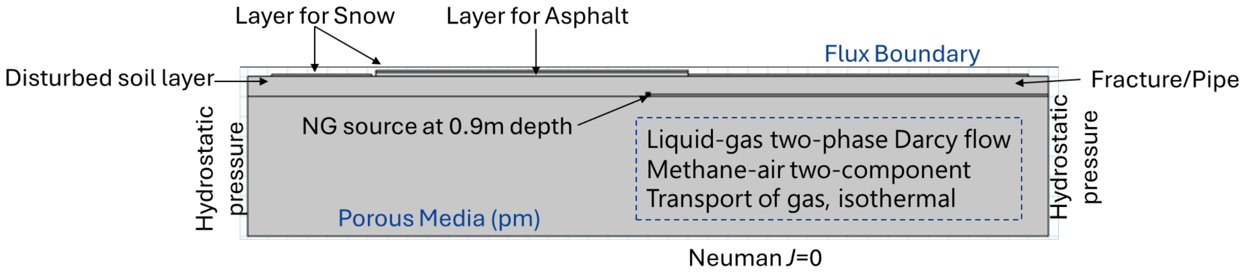
Task 5 Numerical Modeling

Objective: Extend field experimental understanding of belowground migration and rate in different complex leak environments using numerical simulations

Simulation Domain



Porous media (pm)

Two-phase: liquid water and gas (incompressible flow)

Two components: methane and air

Scale of the 2D vertical domain:

Width: 40 m

Height: 8 m

Gao et al., 2021, *Elementa, Sci. Anthro.*
Gao et al., 2021, *Water Resour. Res.*
Jayarathne et al., 2023, *J. of Hydrology*
Jayarathne et al., *2020, Soil Sci. Soc. J.*
Vanderborght, Smits et al., *2017 Water Resour. Res.*

