ENERGY INSTITUTE

COLORADO STATE UNIVERSITY

Introduction to Measurement Informed Inventories (MII)

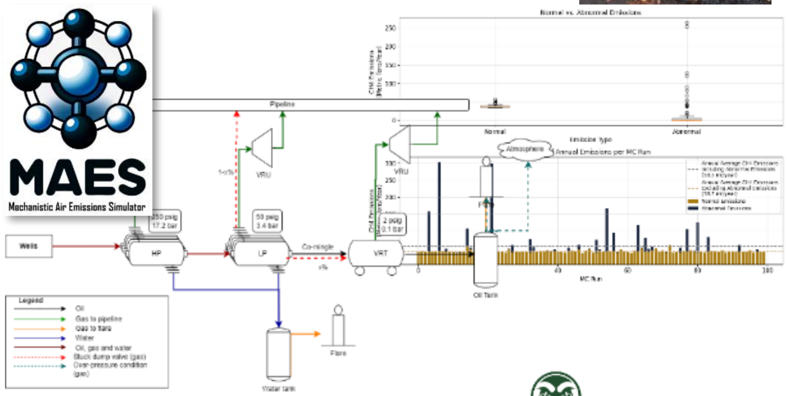
Daniel Zimmerle, Anna Hodshire, Arthur Santos

& Teams

METEC Group: What We Do

47 Peer-reviewed papers since 2020

1. **Solution R&D Program / METEC Facility**
   - Test leak detection solutions – downwind and in-process
   - Aid / support companies doing solution development
   - Controlled release testing at METEC facility and at field sites
   - Develop common methods for research or operations
   - Provide mitigation, safety, and operational guidance
2. **Field Measurements and Experiments**
   - "As operating" measurements across most sectors of NG industry
   - Specialty measurements for difficult / high impact sources
3. **Modeling, Simulation & Inventory Methods**
   - Simulation tools for high temporal and spatial resolution
   - Advanced modeling for measurement informed inventory
   - Emissions modeling from facility to basin scale

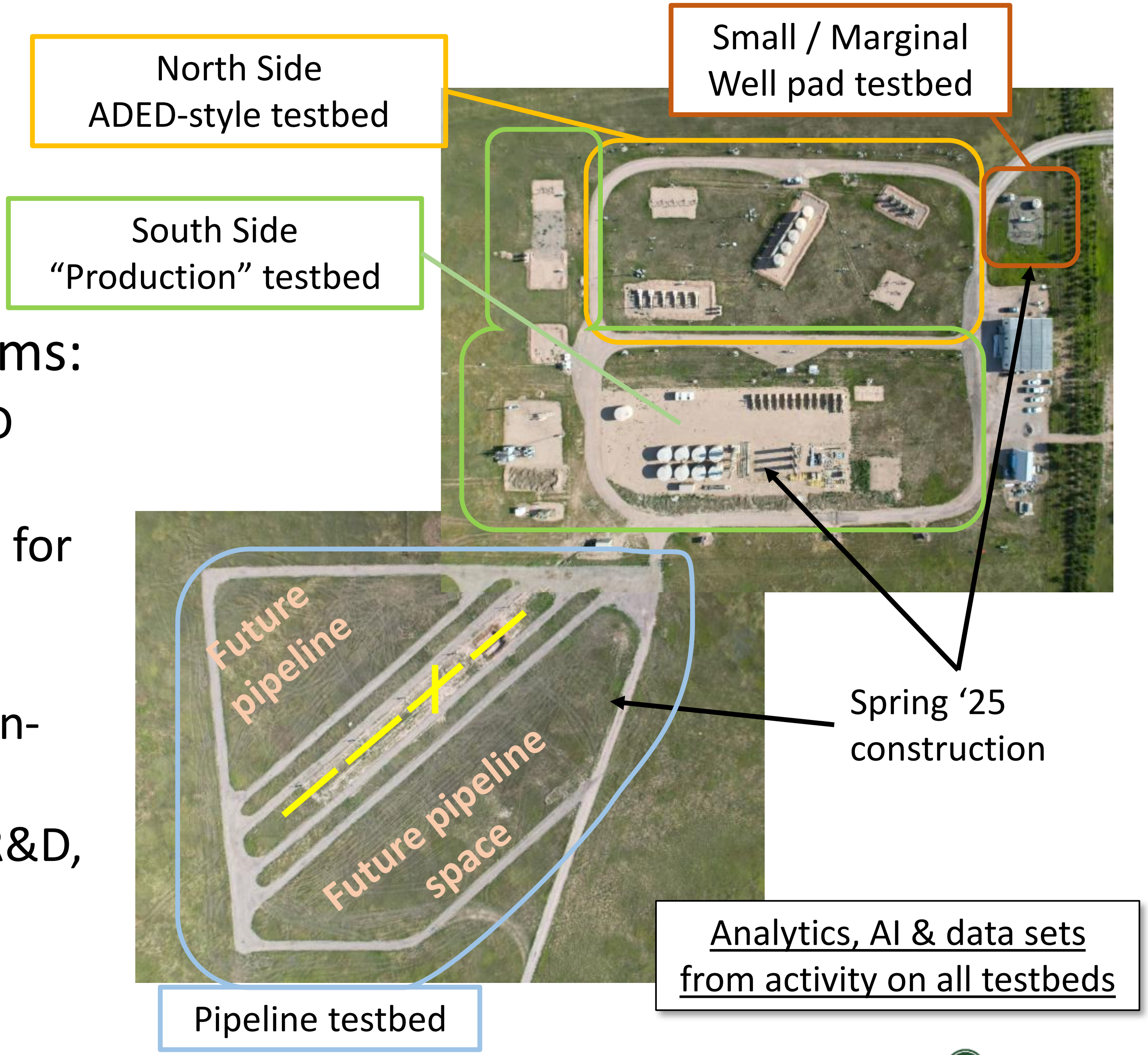


METEC Facility Overview

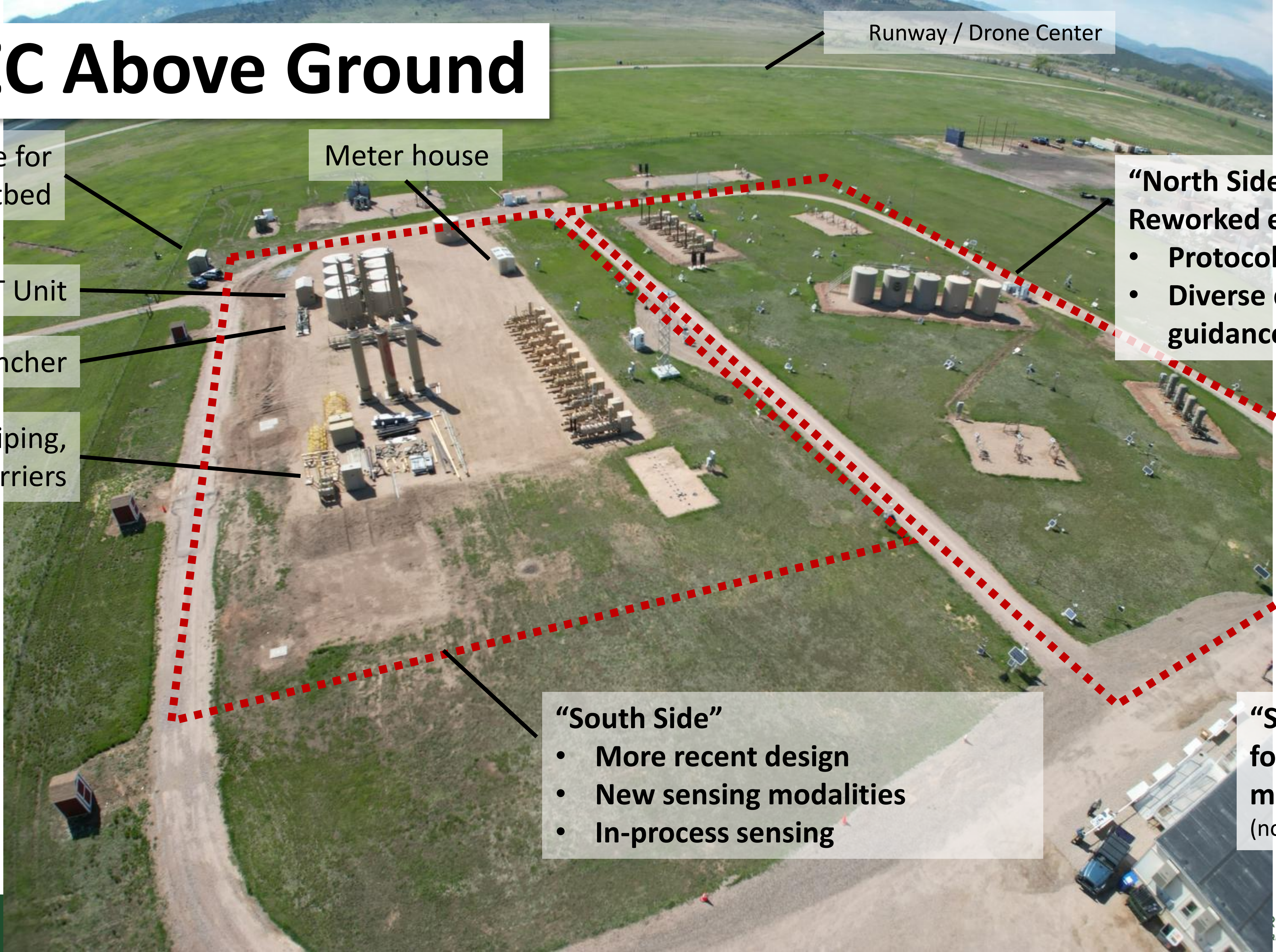
Build/use for specific R&D programs:

1. North Side: Protocol testing & R&D programs
2. Small Pad: Test and R&D programs for marginal wells
3. South Side: Targeted R&D on new technologies, sensing modalities, in-process sensing
4. Pipeline: Leak detection test and R&D, moving into multi-mode sensing

Testing and R&D also occurring at remote sites (see below)

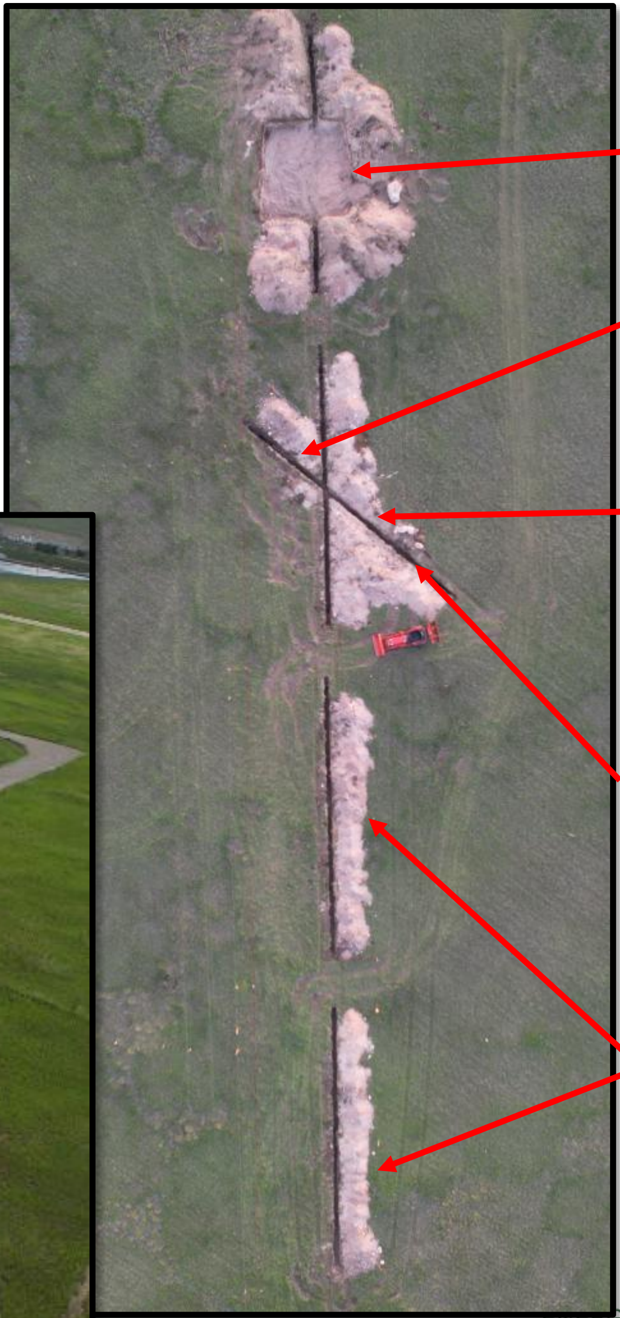


METEC Above Ground



METEC Underground

- Realistic installation of pipelines – bedding, backfill, etc.
- Changing conditions over multi-year test programs – movable structures, ground cover, access routes …
- Ability to do long-duration leaks – months, not hours



