MONITOR

Developing low-cost, highly-sensitive systems that detect and measure methane associated with the production and transportation of oil and natural gas

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On a lifecycle basis, natural gas emits nearly half the level of greenhouse gases as coal when burned; the challenge is ensuring that environmental risks throughout the supply chain are effectively mitigated.

Source: IPCC AR4 Annex II (2007)
The Importance of Focusing on Methane

Methane – the main component of natural gas – accounts for about one-tenth of U.S. greenhouse gas emissions.

However, over a 20-year period, one gram of methane has 84 times the global warming potential as the same amount of carbon dioxide.

U.S GHG Emissions (2012)

- Carbon Dioxide: 82%
- Methane: 9%
- Fluorinated Gases: 6%
- Nitrous Oxide: 3%

Source: EPA Greenhouse Gas Inventory, IPCC AR5 (2013)
## MONITOR Metrics & Targets

<table>
<thead>
<tr>
<th>Metric</th>
<th>Target/Feature</th>
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<tbody>
<tr>
<td><strong>Detection Threshold</strong></td>
<td>1 ton per year (6 standard cubic feet per hour)</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>$3,000 per site per year (for basic functionality)</td>
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<tr>
<td><strong>Resulting Leak Reduction</strong></td>
<td>90% methane leakage reduction with a 90% confidence level</td>
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<tr>
<td><strong>False Positives</strong></td>
<td>No more than 1 per year</td>
</tr>
<tr>
<td><strong>Mass Flow Rate</strong></td>
<td>Able to estimate mass flow rate within 20% margin of error</td>
</tr>
<tr>
<td><strong>Leak Location</strong></td>
<td>Able to estimate location within 1 meter</td>
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<tr>
<td><strong>Communications</strong></td>
<td>Transmits results wirelessly to remote receiver</td>
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<tr>
<td><strong>Enhanced Functionality</strong></td>
<td>Methane selectivity, speciation capability, thermogenic/biogenic differentiation, continuous measurement, enhanced stability</td>
</tr>
</tbody>
</table>
The Portfolio: 11 Projects in 9 States

**SYSTEM SOLUTIONS**

**Bridger Photonics**
Mobile LiDAR Sensors for Methane Leak Detection
Bozeman, MT

**PARC**
Printed Carbon Nanotube Sensors for Methane Leak Detection
Palo Alto, CA

**IBM**
On-Chip Optical Sensors and Network for Methane Leak Detection
Yorktown Heights, NY

**Rebellion Photonics**
Portable Imaging Spectrometer for Methane Leak Detection
Houston, TX

**physical Sciences Inc.**
UAV-based Laser Spectroscopy for Methane Leak Detection
Andover, MA

**Aeris Technologies**
Miniaturized Tunable Laser Spectrometer for Methane Leak Detection
Redwood City, CA
Miniaturized Tunable Laser Spectrometer for CH4 Leak Detection

TECHNOLOGY SUMMARY

- Compact mid-IR CH4 sensor with Aeris’ patent pending multi-pass absorption cell enabling ppb/s detection using simple direct absorption spectroscopy
- New architecture to achieve a long path length in a small volume
- Artificial neural network-leak characterization algorithm (ANN-LCA) to allow abstraction of complexity through pre-deployment, sophisticated-forward-model training.

TECHNOLOGY IMPACT

- Equivalent performance of ICOS or CRDS (2 ppb at 1 Hz) while being order of magnitude smaller and consuming less power (20-30W)
- ANN-LCA approach will lead to other energy industry impacts through in-situ meteorology-aware real-time decision-making (e.g. wind turbine/farm control systems)

PROJECT PARTNERS

- Los Alamos National Laboratory
- Rice University

Aeris Technologies

$2.4 million
On-Chip Optical Sensors and Distributed Mesh Networks for Methane Leak Detection

**TECHNOLOGY SUMMARY**

- Multi-modal, highly secure and reliable distributed methane monitoring and management system
- Novel on-chip optical sensors with high methane selectivity using state of the art silicon photonics technology
- Highly energy efficient, time-synchronized mesh networks
- Intelligent remote gateway
- Cloud-based analytics for source detection and localization as well as system self-verification coupled with enterprise-level integration capabilities

