MONITOR Program Overview

B. PROGRAM OVERVIEW

1. SUMMARY

The goal of the MONITOR[1] program is to support the development of disruptive approaches for methane emission detection and measurement that will enable widespread utilization and facilitate reductions in methane emissions. The program implementation focus is on "oil and gas systems" from the wellhead to the end-user. Cost-effective measurement of methane emissions will facilitate detection and early mitigation of leaks and process upsets, thus reducing the overall emissions of methane from the production of natural gas.

2. MOTIVATION

ARPA-E's authorizing statute directs the agency to support the development of technology that could result in "reduction of energy-related emissions, including greenhouse gases", which this program addresses directly. The statute also promotes the development of technologies that could result in "reduction of imports of energy from foreign sources". To the extent that reduction of methane loss preserves the natural gas supply for domestic use, this is also supported.

Methane is estimated to be the second largest contributor to global warming (after CO_2), although there is some debate about the magnitude of its impact due to uncertainties around: 1) the most appropriate global warming potential (GWP)[2] for methane, 2) the quantity of methane entering the atmosphere from all sources, and 3) distribution of emissions between anthropogenic and non-anthropogenic sources. GWP values for methane range from 21 to 86[3] due to varying time periods used for the calculation and developing knowledge about the complex chemistry of methane in the atmosphere. The U.S. Environmental Protection Agency (EPA) estimated that in 2011, methane accounted for 8.8% of the global warming impact from domestic human activity.[4] This estimate used the 100-year GWP_{100} factor of 21, which is at the lowest end of the GWP spectrum; however, if the higher range value for 20-year GWP_{20} of 86 is used instead,[5] the global warming impact from anthropogenic methane in the U.S. would increase to 31.9%.

EPA also estimates that oil and natural gas systems comprise approximately 30% of the U.S. anthropogenic methane emissions. This corresponds to a methane leakage rate of around 1.65%[6] of production. While some recent literature, such as Allen's "bottom up"[7] analysis generally support this estimate,[8] other "top down"[9] studies have called these estimates into question. For example, Miller's top down study proposes that "current inventories from the U.S. Environmental Protection Agency and the Emissions Database for Global Atmospheric Research underestimate methane emissions nationally by 150% and 170%, respectively"—suggesting a leakage rate between 2.5% and 2.8% of production.[10] Similarly, Brandt's recent paper suggests that methane emissions from all sources range from 125% to

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1 Methane Observation Networks with Innovative Technology to Obtain Reductions

2 Global warming potential (GWP) is a measure of the effectiveness of a gas in trapping heat in the atmosphere, referenced to CO2.

3 From the Second Assessment Report (SAR) of the Intergovernmental Panel on Climate Change (IPCC) (1996) and Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) (2014).

4 EPA 430-R-13-001. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2011. April 12, 2013.

5 Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) (2014).

6 Calculated from data presented in EPA 430-R-13-001. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2011. April 12, 2013. (see http://static.berkeleyearth.org/memos/epa-report-reveals-lower-methane-leakage-from-natural-gas.pdf)

7 "Bottom up" estimates attempt to estimate methane emissions by combining inventories of potential sources (natural gas wells, compressor engines, field processing equipment, etc.) with estimates of their "typical" emissions and "snapshot" measurements to estimate total emissions from the system.

8 D.T. Allen, et al. Measurements of methane emissions at natural gas production sites in the United States. PNAS 110(44):17768–17773 (2013).

9 "Top down" estimates attempt to estimate emissions through measurements in the atmosphere, typically from tall towers or aircraft.

10 S.M. Miller, et al. Anthropogenic emissions of methane in the United States. *PNAS* 110(50):20018-20022 (2013).

175% of EPA estimates.[11] Other studies have indicated that localized emissions in production zones can be much higher, such as a study of the Uintah basin that estimated emissions rates at 6.2%-11.7% of production[12] and a study of the Los Angeles basin that estimated rates as high as 17% of production.[13]

These studies illustrate two important conclusions: 1) methane emissions are a significant contributor to environmental forcing effects, even if the lower range of GWP values are assumed; and 2) there is a bona fide need to improve the measurement of anthropogenic methane emissions. These conclusions provide the motivation for this FOA's focus on the development of technological solutions that facilitate improved, cost effective detection and measurement of methane emissions.