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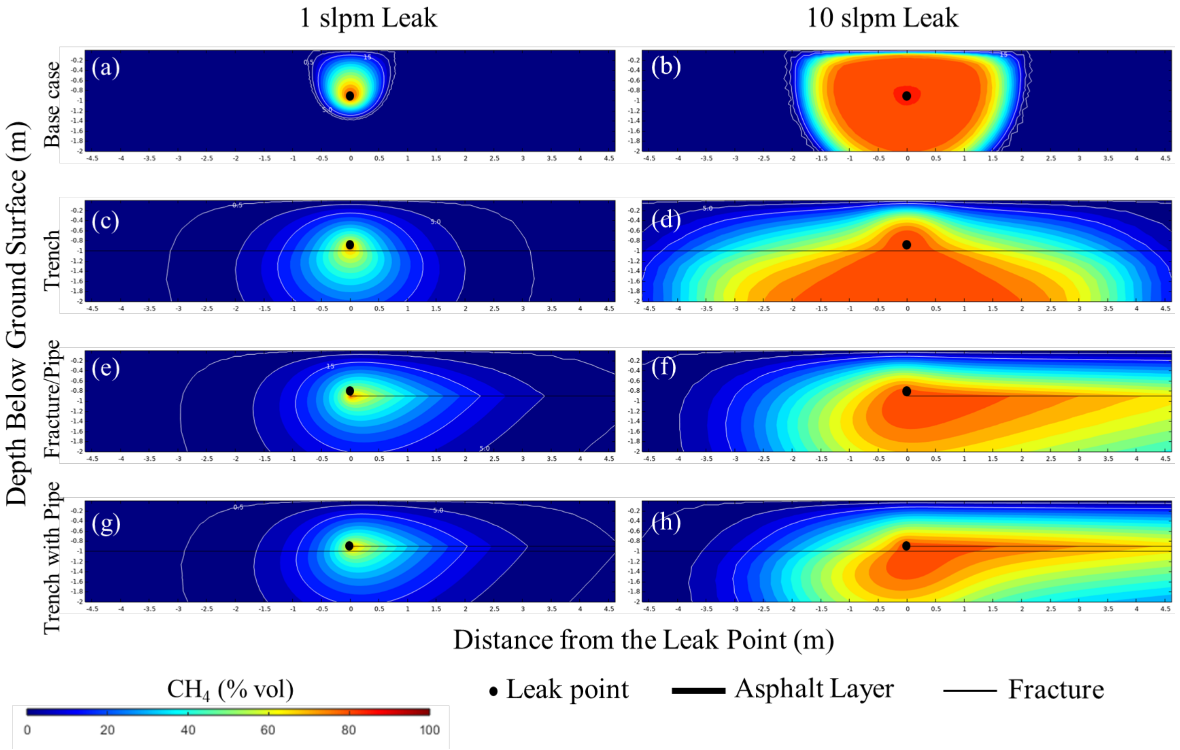
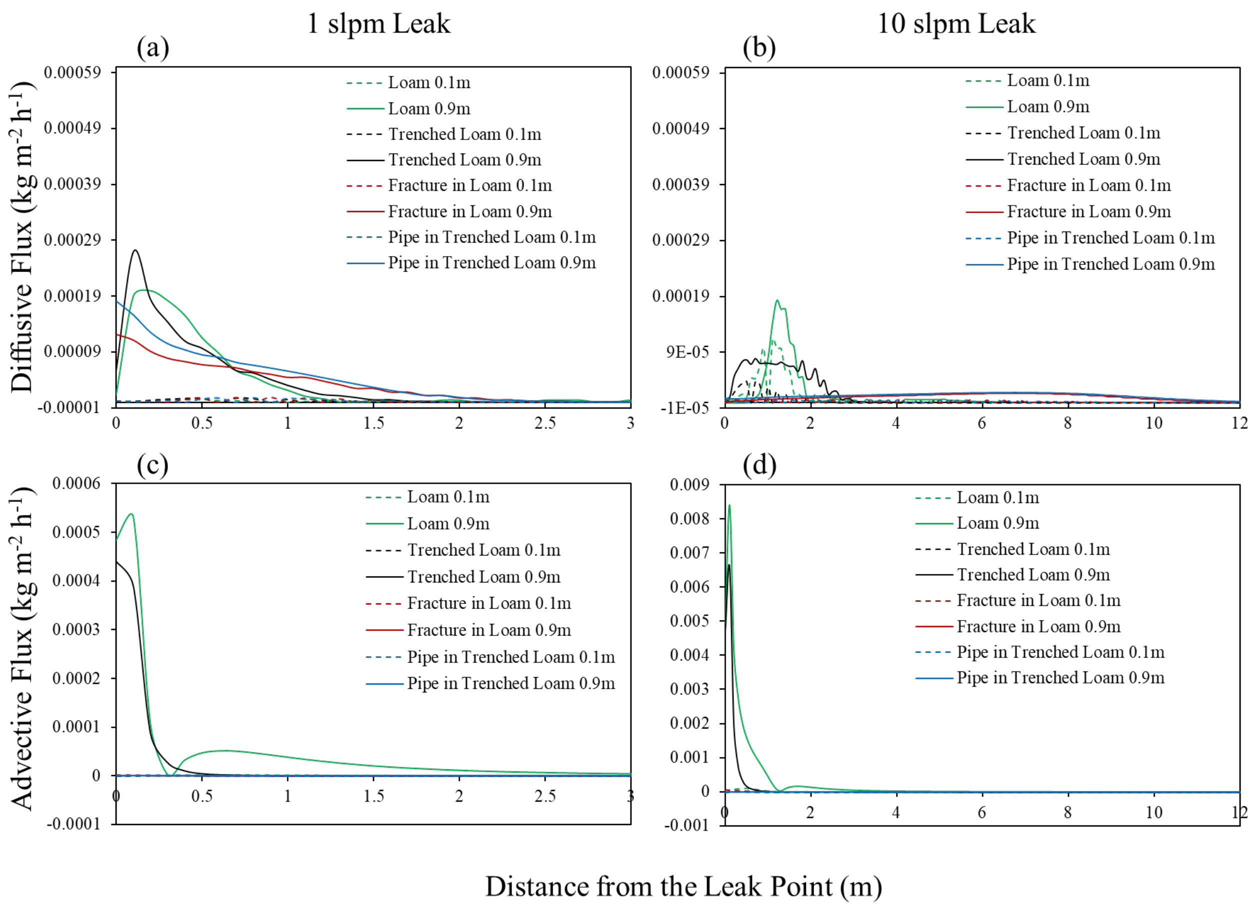
Selected Surface, Subsurface Complexities