Sand testbed

Crossing Pipe

Metal Pipeline Segment

Leak Point Under Road

Pipe Segments

Measurement Informed Inventory (MII)

Overview of MII

- Inventories
  - Review
  - New versus traditional inventories
- Measurements
  - What you get
  - How to think about results
- Informing
  - Process CSU uses per-company and per-basin
  - Learning from the process

Measurement-Informed Inventory

Inventory reporting covers **all time**.
Measurement covers only ***part of the time***

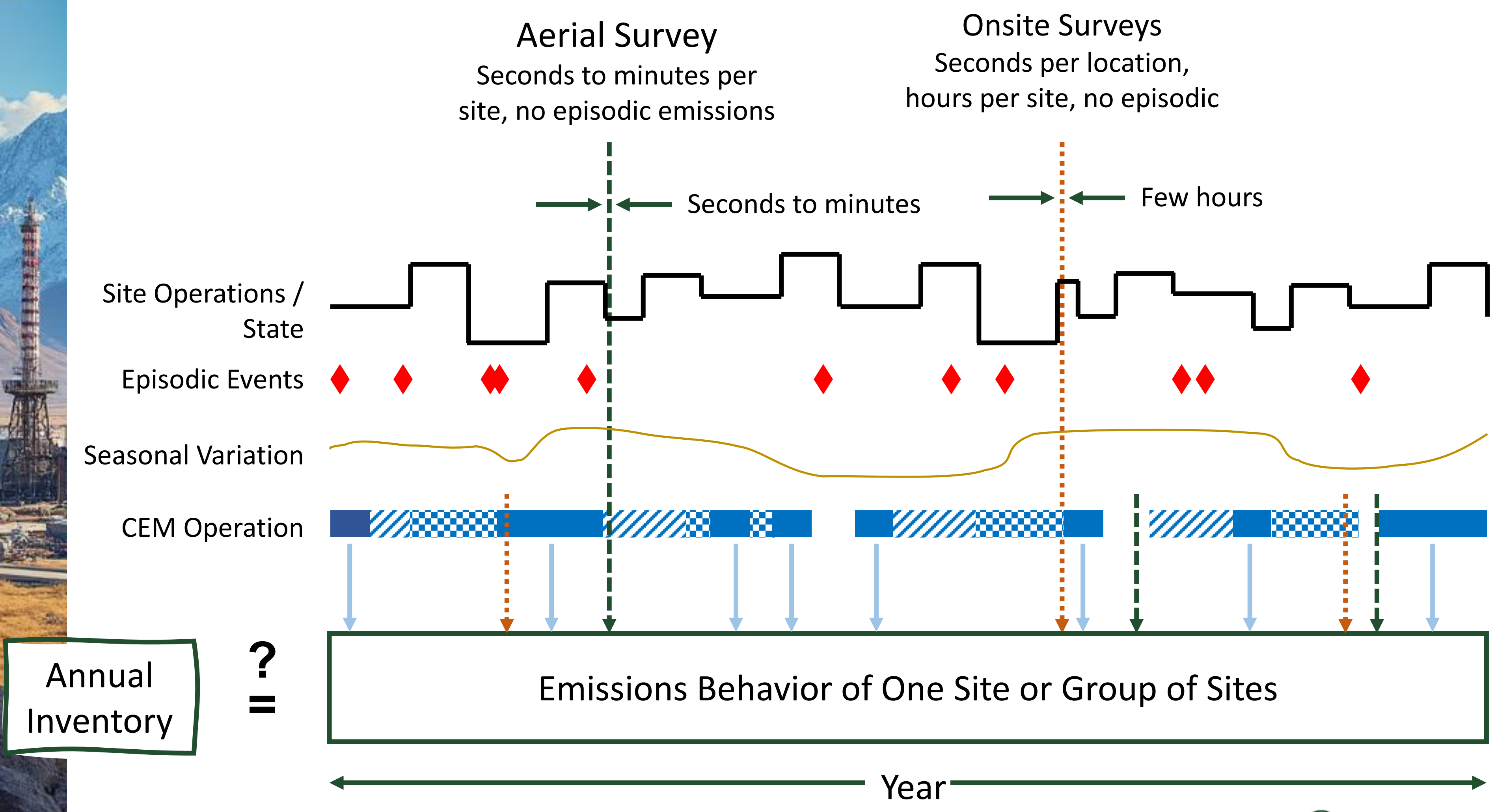


Photo generated with ChatGPT. Figure by D. Zimmerle, from Charting the Course: Reducing GHG Emissions from the U.S. Natural Gas Supply Chain, Chapter 3. Detection and Quantitative Tracking of Greenhouse Gas Emissions from Oil and Natural Gas Supply Chains.

Measurement Informed **Inventory**:
The Inventory … a quick review

Inventories

An inventory is an **estimate of total emissions** created by scaling limited observations to a population of potential emitters for a defined time period

- *Emission Mechanism*: An action that causes emissions.
  - Multiple *mechanisms* may occur at one physical location
  - Mechanisms may vary by orders-of-magnitude in emission rate, frequency, etc.
- *Activity*: Estimates of *frequency and duration* at which the mechanism creates emissions. Examples:
  - Counts of units and count of emitting units → frequency of emissions
  - Facilities scanned with aerial method X fraction of facilities with emissions

  } and duration estimate
- **Emission (Factor)**: Emission rate *for this mechanism* per unit of activity

Mechanistic View of Emissions

- Energy input driven:
  - Gas pneumatics
  - Gas pneumatics & venting
  - Incomplete fuel co...
- Failure conditions:
  - Leaks … "a leak"
  - Gas through liquid valves
    - 'stuck' valves
    - malfunctioning controllers
  - Heater malfunction
  - Pilot

  …
- Maintenance
  - Depressurization

The Mechanism

Happens at a frequency → **For some duration** → **At some emission rate**

Activity Basis
"type of component"

Activity Factor
"fraction of components leaking at any time"

Emission Factor
"leaking at this rate"

Universal Model of Emissions Scaling

Mechanism → **Happens at a frequency** → **For some duration** → **At some emission rate**

Estimation Method	Mechanism	Frequency	Duration	Emission Rate
Aerial, identifies plumes on individual units of equipment at rates $r > X\frac{kg}{h}$				
Onsite leak survey of ‘components’				
Drone flights, estimate facility emissions by mass balance of air moving across site				
Monitoring system that produces an estimate of emissions for a tank battery every hour				

Example Inventory*

Mechanism → **Happens at a frequency** → **For some duration** → **At some emission rate**

Aerial, identifies plumes on individual units of equipment at rates $r > X \frac{kg}{h}$ →

Any (distinct or combined) source on identifiable unit of equipment (from any cause)

$$\frac{\#\ of\ plumes}{\#\ of\ units\ of\ equip\ screened}$$

No estimate

Fill in with some type of persistence estimate

Plume rate estimate

* Purposely chosen to *not* be a traditional inventory

Universal Model of Emissions Scaling

Mechanism → **Happens at a frequency** → **For some duration** → **At some emission rate**

Estimation Method	Mechanism	Frequency	Duration	Emission Rate
Aerial, identifies plumes on individual units of equipment at rates $r > X\frac{kg}{h}$	Distinct or combined sources with emissions from any cause	$\frac{\#\ of\ plumes}{\#\ of\ units\ of\ equip\ screened}$	*No estimate*	Plume rate estimate
Onsite leak survey of 'components'	Emissions from components checked, by component category	$\frac{\#\ of\ leaks\ detected}{\#\ of\ components\ screened}$	½ time between surveys	None unless measured. Often use emission factors
Drone flights, estimate facility emissions by mass balance of air moving across site	Emitting facility; emissions of any type or cause	100% (all facilities screened)	No estimate Often use time between surveys	Flux plane rate estimate
Monitoring system that produces an estimate of emissions for a tank battery every hour	Anything emitting on the tank	100% (of hours with estimates)	Estimate from hourly reports, with gaps for non-reporting hours	Emission rate estimate of method

Key Point:

Any method that does not estimate an emission rate *for a defined activity basis* (mechanism) *at all times for the entire population* requires an inventory method to scale from observations to a useful reporting or comparison period (duration)

- Data presented as ‘not an inventory’ is often an inventory method with ambiguous activity bases and sweeping assumptions for duration
- Many newer methods ignore emission mechanisms and lump multiple activity bases together with little differentiation for site characteristics or emission causes

<u>Estimates from survey methods are not a magic way to eliminate inventory calculations</u>

Corollary: Be sure you understand what inventory methodology your survey vendor is using.

Measurement Informed Inventory:
The Measurement … what is it?

Survey ~~Measurements~~ Estimates

- Few times per year
- Short visit to each facility
- Was anything detected? What quantity was estimated? Where was emitter located?

