DOCKETED

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ARPA-E's MONITOR Program

Technology to Quantify Methane Emissions

Nate Gorence
ARPA-E

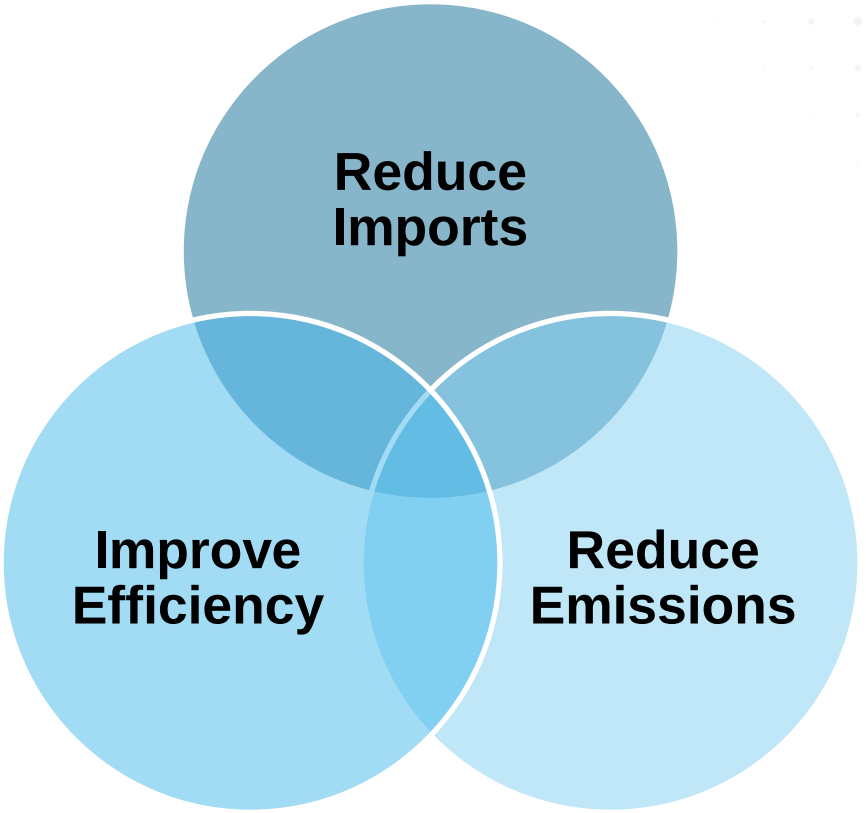
arpa·e
CHANGING WHAT'S POSSIBLE

The ARPA-E Mission

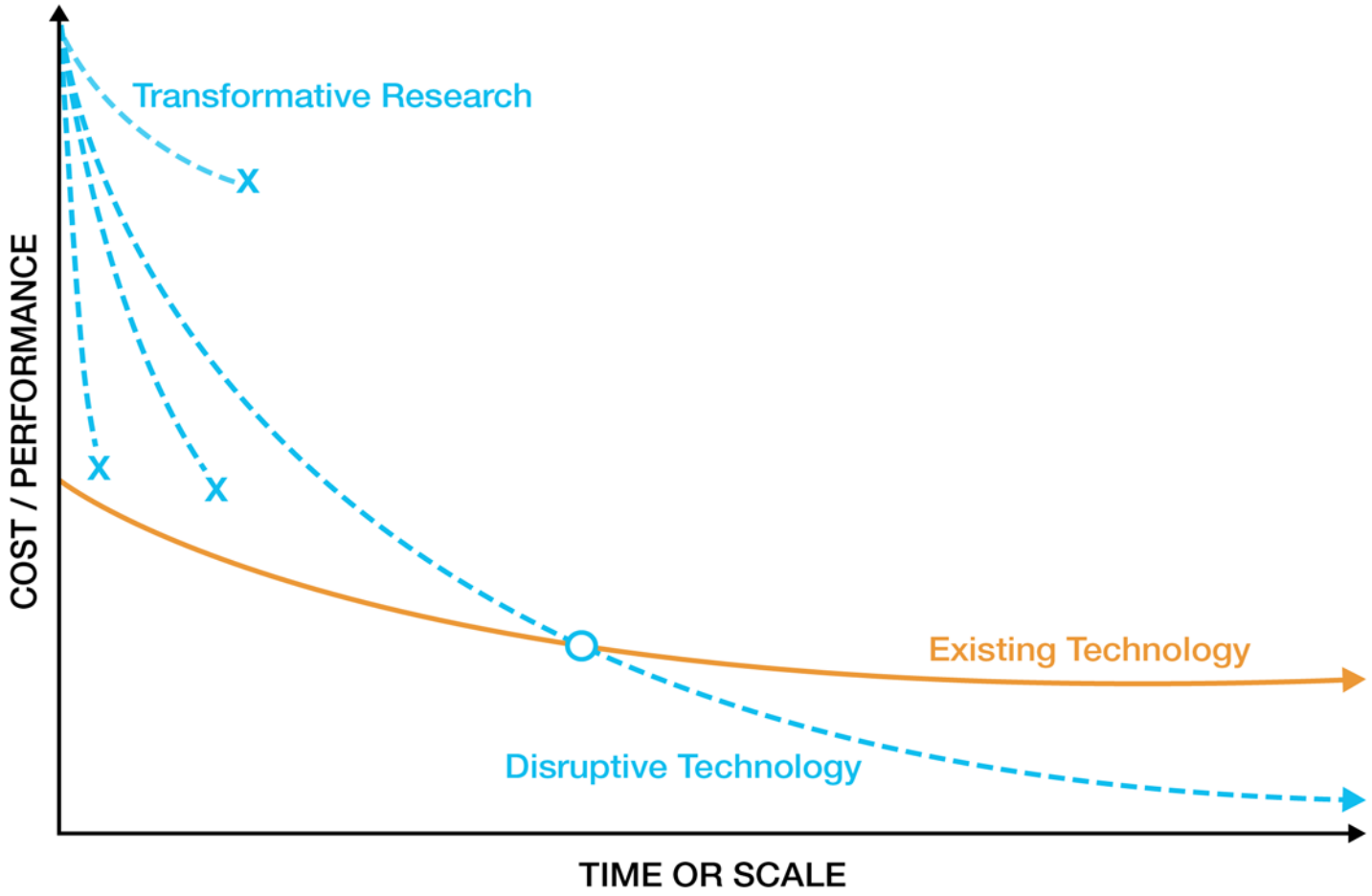
Catalyze and support the development of transformational, high-impact energy technologies

Ensure America's

- Economic Security
- Energy Security
- Technological Lead

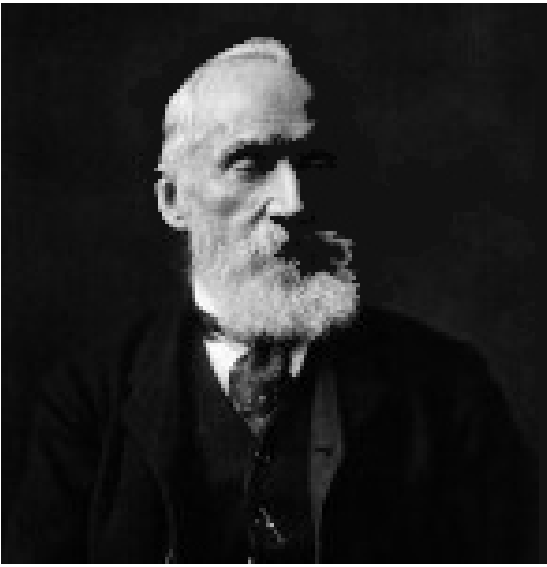


Creating New Learning Curves



“You can't manage what you don't measure.”