No	Simulation Scenario name	Complexity description	Complexity Category
1	Dry Undisturbed Loam	Unpaved undisturbed dry loam soil	Base case scenario
2	Sand	Unpaved undisturbed dry sand	Soi Type
3	Clay	Unpaved undisturbed dry clay	
4	Moist Loam	A moisture profile with 90% saturation at the surface	Soil Moisture Saturation
5	Moist Sand	A moisture profile with 90% saturation at the surface	
6	Moist Clay	A moisture profile with 90% saturation at the surface	
7	Short Asphalt Cover	Paved surface	Surface complexity
8	Long Asphalt Cover	Paved surface	
9	Moist soil layer	Venting condition change due to surface cover	
10	Snow Cover	Venting condition change due to surface cover	
11	Trench	Disturbed soil	Subsurface complexity
12	Trench Moist soil	Disturbed partially saturated soil	
13	Fracture / Pipe	Subsurface fault	
14	Trench with Fracture	Integrated disturbed soil and subsurface fault	
15	Trench Short Asphalt	Disturbed soil with paved surface	Combined surface and subsurface complexities
16	Trench Long Asphalt	Disturbed soil with paved surface	
17	Trench/Fracture Short Asphalt	Disturbed soil, subsurface fault with paved surface	
18	Trench/Fracture Short Asphalt	Disturbed soil, subsurface fault with paved surface	

Influence of subsurface complexities on CH_4 transport: Numerical Analysis



- » Increased migration along fractures or bulk distribution across disturbed soil
- » Wider concentration gradients
- » Maximum migration extents of 7 xs base case



- » Diffusive fluxes spanned throughout the subsurface complexity
- » Advective fluxes are 10 x Diffusive fluxes

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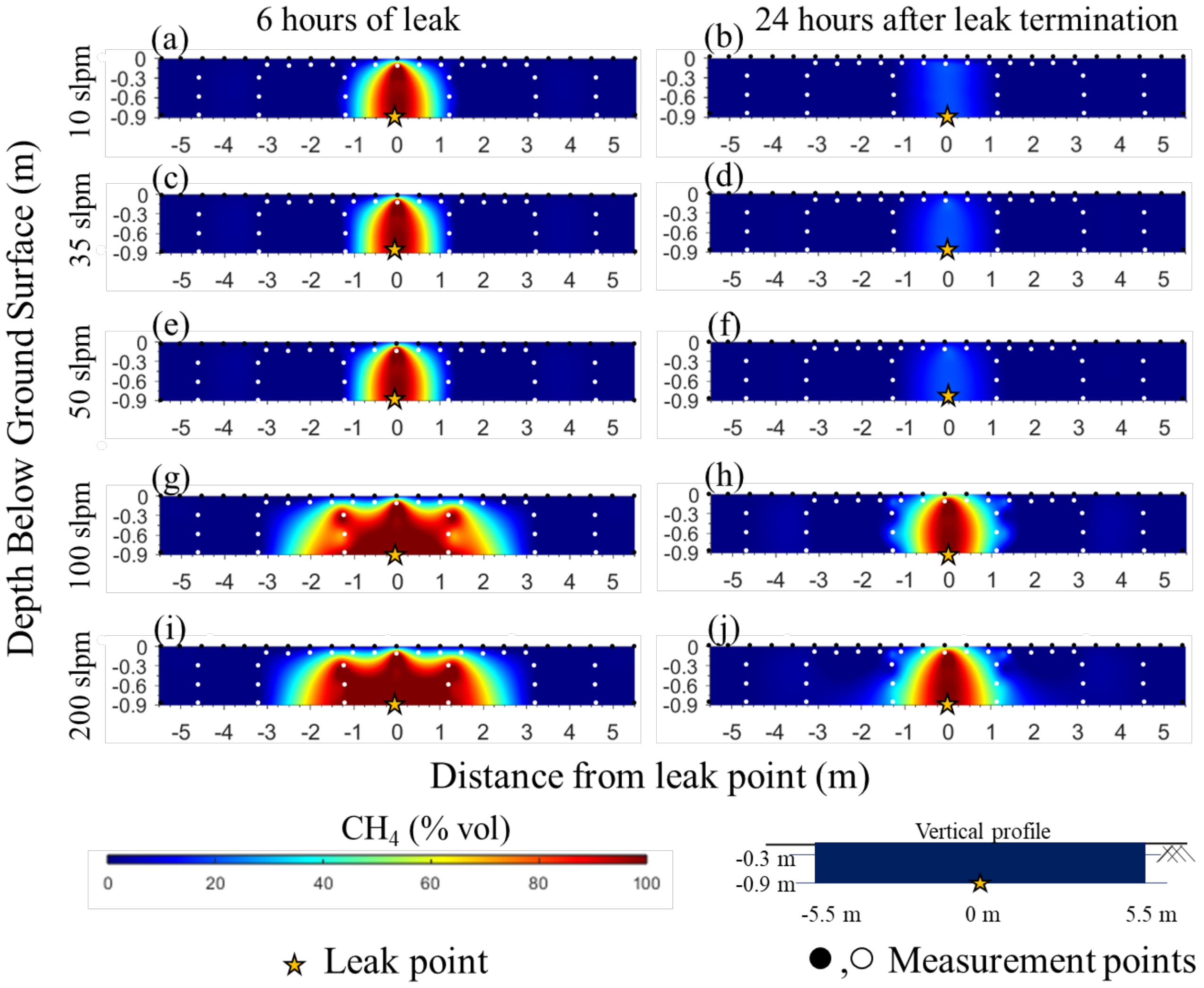
Effect of leak rate on gas migration –Experimental Results