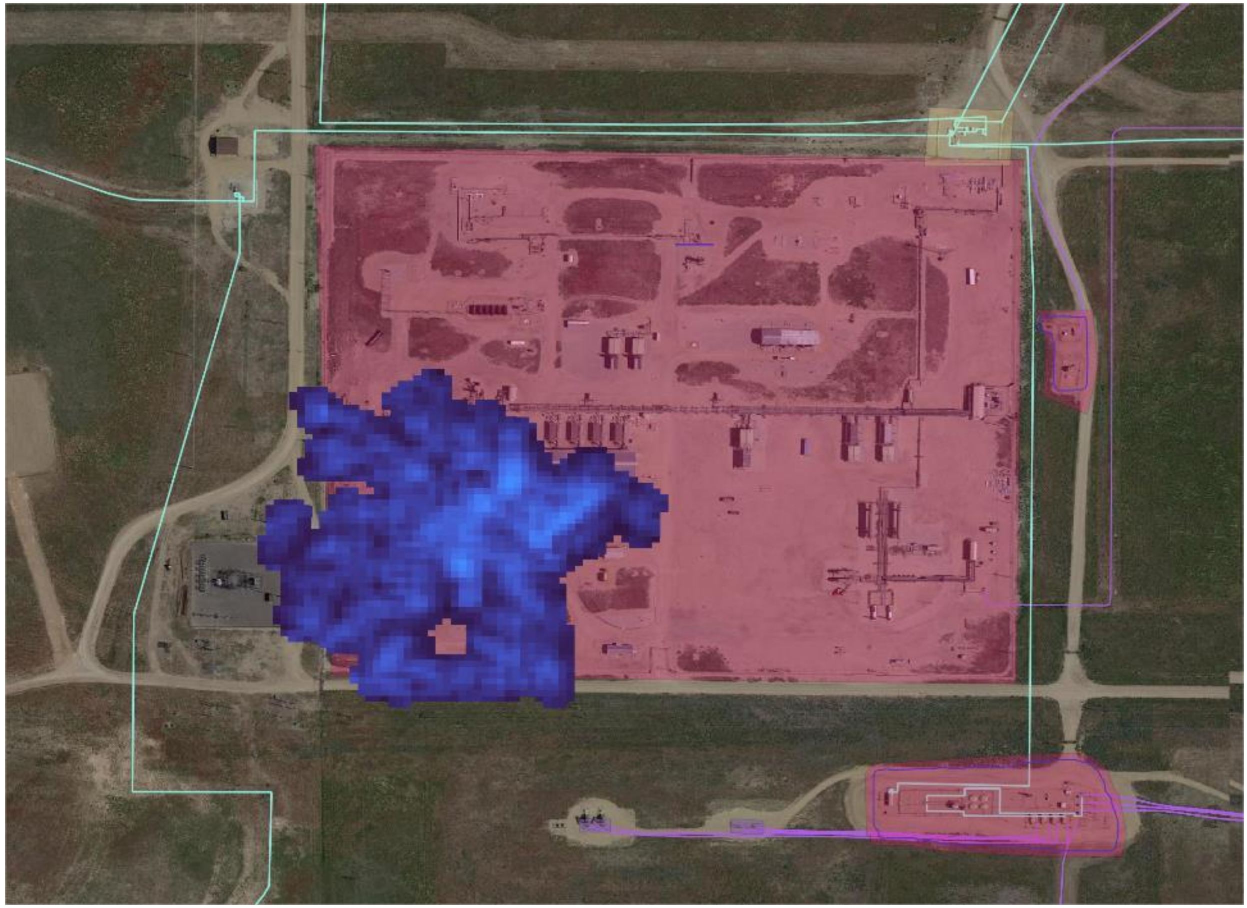
Thinking About Survey Methods

- All methods have blind spots
  - *Always* something the method cannot detect, resolve, or estimate accurately
  - Useful and accurate in a limited range of environmental conditions
- Method duration
  - Seconds to hours
  - Short estimates snapshot 'what just happened' in the recent past
  - Longer estimates 'integrate' emissions behaviors over longer period and produce a 'more nearly average' emission rate at time of measurement
- Transport
  - Downwind methods → look at the plume after transported away from equipment → need wind within set range of speeds (and sometimes, direction)
  - (Traditional) Direct methods → measure emissions at source → limited-to-no dependence on environmental conditions

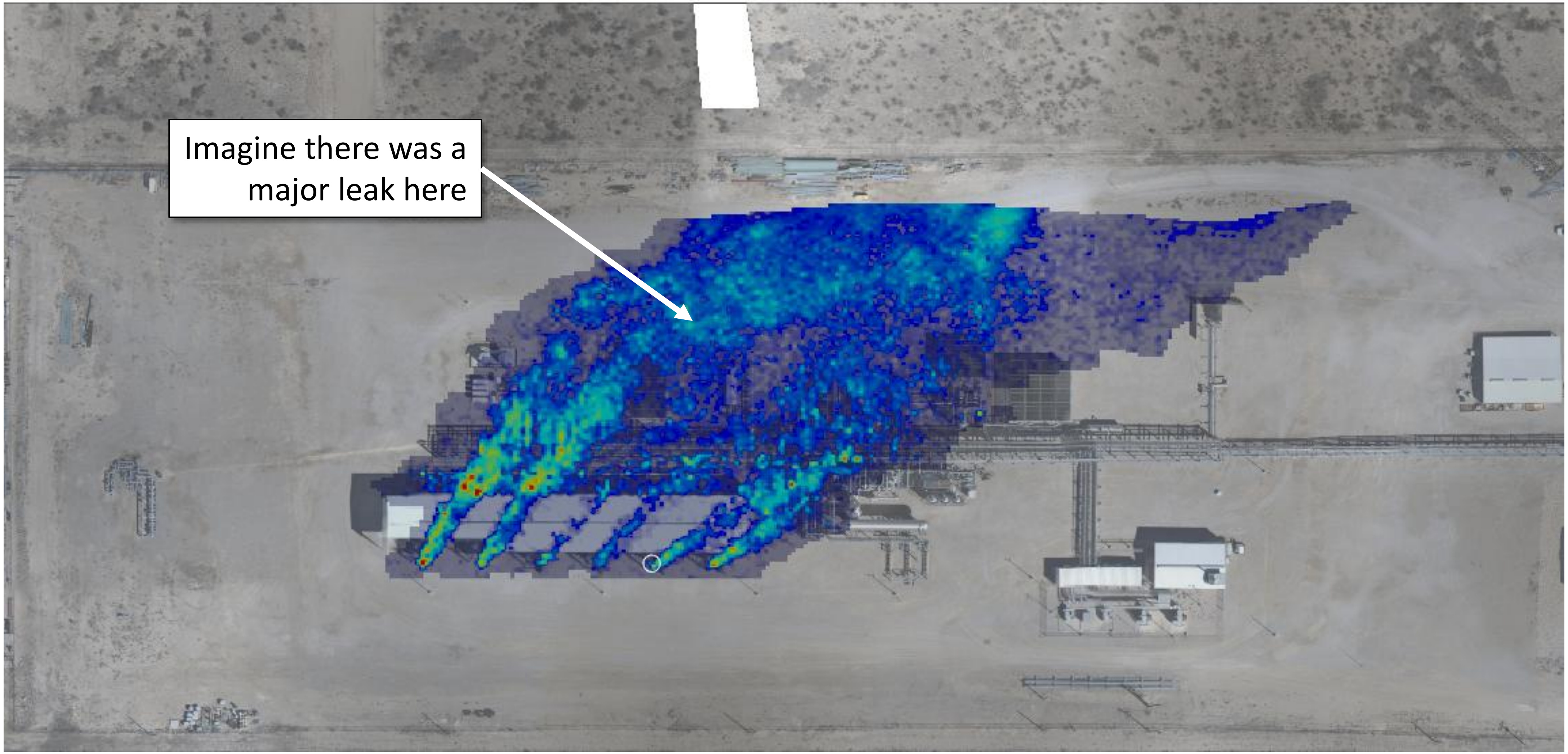
Dilute Sources

Likely Cold Point Source

Likely Compressor Exhaust

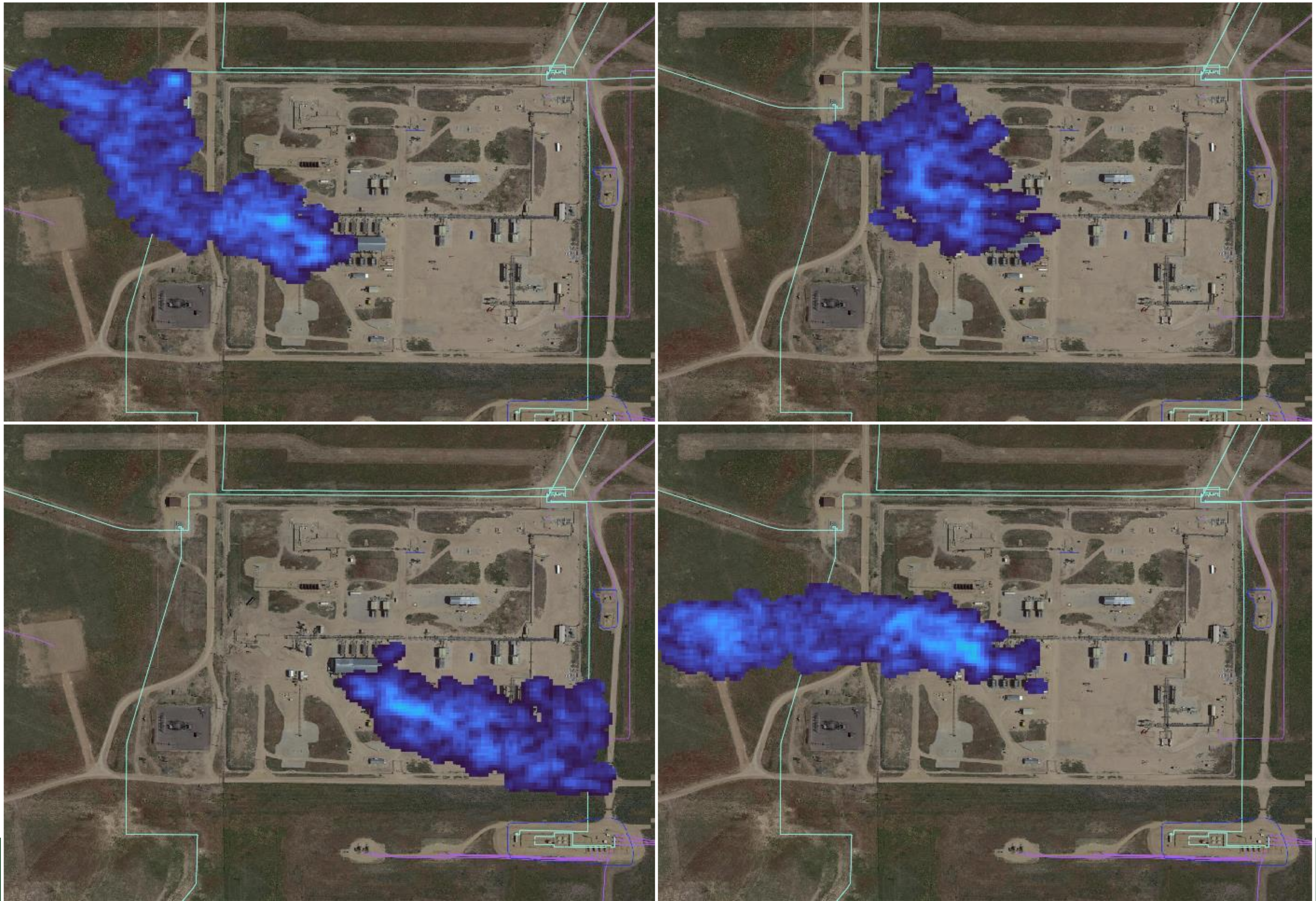


Source Resolution



Engines are large-bore (prechamber), lean-burn, 4-stroke, engines

Variable Detection Behavior



Compressor station detected most often in *Colorado Coordinated Campaign*

≈largest combustion slip estimate at time in basin (≈80 kg/h from 4x 2SLB engines)

Overflown 10 or 11 times

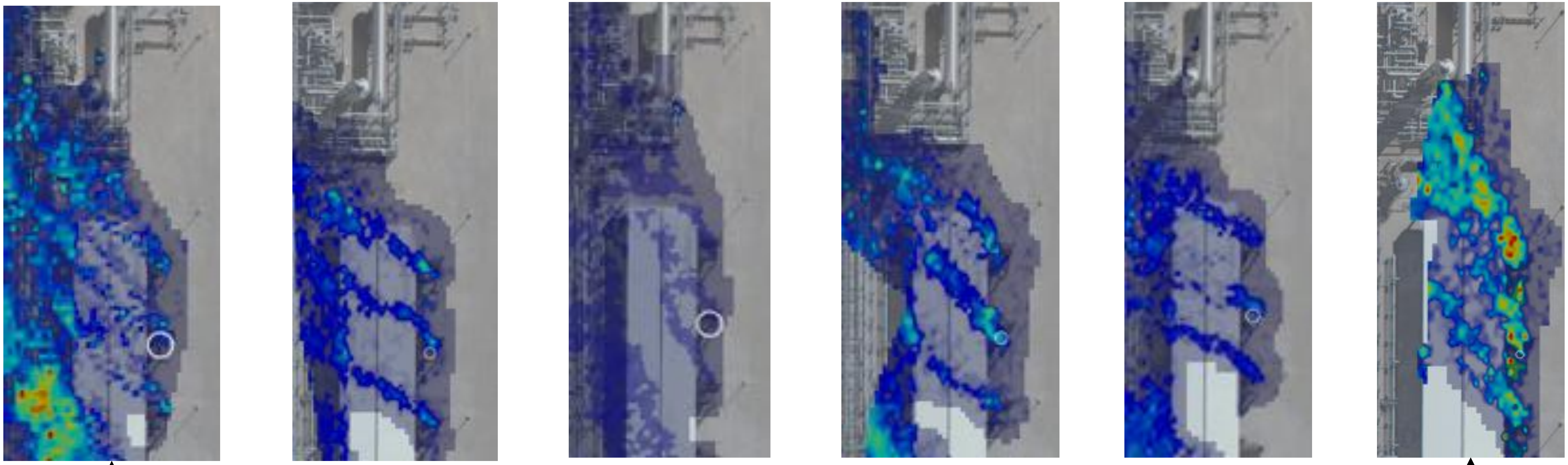
Detected … <50% of overflights while compressors run >95% of time