**TECHNOLOGY IMPACT**

- Cost is < $300 per sensor, 10-100x lower than current commercial TDLAS
- Low maintenance, robust, continuous measurement
- Low power requirements enables long-term solar-powered battery operation

**PROJECT PARTNERS**

- Princeton University
- Harvard University
UAV-based Laser Spectroscopy for Methane Leak Measurement

TECHNOLOGY SUMMARY
- Autonomous natural gas leak detection, measurement, and reporting system
- Innovative system combines:
  - Laser Backscatter Detection
  - Miniature fully-autonomous quadrotor aircraft
    - Field-validated by DoD
  - Algorithms for plume transport, leak detection, localization and mass flux quantification

TECHNOLOGY IMPACT
- Continuous leak monitoring with real-time alarm notification
- Speciation of methane and ethane differentiates thermogenic vs. biogenic emission
- Improved production processes reduce costs of mid-IR Interband Cascade Laser (ICL) sources
- Provides foundation for rapid commercialization

PROJECT PARTNERS
- Heath Consultants Inc.
- Thorlabs Quantum Electronics, Inc.
- Princeton University
- University of Houston
- Cascodium Inc.
Mobile LiDAR Sensors for Methane Leak Detection

TECHNOLOGY SUMMARY

- Light-detection and ranging (LiDAR) system capable of simultaneous, rapid, and precise 3D topography and methane gas sensing
- Measurements performed from an airborne or ground vehicle
- Novel near-IR fiber laser source and a mobile measurement strategy for rapid and sensitive pinpointing of methane leak plumes across multiple well platforms per day

TECHNOLOGY IMPACT

- Long range: a frequency-swept laser beam is transmitted to a topographical target ranging from 1 to 300 m from the sensor
- Potentially achieve a minimum leak rate detection of 1 gram per minute
- Low cost: proposed system estimated between ~$1.4k and $2.2k per well per year

Bridger Photonics

$1.5 million
Printed Carbon Nanotube Sensors for Methane Leak Detection

TECHNOLOGY SUMMARY
- High-sensitivity, high-selectivity, robust gas leak detection system with low-cost printed chemical sensor arrays based on doped carbon nanotubes
- Leverages previous gas sensor development by NASA and combines with PARC’s scalable, low-cost additive printing methods
- Sensor multiplicity reduces false positives and enables accurate calculation of leak location and leak rate with parameter estimation algorithms

TECHNOLOGY IMPACT
- A total system cost of under $350/site/year, to enable a low-cost disruptive approach to deploy and operate leak-detection systems
- 1 ppm sensitivity and leak localization of 1 m
- Technology transfer support from BP and Xerox
- Printing-enabled distributed gas leak detection at market-disruptive cost

PROJECT PARTNERS
- NASA Ames Research Center
- BP
- Xerox Corporation

PARC
$3.4 million
Portable Imaging Spectrometer for Methane Leak Detection

TECHNOLOGY SUMMARY

- Miniaturization of Rebellion’s Gas Cloud Imager (GCI), a long-wave infrared imaging spectrometer
- Image contains multiple bands of spectral data for detection and quantification of methane leaks
- Camera will be lightweight and incorporated with hard-hat/protective equipment for portability
- Data processing performed using a cloud-based computing architecture that streams results to smartphones or Google glass

TECHNOLOGY IMPACT

- High portability will enable widespread deployment and fast identification of leaks
- Visualization of leak leads to faster time to fix leak
The Portfolio: 11 Projects in 9 States

PARTIAL SOLUTIONS

Maxion
Tunable Mid-infrared Laser for Methane Sensing
Jessup, MD

GE
Microstructured Optical Fiber for Methane Sensing
Niskayuna, NY

Duke
Miniaturized Coded Aperture Mass Spectrometer for Methane Sensing
Durham, NC

Li-Cor
Laser Spectroscopic Point Sensor for Methane Leak Detection
Lincoln, NE

University of Colorado Boulder
Frequency Comb-based Methane Sensing
Boulder, CO
Tunable Mid-infrared Laser for Methane Sensing

TECHNOLOGY SUMMARY

- Mid-infrared vertical cavity surface-emitting laser (VCSEL) based on an interband cascade active region
- Utilizes an integrated micro-electro-mechanical system (MEMS) mirror enabling a wide tuning range around 3.3 micrometers

