British Columbia Top-down Survey and Root Cause Analysis

# 2021 Measurement-Based Methane Inventory, Source Attributions, and Root Cause Analysis

*BC OGC Methane Research Workshop, May 31, 2022*


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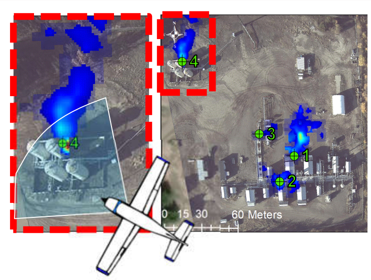
## British Columbia Top-down Survey and Root Cause Analysis

- Ambitious project building on previous pioneering aerial- and ground-based survey work in BC
- Several broad objectives:
  - Comprehensive aerial measurements with on-site ground-based follow-up investigations
  - I. Create a 2021 measurement-based methane inventory including comprehensive uncertainty analysis
  - II. Attribute to specific source types and investigate root causes
  - III. Analyze results to consider implications for mitigation and emerging regulations





BC OGRIS BC Oil and Gas Research and Innovation Society
BC Oil & Gas COMMISSION
BRIDGER PHOTONICS
GREENPATH ENERGY LTD
Natural Resources Canada / Ressources naturelles Canada
Canada
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## I. Creating a Measurement-Based Methane Inventory

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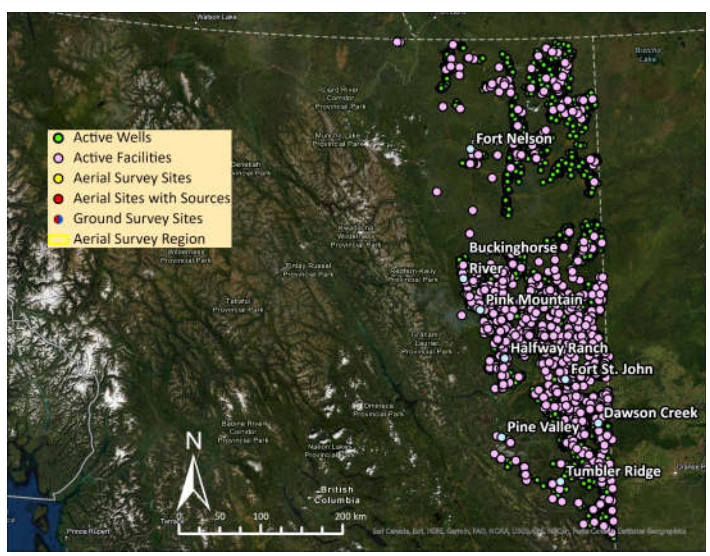
## 2021 British Columbia Top-down Survey and Root Cause Analysis

- ~10324 active wells
- ~1244 active facility IDs

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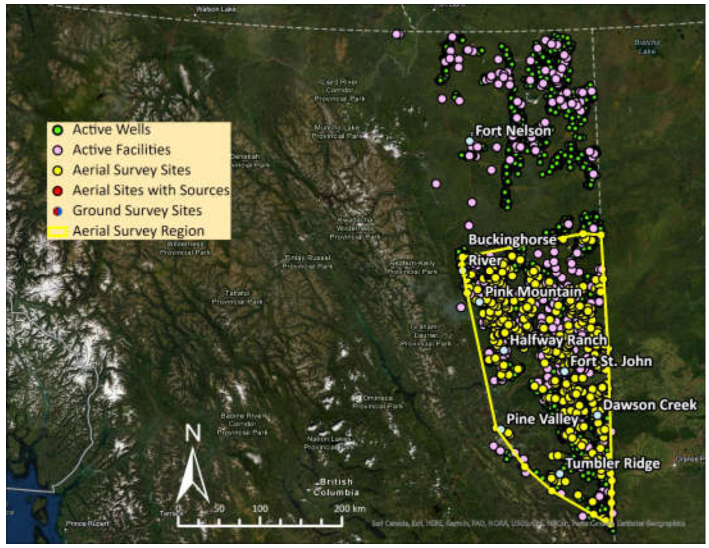
## 2021 British Columbia Top-down Survey and Root Cause Analysis

- ~10324 active wells
- ~1244 active facility IDs
- Sample of 508 ***sites*** chosen:
  - 718 active Petrinex IDs
  - 1004 active wells
  - Distribution of subtypes representative of province
  - Includes 137 still active sites from prior 2018/2019 surveys

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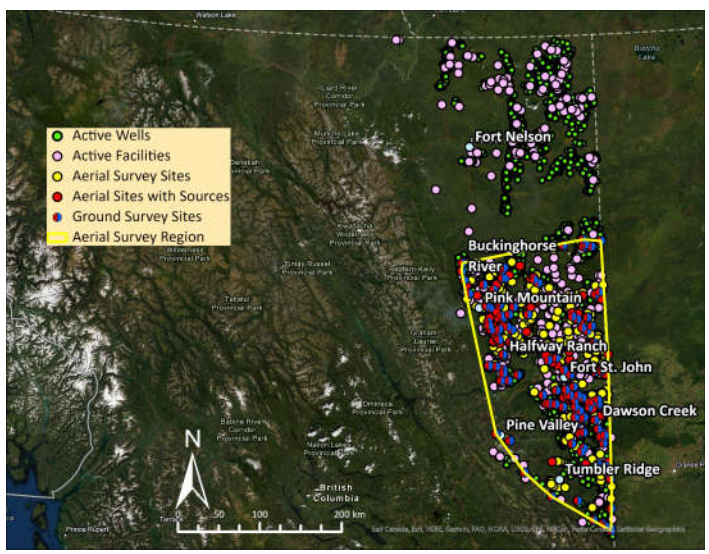
## 2021 British Columbia Top-down Survey and Root Cause Analysis

Within sample of 508 sites:

- Final data from Bridger contained 527 quantified sources at 184 sites
  - 16 additional sources detected but not quantified for 543 total final detections
  - Four additional sites with unquantified plumes
- Ground team sent to inspect 227 sources
  - Included 195 identified as final sources by Bridger at 75 sites

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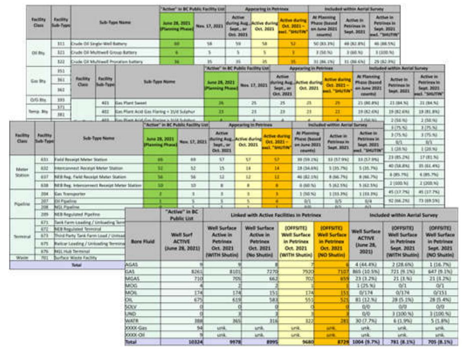
## 1. Survey Design

- Multiple challenges to work through:
  - Count data quality
    - "Active" vs. reporting
  - Location limits (DLS/LSD and NTS)
  - Well surface locations and identification of offsite wells
  - Non-reporting facilities (i.e., compressor stations )
  - Confidential wells
  - Missing or out of date satellite imagery, etc., etc.,



- Final stratified sample of subtypes includes:
  - Nearly 60% of active facilities (with higher samling at key subtypes)
  - 10% of active wells, and 8% of active off-facility wells

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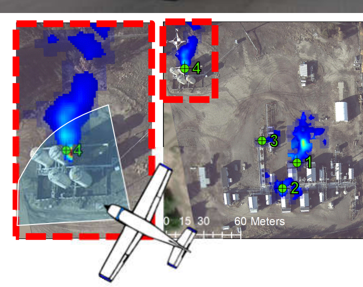
## 2. Aerial Surveys using Bridger Photonics Gas Mapping LiDAR (GML)

- Aerial scanning laser plus high res. GPS & camera
  - Detection sensitivities ~0.25-3 kg/h
  - ~100-m wide swath with ~1-2 m resolution


- Relatively new technology that continues to improve
  - **100-1000 times more sensitive than satellites**
  - **50+ times better resolution**

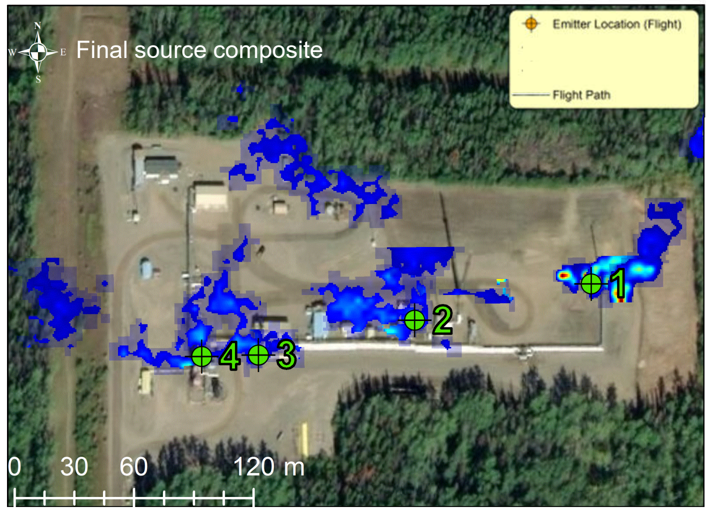
- **Extensively characterized by EERL to quantify probabilities of detection and measurement uncertainty**




*Johnson et al., Remote Sensing of Environment, 2021*
(doi: 10.1016/j.rse.2021.112418)

## 3. Quantification of Source Emission Rates across Multiple Passes & Flights

- Sites have one or more passes
- Flights with detected emissions are revisited in a subsequent day
- Source quantification for inventory development purposes requires interpretation of data from each pass

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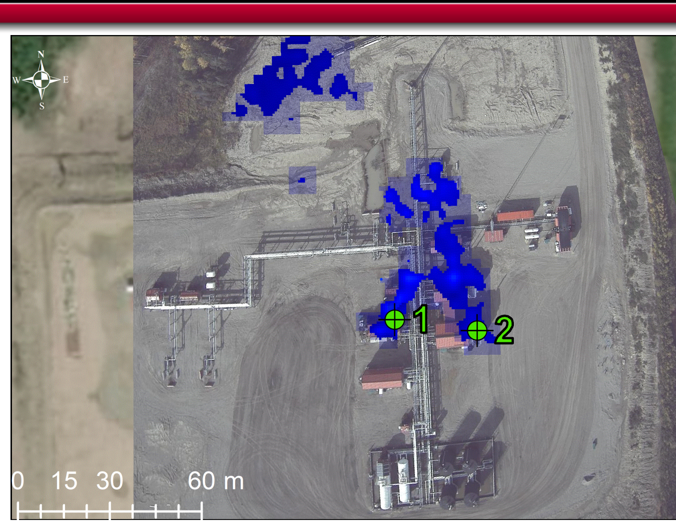
## 4. Attribution of GML-Detections to Sources