Method Intro for Next Slides

- Aerial method
- Uncertainty is approximately ±70% (95% confidence interval)
- One of the best-in-class survey services, with the most published controlled test results

Visualizing Uncertainty

12:20 / 917 scfh | 12:27 / partial | 12:31 / 531 scfh | 12:37 / partial | 12:39 / 765 scfh | 12:44 / 451 scfh



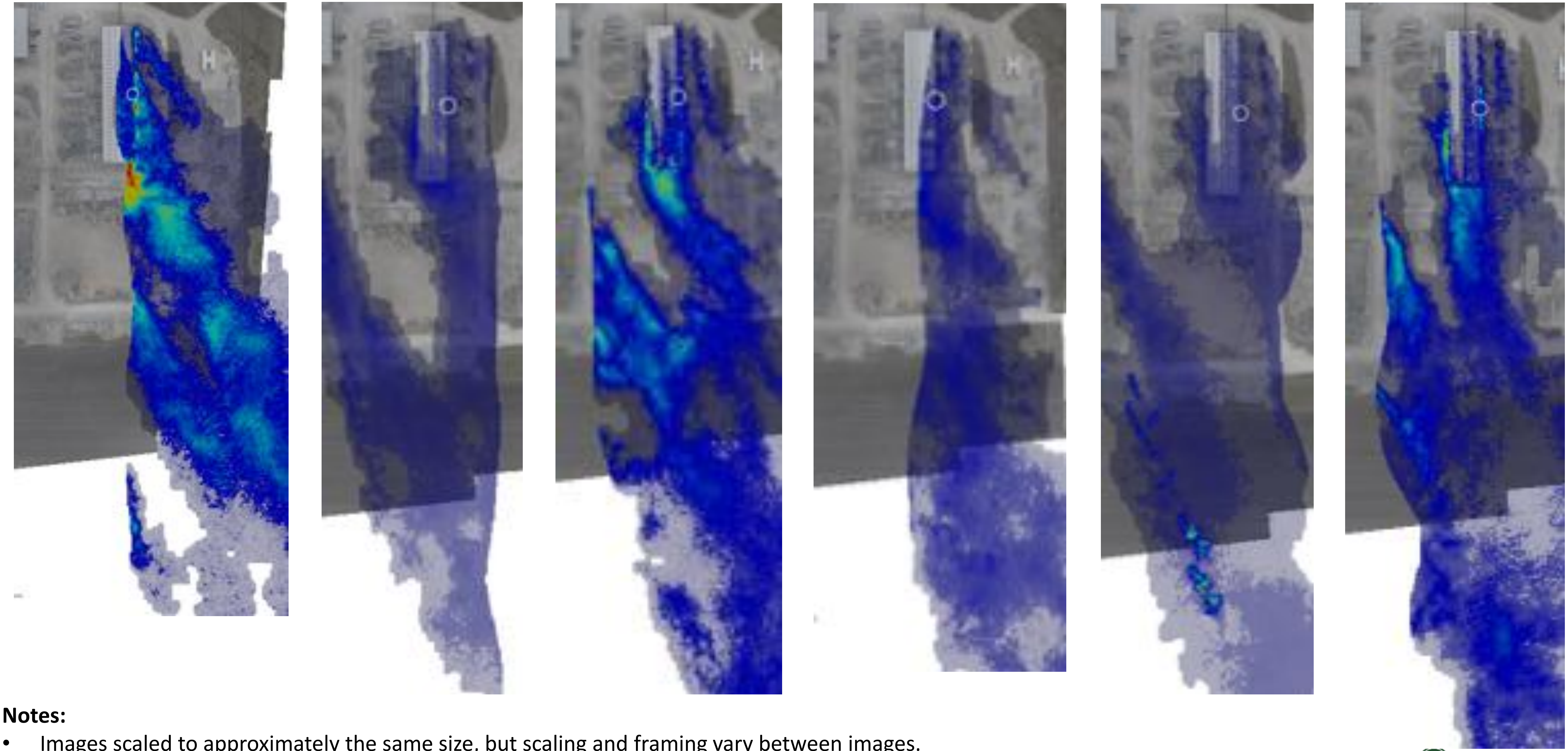
Your survey was one (or possibly two) of these passes

Notes:

- Images from period when no change to compressor operating state
- Images scaled to approximately the same size, but scaling and framing vary between images.
- Smooth edges represent edge of the plume on each overpass
- Times rounded to nearest minute. Onsite observer indicates no change in compressor operating state.

ENERGY INSTITUTE
COLORADO STATE UNIVERSITY

9:28 / 1066 scfh | **9:31 / 2500 scfh** | **9:36 / 918 scfh** | **9:41 / 766 scfh** | **9:43 / 1156 scfh** | **9:49 / 1213 scfh**



Notes:

- Images scaled to approximately the same size, but scaling and framing vary between images.
- Smooth edges represent edge of the plume on each overpass
- Times rounded to nearest minute. Onsite observer indicates no change in compressor operating state.

ENERGY INSTITUTE
COLORADO STATE UNIVERSITY

Key Points:

Survey methods estimate *emissions: High variability / uncertainty in both probability of detection and in quantification*

- See examples next page

*Solid **well-tested** methods have low bias averaged over many samples*

- Your results over *all facilities* are likely ‘pretty close’ …
- Results for any one facility likely have high uncertainty

Takeaway Tests on Survey Methods

• No detection does not mean no emissions above the method's 'detection limit'	• @50% probability of detection means the method detects ½ of the emitters
• One 'measurement' is not *the emission rate* – it is an *estimate* with uncertainty	• ±50% means estimate could be double or ½ of reported value • Beware of 1σ confidence intervals
• Most methods miss some type of source entirely	• You know there is combustion slip … did method see it?
• Survey sees only where it looked – particularly important for ground / drone based methods	• Did drone fly high enough to see exhaust from compressor drivers?

Measurement *Informed* Inventory: **Informing annual inventories using snapshot estimates**

MII Technical Challenges

1. Translate inventory and measurement to same time basis
2. Make comparisons that are tolerant of uncertainties
3. It’s expensive → Need a systematic approach that supports cross-organization learning

Measurement Informed Inventory is …

… a comparison of one inventory with *another inventory*

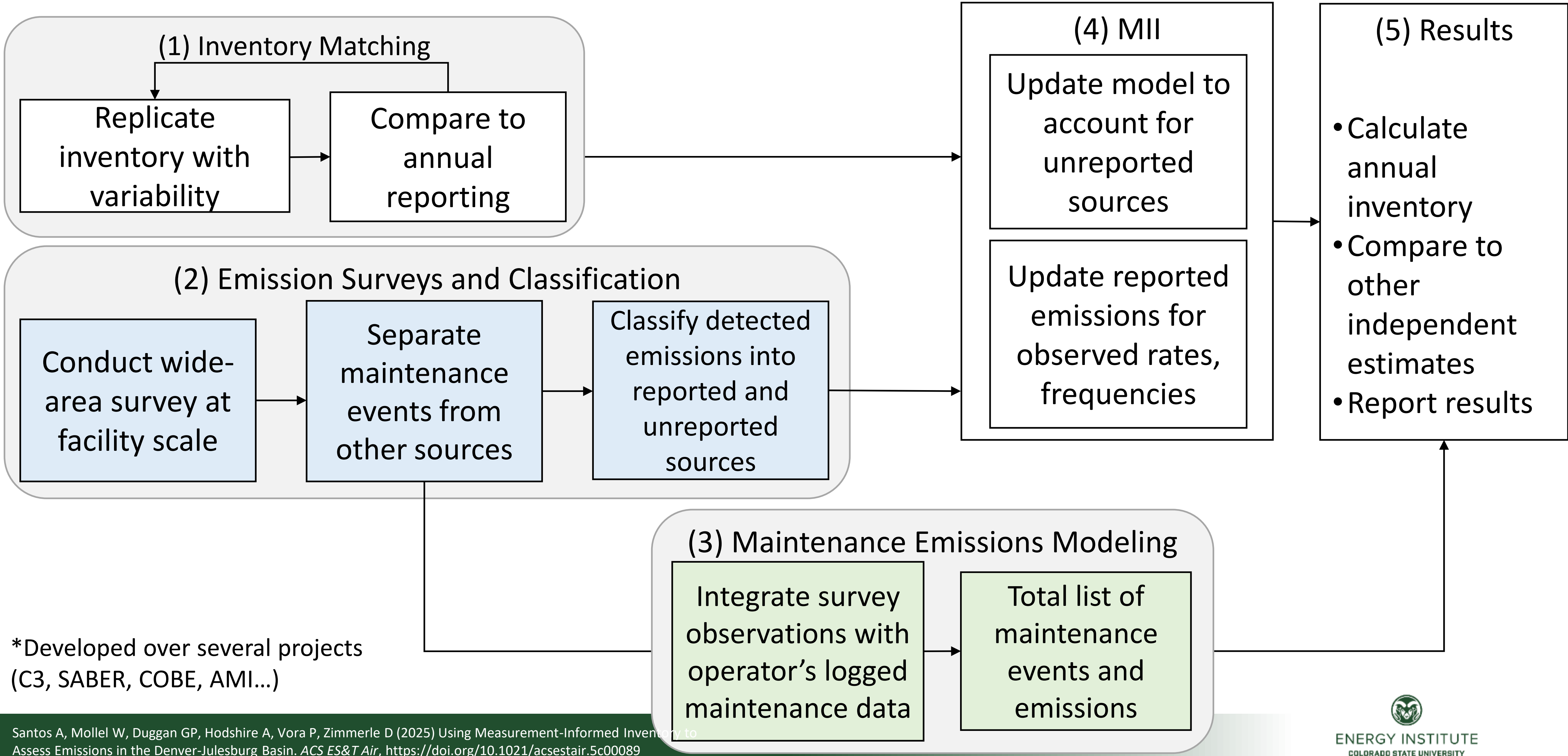
Typically:

- Bottom-up *traditional* inventory
  - Traditional activity factor x emission factor
  - Often supplemented by measurements, logged data, etc.
  - Typically, more focused on capturing unique *activity* than on making comprehensive source measurements

to

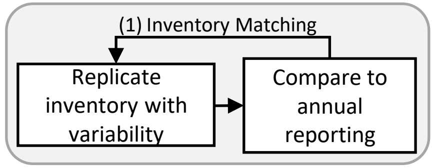
- Snapshot measurement of some portion of the stuff in the bottom-up inventory
  - Most a survey methods estimate emission rate for a subset of the bottom-up activity
  - Estimates are snapshots in time
  - For MII, typically white-box data rather than anonymous sampling

Algorithmic steps for MII*



*Developed over several projects (C3, SABER, COBE, AMI…)

Santos A, Mollel W, Duggan GP, Hodshire A, Vora P, Zimmerle D (2025) Using Measurement-Informed Inventory to Assess Emissions in the Denver-Julesburg Basin. *ACS ES&T Air*, https://doi.org/10.1021/acsestair.5c00089