- W. Edward Deming



“to measure is to know – if you cannot measure it, you cannot improve it”
– Lord Kelvin

Today's Methane Sensing Solutions

?

- Ability to Locate Leaks ✓
- Low Cost ✗
- Ability to Quantify ✗

Tomorrow's Methane Detection Solutions

CH_4
SCFH

- Ability to Locate Leaks ✓
- Low Cost ✓
- Ability to Quantify ✓

MONITOR Metrics & Targets

Detection Threshold	1 ton per year (6 standard cubic feet per hour)
Cost	$3,000 per site per year (for basic functionality)
Resulting Leak Reduction	90% methane leakage reduction with a 90% confidence level
False Positives	No more than 1 per year
Mass Flow Rate	Able to estimate mass flow rate within 20% margin of error
Leak Location	Able to estimate location within 1 meter
Communications	Transmits results wirelessly to remote receiver
Enhanced Functionality	Methane selectivity, speciation capability, thermogenic/biogenic differentiation, continuous measurement, enhanced stability

Complete & Partial Solutions to Detection

Complete measurement systems: *6 projects*

- Systems that include:
  1) Methane emission sensing
  2) Leak rate characterization and data analytics
  3) Provisions for data quality control
  4) Digital communication
  5) Enhanced functionality

parc, A Xerox Company — Palo Alto, CA

PSI Physical Sciences Inc. — Andover, MA

AERIS Technologies — Redwood City, CA

BRIDGER PHOTONICS — Bozeman, MT

IBM — Yorktown Heights, NY

REBELLION PHOTONICS — Houston, TX

Partial measurement systems: *5 projects*

- Nascent technologies that may be too early in the development process for incorporation into a complete system
- Could significantly contribute to meeting system-level objectives
- Primarily envisioned as advances in detector technology or data analytics

THORLABS — Jessup, MD

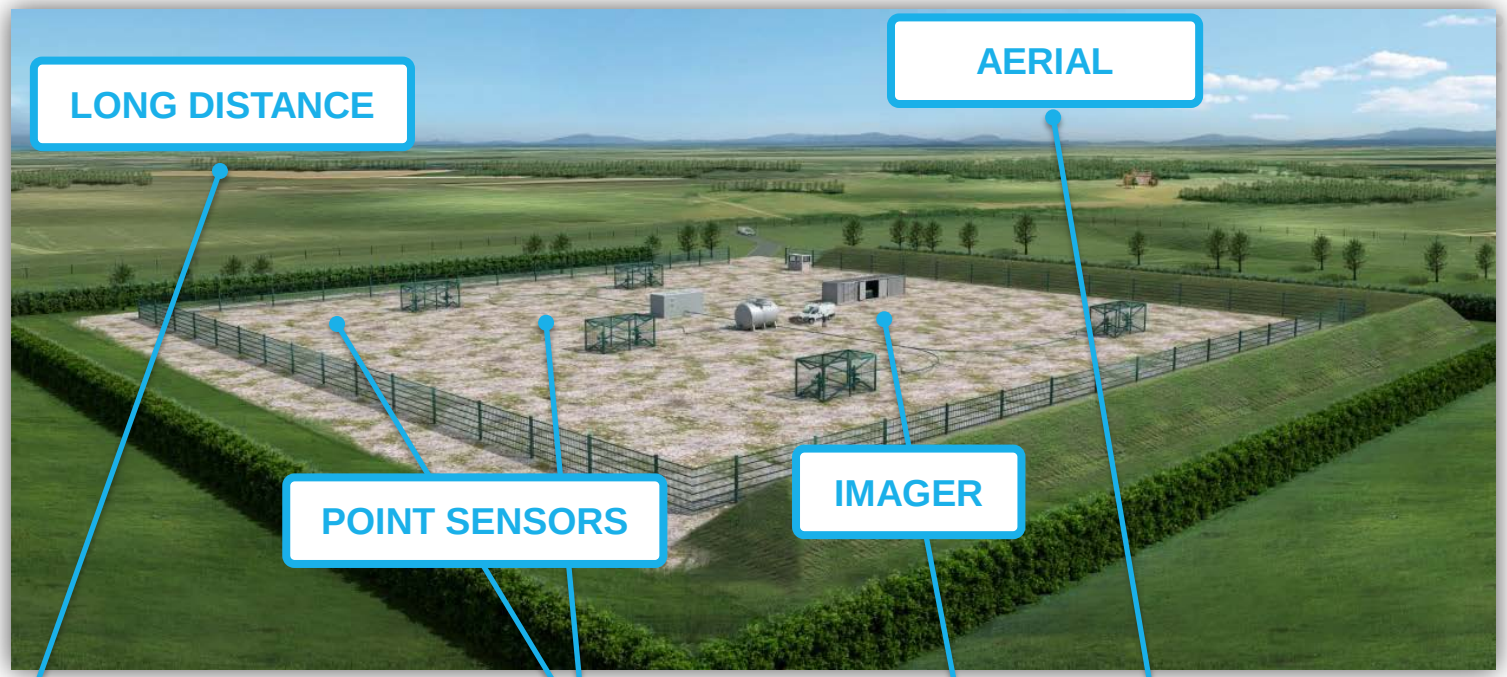
LI-COR — Lincoln, NE

GE — Niskayuna, NY

Duke University — Durham, NC

University of Colorado Boulder — Boulder, CO

The Portfolio: Four Approaches



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University of Colorado Boulder

parc A Xerox Company

IBM

AERIS TECHNOLOGIES

LI-COR

MOBILE

Duke UNIVERSITY

REBELLION PHOTONICS

BRIDGER PHOTONICS

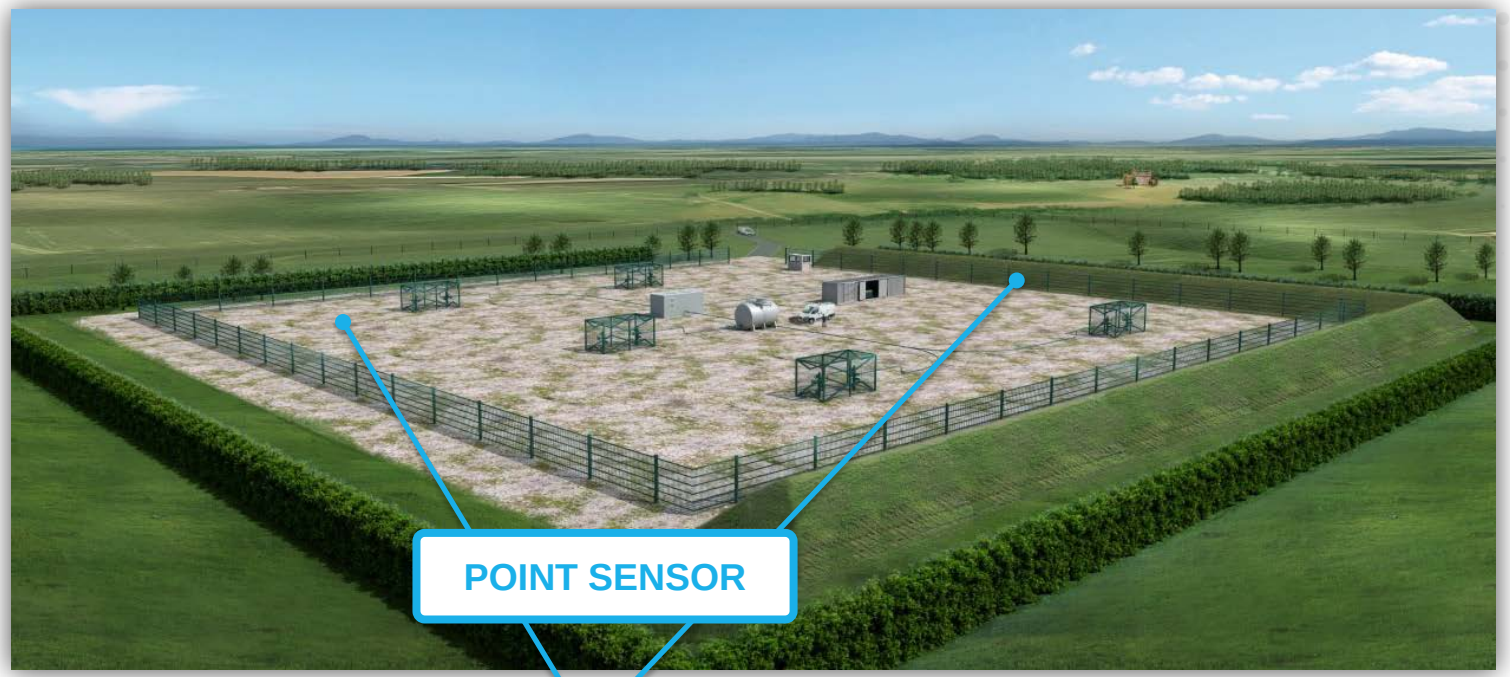
Physical Sciences Inc.