- Combining satellite imagery, geo-located aerial photos, plot plans, & ground survey data to attribute

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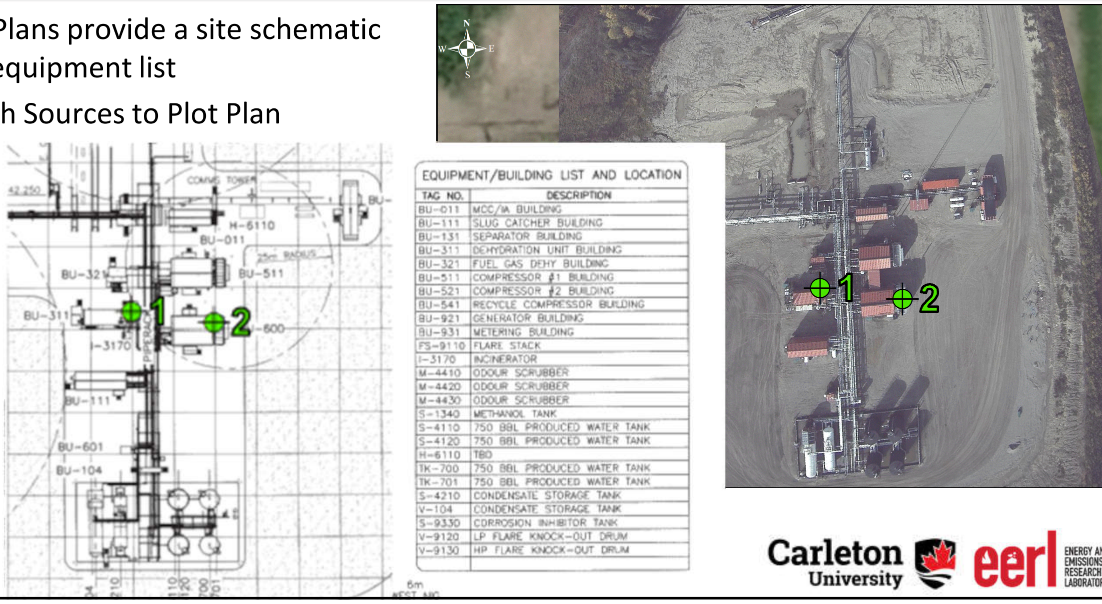
## 4. Attribution of GML-Detections to Sources

- Plot Plans provide a site schematic and equipment list
- Match Sources to Plot Plan




EQUIPMENT/BUILDING LIST AND LOCATION

| TAG NO. | DESCRIPTION |
|---|---|
| BU-011 | MCC/IA BUILDING |
| BU-111 | SLUG CATCHER BUILDING |
| BU-131 | SEPARATOR BUILDING |
| BU-311 | DEHYDRATION UNIT BUILDING |
| BU-321 | FUEL GAS DEHY BUILDING |
| BU-511 | COMPRESSOR #1 BUILDING |
| BU-521 | COMPRESSOR #2 BUILDING |
| BU-541 | RECYCLE COMPRESSOR BUILDING |
| BU-921 | GENERATOR BUILDING |
| BU-931 | METERING BUILDING |
| FS-9110 | FLARE STACK |
| I-3170 | INCINERATOR |
| M-4410 | ODOUR SCRUBBER |
| M-4420 | ODOUR SCRUBBER |
| M-4430 | ODOUR SCRUBBER |
| S-1340 | METHANOL TANK |
| S-4110 | 750 BBL PRODUCED WATER TANK |
| S-4120 | 750 BBL PRODUCED WATER TANK |
| H-6110 | TBD |
| TK-700 | 750 BBL PRODUCED WATER TANK |
| TK-701 | 750 BBL PRODUCED WATER TANK |
| S-4210 | CONDENSATE STORAGE TANK |
| V-104 | CONDENSATE STORAGE TANK |
| S-9330 | CORROSION INHIBITOR TANK |
| V-9120 | LP FLARE KNOCK-OUT DRUM |
| V-9130 | HP FLARE KNOCK-OUT DRUM |

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## 5. Attribution of Detected Sources to Subtypes

- Each detected source is manually reviewed
  - Linked with a specific Petrinex facility ID and subtype or well type
  - Much better data quality and resolution than federal inventory approach, but same premise
- Attribution is often straightforward, but becomes complicated when multiple Petrinex IDs located within same location / site
  - Solved through painstaking review of:
    - facility plans,
    - high-resolution aerial photos plus plume imagery,
    - production accounting data,
    - well locations,
    - pipeline connections,
    - ground logs

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## Subtype Attribution Example 1: BC_137
## (Simple site with single Petrinex ID)

- Site 137:
  - Contained within a single land unit (LSD-SEC-TWP-RGWM)
  - Single Petrinex facility ID (pink dot)
- BCBTXXXXXXX
  - Petrinex subtype 361
    - Gas Multiwell Group Battery
  - Only active facility contained in Site 137's land unit (LSD-SEC-TWP-RGWM)
- Flare emission assigned to subtype 361


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## Subtype Attribution Example 2: BC_96
## (Large complex location with multiple Petrinex IDs)

- Site 96 spans several land units (LSD-SEC-TWP-RGWM)
- Site 96 contains:
  - 5 detected source; and
  - 7 Petrinex facility IDs (pink dots) in main land unit
    - GP, GS, Gas BT (2x), Oil BT, IF, MS
- Sources attributed to facility IDs analyzing plot plans, meter schematics, and volumetric activity data


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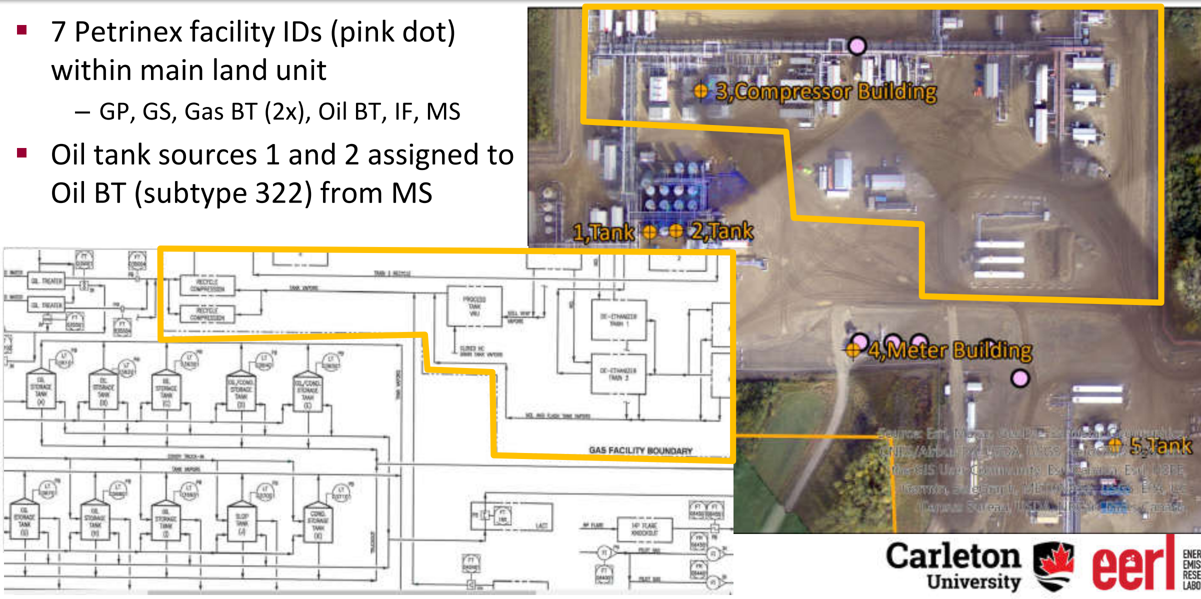
## Subtype Attribution Example 2: BC_96
## (Large complex location with multiple Petrinex IDs)

- 7 Petrinex facility IDs (pink dot) within main land unit
  - GP, GS, Gas BT (2x), Oil BT, IF, MS
- Oil tank sources 1 and 2 assigned to Oil BT (subtype 322) from MS

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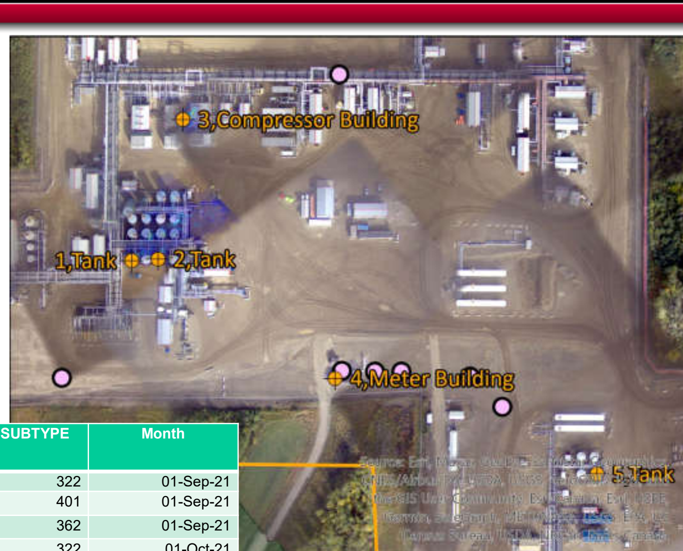
- 7 Petrinex facility IDs (pink dot) within main land unit
  - GP, GS, Gas BT (2x), Oil BT, IF, MS
- Oil tank sources 1 and 2 assigned to Oil BT (subtype 322) from MS
- Compressor source assigned to GP (subtype 401) by reported fuel use during survey month
  - GS, 1 Gas BT reported 0 fuel use




| FACILITY | ACTIVITY | PRODUCT | VOLUME | LOCATION | SUBTYPE | Month |
|---|---|---|---|---|---|---|
| BT | FUEL | GAS | 18.1 | 03-XX-XXX-XXW6 | 322 | 01-Sep-21 |
| GP | FUEL | GAS | 842.1 | 03-XX-XXX-XXW6 | 401 | 01-Sep-21 |
| BT | FUEL | GAS | 26.6 | 03-XX-XXX-XXW6 | 362 | 01-Sep-21 |
| BT | FUEL | GAS | 20.6 | 03-XX-XXX-XXW6 | 322 | 01-Oct-21 |
| BT | FUEL | GAS | 41.6 | 03-XX-XXX-XXW6 | 362 | 01-Oct-21 |
| GP | FUEL | GAS | 881.4 | 03-XX-XXX-XXW6 | 401 | 01-Oct-21 |