- For **higher leak rates** the **CH_4 plume** experienced a **2.3 times increase in width** and roughly **5 times increase in volume** compared to the 10 slpm case.
- **Higher leak rates** caused **faster and initially more extensive migration** of high-concentration gas, with ground cover impacting the distribution at further distances.
- **Lower leak rates** returned to normal concentrations **within 24 hours**
- **Larger leaks stored** more gas below surface, rendering a **24-hour termination period insufficient**

Subsurface methane distribution for different leak rates



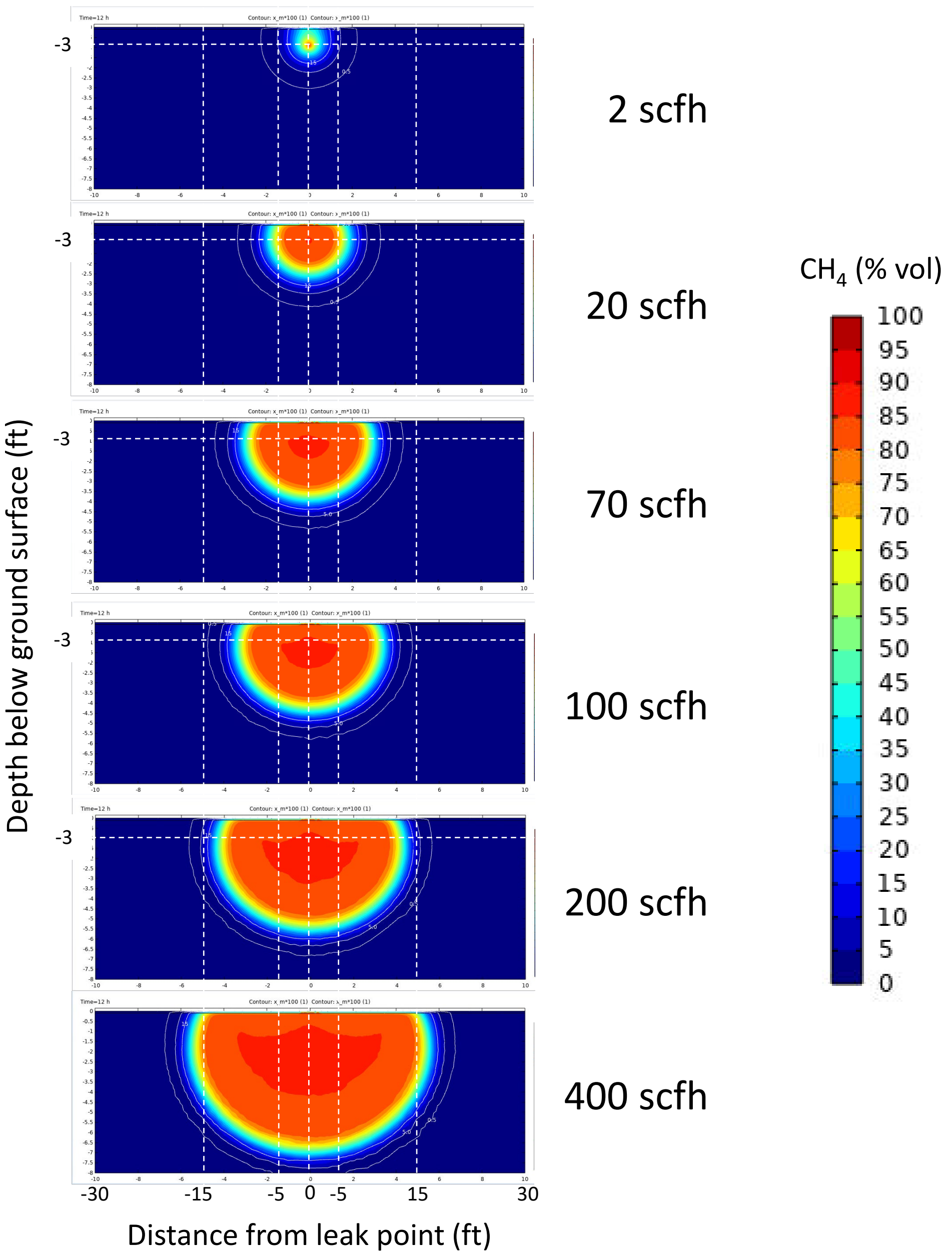