ENABLING

THORLABS

Image courtesy of Cuadrilla Resources

Portfolio:
Five Point Sensing Technologies



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AERIS TECHNOLOGIES
LI-COR

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Duke UNIVERSITY
BRIDGER PHOTONICS
REBELLION PHOTONICS
Physical Sciences Inc.

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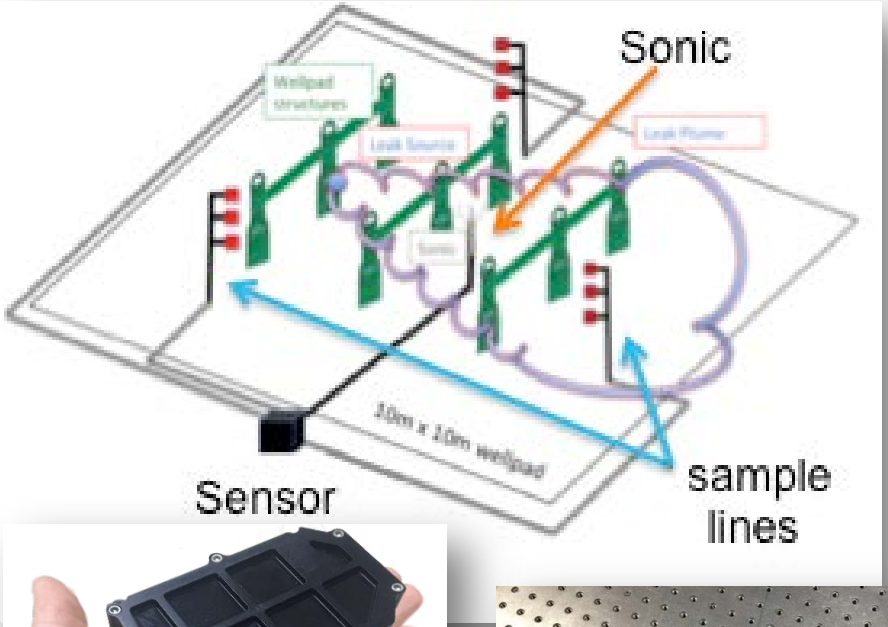
THORLABS

Image courtesy of Cuadrilla Resources

Miniature, High Accuracy Tunable Laser Spectrometer for CH_4/C_2H_6 Leak Detection



PROJECT HIGHLIGHTS

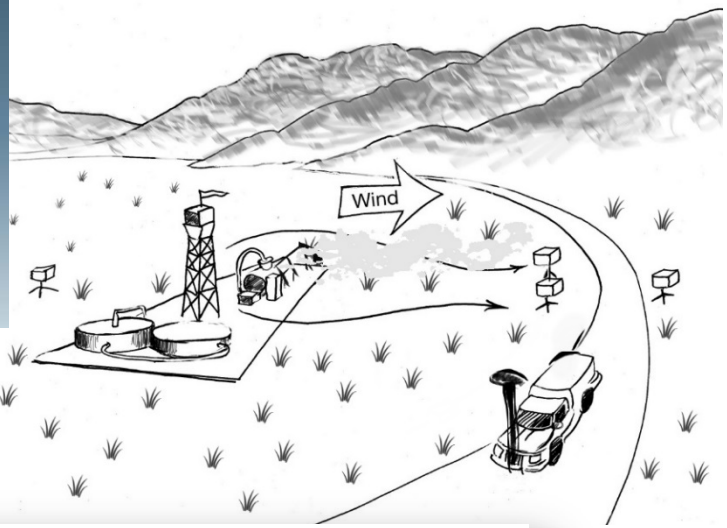
- Enables ppb/s sensitivity via simple and robust direct absorption spectroscopy
- Discriminates biogenic vs. thermogenic emissions
- 1/15th the size and power of existing in-situ laser sensors
- 100x+ more sensitive/accurate than legacy FID/NDIR
- Compatible with other industry applications that require high accuracy, real-time analyses (e.g. process control, CEMS, environmental/GHG monitoring)

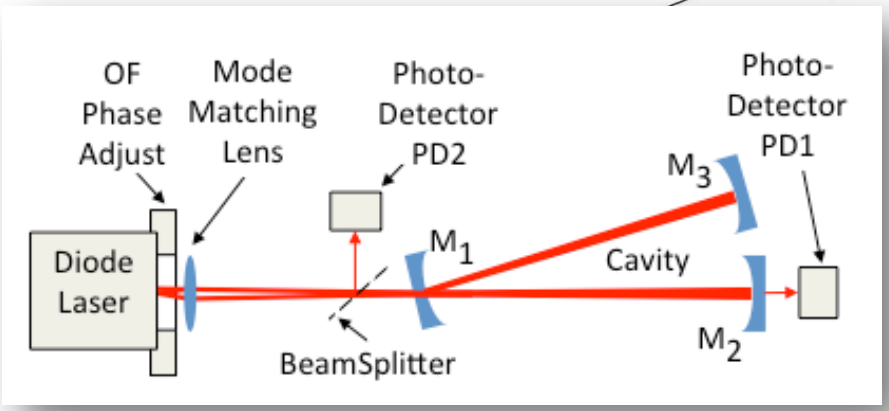
AWARD AMOUNT: $2.4 million

PROJECT PARTNERS: Los Alamos National Laboratory, Rice University

Laser Spectroscopic Point Sensor for Methane Leak Detection

LI-COR®





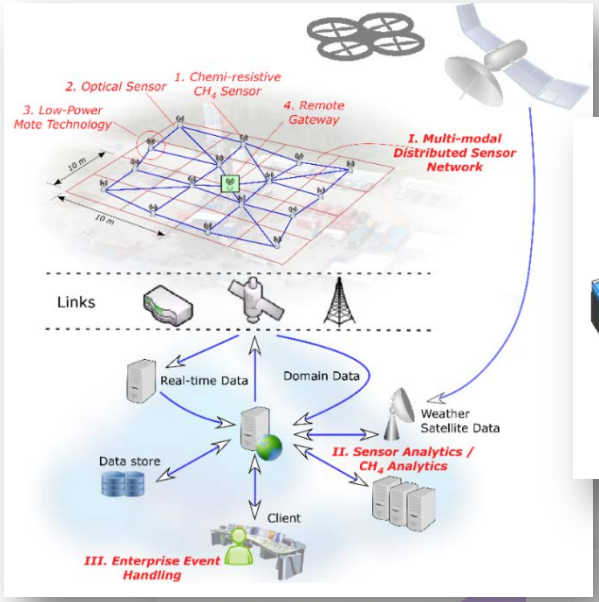
PROJECT HIGHLIGHTS

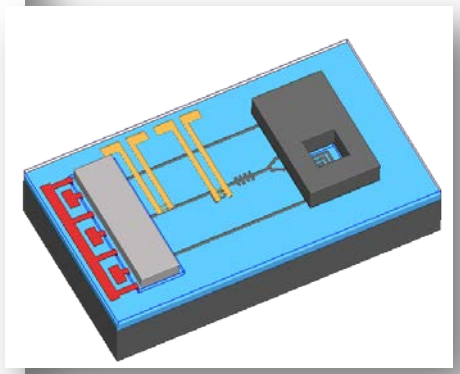
- Performance of state of the art cavity-based point sensors at reduced cost
- High sensitivity, selectivity, and stability measurements with low maintenance
- Closed path instrument is weather-proof, high-performance, and low power consumption
- Suitable for continuous or intermittent stationary and mobile applications
- Advanced spectral models and high instrument stability allow unattended operation
- Advanced manufacturing and novel design/alignment enable cost reductions