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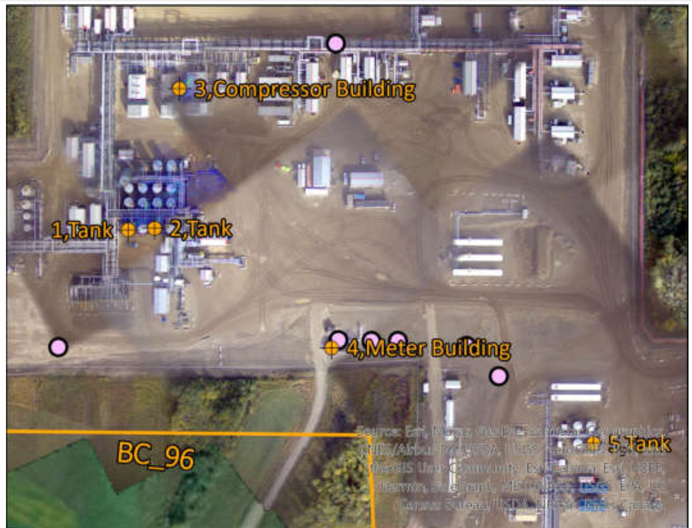
## Subtype Attribution Example 2: BC_96
## (Large complex location with multiple Petrinex IDs)

- 7 Petrinex facility IDs (pink dot) within main land unit
  - GP, GS, Gas BT (2x), Oil BT, IF, MS
- Oil tank sources 1 and 2 assigned to Oil BT (subtype 322) from MS
- Compressor source assigned to GP (subtype 401) by reported fuel use during survey month
- Meter Building assign to Meter Station (subtype 637)
- Tank source 5 assigned to GP






## 6. Field Work to Quantify GML Sensitivity Limits

- Blinded, controlled release studies to infer GML detection sensitivity
- Three years of field data (N = 190):
  1. B.C., September 2019: N = 23
  2. Saskatchewan, August 2020: N = 52
  3. Saskatchewan, September 2021: N = 115
- Small fully-blinded release rates (< 5.2 kg/h)

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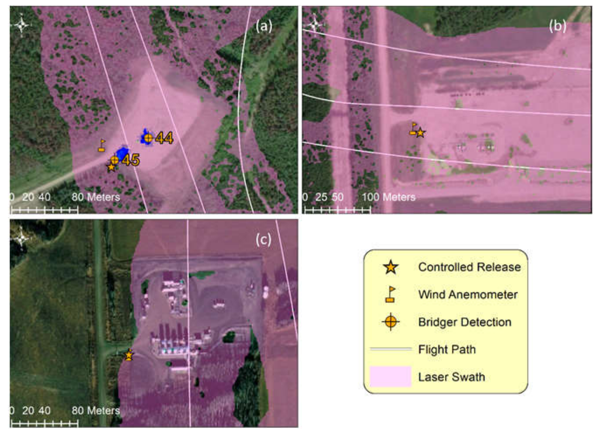


M.R. Johnson, D.R. Tyner, A.J. Szekeres (2021) Blinded evaluation of airborne methane source detection using Bridger Photonics LiDAR, *Remote Sensing of Environment*, 259, 112418. (doi: 10.1016/j.rse.2021.112418)

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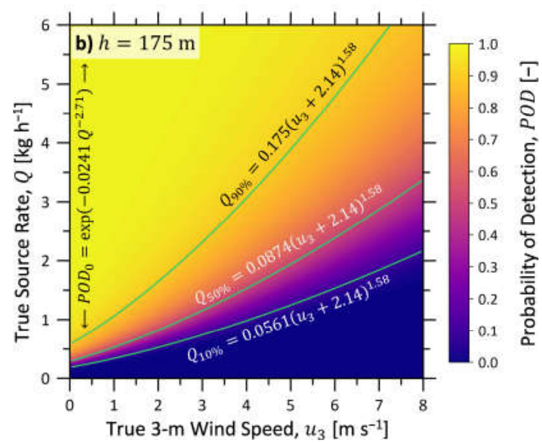
- Three years of field data (N = 190):
  1. B.C., September 2019: N = 23
  2. Saskatchewan, August 2020: N = 52
  3. Saskatchewan, September 2021: N = 115
- Small fully-blinded release rates (< 5.2 kg/h)
- ***Generalized continuous*** sensitivity function
  - Probability of detection at any altitude, wind speed, or source rate
  - Bounds missed detections when comparing pass data within Monte Carlo analysis
  - Major accomplishment to be reported in upcoming publication comparing airborne platforms

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## 7. Field Work to Quantify GML Accuracy

- Semi-blinded larger releases to test Bridger quantification uncertainty
- Two years of “racetrack” data (N = 313):
  - Saskatchewan, August 2020 : N = 151
  - Saskatchewan, September 2021 : N = 162
    - Releases up to 66 kg/h


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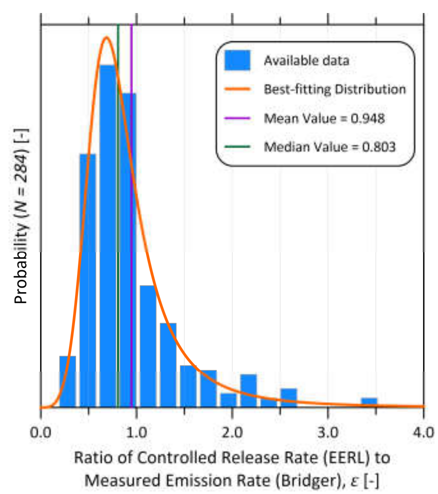
## 7. Field Work to Quantify GML Accuracy

- Semi-blinded larger releases to test Bridger quantification uncertainty
- Two years of “racetrack” data (N = 313):
  - Saskatchewan, August 2020 : N = 151
  - Saskatchewan, September 2021 : N = 162
    - Releases up to 66 kg/h

- Quantified uncertainty distribution over a relevant range of source rates
  - Allows uncertainties to be propagated into inventory calculations

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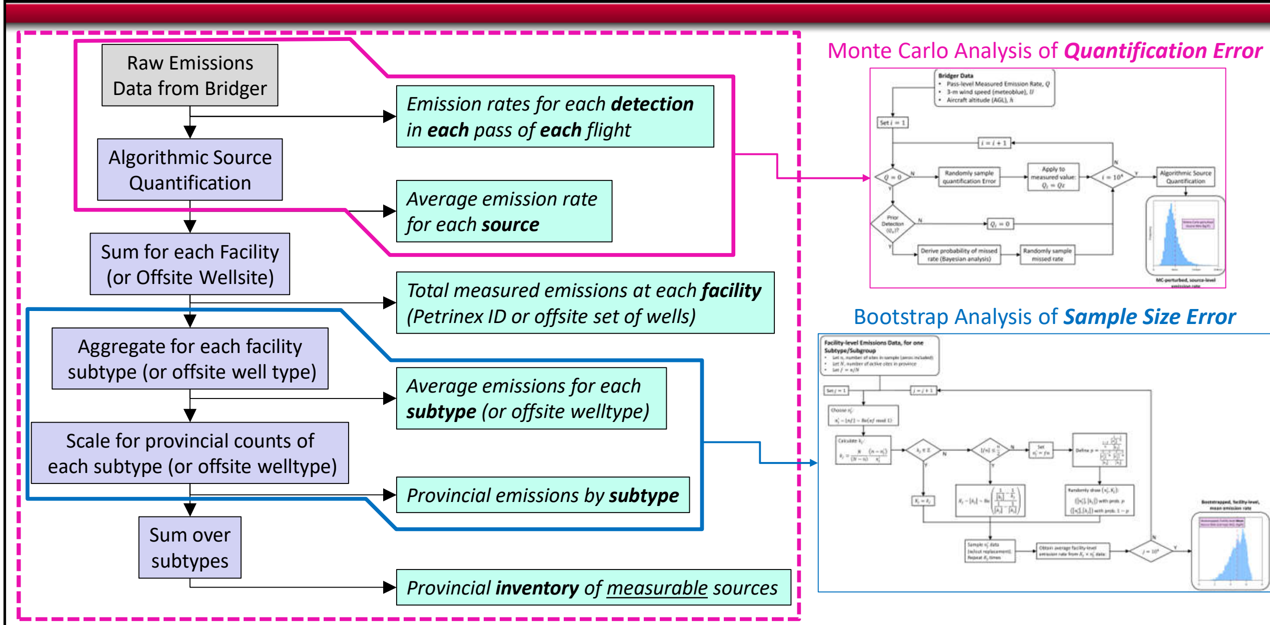
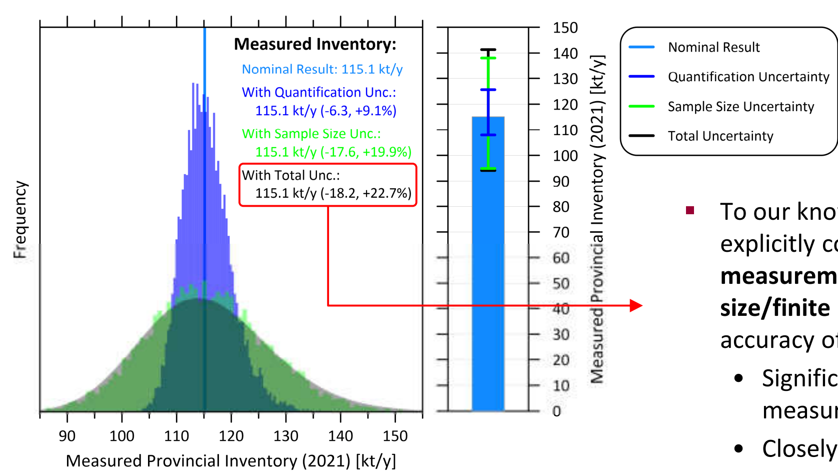
## Framework for Calculating Measurement & Sample Size Uncertainties




## 2021 *Measured Source* Inventory




- To our knowledge, this is the first study to explicitly consider contributions of ***both* measurement uncertainty** and **sample size/finite population effects** to the overall accuracy of the measured inventory
  - Significant advance for creating robust, measurement-based inventories
  - Closely followed by UNEP/IMEO

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## 9/10. Unmeasured Source Contributions to the Inventory

- Bridger technology does not capture all sources:
  - Expected to miss sources below its sensitivity limit such as
    - Leaking fittings, valves, small vent lines etc.
    - Normally operating pneumatic instruments and pumps
  - Intermittent sources that may be important yet infrequent
  - Other sources missed for various reasons
    - e.g., near standing water or moist ground, obscured by other equipment or sources, near edge of laser swath, etc.