(1) Inventory Matching

MAES
Mechanistic Air Emissions Simulator

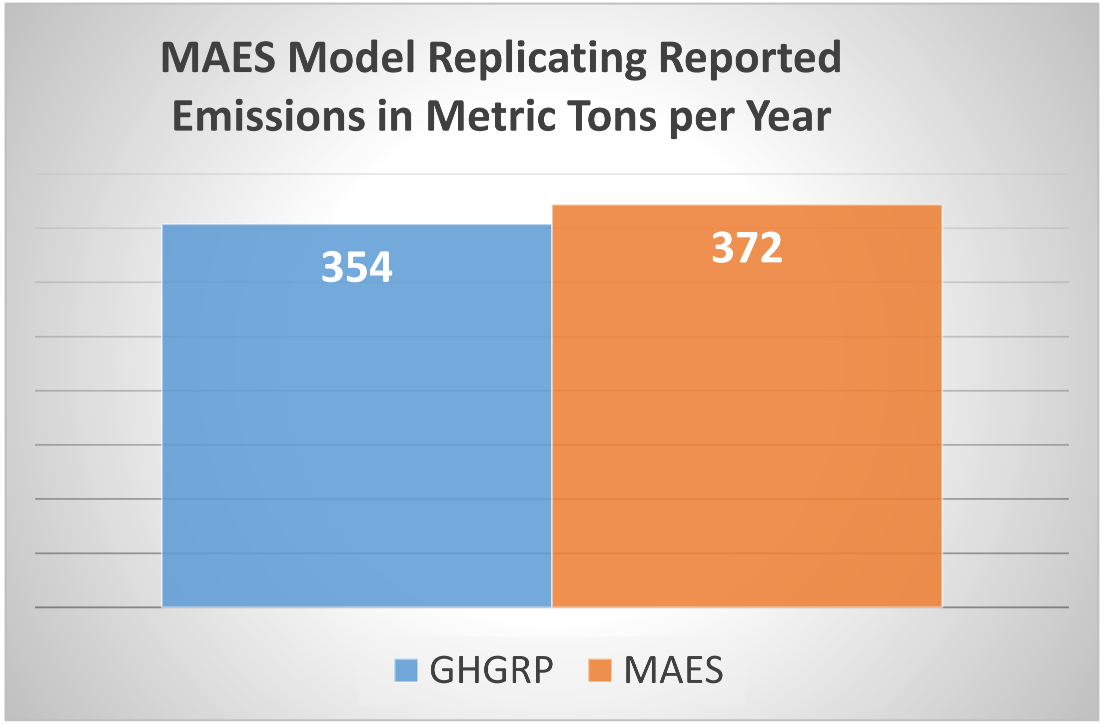
Company's best annual emission estimate:

- What's being reported
- Key program or regulatory requirement

MAES replicates of company's estimate

- Same activity data
- Estimate inherent variability

Example Site



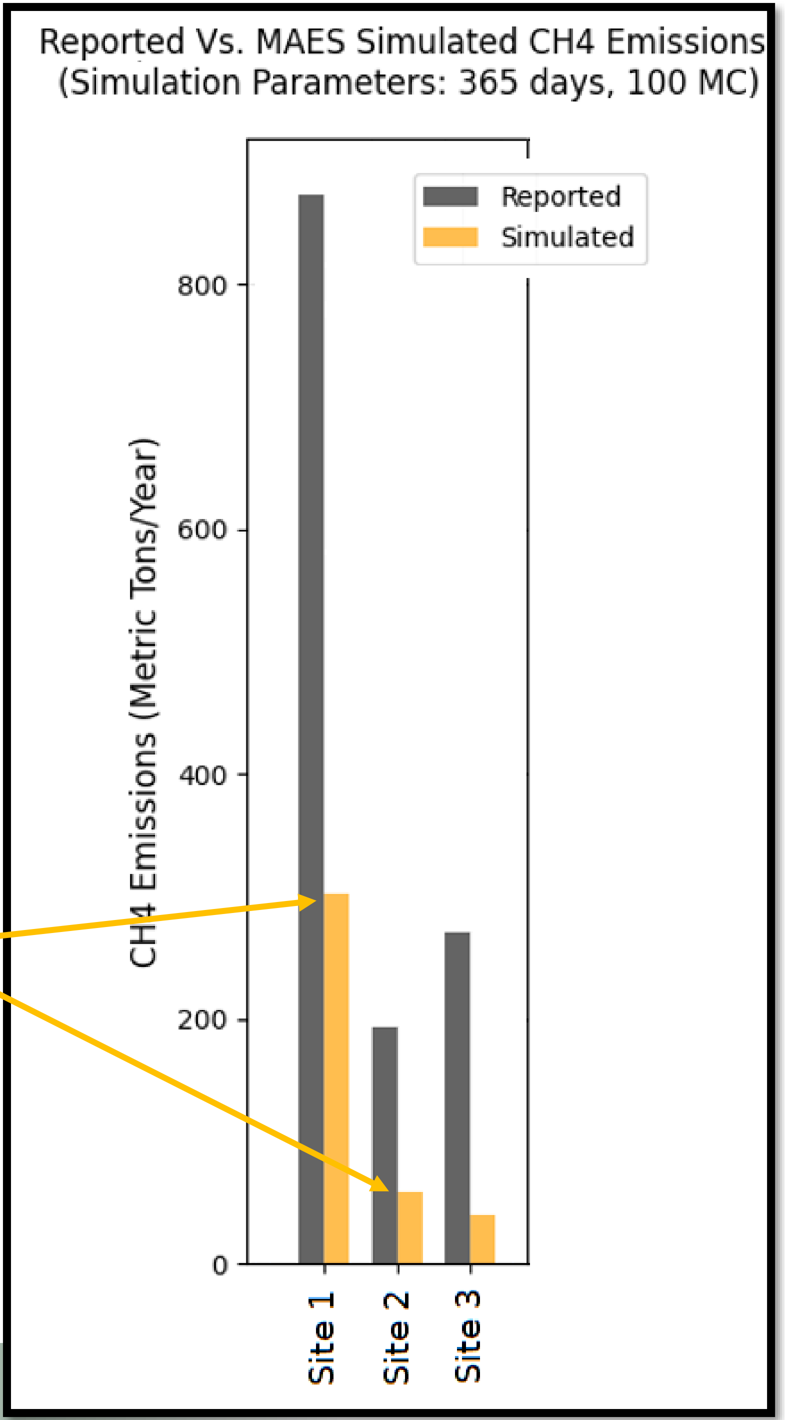
- Comparison is *same sources, same emission mechanisms*
- Company's current understanding .vs. MAES simulation of same sites

(1) Inventory Matching

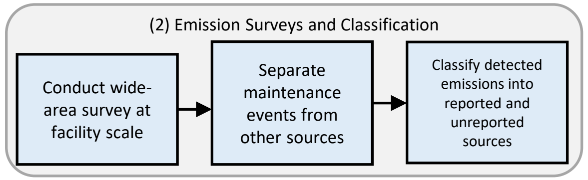
- Often exposes **model errors** / **limitations** and/or **operational field issues**, providing valuable insights for both modelers *and* company.
- Recent example: Dehydrator modeling

  Same activity data – gas flows, recirc rates, etc.
  - *Modelers*: MAES model was underestimating emissions – missing glycol pumps
  - *Operators*: Circulation ratios significantly exceeded recommended range of 3-5 gallons of glycol per pound of water removed

Result: Improved MAES model / improved field process



(2) Emissions Surveys and Classification



Classification goal: For each detected emitter, classify as …

1. Emissions from **normal operations** *(reported source)*
2. Emissions from **maintenance events** *(reported source)*
3. Emissions from a source *not in the inventory.*
   - While source types may be omitted from inventory, more often these are abnormal process conditions not included in inventory.

Classification *criteria*

1. Is this detection a source already included in inventory, emitting within the range of expected rates?
2. Is this detection traceable to a *documented* maintenance event? (if not in inventory, add to inventory)
3. If not (1) or (2) … needs to be added to, or cause an adjustment of, the inventory

(2) Constrain Judgements to *Comparison* Only

Classification goal: For each detected emitter, classify as …

1. Emissions from **normal operations** *(reported source)*

2. Emissions from **maintenance events** *(reported source)*

Already in inventory
Observed emission rate matches inventory range
Observed frequency matches inventory

3. Emissions from a source *not in the inventory.*
   - While source types may be omitted from inventory, more often these are abnormal process conditions not included in inventory.

Not in inventory
Emission rate outside inventory range
Frequency outside inventory range

Facility A scanned three times

Background image from Google Earth

3 passes over several days:

- 1 pass → no emissions seen
- 2 passes → emissions detected

To determine cause, we score:

1) Is emission on site?

1 = Yes

0 = No

2) Plume origin

0 = no concentration near equipment

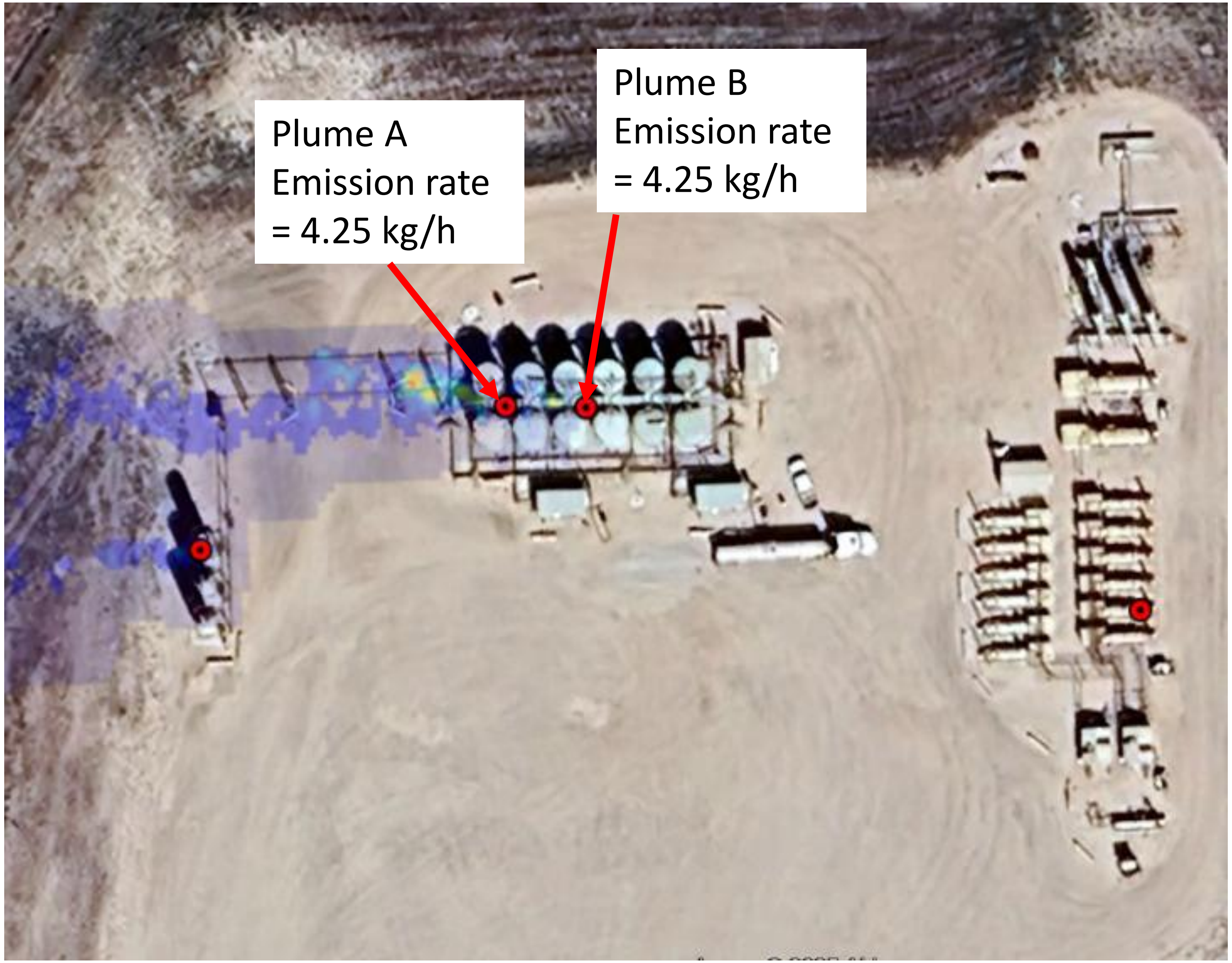
1 = clear emission concentration from equipment