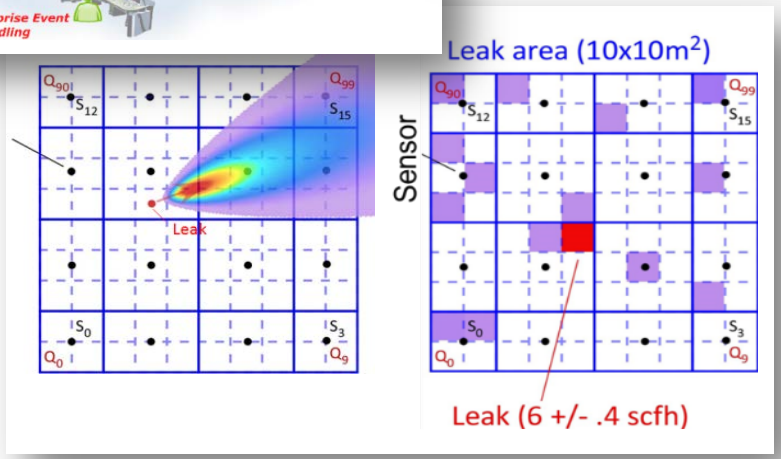
AWARD AMOUNT: $2.85 million

PROJECT PARTNERS: Colorado State University, Gener8

On-Chip Optical Sensors and Distributed Mesh Networks for Methane Leak Detection







PROJECT HIGHLIGHTS

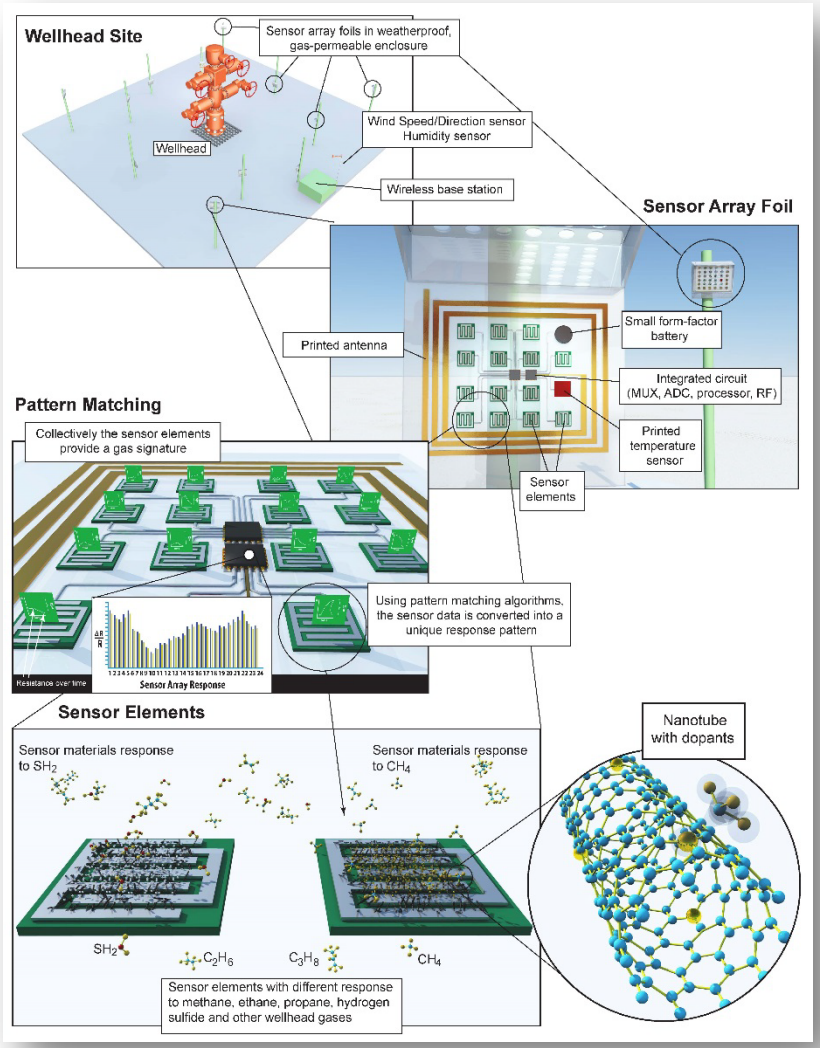
- Developing novel, low cost, on-chip optical sensors with high methane selectivity
- Distributed and modular system with self-organizing network of low-power motes
- State of the art silicon photonics technology for on-chip TDLAS
- Allows for selectivity to molecule of choice
- Orders of magnitude lower cost ($250/sensor target)
- Low power consumption (<1 Watt)
- Cloud-based analytics for source detection and localization

AWARD AMOUNT: $4.5 million

PROJECT PARTNERS: Princeton University, Harvard University, Southwestern Energy

Printed Carbon Nanotube Sensors for Methane Leak Detection

parc
A Xerox Company



PROJECT HIGHLIGHTS

- Developing a mesh network of ultra-low-cost printed sensor arrays that can detect multiple gases
- Uses scalable low-cost, additive printing methods to print chemical sensor arrays based on modified carbon nanotubes
- Sensor elements with different responses to methane, ethane, propane and other wellhead gases
- Total system costs under $350 per site per year
- Multiple sensors reduces false positives
- Sub-ppm sensitivity with leak localization within 1 m

AWARD AMOUNT: $3.4 million

PROJECT PARTNERS: NASA Ames Research Center, BP, Xerox Corporation

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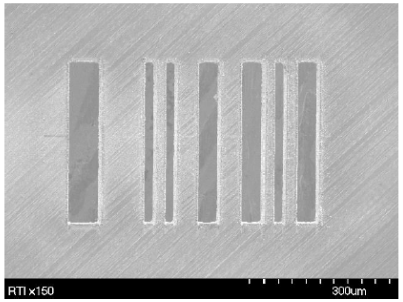
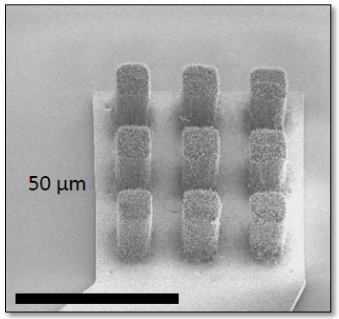
Coded Aperture Miniature Mass Spectrometer for Methane Sensing