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## Missed Sources Example #1: BC_286 (Tanks)

- Aerial survey detected 8 sources
  - No tank sources
- Ground team inventoried 10 active onsite tanks
  - 3 controlled (VRU) tanks
  - 7 uncontrolled tanks
- Ground team detected emissions at 6 of 7 uncontrolled tanks
  - All missed by Bridger

## Missed Sources Example #2: BC_253 (Tanks)

- Aerial survey detected 3 sources
  - No tank sources
- Ground team inventoried 2 active uncontrolled tanks
  - Emissions observed by the ground team at both tanks
  - Both missed by Bridger


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## Missed Sources Example #3: BC_438 (Tanks)

- Aerial survey detected 1 source
  - No tank sources
- Ground team inventoried 2 active uncontrolled tanks
  - Emissions observed at both tanks
  - Both missed by Bridger


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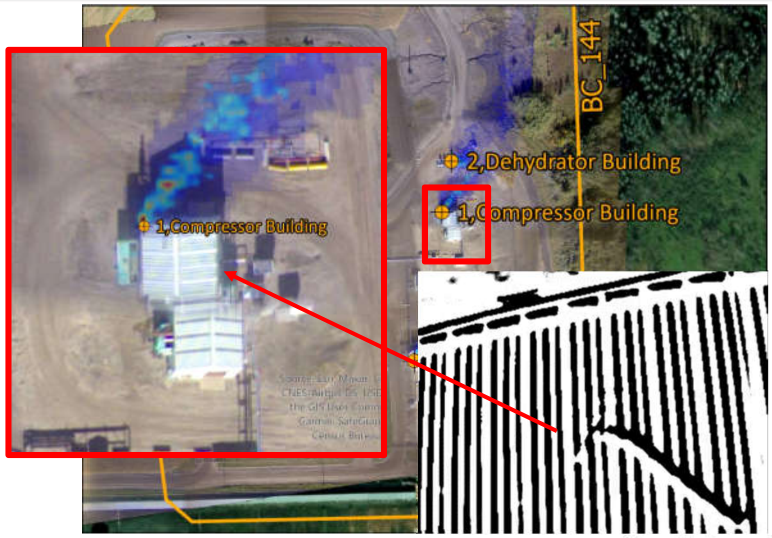
## Missed Sources Example #4: BC_144 (Compressor Rod Packing Vent)

- Aerial survey compressor emissions dominated by exhaust emissions
  - Plume is directly over exhaust (muffler)
- Ground team noted rod packing emissions at the same compressor
  - Not detected in aerial survey

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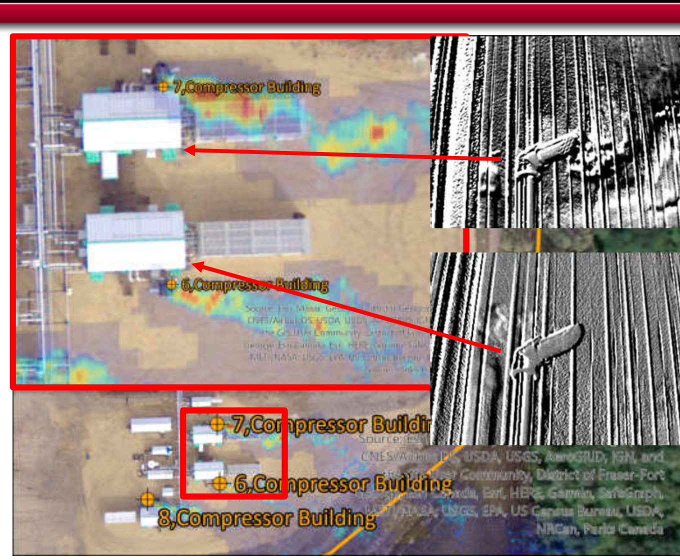
## Missed Sources Example #5: BC_41 (Compressor Rod Packing Vent)

- Aerial survey measured compressor exhaust emissions
  - Plumes directly over exhaust (mufflers)
- Ground team observed rod packing emissions at the same compressors
  - Not detected in aerial survey

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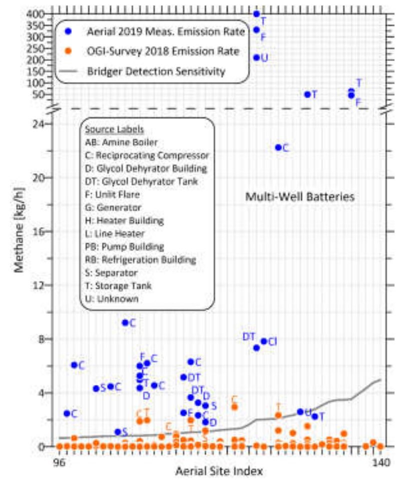
## 9/10. Calculating Contributions from Unmeasured Sources

- 2019 BC aerial & 2018 ground surveys
  - Gives direct insight into frequency and potential importance of missed sources
  - At same subset of facilities:
    - Aerial survey: 80 sources (1802 kg/h)
    - OGI survey: 357 source (74 kg/h)
- **OGI data a good measure of missed sources below Bridger sensitivity limit (*excl. pneumatics*)**
  - Update with 2021 sensitivity limit Key data sets for BC




D.R. Tyner, M.R. Johnson (2021) here the Methane Is—Insights from Novel Airborne LiDAR Measurements Combined with Ground Survey Data, *Environmental Science & Technology*, 55(14):9773-9783. (doi: 10.1021/acs.est.1c01572)



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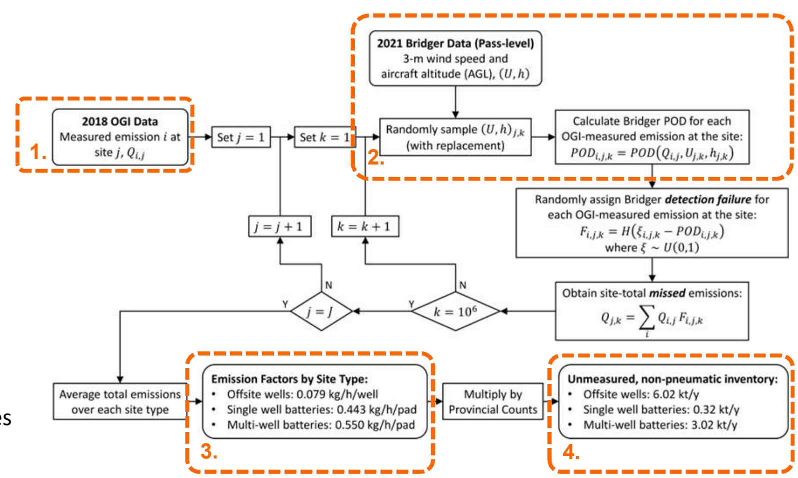
## Inventory Contribution of Unmeasured, Non-Pneumatic Sources

- Combine:
  1. 2018 OGI survey data
  2. 2021 Bridger sensitivity by pass
3. Derive updated emission factors non-pneumatic sources ***below detection limits***:
   - Offsite wells: 0.079 kg/h/well
   - SWB: 0.443 kg/h/pad
   - MWB: 0.550 kg/h/pad
4. Scale by provincial counts
   - Conservatively assume ***zero*** unmeasured non-pneumatic sources at subtypes:
     - 631-640 (meter stations)
     - 621 (gathering systems)
     - 204-209, 371, 381, 395, 503-505



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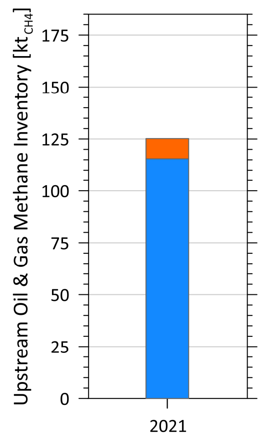
## Inventory Contribution of Unmeasured, Non-Pneumatic Sources

- Unmeasured, non-pneumatic sources are approximately 8% of the *measured* inventory

| Site Type | EF, [kg/h/pad] | Unmeasured, non-pneumatic B.C. Inventory, [kt/y] |
|---|---|---|
| Offsite Well | 0.0787 | 6.02 |
| Single-well Battery | 0.443 | 0.32 |
| Multi-well Battery | 0.550 | 3.02 |
| **Total** | | **9.36** |




- Decreased by ~15% from 2019 estimate

- Source OGI data ***exclude*** normally-operating pneumatic equipment and pumps…

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## 10. Inventory Contribution from Pneumatic Sources

- Bridger's GML not expected to detect pneumatic device emissions
  - Manufacturer bleed rates always well below Bridger sensitivity limits
  - In-field emission factors (e.g., Allen et al., Prasino, etc.) also below GML
- Analysis of ground-team further suggests **normally-operating pneumatics not captured** by Bridger
- Estimate inventory contribution using BC-specific count data with updated facility and well counts
  - Also run scenarios to ***conservatively exclude*** prorated fraction of pneumatics where there is potential to be included in Bridger data (even if abnormally operating)
  - ***Conservatively* assume <u>no</u> pneumatic emissions** at following subtypes:
    - 601 (Compressor Stations), 401-407 (Gas Plants), 621 (Gas Gath. Sys.), 631-638 (Meter Stations), 204-209, 371, 381, 395, 451, 501-505, 611, 671-676, 901-902
    - Ground data shows at least some of these will have emissions

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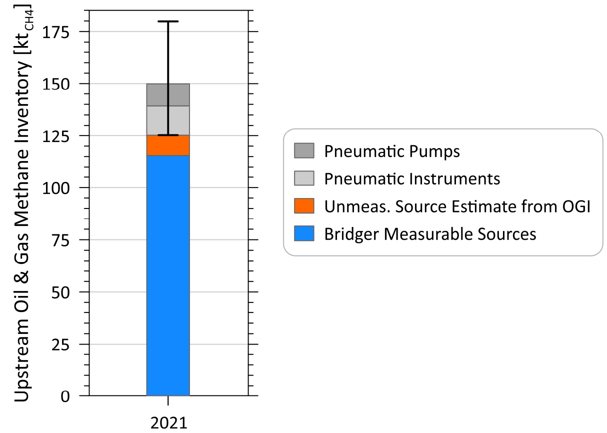
## Inventory Contribution from Pneumatic Sources