TECHNOLOGY IMPACT

- Innovative, low-cost mid-IR laser with VCSEL architecture
- Approximately 40x reduction in laser cost, enabling a system cost below $2,600 / well pad

PROJECT PARTNERS

- Thorlabs Quantum Electronics
- Praevium Research
- Rice University

Maxion Technologies
$1.9 million

A wholly-owned subsidiary of Thorlabs, Inc.
Frequency Comb-based Methane Sensing

TECHNOLOGY SUMMARY

- Produces $10^5$ spaced, sharp, single frequency laser lines over a broad bandwidth
- Drift-free intrinsic calibration and high sensitivity
- Long path length (over 2 km)
- Multispecies sensing: CH$_4$, $^{13}$CH$_4$, H$_2$O, propane, ethane
- Capable of being deployed as part of a full methane detection system

TECHNOLOGY IMPACT

- Reduces cost of frequency comb spectroscopy
- High sensitivity (ppb) long-path measurements with specificity of FTIR
- Able to provide enhanced capability (measure multiple species, isotopic differentiation)

PROJECT PARTNERS

- NIST
- CIRES/NOAA

UC-Boulder
$2.1 million
Microstructured Optical Fiber for Methane Sensing

TECHNOLOGY SUMMARY

- Hollow core photonic crystal fiber fabricated for long path length transmission of infrared radiation at methane absorption wavelengths
- Includes micro side-holes for fast penetration of gases into the core
- Microstructure of fiber will be designed to minimize optical losses
- Capable of being deployed as part of a full methane detection system

TECHNOLOGY IMPACT

- High sensitivity technique broadly applicable in the oil and gas industry
- Enables low cost, high sensitivity measurements of methane

PROJECT PARTNERS

- Virginia Tech
Coded Aperture Miniature Mass Spectrometer for Methane Sensing

TECHNOLOGY SUMMARY

- Miniature mass spectrometer enabled by coded apertures optimized for natural gas and methane
- Combines aperture coding, microfabrication, computational sensing, double focusing sector mass analyzer, and search/location algorithms
- Natural gas speciation and identification of volatile organic compounds (VOCs), such as benzene
- Provides:
  - Short time to detection
  - High selectivity
  - High performance with low SWAP-C

TECHNOLOGY IMPACT

- Miniature mass spectrometer that can be used for methane detection, natural gas speciation, and a variety of other environmental sensing applications (e.g. CO₂ detection from carbon sequestration)

PROJECT PARTNERS

- RTI International
Laser Spectroscopic Point Sensor for Methane Leak Detection

TECHNOLOGY SUMMARY

• Laser spectroscopic CH₄ sensor that improves upon optical feedback-cavity enhanced absorption spectroscopy (OF-CEAS)
• Exploits an optical cavity with a small sampling volume (30 cc) and long optical path length (1000s m) for high sensitivity
• Advanced manufacturing to further reduce cost

TECHNOLOGY IMPACT

• Same cost as tunable laser diode absorption spectroscopy (TLDAS) at better performance
• High stability measurement
• Suitable for both stationary and mobile applications

PROJECT PARTNERS

• Colorado State University
• Gener8

LI-COR Biosciences
$2.7 million
Example Test Site Layout

**SITE LAYOUT**

- Pad 1
- Pad 2
- Control Room
- Pad 3
- Pad 4

**INDIVIDUAL PAD LAYOUT**

- Typical well pad equipment (tanks, separators, etc.)
- Anemometer
- Trailer/storage enclosure
- CRDS perimeter measurement (4)
- TLDAS (laser source, reflectors)
- Gas tank bundle (CH4 and other hydrocarbons) and mass flow controller

Not all objects are drawn to scale

*1x3 size ratio is approximate
The MONITOR Timeline: ARPA-E & Beyond

**General Program**
- Project Selections
- Year 1: Program Kickoff

**Year 1**
- Year 2: Continued Technology Development

**Year 2**
- Issue field testing RFI*
- Issue field testing RFP*
- Field test site selection*
- Performers conduct laboratory tests

**Year 3**
- Final Year of Technology Development

**2014**
- 2015
- 2016
- 2017
- 2018

*Subject to change