Duke UNIVERSITY

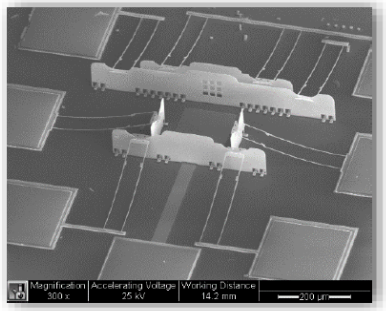
1) Aperture Coding



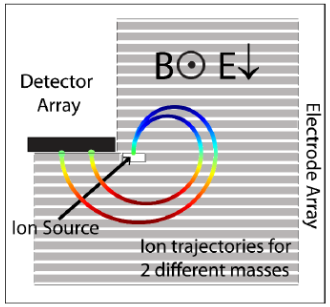
2) CNT field emission cathodes



3) Microfabricated ion sources and detectors



4) Cycloidal double focusing mass analyzer



PROJECT HIGHLIGHTS

- Miniaturizing a mass spectrometer utilizing microfabrication and aperture coding
- High selectivity measurements at short detection times for methane as well as VOCs (such as benzene, C2-C7)
- Capable of thermogenic vs. biogenic differentiation
- Developing advanced search/location algorithms for optimum sampling

AWARD AMOUNT: $2.9 million

PROJECT PARTNERS: RTI International

Portfolio:
Two Long Distance Technologies

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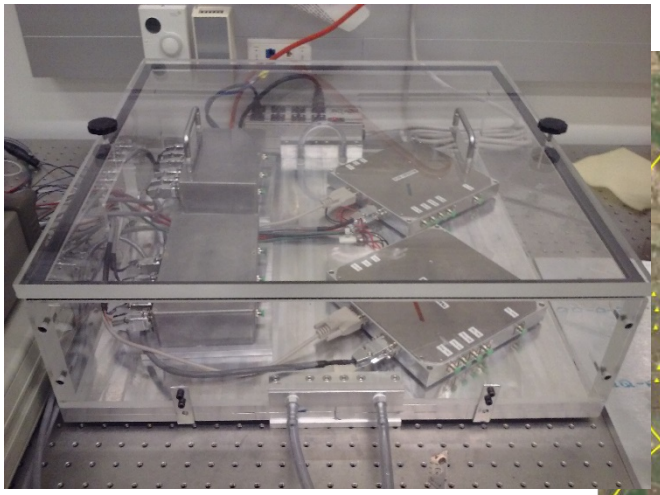
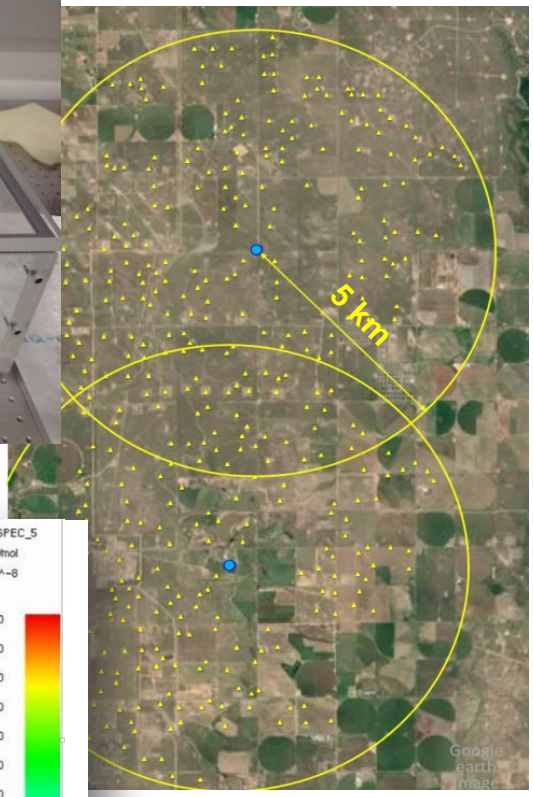
Image courtesy of Cuadrilla Resources

Frequency Comb-based Methane Sensing

University of Colorado Boulder





PROJECT HIGHLIGHTS

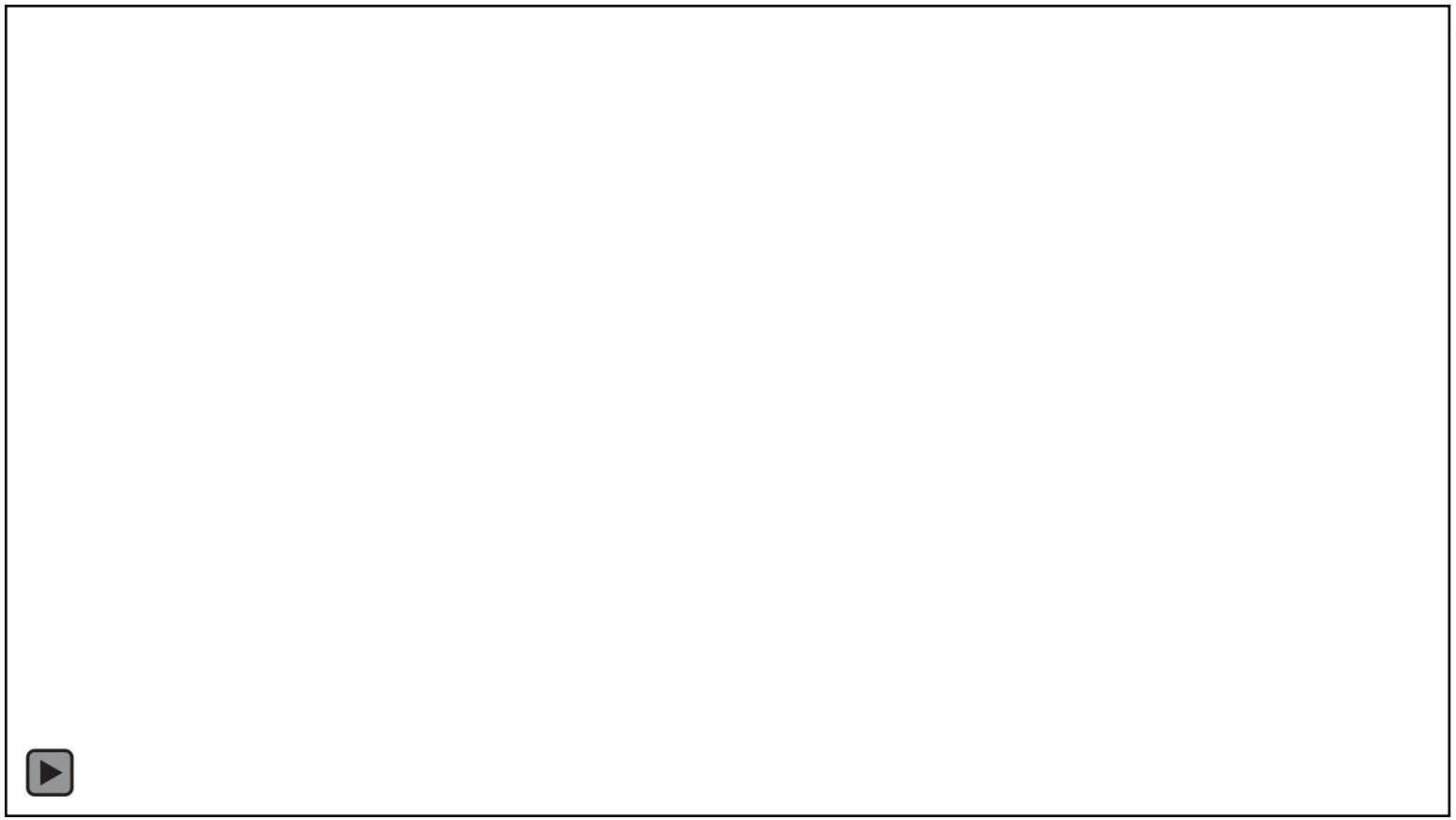
- High sensitivity (ppb-m) kilometer-scale path length measurements with specificity of FTIR
- Ability to monitor 100s of sites from a central location
- Simplifying design to reduce the cost of dual comb spectroscopy
- Multispecies sensing includes CH_4, CH_4, H_2O, propane, and ethane
- Coupled to large eddy dispersion modeling to provide localization