- Normally operating pneumatic instruments and pumps expected to add ~24.8 kt to inventory
  - 14.0 kt pneumatic instruments
  - 10.7 kt pneumatic pumps
- Likely misses some contributions from abnormal pneumatics
  - Conservatively assumes zero pneumatic emissions at many subtypes ignoring counter-examples in ground data

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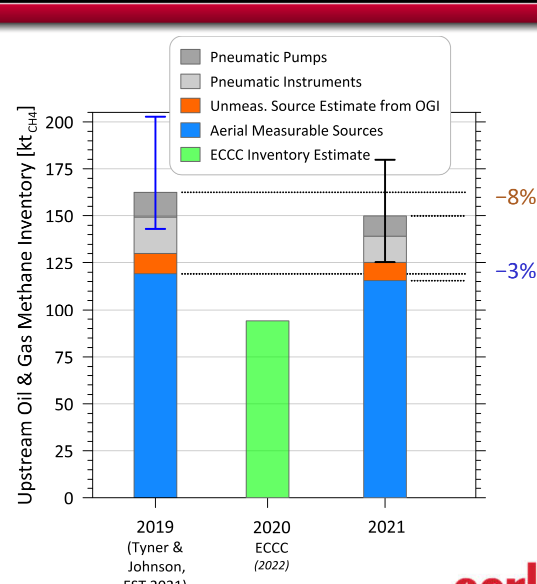
## 2021 BC Upstream Oil & Gas Methane Inventory

- 2021 Methane Inventory
  - 149.9 kt $CH_4$ (125-180 kt $CH_4$)
  - Measurable sources alone remain well above ECCC inventory
- Change from 2019 within error bars
  - Nominal 8% decrease in overall inventory
    - Difference driven largely by changes in counts in bottom-up calculation
    - Contributions from pneumatics / unmeasured sources largest source of uncertainty
  - Measurable sources similar (nominal 3% decrease)

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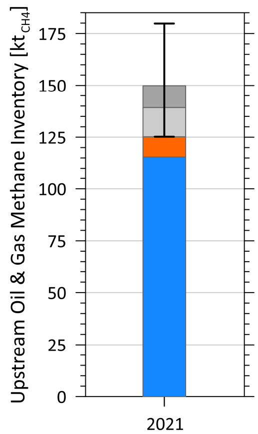
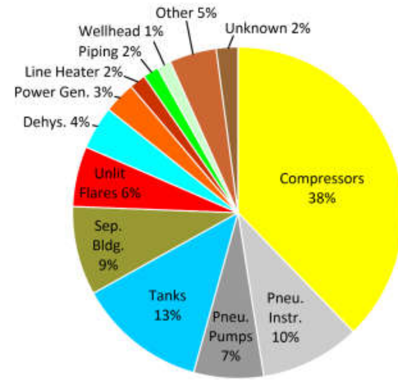
## Derived Measurement-Based Methane Inventory

- **British Columbia** 2021 Measurement-Based Inventory




**"Where the methane is…"**

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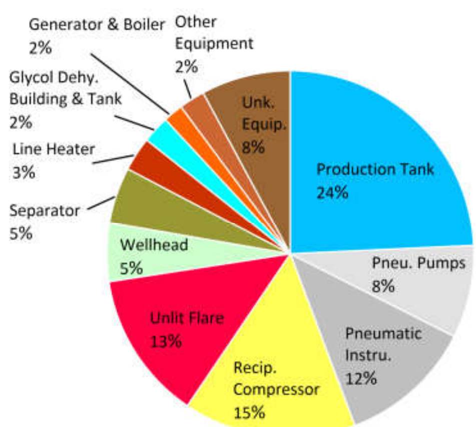
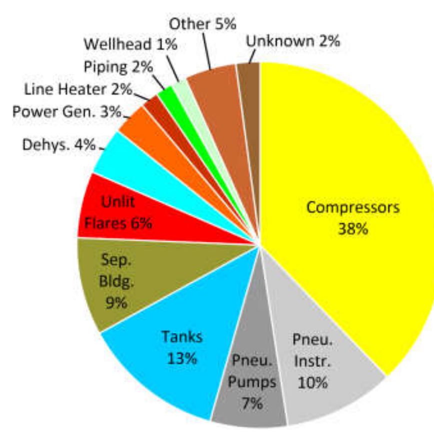
## Comparing 2021 with 2019 Methane Contributions

**2019**




**2021**

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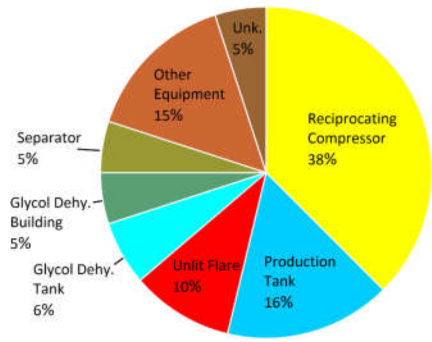
## Comparison of *Measured* Source Frequencies 2019 vs. 2021

***Measured Sources ONLY***

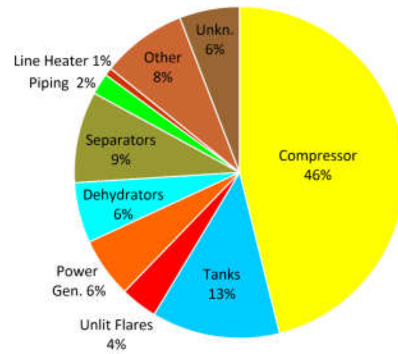
**2019**

**Source Fraction**




**2021**

**Source Fraction**






## Intermediate Observations

### I. Creating a Measurement-Based Methane Inventory

- Demonstrated the potential for measurement-based inventories with rigorously defined uncertainties
  - Important need/opportunity to move past perpetually inaccurate, slow to update, bottom-up approaches that are expected to grow more inaccurate in time
- Measurement approach shows true breakdown of sources
  - Vital data to drive mitigation and track progress
- Inventory can/should rapidly evolve
  - Expect/want inventory to be changing year-over-year if we are to make 2030 targets
  - Critical data to stay on track and ensure efforts are appropriately focussed and costs are not wasted

## II. Major Sources and Root Causes of Emissions

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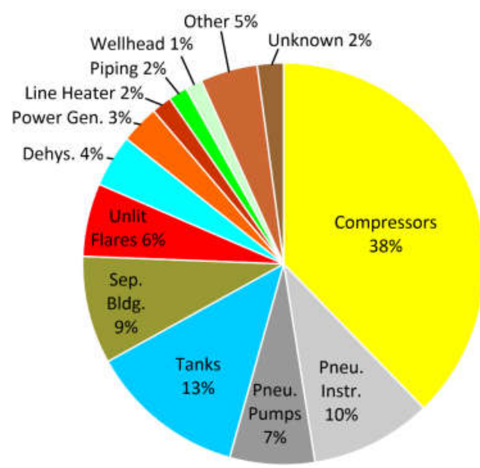
## Contribution of Major Source Types to 2021 Methane Inventory

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## Compressors



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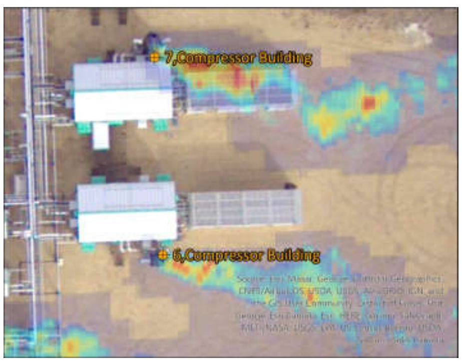
## Root Cause Analysis: Compressors




- Most important source in BC 2021 inventory
  - 38% of BC methane inventory;
  - 55% of aerial measured methane
- Ground team attempted root cause analysis at 93 compressors
- Visited 192 active reciprocating compressors in total to document engine make/model and use of controls
  - 74% (143 of 192) driven by natural gas combustion engines
  - 26% using electric drive!

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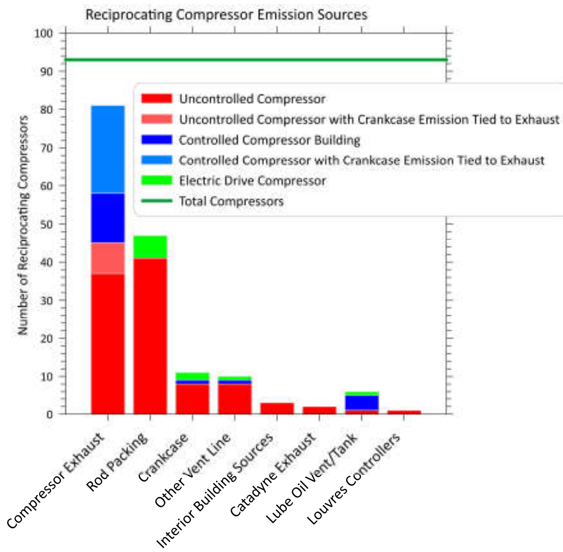
## Root Cause Analysis: Compressors




- Compressors can comprise several sources but exhaust emissions dominate
- Uncontrolled compressors also include:
  - Rod packing vents
  - Crankcase
  - Other (common) vent lines
  - Lube oil vents (which can include rod packing)
  - Interior (exceeded LEL)
- Controlled compressors
  - Exhaust and occasionally lube oil vents

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## Methane Detection Rates for Compressors at Ground Follow-Up Sites

***Derived Compressor Source Occurrence Rates:***

| Equipment | Control | Bridger Detection Rate | Ground Crew Detection Rate |
|---|---|---|---|
| Compressor Buildings | Gas-Driven – Uncontrolled | **68%** (63/93) | **87%** (76/87) |
| | Gas-Driven – Controlled | **78%** (39/50) | n/a[c] |
| | Electric-drive – Uncontrolled | **37%** (10/27) | **96%** (26/27) |
| | Electric-drive – Controlled | **0%** (0/22) | n/a[c] |

[c] Since OGI cannot distinguish methane in exhaust, no other sources for ground team to inspect on a controlled compressor

- Higher ground detection rates indicate additional, *non-combustion* sources missed by Bridger GML