Leak rate: Numerical extension

An increase in leak rate (20 to 400 SCFH) does not proportionally increase the migration rate and distance

- Leak rate ↑ ∝ CH_4 accumulation around the leak ↑
- Leak rate ↑ ∝̸ Gas migration distance
- Leak rate ↑ ∝̸ Gas migration rate

Leak rate (scfh)	Maximum Migration Distance*
20	4ft
70	4 x distance @ 20 scfh
100	2.5 x distance @ 20 scfh
200	3 x distance @ 20 scfh
400	3.2 x distance @ 20 scfh

*Distances specific to METEC sandy loam soil



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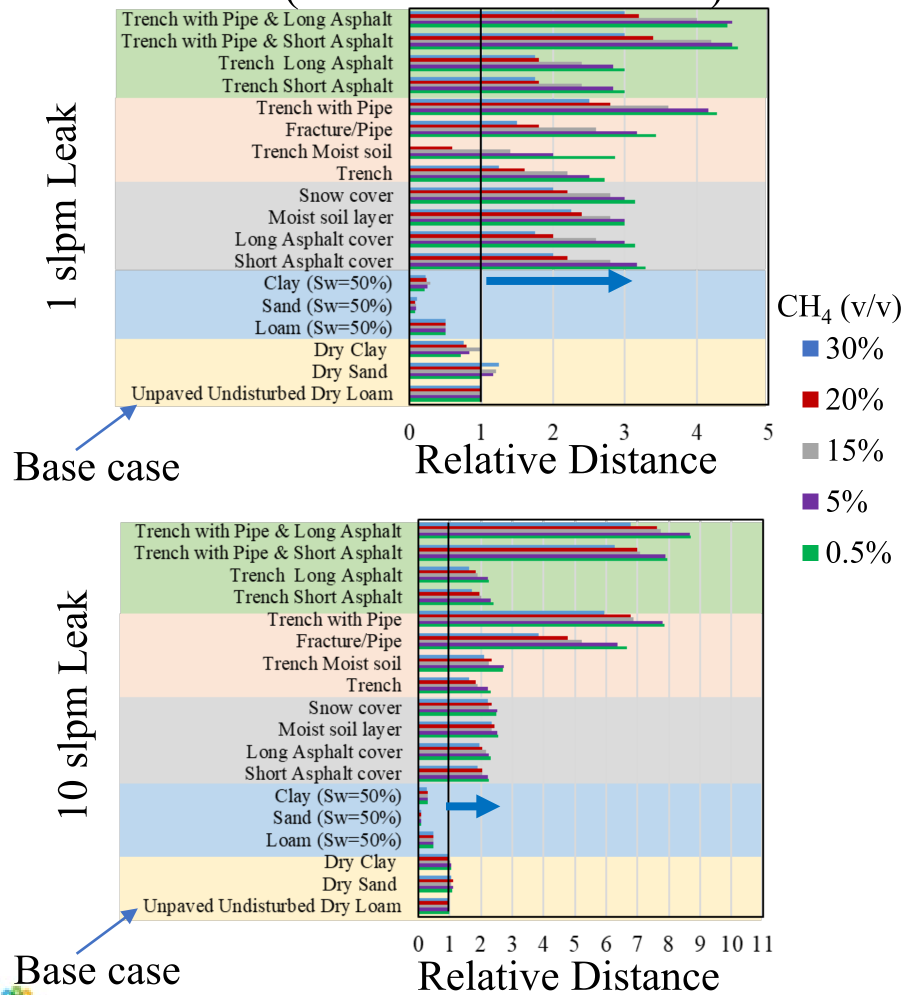
Task 6 – Extend Results via Modeling