AWARD AMOUNT: $2.1 million

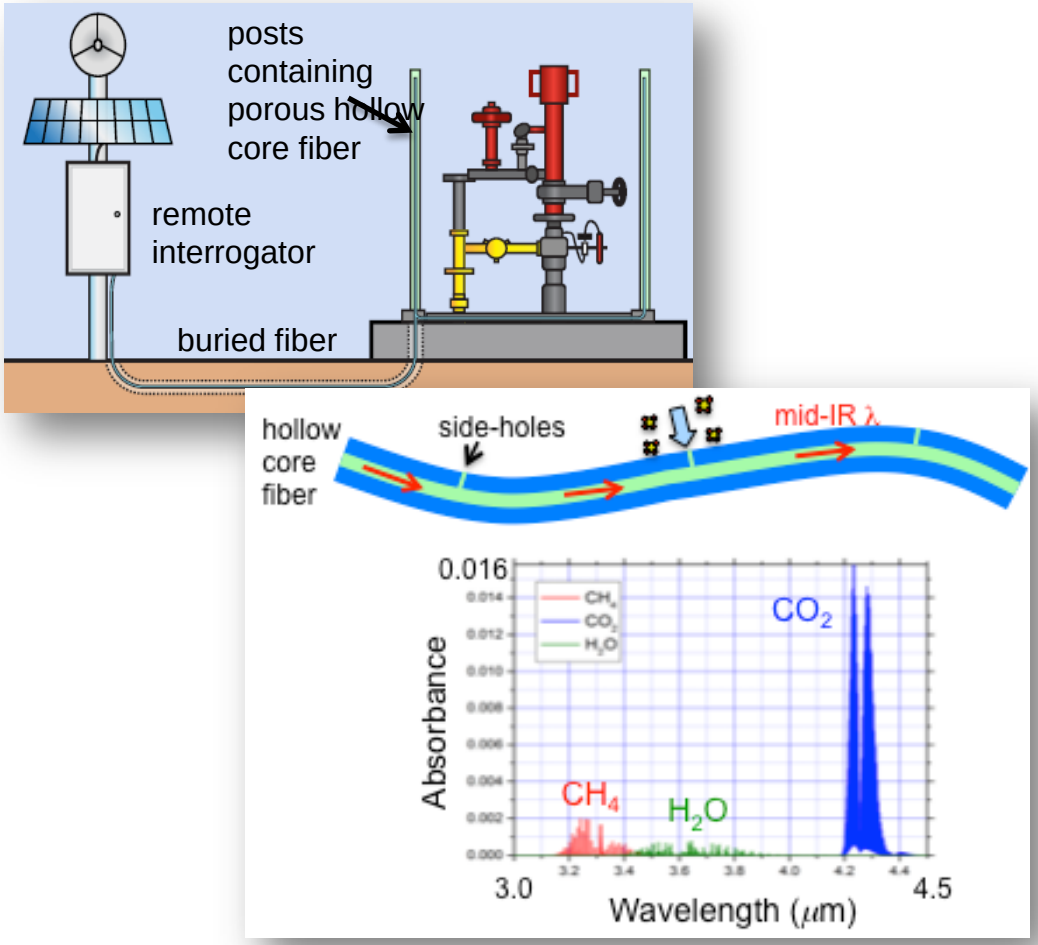
PROJECT PARTNERS: NIST, NOAA

Frequency Comb-based Methane Sensing

University of Colorado Boulder



Microstructured Optical Fiber for Methane Sensing



PROJECT HIGHLIGHTS

- Fiber optic sensor is broadly applicable throughout the oil and gas industry, particularly for large-scale infrastructure (such as transmission lines)
- Photonic crystal fiber design will minimize optical losses while permitting ambient gas to enter hollow core

AWARD AMOUNT: $1.4 million

PROJECT PARTNERS: Virginia Tech

Portfolio:
Two Aerial Technologies

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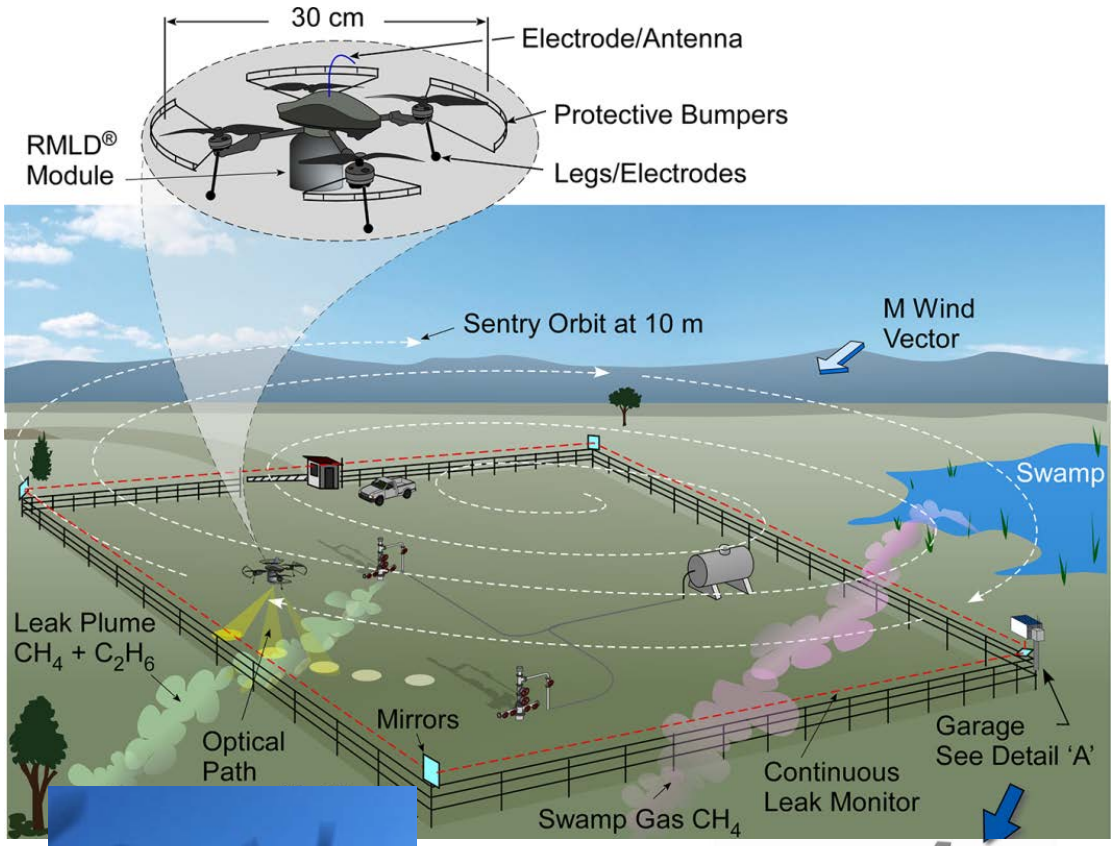
Image courtesy of Cuadrilla Resources

UAV-based Laser Spectroscopy for Methane Leak Measurement

Physical Sciences Inc.