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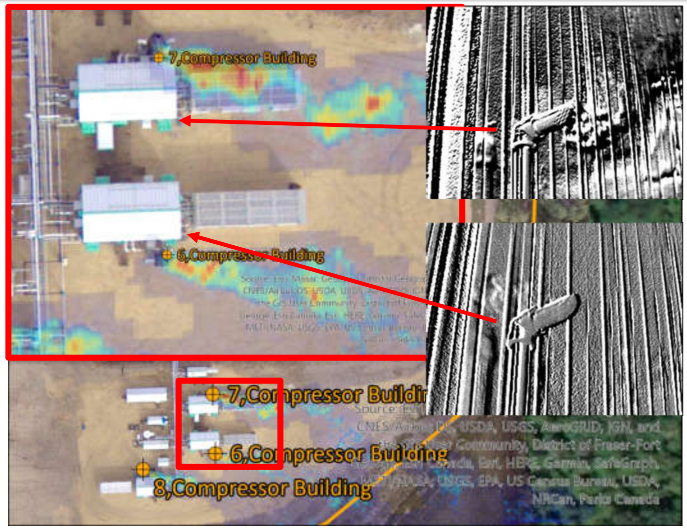
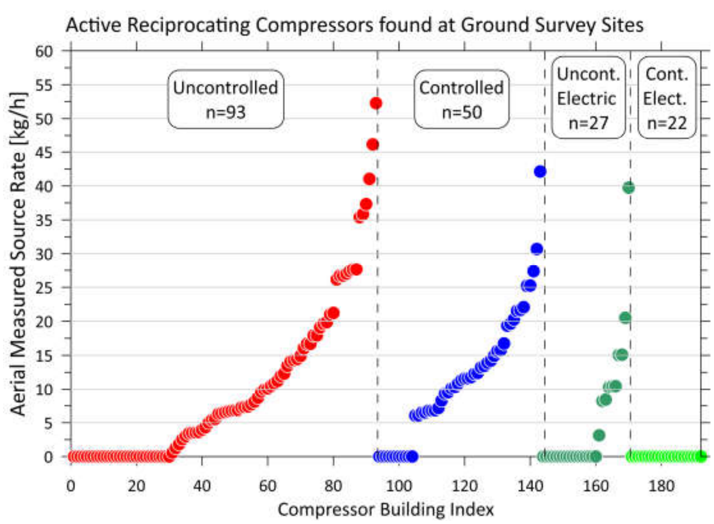
## Missed Compressor Rod Packing Vent Example (BC_41)

- Aerial survey measured compressor exhaust emissions
  - Plumes directly over exhaust (mufflers)
- Ground team observed rod packing emissions at the same compressors
  - Not detected in aerial survey






## Root Cause Analysis: Analysis of Measured Compressors

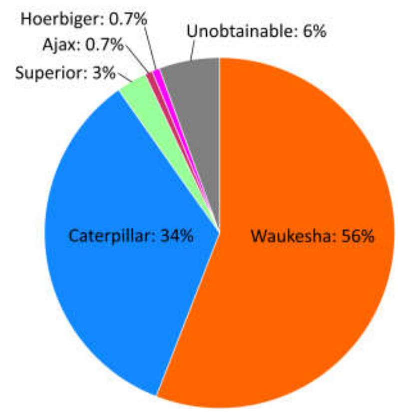



- **Population emission factors (from aerial detections):**
  - Uncontrolled NG Driven (*n*=93):
    - 9.9 kg/h/comp.
  - Controlled NG Driven (*n*=50):
    - 11.5 kg/h/comp.
  - Uncontrolled electric (*n*=27):
    - 5.2 kg/h/comp.
  - Controlled electric (*n*=22):
    - 0 kg/h/comp.
- Similar controlled vs. uncontrolled EFs shows aerial measured emissions dominated by methane slip in exhaust

## Breakdown of Compressor Engine Manufacturers

- Manufacturers of 143 natural gas engines driving compressors in BC sample:
  - Waukesha: 56% (80)
  - Caterpillar: 34% (49)
  - Superior: 3% (4)
  - Ajax: 0.7% (1)
  - Hoerbiger: 0.7% (1)
  - Unidentifiable: 6% (8)
- 102 of the 143 natural gas driven engines identified by ground team had aerial measured sources

Nat. Gas Compressor Engine Manufacturers

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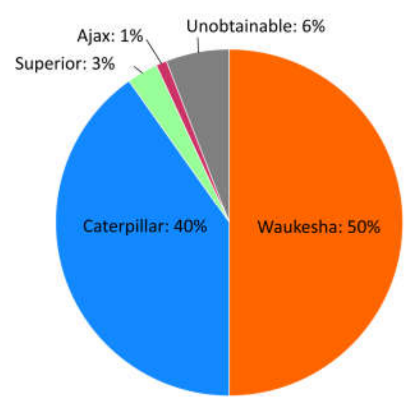
## Breakdown of Engine Manufacturers with Methane Emissions

- Breakdown of aerial methane detections by manufacturer:
  - Waukesha: 50% (51)
  - Caterpillar: 40% (41)
  - White Superior/Superior: 3% (3)
  - Ajax: 1% (1)
  - Unidentifiable: 6% (6)

Engine Manufacturers With Detected Emissions

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## Estimated Expected Methane Emissions from Manufacturer Specifications

| Manufacturer | Model | Count in Sample | Full Load Rating [bhp] | THC [g/bhp-hr] | NMHC [g/bhp-hr] | Est. Full Load $CH_4$ Emission Rate [kg/h] |
|---|---|---|---|---|---|---|
| Waukesha | L7042GL | 18 | 1480 | 5.5 | 1 | 6.7 |
| Waukesha | 7042GL | 3 | n/a | 0 | 0 | n/a |
| Waukesha | L7042GL-E | 2 | n/a | 0 | 0 | n/a |
| Waukesha | L7042GSI | 9 | 1480 | 2 | 0.3 | 2.5 |
| Waukesha | L7042GSIU | 1 | n/a | n/a | n/a | n/a |
| Waukesha | L7042GL ESM | 10 | 1480 | 4.62 | 0.7 | 5.8 |
| Waukesha | L7042GSI ESM Series 4 | 0 | 1480 | 2.3 | 0.34 | 2.9 |
| Waukesha | L7042GSI ESM Series 5 | 0 | 1500 | 0.6 | 0.15 | 0.7 |
| Waukesha | L7044GSI | 3 | 1680 | 2.4 | 0.35 | 3.4 |
| Waukesha | F3521GSI | 4 | 840 | n/a | n/a | n/a |
| Waukesha | F3521GSIU | 1 | n/a | n/a | n/a | n/a |
| Waukesha | F3521 | 1 | n/a | n/a | n/a | n/a |
| Waukesha | 12V-AT25GL | 7 | 2590 | 13.2 | 2 | 29.0 |
| Waukesha | 5790GL | 2 | n/a | n/a | n/a | n/a |
| Waukesha | L5790GU | 1 | 1215 | n/a | n/a | n/a |
| Caterpillar | G3612LE | 5 | 3750 | 4.31 | 1.53 | 10.4 |
| Caterpillar | G3608TAW | 1 | 2370 | 6.3 | 0.94 | 12.7 |
| Caterpillar | G3608LE | 9 | 2225 | n/a | n/a | n/a |
| Caterpillar | 3608 | 1 | 2350 | n/a | n/a | n/a |
| Caterpillar | G3612 | 6 | 3228 | 8.84 | 1.33 | 24.2 |
| Caterpillar | 251-2053 | 1 | n/a | n/a | n/a | n/a |
| Caterpillar | G3616LE | 5 | 4375 | n/a | n/a | n/a |
| Caterpillar | G3608 | 5 | 2350 | n/a | n/a | n/a |
| Caterpillar | G3616TA | 2 | 1053 | 1.42 | 0.22 | 1.3 |
| Caterpillar | G3516TAW-LE | 2 | 1340 | n/a | n/a | n/a |
| Caterpillar | G3306 | 2 | 110 | 1.93 | 0.29 | 0.2 |
| Caterpillar | G3616 | 4 | 4292 | 8.84 | 1.33 | 32.2 |
| Caterpillar | G3516TALE | 1 | 1380 | 4.77 | 0.72 | 5.6 |
| Caterpillar | G3516LE | 0 | 1148 | 5.26 | 0.79 | 5.1 |
| Superior/White Superior | 12SGT | 1 | 2000 | 3.3 | 0.5 | 5.6 |
| Superior/White Superior | 8GTL-825 | 1 | 1100 | 4.95 | 0.75 | 4.6 |
| Superior/White Superior | 16 GTL | 1 | 900 | 3.3 | 0.5 | 2.5 |

- Attempted to locate manufacturers emission data for all identified compressors
  - Many too old / not possible to find or no manufacturer's methane data
  - Calculated expected methane emissions at full load based on nameplate data and found spec sheets

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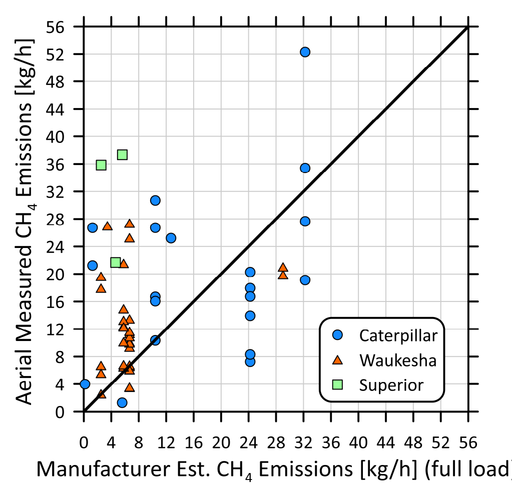
## Manufacturer Vs. Measured $CH_4$ Engine Exhaust Emissions

- General alignment of aerial measured methane with expected full load emissions
  - Further confirms aerial detected methane dominated by combustion slip in engine exhaust
- **Many compressors emitting well-above expected *full-load* emissions**

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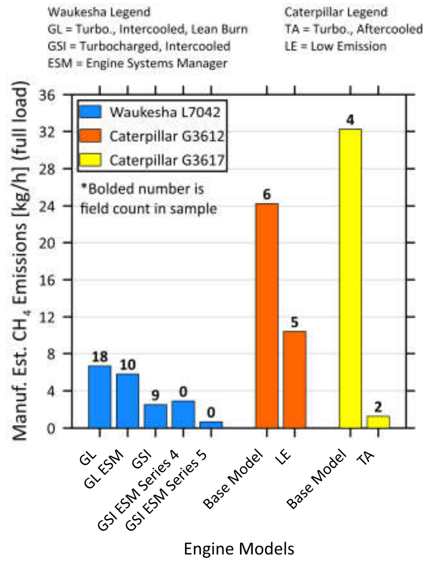
## Comparing Methane Emissions of Common Field Engine Types

- Up to >10x variation in methane emissions for similar models
  - Suggests important mitigation potential by upgrading field engines
    - E.g., See Waukesha Gas Engine Upgrades Program
  - Prevalence of engines emitting well-above expected max load methane emissions suggests further mitigation potential from maintenance
- Prevalence of zero-emission electric-drive compressors encouraging
  - 26% of compressors at ground sites were electric-drive
  - Potentially even higher among all sites
  - Obvious best solution for any new installation




## Storage Tanks

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## Root Cause Analysis: Storage Tanks

- Second largest methane contributor to the 2021 inventory
  - 13% of BC methane inventory;
  - 18% of aerial measured methane
- Significant detections from both uncontrolled and controlled tanks

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## Methane Detection Rates of Tanks at Ground Follow-Up Sites

***Derived Tank Source Occurrence Rates:***

| Equipment | Control | Bridger Detection Rate | Ground Crew Detection Rate |
|---|---|---|---|
| Tanks | Uncontrolled | **18%** (16/91) | **57%** (44/77[a]) |
| | Controlled | **9%** (18/192) | n/a[b] |

[a] Ground team visited 91 uncontrolled tanks but could only visually access 77 to check for emissions
[b] Ground team only inspected controlled tanks when specifically directed to a source (i.e., not a survey) but did attempt to count/identify all controlled vs. uncontrolled tanks at each site.