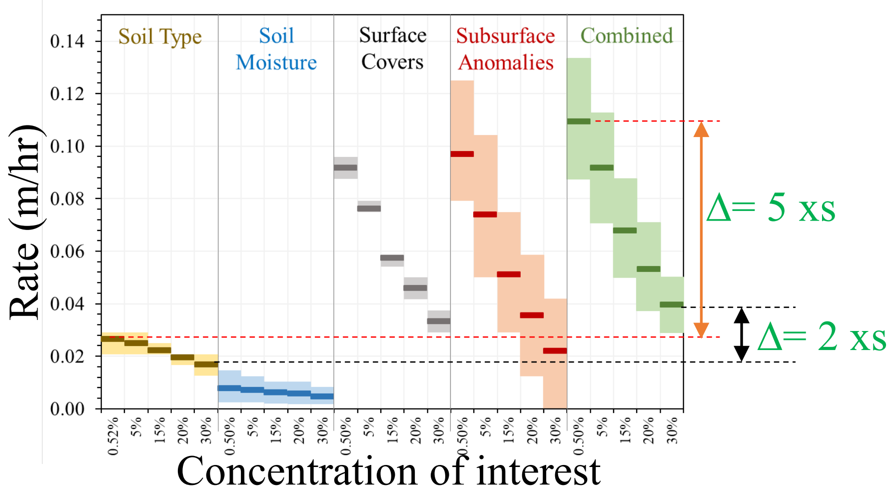
Migration Distance after 24 hours*

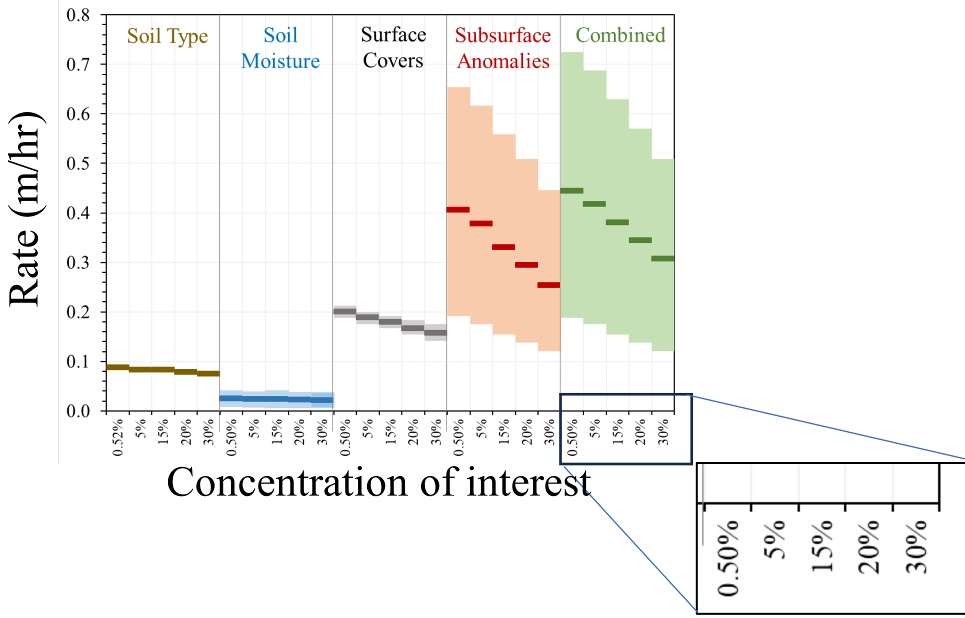
(*relative to base case)



- 2-5xs migration distances and rates under conditions including surface and subsurface complexities
- Largest increases in the smallest contours
- Complexity order of dominance
  1. Fractures
  2. Surface covers
  3. Soil disturbance
  4. Soil type - minimal effect
  5. Moisture saturation – negative effect