3) Plume Transport

0 = Poor or no visible transport

1 = Plume is visible with coherent structure and atmospheric transport

Detection Scan #1

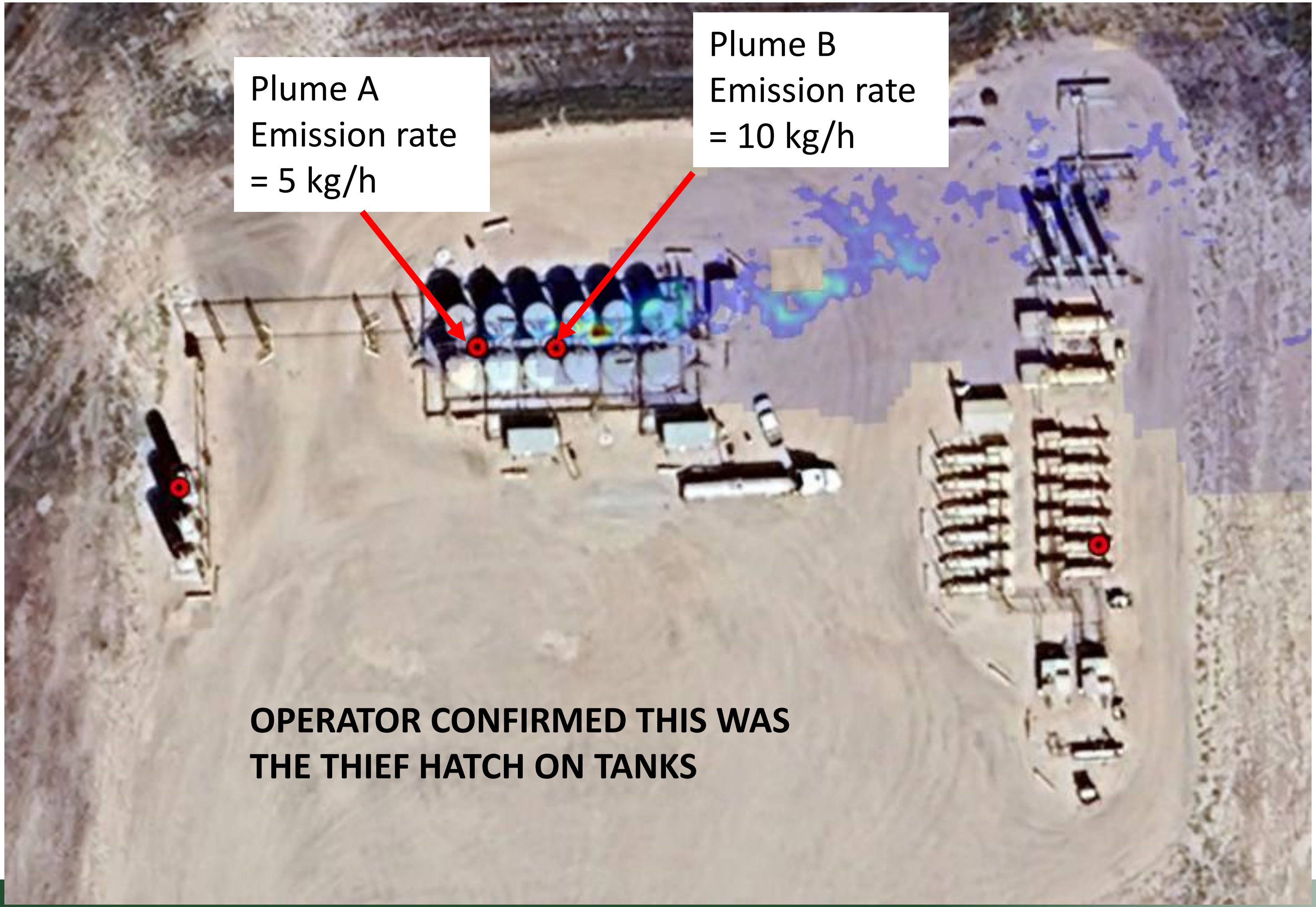


Plume A and B:

1) Emission onsite: 1
2) Plume origin: 0.7, not clearly two distinct plumes
3) Plume location: 1, clearly from tank

Both plumes: **1*0.7*1 = 0.7**

Detection Scan #2 – 3 days later



Plume A:

1) Emission onsite: 1
2) Plume origin: 0.6, very faint concentration
3) Plume location: 0.6, not defined plume

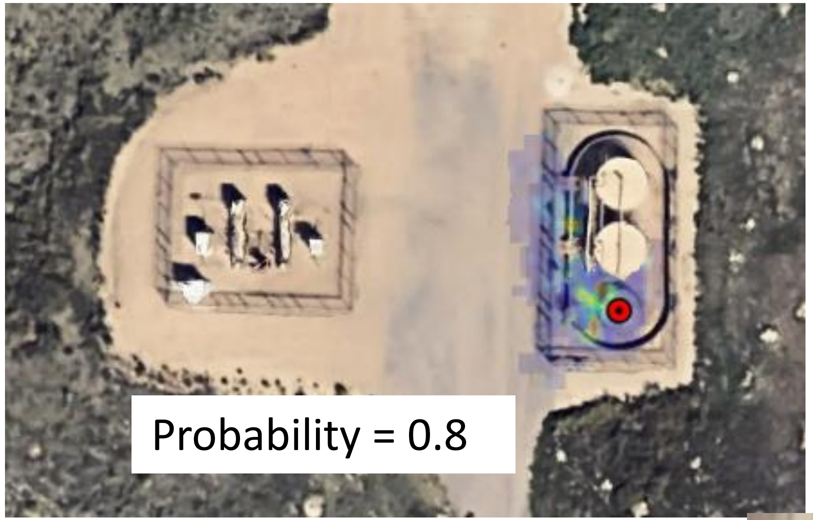
1*0.6*0.6 = **0.36**

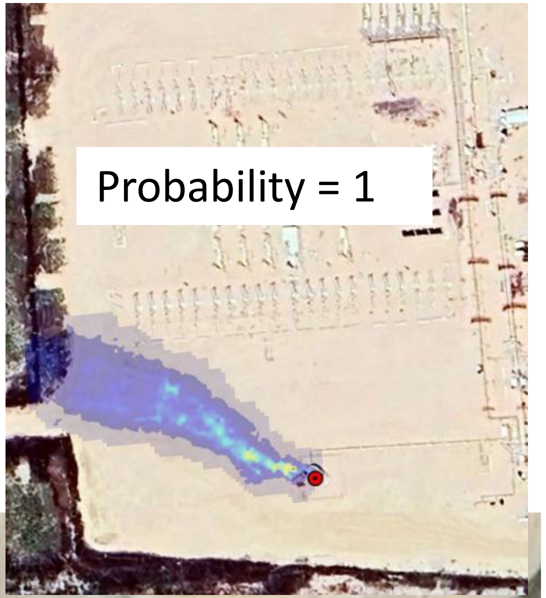
Plume B:

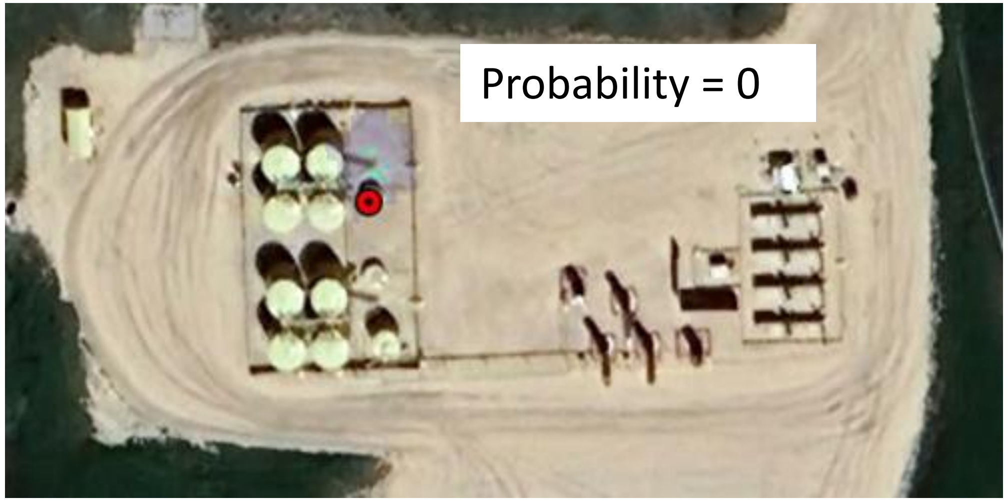
1) Emission onsite: 1
2) Plume origin: 1, clear concentration
3) Plume location: 1, transport good

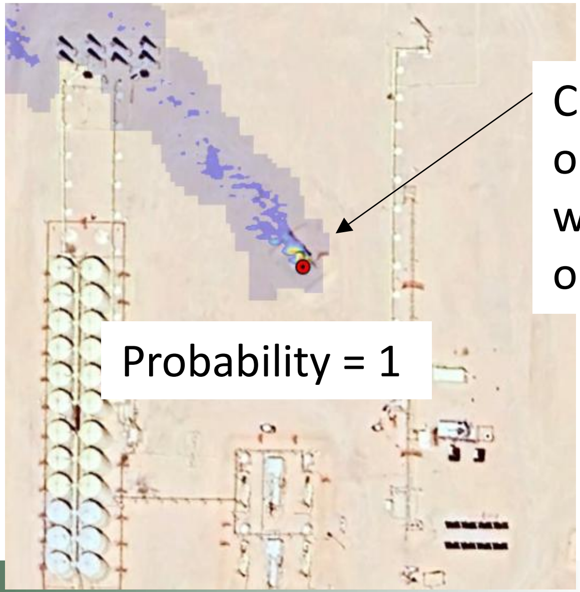
1*1*1 = **1**

Do this for all other facilities scanned..









Conversation with operator confirmed this was a maintenance operation

Probability of Tank CVS Failure

$$\mathbf{pLeak} = \frac{\#\ tanks\ emitting}{\#\ tanks\ scanned}$$

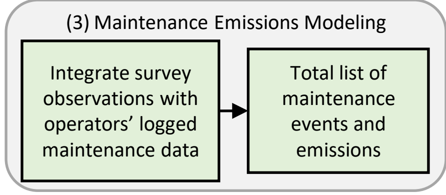
Failure Data:

Discovery	Score	Comment	Filtering	Net Score
1	0.7		Fugitive	0.7
2	0.7		Fugitive	0.7
3	0.36	Poor transport	Fugitive	0.36
4	1		Fugitive	1
5	0.8		Fugitive	0.8
6	1		Fugitive	1
7	0	Rejected plume	Fugitive	0
8	1		Fugitive	1
9	0.4	Poor transport	Fugitive	0.4
10	1		Maintenance	0
Total	**6.96**			**5.96**
		Total number of tanks screened:		**126**
		Estimated leak probability:		***4.7%***

Maintenance Data:

Assure that detected maintenance event was:

a) Factored into inventory
b) Observed emission rate was reasonable for the maintenance being applied



(3) Maintenance Emissions Modeling

- Maintenance emissions excluded primarily due to measurement method reasons:
  - Highly variable rates → instantaneous rate estimate does not accurately reflect total emissions needed for invenotry
  - Short durations → hard to acquire enough samples for accurate count or duration estimate
  - Biased to daytime hours → oversampled by most measurement methods
- MII Approach
  - Remove from analysis → track separately → add to inventory
  - Typically logged events × engineering estimates using operational data
- Note serious issues: Were maintenance events:
  - **Tracked accurately** – duration, settings, monitoring, etc.
  - **Calculated accurately** – method and data issues
- Possible to simulate many typical maintenance events (useful for other analyses)