- Much higher ground detection rate shows prevalence of sources missed by Bridger's GML
  - Underscores importance of parallel controlled release work to quantify probabilities of detection

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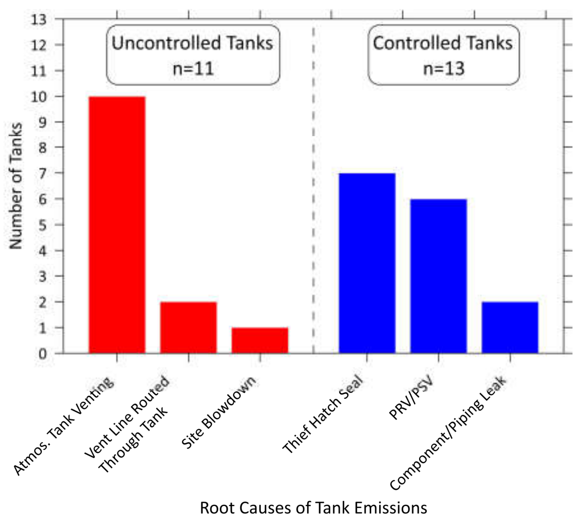
## Root Cause Analysis: Tanks




Detailed Analysis of Tanks at Ground Follow-Up Sites

- Uncontrolled tanks:
  - Different forms of intentional venting
- Controlled tanks:
  - Thief hatch seals
  - Pressure / vacuum valves
  - Piping / component leaks

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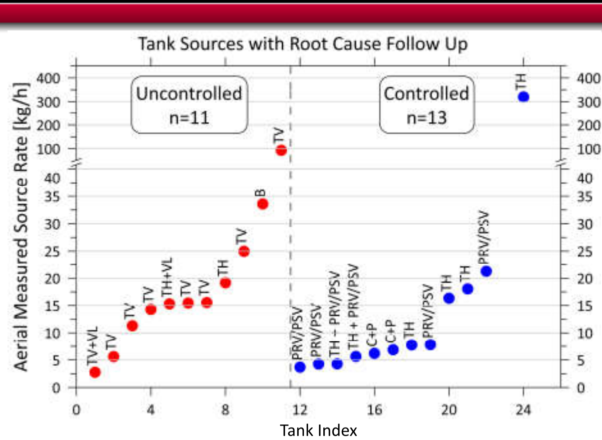
## Root Cause Analysis: Tanks




| | |
|---|---|
| B | Blowdown |
| C+P | Component/Piping Leak |
| PRV/PSV | PRV/PSV (Pressure Relief Valve) |
| TH | Thief Hatch Seal |
| TV | Tank Venting (Gooseneck) |
| VL | Vent Line (Fuel Gas Devices) Routed Through Tank |

- Population emission factors (from aerial detections):
  - Uncontrolled tanks (*n*=91):
    - 3.0 kg/h/tank
  - Controlled tanks (*n*=192):
    - 2.7 kg/h/tank*
- *Controlled tank emissions highly skewed
  - Largest tank (thief hatch at controlled tank) = 320 kg/h
  - Emission factor without = 1.0 kg/h/tank

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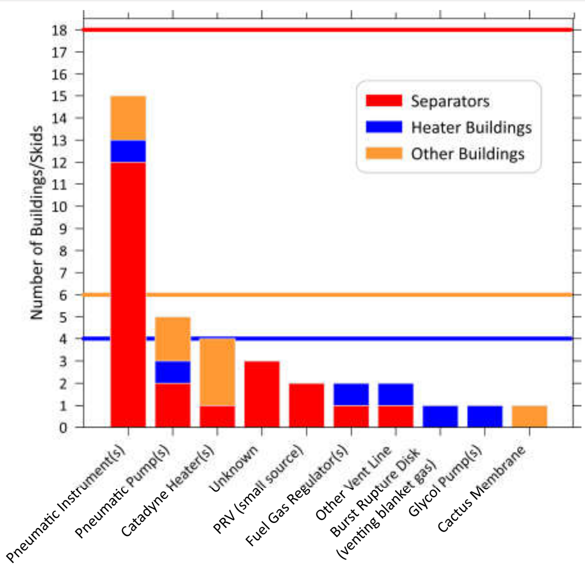
## Separator Buildings, Heater Buildings, and Other Buildings

## Separators and Other Buildings: Suggested Root Causes




- Ground team suggested several potential contributing sources including
  - Pneumatic instruments and pumps
  - Catadyne heaters
  - Pressure relief + rupture disc
  - Regulators

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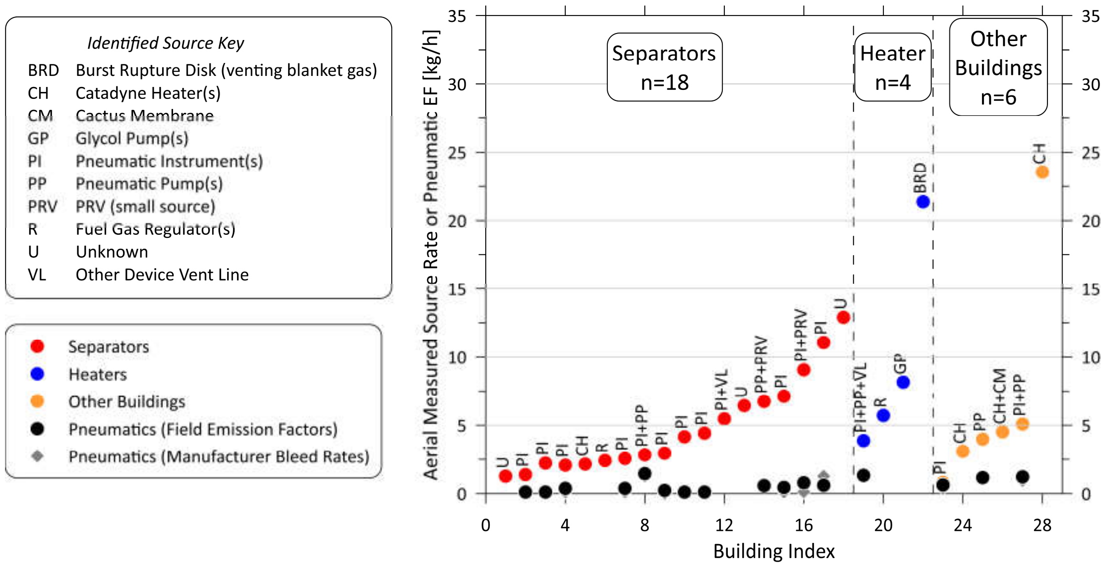
## Separators and Other Buildings: Measured Rates vs. Pneumatic EFs

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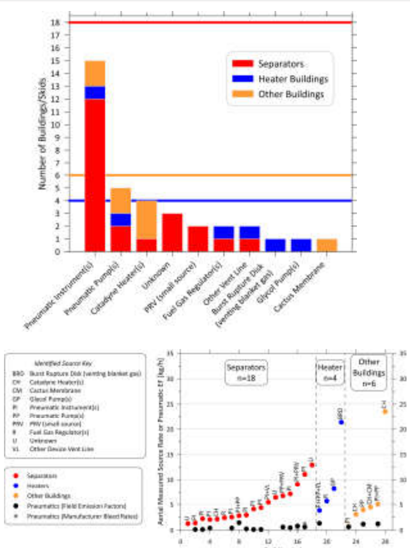
## Separators and Other Buildings: Measured Rates vs. Pneumatic EFs




- Pneumatic equipment most often suggested as root cause at separators and other buildings, BUT median measured emissions:
  - ~12x higher than expected manufacturer bleed rates
  - ~9x higher than field emission factors
  - If pneumatics are cause, they are abnormal
- Catadyne heaters another potentially significant but poorly understood source
- Largest six sources (as meas. by Bridger) attributed to:
  (1) catadyne heaters, (2) burst rupture disk, (3) unknown, (4) pneumatics, (5) pressure release valve, (6) glycol pump

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# III. Implications for Mitigation and Emerging Regulations

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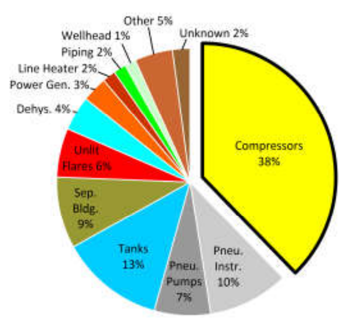
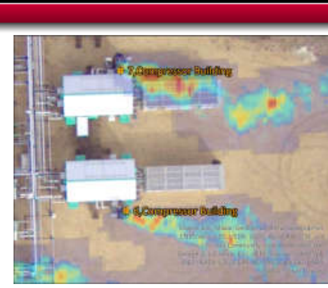
## Inventory, Root Cause Analysis, and Implications for Methane Regulations

- **Compressors**
  - Largest methane contributor to the 2021 inventory
    - 38% of BC methane inventory; 55% of aerial meas. methane
    - **75% reduction targets not possible without at least partially addressing compressor emissions**





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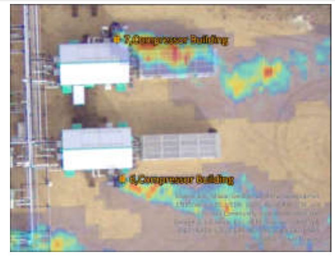
## Inventory, Root Cause Analysis, and Implications for Methane Regulations