Average Migration Rate within first 24 hours





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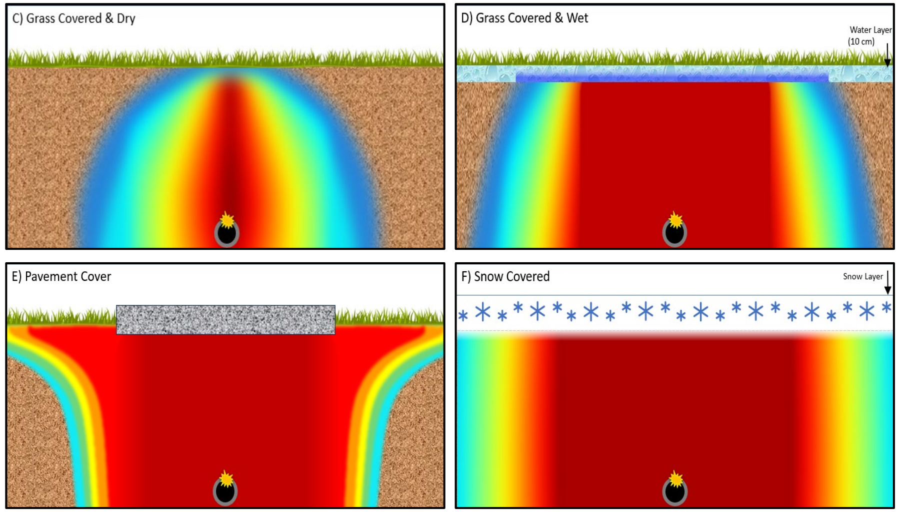
Task 7 – Develop recommended practices on development and dissipation of leaks with significant flow rates

- Objective: To link our experimental and numerical findings to first responder practice.
- The understanding from the field scale experiments and the numerical simulations were integrated to obtain a scientific understanding for the following topics:
  - Effect of soil moisture on gas behavior
  - Surface cover
  - Surface concentration
  - Leak rate
  - Subsurface complexity
  - Leak termination
  - Gas composition



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Key Findings

- Subsurface gas plumes are typically four times larger than what is detected at the surface in dry, uncovered soil conditions.
- Elevated soil moisture leads to narrower surface plume formations, requiring careful identification of the leak's center and expectations of more extensive gas accumulation.
- Under surface covers like asphalt or concrete, or in snowy or moist soil, subsurface natural gas (NG) plumes can be 3-4 times wider and migrate faster than in dry, uncovered conditions.
- Large leaks tend to accumulate more NG around the leak point rather than cause extensive lateral migration, and both large leaks and small, longstanding leaks present similar risks.
- Gas is observable three times farther along trenches and fractures compared to undisturbed soil, and such features can disguise the true leak location.
- Shut off of a leak doesn't immediately eliminate the hazard, with high concentrations persisting and spreading laterally; venting a leak can take up to 7 days or more under conditions that impede venting, such as surface covers or moist soil.

Key Findings

- Subsurface Conditions:
  - Primary Influencers:
    - Soil fractures or open utilities significantly enhance gas movement.
  - Minor Influencers:
    - Soil type and depths between 3 ft and 6 ft have minimal impact.
  - Negative Impact:
    - Increased soil moisture notably reduces lateral gas migration.
- Surface Conditions:
  - Significant Impact:
    - Wet conditions (snow, rain, asphalt) increase gas spread up to 4x further and 3.5x faster than under dry soil.
- Methane Indicators:
  - Misleading Surface Levels:
    - Negligible methane at surface; major accumulations below surface under wet conditions
- Leak Dynamics:
  - Leak Rate Effects:
    - High leak rates influence immediate gas distribution but not extended area influence over time
  - Post-Leak Persistence:
    - Gas remains in soil at high concentrations for up to 14 days post-leak under non-venting conditions
- Safety Recommendations:
  - Hot Zone Adjustments:
    - Expand criteria and increase safety radius based on environmental impact assessments to ensure thorough safety measures