(4) Informing Using Measurements

A field campaign samples many facilities in quick succession. Assuming unbiased sampling, the observed failure frequency can be defined as:

$$p_f \cong \frac{n_f}{n_c}$$

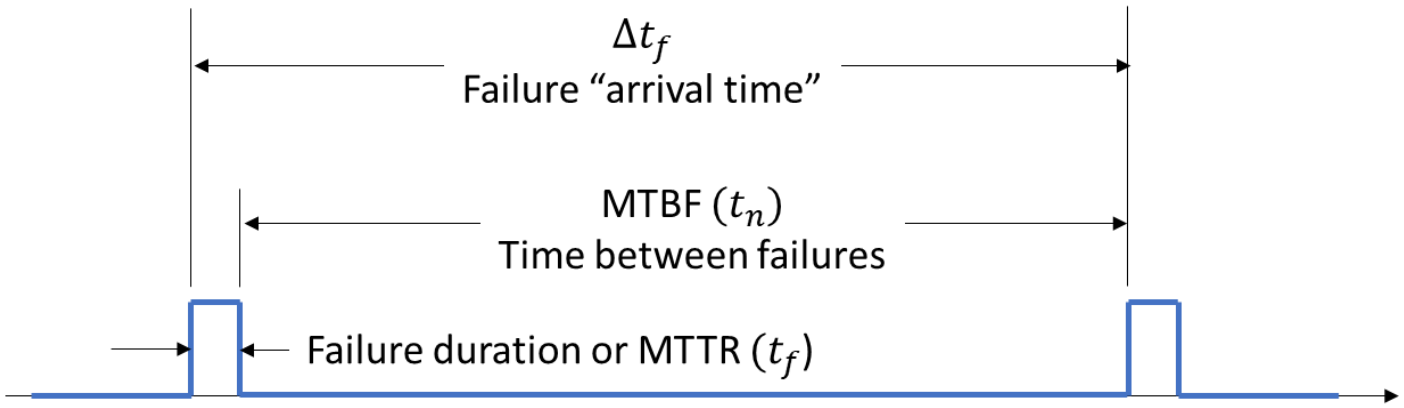
Number of *failed things* in the sampled population (n_f)

Number of *things* in the sampled population (n_c)

(4) Informing Using Measurements

- Assume a familiar failure model:
  MTBF (mean time before failure) / *MTTR* (mean time to repair)
- Over long periods / many units, p_f should represent the fraction of time that member is in the failed condition

$$p_f = \frac{t_f}{t_n + t_f} = \frac{\text{MTTR}}{\text{MTBF} + \text{MTTR}}$$



(4) Estimating Frequency ←→ Duration

$$p_f = \frac{n_f}{n_c} = \frac{\mathrm{MTTR}}{\mathrm{MTBF} + \mathrm{MTTR}}$$

Known - Estimated from measurement survey

Given 1, estimate the other

Note: Calculation done by class/type and location of the emitter

$$MTTR\left(\frac{1}{p_f} - 1\right) \rightarrow MTBF$$

You can find it this fast

I'll tell you how often it fails

$$\left(\frac{p_f}{1 - p_f}\right) * MTBF \rightarrow MTTR$$

Exactly the Model in Traditional Inventories

Mechanism → **Happens at a frequency** → **For some duration** → **At some emission rate**

Study had list of things it 'looked at'

Looked at n_c things and found n_f emitting

Assumed the n_f things that were found were emitting for the year*

Measured emission from n_f emitters

Activity Factor

Emission Factor

*Formally, assumes that frequency of emitters found in the underlying study were representative of emitter frequency in any potential application of the data

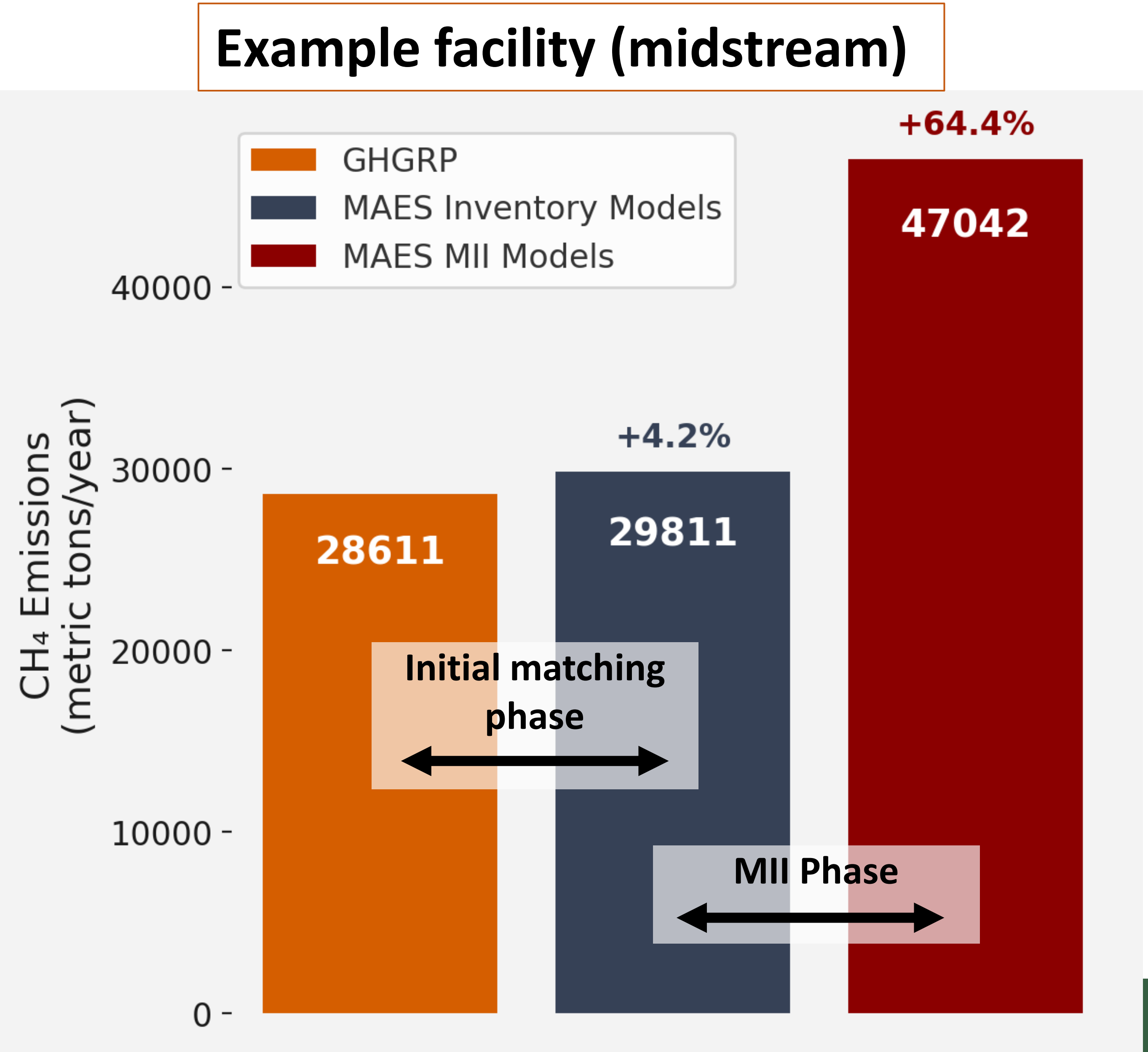
(5) Computation & Learning

- Now have:
  - Updated inventory
  - Refreshed list of maintenance events
- Calculate emissions on required time scales

What do results look like?

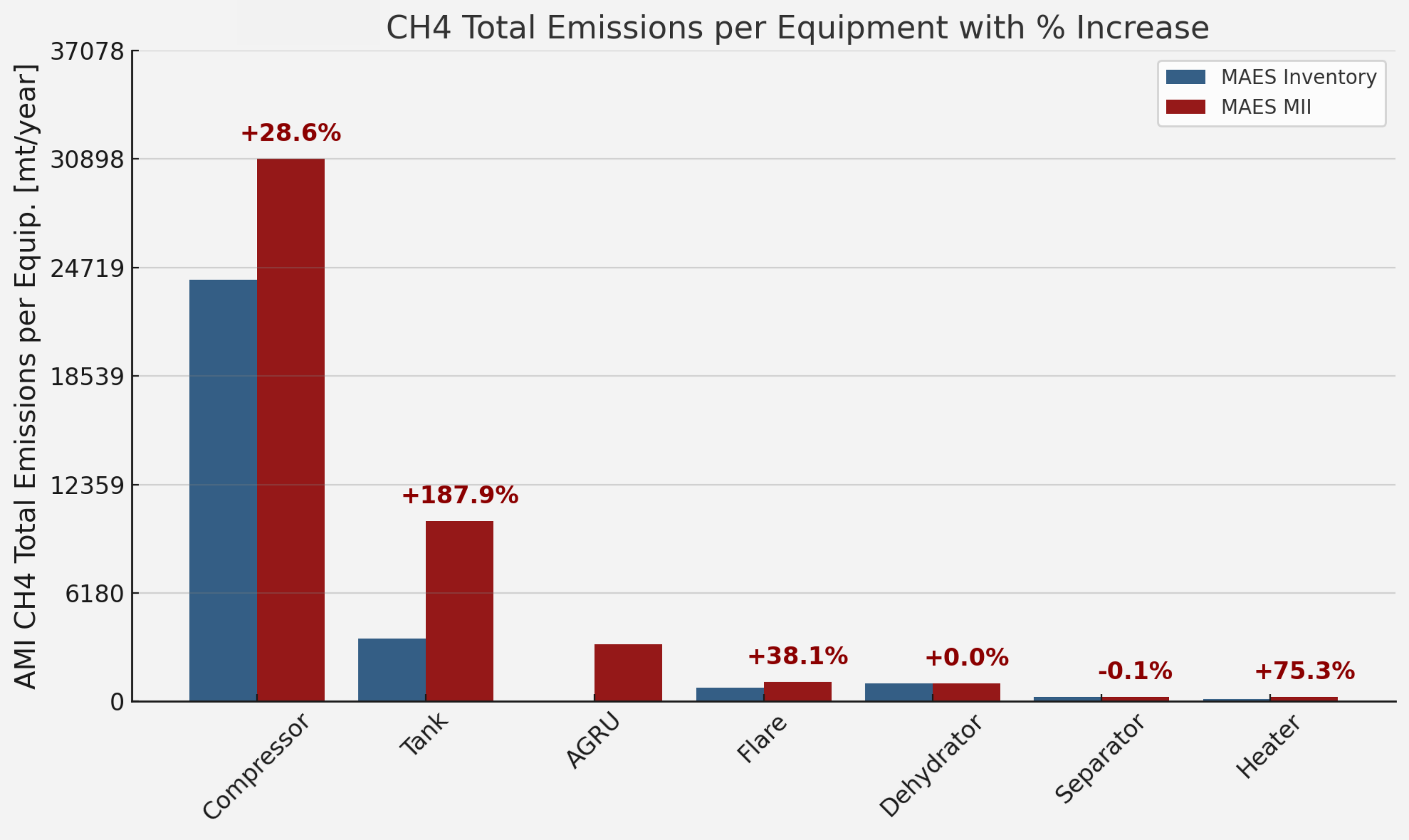
What do results tell you?