- **Compressors**
  - Largest methane contributor to the 2021 inventory
    - 38% of BC methane inventory; 55% of aerial meas. methane
    - **75% reduction targets not possible without at least partially addressing compressor emissions**
  - Root cause suggests emissions are dominated by methane slip in combustion exhaust
    - **Key gap in current regulations**
  - Non-combustion emissions from uncontrolled compressors smaller but still important
    - Ground data suggest 38% of compressors already controlled



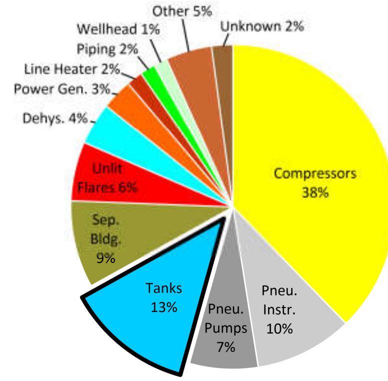



## Inventory, Root Cause Analysis, and Implications for Methane Regulations

- **Mitigation of Compressor Emissions**
  - Controlled NG Driven (*n*=50): **11.5 kg/h/comp**. (indicative of combustion slip)
  - Uncontrolled electric (*n*=27): **5.2 kg/h/comp**. (indicative of vented emissions)
  - Controlled electric (*n*=22): **0 kg/h/comp**. (zero emission solution)
  - Many aerial detected compressors emitting well above manufacturer specifications
    1. Potential opportunity for mitigation through maintenance
  - High-level review suggests up to >10x variation in emissions among similar models
    2. Potential opportunity for mitigation through upgrades (e.g., see Waukesha/INNIO Upgrades)
    3. Available oxidation catalysts a further option for to destroy methane in exhaust
  - Electric drive offers a true zero emissions solution
    4. **Already one-quarter (26%) of compressors in sample in BC are electric drive**
       - High market penetration suggests competitive advantages (e.g., greatly reduced maintenance)
       - Obvious solution for new installations and essential solution for -75% and net-zero

## Inventory, Root Cause Analysis, and Implications for Methane Regulations

- **Tanks**
  - Second largest methane contributor to the 2021 inventory
    - 13% of BC methane inventory; 18% of aerial measured methane
    - Further 4% of inventory and 5% of aerial measured methane from dehydrators commonly routed through associated tanks

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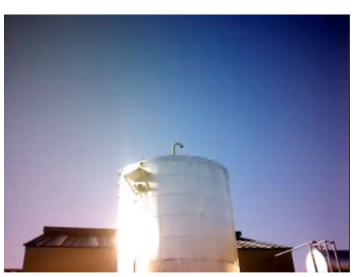
## Inventory, Root Cause Analysis, and Implications for Methane Regulations

**Tanks:** Root causes

- Uncontrolled tanks:
  - Intentional venting to atmosphere
  - 18% of uncontrolled tanks measurable from the air
  - Average of 3.0 kg/h/tank
- Controlled tanks:
  - Thief hatches, pressure relief valves
  - 9% of controlled tanks measurable the air
  - Average of 2.7 kg/h/tank



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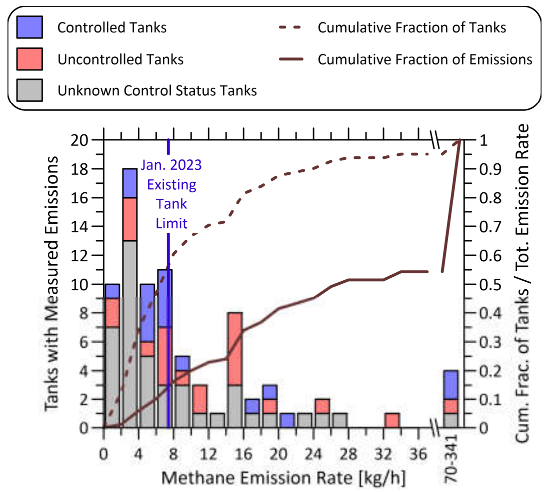
## BC 2021 Measured Tanks and Implications for Methane Regulations

### Tanks in 2021 Aerial Survey

- 81 tank sources detected at 508 sites
- Mean 14.7 kg/h (Median 6.2 kg/h, Max 320 kg/h)

- 30% of quantified tanks individually >7.4 kg/h site limit for tanks (Jan. 2023)
- 50% of sites with quantified tanks >Jan. 2023 limit

- Under current rules, controlled tanks should should not have emissions
  - Should be captured in LDAR inspections and repaired

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## Inventory, Root Cause Analysis, and Implications for Methane Regulations

- **Mitigation of Tank Emissions**
  - Tank controls, i.e., vapour recovery units, using blanket gas routed to engine or flare etc., are a widely available solution
  - Ground inspections suggest >2/3 (68%) of tanks in BC are already controlled
  - **High magnitudes of emission from controlled tanks a concern**
    - Controlled tanks (*n*=192): 2.7 kg/h/tank
    - Should not be emitting under current LDAR rules
  - Potential regulatory gap in finding an identifying tank sources as well as verifying compliance with limits
    - OGI-based LDAR surveys are not suitable / capable of quantifying tanks as needed
    - Many sites with emitting tanks found to be above upcoming regulatory tank limit for Jan. 2023

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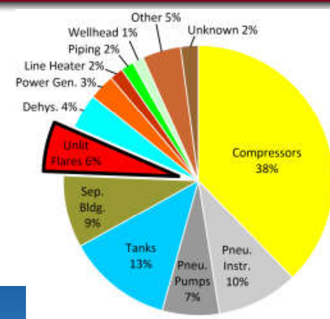
## Inventory, Root Cause Analysis, and Implications for Methane Regulations

- **Unlit Flares**
  - 6% of overall inventory; 3rd largest contributor to aerial meas. sources
    - Much lower fraction than in 2019 aerial survey
      - Good news that confirms ease of mitigation once identified
      - Highlights need for continued monitoring as part measurement reporting & verification (MRV)
    - Because individual unlit flares can be important sources, active monitoring is vital for broader mitigation



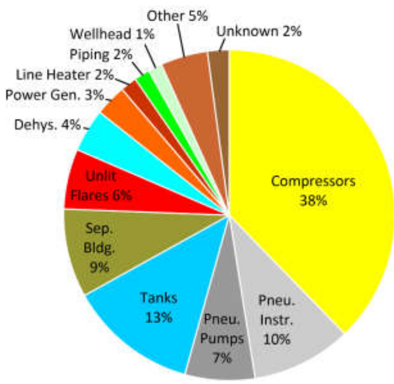


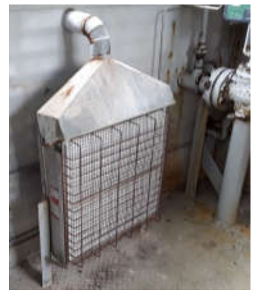

## Inventory, Root Cause Analysis, and Implications for Methane Regulations

- **Unlit Flares**
  - 17 unlit flares detected with emission rates of up to 102 kg/h averaged over two separate days
    - One partially lit flare and one pit flare also detected
  - One on-site operator told ground-crew that unlit flare was an “approved conversion to a vent stack”
    - Key gap in regulations if this is allowed to occur
  - Review of specific flares suggests:
    - 11 should not be unlit (approved as continuous flare)
    - 3 approved as intermittent but had rates justifying continuous flares
    - 1 approved as a continuous vent but releasing 25 kg/h!
    - 2 unknown

## Inventory, Root Cause Analysis, and Implications for Methane Regulations

- **Separators, Other Buildings, etc.**
  - *Combination of potential sources*



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## Inventory, Root Cause Analysis, and Implications for Methane Regulations

- **Separators, Other Buildings, etc.**
- **Pneumatic Instruments and Pumps**
  - Together, third largest contributor to the 2021 inventory
  - Identified as a potential contributor to emissions in root cause investigations of 24 sources
    - Analysis shows that if pneumatics were the cause, these were emitting a median of 9–12 times higher than expected
  - **Conversion to zero bleed (air or electric) is common**
    - **Easiest/best way to eliminate these sources**

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## Inventory, Root Cause Analysis, and Implications for Methane Regulations

- **Separators, Other Buildings, etc.**
- **Catadyne heaters**
  - Suspected large source but not easily measured and completely unknown
    - Flagged as a possible source or contributor during root cause analysis but speculative at this stage
    - OGI can't distinguish methane from exhaust
    - Aerial surveys to date conducted in mostly warmer months
  - Key gap in current understanding of methane sources

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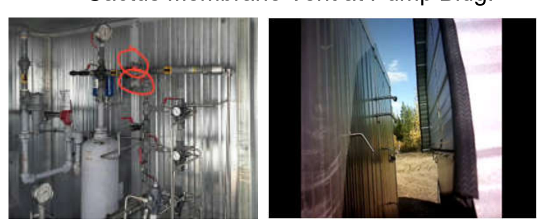
## Inventory, Root Cause Analysis, and Implications for Methane Regulations

- **Separators, Other Buildings, etc.**
- **Other Sources**
  - Many "vent-like" sources
  - Missed in LDAR programs focused on "fugitives"?
  - Regulatory gap in lack of venting limits?

Burst disc at Heat Medium Building

Separator Pressure Safety/Relief Valves

Cactus Membrane Vent at Pump Bldg.



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## Inventory, Root Cause Analysis, and Implications for Methane Regulations

- **Separators, Other Buildings, etc.**
- **Other Sources**
  - Many "vent-like" sources
  - Missed in LDAR programs focused on "fugitives"?
  - Regulatory gap in lack of venting limits?

Regulators

Dehydrator Tank Vents / Relief Valves

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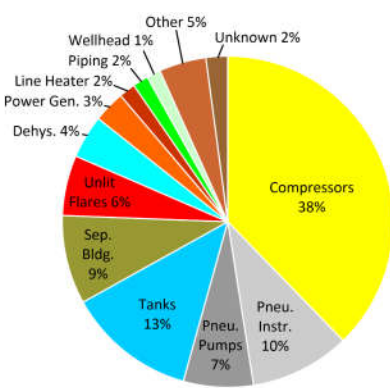
## Key Conclusions




- Inventories are evolving rapidly and will (hopefully) continue to evolve
- Measurement-based inventories are essential for guiding mitigation to meet targets
- Emissions are much higher than official estimates but low relative to many other jurisdictions
- Detailed analysis shows significant mitigation potential exists with several potential gaps in regulations and monitoring
- Opportunity for BC to lead internationally by extending this approach
- Essential for reaching 75% reductions and beyond while also remaining competitive in an MRV world

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