PROJECT HIGHLIGHTS

- Continuous leak monitoring with leak quantification and real-time alarm notification
- Two modes of operation: continuous perimeter monitoring and search mode to pinpoint leak location
- Speciation of methane and ethane differentiates thermogenic vs. biogenic emission
- Improved production processes reduce costs of mid-IR Interband Cascade Laser (ICL) sources

AWARD AMOUNT: $2.9 million

PROJECT PARTNERS: Heath Consultants, Thorlabs, Princeton University, University of Houston, Cascodium

Mobile LiDAR Sensors for Methane Leak Detection

PROJECT HIGHLIGHTS

- Simultaneous, rapid, and precise 3D topography and methane gas sensing on fixed or mobile platform
- Capable of covering a broad range: a frequency-swept laser beam is transmitted to a topographical target 1-300 m from the sensor
- Produces detailed situational awareness reports derived from overlaid methane concentration, 3D topography, and RGB picture data
- Potentially able to achieve a minimum leak rate detection of 1 gram per minute
- Estimated between ~$1,400-2,200 per well per year

AWARD AMOUNT: $1.5 million

Portfolio:
One Imaging Camera Technology

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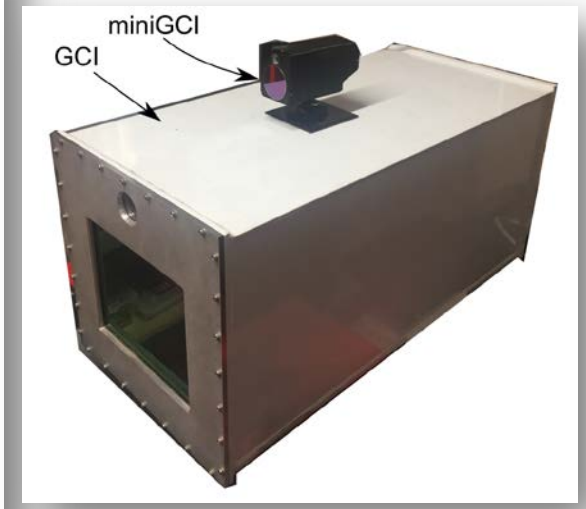
Portable Imaging Spectrometer for Methane Leak Detection

REBELLION PHOTONICS



PROJECT HIGHLIGHTS

- Miniaturization of Rebellion's Gas Cloud Imager (GCI), a long-wave infrared imaging spectrometer
- Camera will be lightweight and portable – the size of a Red Bull can - and capable of being incorporated into personal protective equipment
- Data processing uses cloud-based computing architecture that streams results to mobile device

AWARD AMOUNT: $4.3 million

Portfolio:
One Enabling Technology

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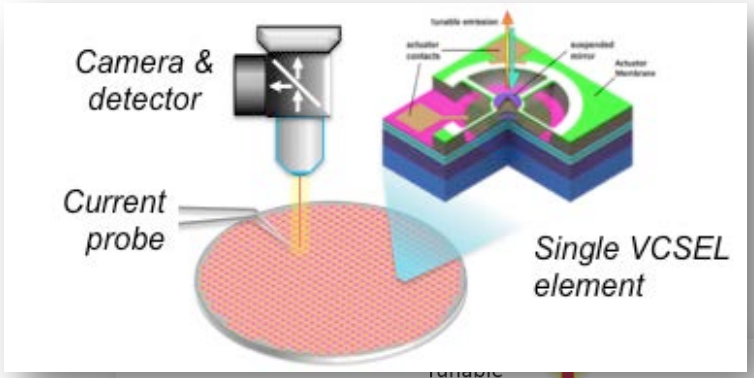
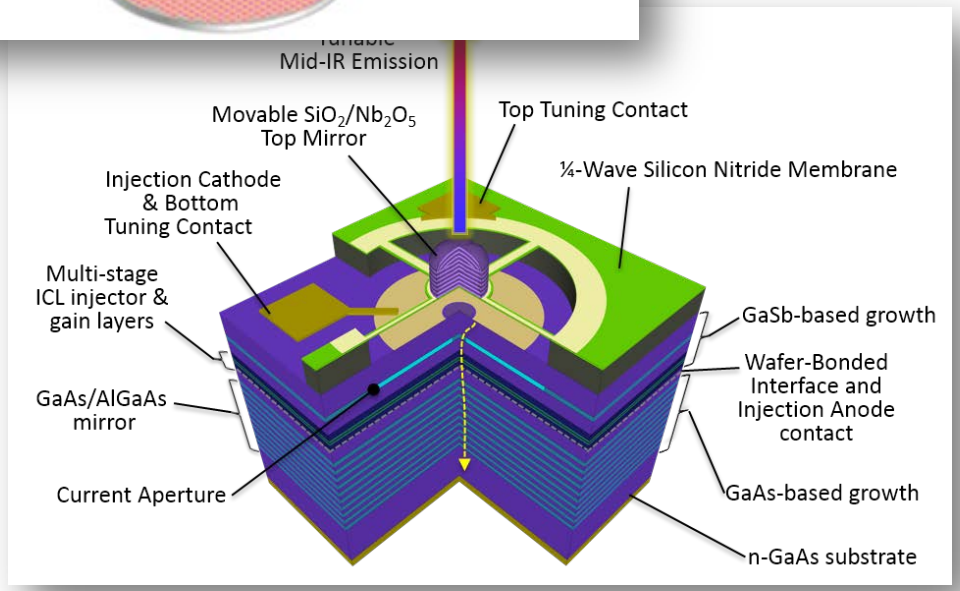
Image courtesy of Cuadrilla Resources

Tunable Mid-infrared Laser for Methane Sensing





PROJECT HIGHLIGHTS

- Innovative, low-cost mid-IR laser with VCSEL architecture
- Integrated micro-electro-mechanical system (MEMS) mirror enables a wide tuning range
- Approximately 40x reduction in laser cost, applicable across a wide array of sensors and applications

AWARD AMOUNT: $1.9 million

PROJECT PARTNERS: Thorlabs Quantum Electronics, Praevium Research, Rice University