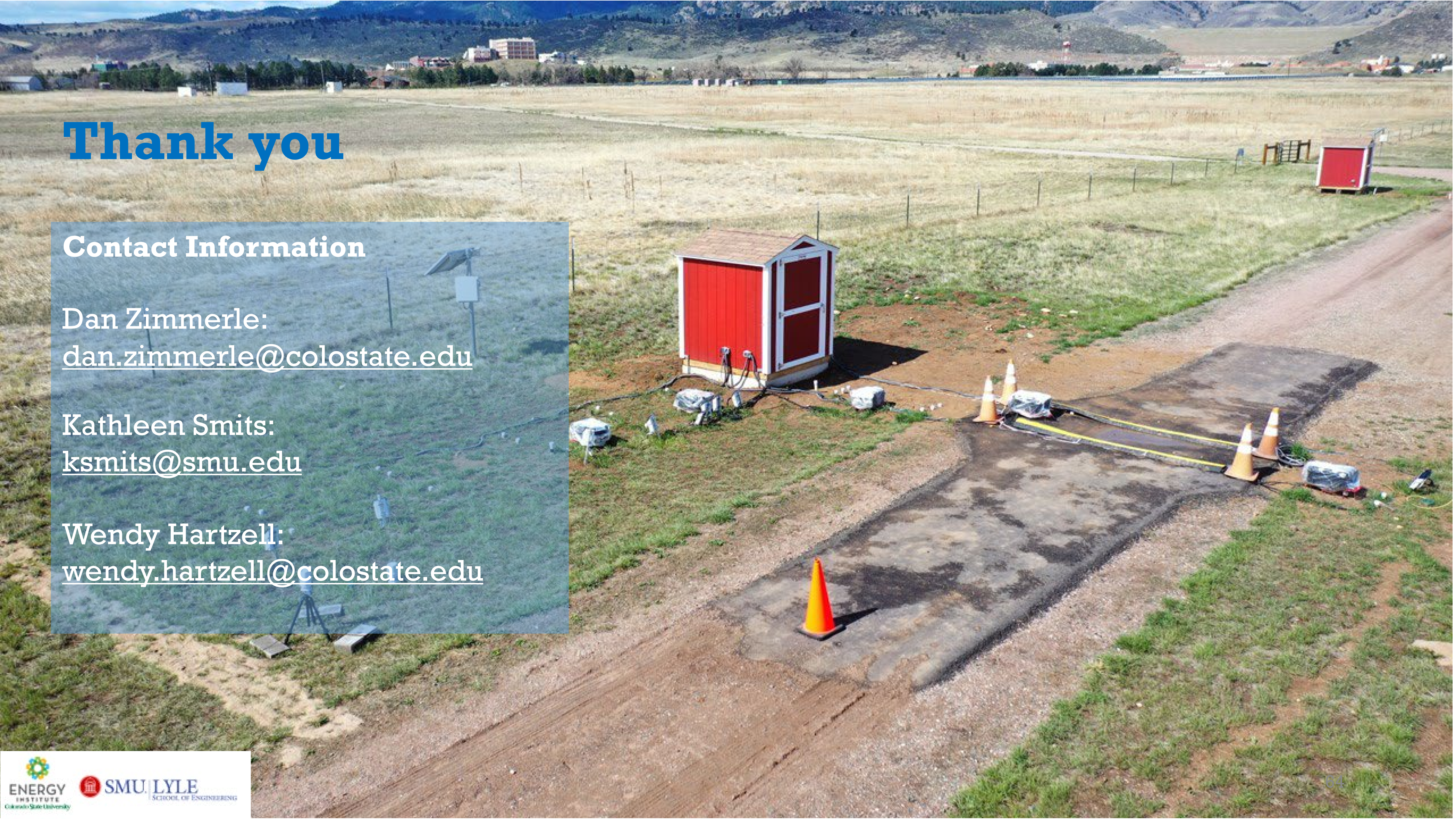
Conclusion: Effective management of gas leaks necessitates adapting safety measures to account for the comprehensive impact of environmental conditions on gas behavior.

Future Work

1. Risk Assessment Method: Develop a risk-based framework to predict gas migration patterns during leaks, aiding in quick operational decision-making at incident sites.
2. Environmental Factor Analysis: Study the influence of varied soil terrains and atmospheric conditions on underground gas leak dynamics.
3. Leak Detection Enhancement: Innovate leak detection and quantification methods that are efficient, field-deployable, and integrate with current instruments.
4. Soil Aeration Optimization: Conduct research to refine soil aeration systems, considering subterranean processes to improve gas mitigation effectiveness.

Task 8: Final Report and Presentation

The final report and presentation – "**Response Protocol for Large Underground Methane Emissions** - RPLUME (DOT-PHMSA # **693JK32010011POTA**)" are posted and available at: https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=917&s=6F3C431235FD413B8CF6C9445E6124A8



Thank you

Contact Information

Dan Zimmerle:
dan.zimmerle@colostate.edu

Kathleen Smits:
ksmits@smu.edu

Wendy Hartzell:
wendy.hartzell@colostate.edu

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QUESTIONS

Q & A

ANSWERS