(5) MII Results: Totals



- MII models account for emissions from unreported sources not included in underlying inventory.
- With enough samples, may also dial down sources that are over-estimated from traditional factors

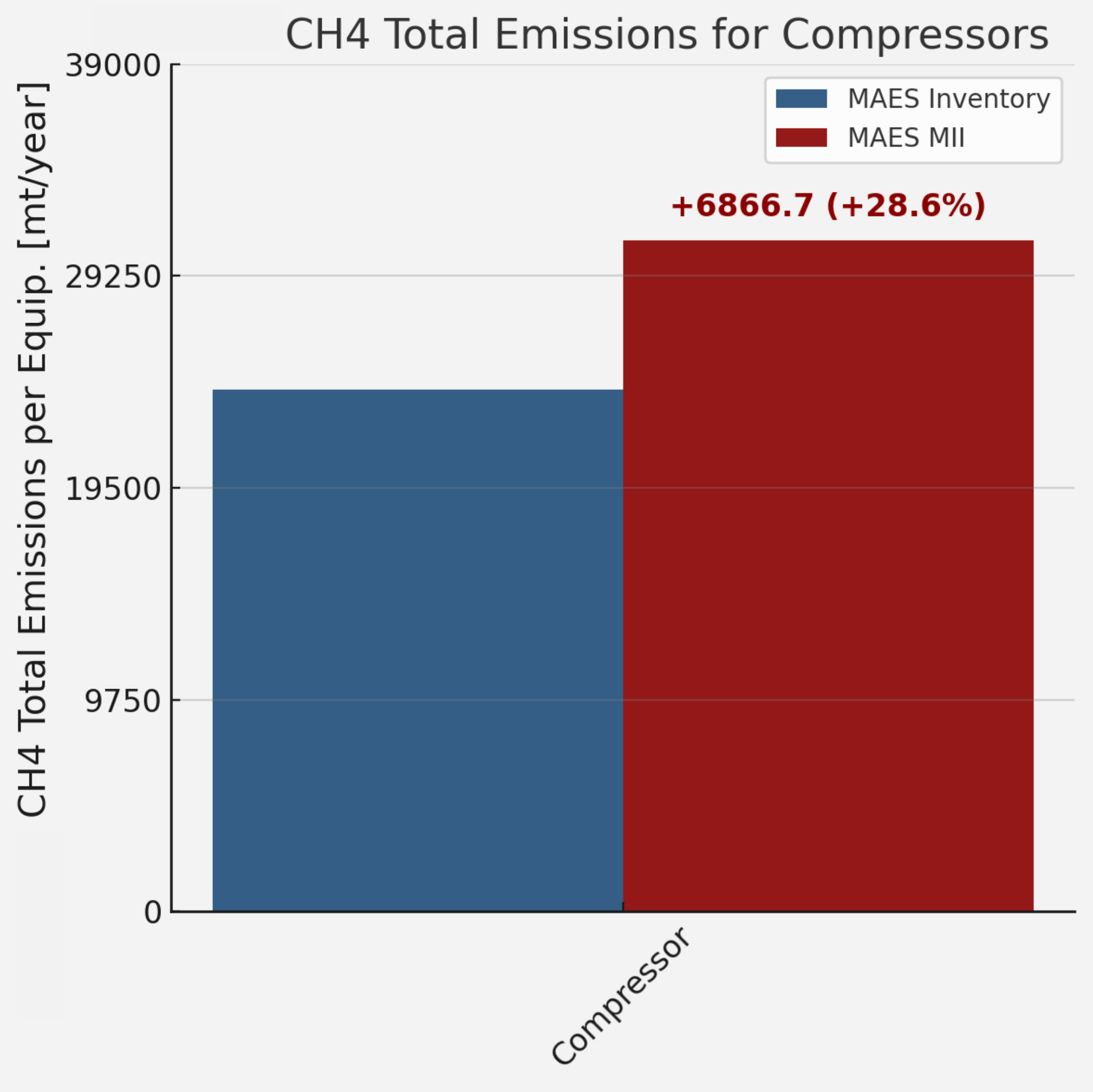
(5) MII Results: Break out by source:
Where to concentrate effort



ITUTE
ERSITY

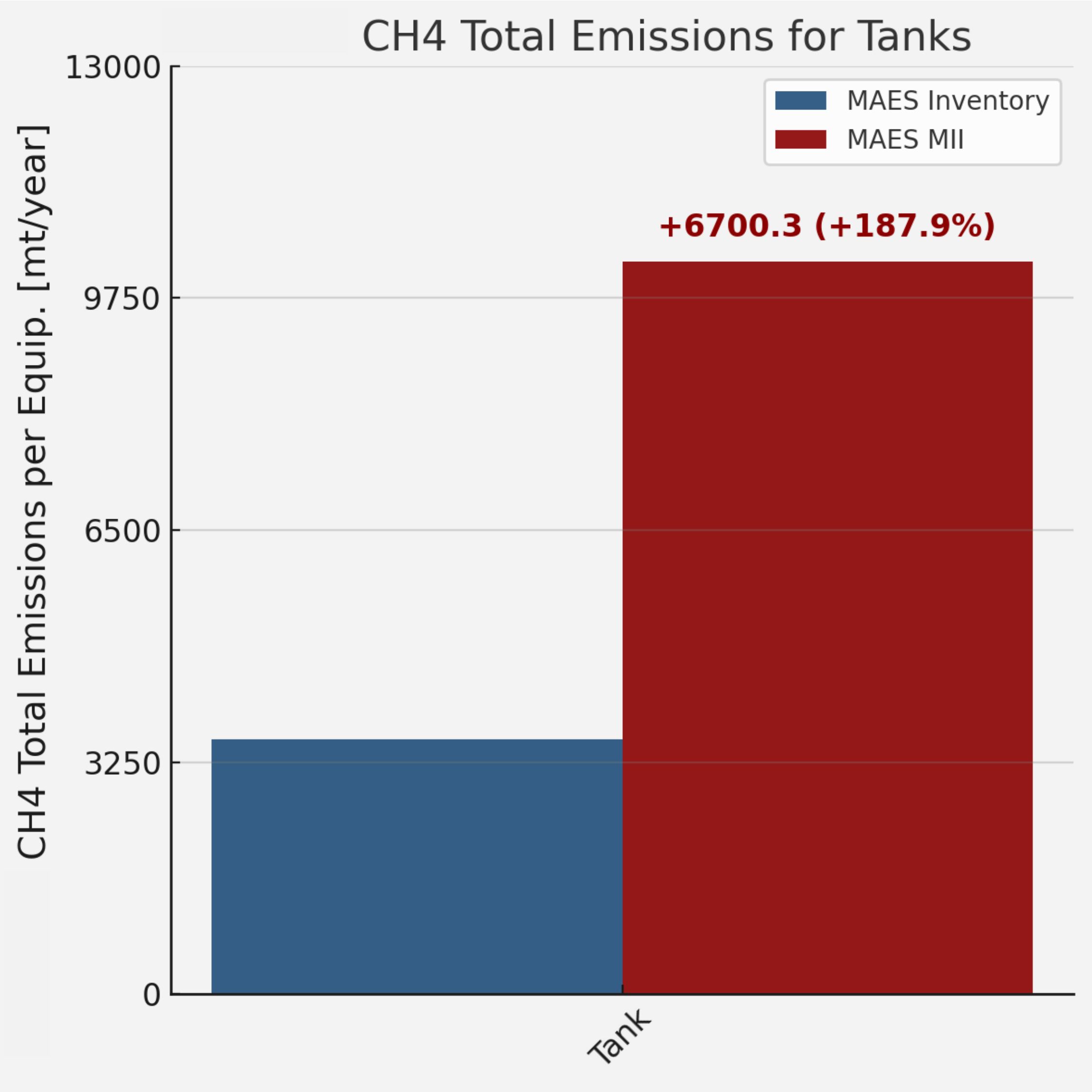
(5) MII Results
Why is MII $\neq$ Inventory?

- **Compressor emissions:**
  - Crankcase emissions are detected via aerial surveys but are **not reported** in the 2023 GHGRP.
  - MAES uses **CH_4 Seal Vent Emission Factors (EFs)** from the **new Subpart W rule**[1]
  - **Rod Packing Failures** have been observed in the field (1.1% of all compressors overflown), contributing to higher emissions.



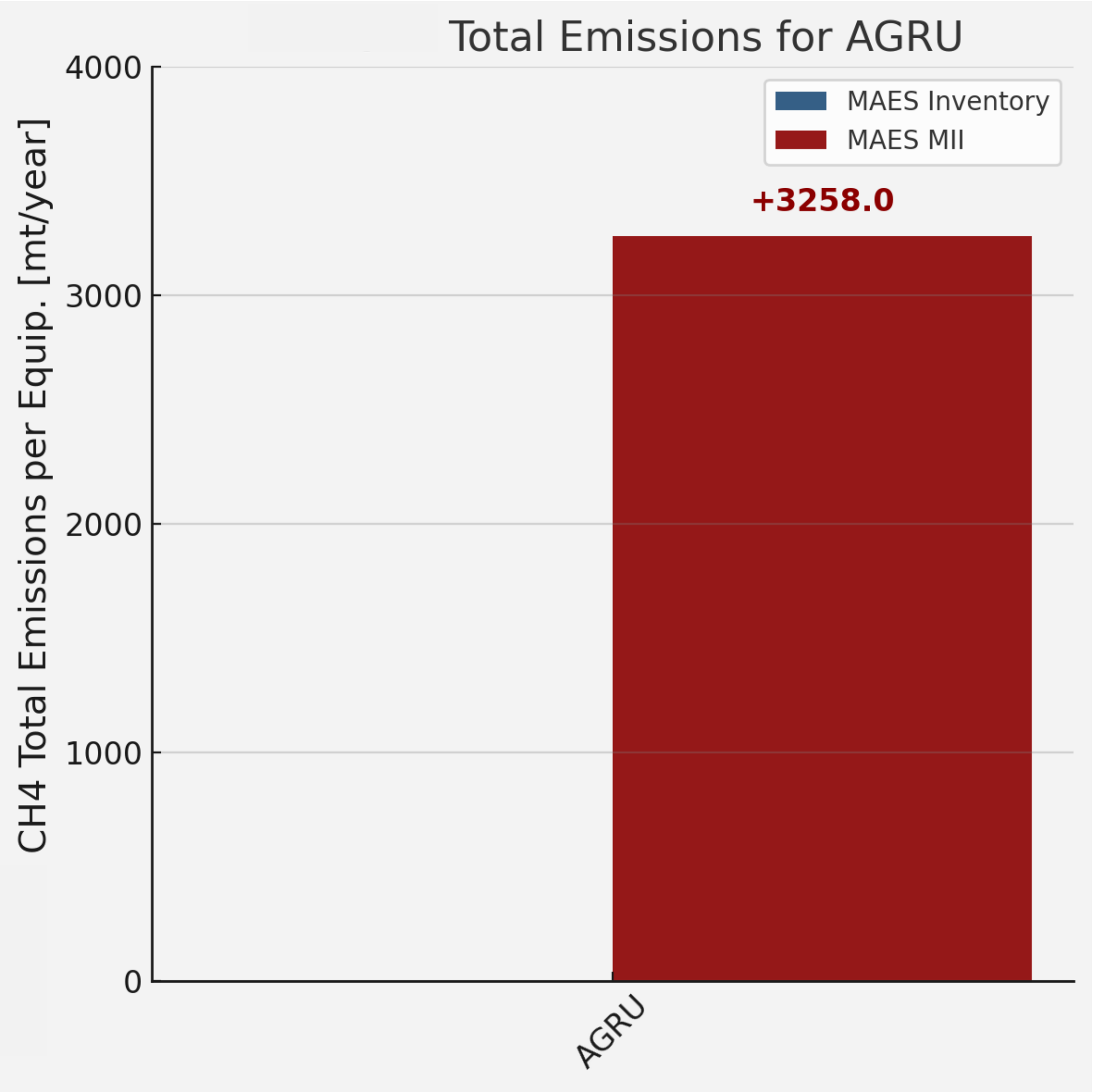
(5) MII Results
Why is MII ≠ Inventory?

- **Tank Emissions:**
  - **Failures** and **uncontrolled tanks** contribute to most of the emissions
  - **40% of tank batteries** at midstream sites in this study were **are uncontrolled**
  - **28%** of all tank batteries **had at least 1 detected emission** between Q1 and Q3



(5) MII Results
Why is MII ≠ Inventory?

- Acid Gas Removal Unit (AGRU):
  - A single **malfunctioning AGRU** was estimated to **emit 3258 CH4 metric tons**
  - This single failure accounts **for 18% of the additional CH4 emissions estimated by the MAES MII** models compared to GHGRP
  - This highlights the importance of mitigating failure conditions as soon as possible



Measurement Informed Inventory
Conclusion

Overview of MII

- Inventories
  - Review
  - New versus traditional inventories
- Measurements
  - What you get
  - How to think about results
- Informing
  - Process CSU uses per-company and per-basin
  - Learning from the process

- Survey methods are not a magic way to eliminate inventory calculations
- Surveys *estimate* not measure
- Well tested / proven methods are essential to the process
- MII can & should be systematic
- While annual estimates are great, the real value is in what you learn

Thank You

Contact

Daniel Zimmerle, Sr. Research Associate, Energy Institute
Dan.Zimmerle@colostate.edu | 970 581 9945

@CSUenergy

www.facebook.com/csuenergyinstutute

Energy.ColoState.edu