Field Testing of MONITOR Technologies

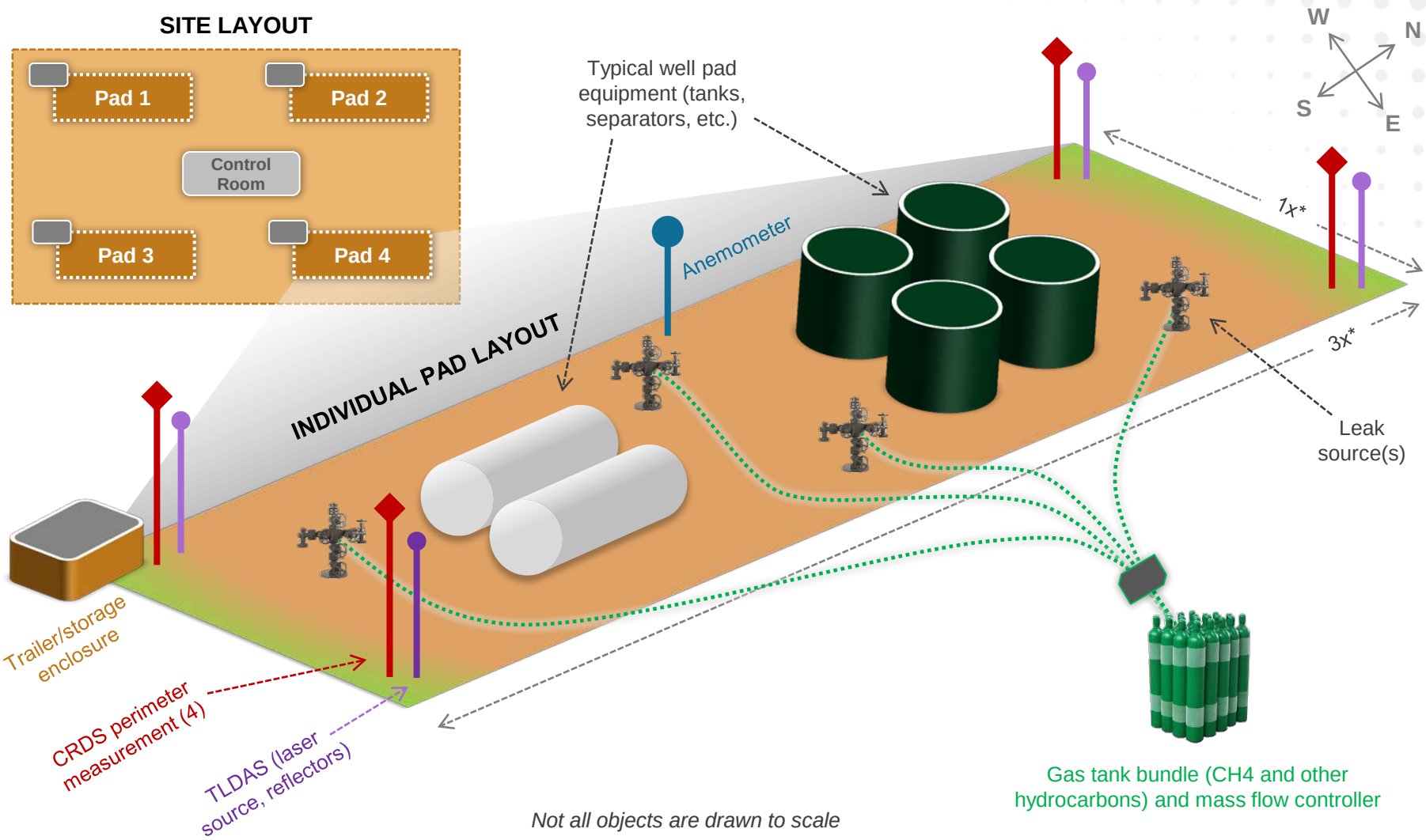
Goal #1: *Gauge technical performance*

- Independent testing and validation will provide a neutral venue to demonstrate technology and system performance
- **First round testing** (year two) will provide an opportunity to demonstrate technologies outside of laboratory tests; this will ensure technologies are tested in a standardized, realistic environment
- **Second round testing** (year three) will provide an opportunity to assess previously undemonstrated capabilities, as well as technical gains made since the first round of testing

Goal #2: *Engage stakeholder community*

- Establishing a testing site also enables MONITOR to materially engage strategic stakeholders early in the program
- This early engagement with industry leaders could facilitate hand-offs and/or post-MONITOR field demonstrations by developers and/or local distribution companies

Example Test Site Layout



*1x3 size ratio is approximate

Engagement and Partnerships

- Engagement with:
  - All sectors of oil and gas industry
  - Environmental community
  - Regulatory community (EPA, BLM, PHMSA and several states)
    - "The BLM also seeks to account for advances in continuous emissions monitoring technology, and also for other advances in leak detection technologies, which may result from ongoing technology development efforts such as the DOE ARPA–E MONITOR program."

- Partnerships:

INTERSTATE TECHNOLOGY & REGULATORY COUNCIL

Advancing Environmental Solutions

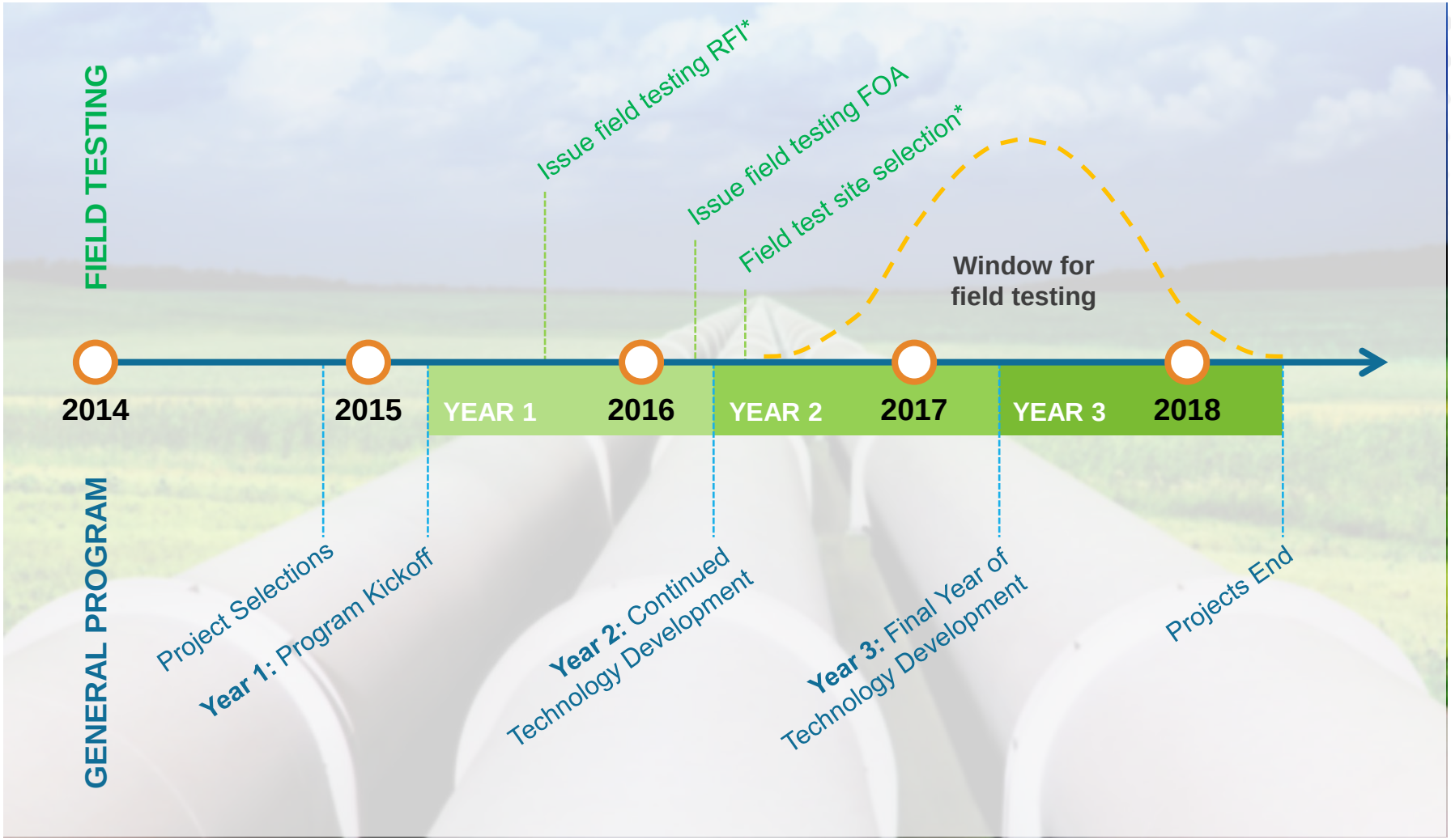
  - Comprised of state, federal, industrial & environmental leaders
  - Commissioned to create technical/regulatory guidelines to produce a comparative methodology to evaluate state-of-the-art methane detection technologies vs traditional technologies (OGI and Method 21)

Policy Needs

Main goal: Avoid technology lock-in; move towards quantification

- MONITOR technologies will enable:
  - Quantification, continuous monitoring, wireless communication—at low-cost and with high sensitivity
  - Result: leak prioritization, non-arbitrary measurement intervals or concentration thresholds, and decreased personnel costs
- Policy needs:
  - Inclusion of a technology onboarding mechanism—i.e. an explicit lookback to ensure that yesterday's technologies aren't "locked in"
- Policy should move towards:
  - Mass flow thresholds and continuous monitoring

The MONITOR Timeline: ARPA-E & Beyond



*Subject to change

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