3. STATE-OF-THE-ART

There are numerous technologies available that allow the measurement of methane levels. These technologies include, but are not limited to gas chromatography (GC), flame ionization detection (FID), Fourier transform infrared spectroscopy (FTIR), tunable laser diode absorption spectroscopy (TLDAS), cavity ring-down spectroscopy, electrochemical sensors, and catalytic sensors. These systems have different degrees of selectivity, sensitivity, accuracy, and cost. For example, catalytic sensors can be quite inexpensive, but their relatively low sensitivity requires that they be deployed in close proximity to potential leakage points, requiring a relatively high number of sensors for complete coverage of a site. At the other end of the spectrum, TLDAS systems have demonstrated very high sensitivity with detection levels of 1 ppb or below that potentially allow the use of fewer sensors, albeit with higher cost per sensor. Regardless of sensitivity, many measurement systems require transport of either the methane to the sensor or the sensor to the methane plume. Moreover, systems can make measurements from a single point, along an open path line, or over an area (as in the case of imaging detectors).

The primary barrier to widespread utilization of continuous or semi-continuous methane measurement is cost. Current high-resolution methane measurement approaches (e.g.; cavity ring-down, TLDAS) have initial capital costs of $75,000-$100,000 as well as additional installation, calibration, and operating costs—yielding an annual measurement cost in excess of $25,000 per site, assuming a 3-5 year equipment life. Lower cost electrochemical or IR approaches are used in safety systems to monitor for flammability that typically do not require sensitivity below 100 ppm.

4. PROGRAM APPROACH

There are numerous approaches to reduce the cost of methane sensing and measurement. Among others, one can reduce the cost of the sensor itself or transport the sensor so that it performs sensing at a number of different sites. With this in mind, ARPA-E is soliciting applications for the development of "sensing systems" rather than focusing solely on sensors.

Potential measurement solutions could consist of, **but are not limited to**:

1. Single high-sensitivity fixed sensor;
2. Network consisting of a number of lower sensitivity fixed sensors;
3. Systems incorporating imaging technology;
4. Sensor(s) mounted on vehicles that drive prescribed or random routes and uses both concentration and wind data to estimate the location of leaks;
5. Sensors mounted in conventional or unmanned aircraft;
6. Satellite imaging; and
7. Biological solutions in which plants might "signal" (change of color, release of chemicals) the presence of methane.

[11] A.R. Brandt, et al. Methane leaks from North American natural gas system. *Science* 343(6172):733-735 (2014).
[12] A. Karion, et al. Methane emissions estimate from airborne measurements over a western United States natural gas field. *Geophys. Res. Lett*. 40(16):4393–4397 (2013).
[13] J. Peischl, et al. Quantifying sources of methane using light alkanes in the Los Angeles basin, California. *J. Geophys. Res. Atmos.* 118(10):4974-4990 (2013).

Each of these would require not only the physical sensing component (laser spectrometer, catalytic sensor, imaging sensor, biological sensor), but also-environmental data (e.g., wind speed and direction) and potentially other weather data (e.g., temperature, precipitation). The concentration and environmental/weather data would be used with an inverse dispersion model to estimate the location and magnitude of a leak. Please note that use of specific environmental and weather data is not required; all data-based methods of estimating the location and magnitude of a leak are acceptable.

B. PROGRAM OBJECTIVES

The goal of the MONITOR program is to support the development of disruptive approaches for methane emission detection and measurement that will enable widespread utilization and facilitate reductions in methane emissions. The specific objective of the FOA is to *detect and measure methane leaks as small as 1 ton per year from a site 10 m x 10 m in area with a certainty that would allow 90% reduction in methane loss for an annual site cost of $3,000*. The system should be capable of estimating the location and mass flow rate of a leak, should be able to transmit results wirelessly to a remote receiver, and should incorporate data processing to minimize false positive events. Additional cost will be allowed for systems that demonstrate enhanced measurement capabilities, as discussed in Section I.C.4 below.

1. TARGET LEAK SIZE

This FOA establishes a detection threshold of 1 ton/year. This corresponds to 1.9 grams/minute, which is approximately 6 standard cubic feet per hour (scfh). Significant stochastic uncertainty may be present in field measurements; these should be be considered when reporting the presence and/or magnitude of a leak in order to minimize reporting of false positive events. Finally, Applicants to this FOA should include strategies to account for the local background level of methane because inaccurate background assumptions could lead to significant errors in leak detection and determination of leakage rates.

2. TARGET FACILITY

This FOA seeks detection solutions that can be applied at facilities of all sizes, including individual wellpads, gathering and field compression sites, gas processing plants, and compressor stations, and local distribution systems. In order to bound the problem, a production well pad has been selected as the focus of this FOA; however, systems approaches to other segments of natural gas infrastructure will be considered.

A square production well pad has been chosen as the "model site," with dimensions of 10 meters by 10 meters; leakage is possible from anywhere on the site, and time varying winds of 2.75 m/s (average wind speed) are typical. For systems that depend on or are affected by wind, the reference wind profile chosen for this analysis is a 2 meter data set (taken 2 meters above ground) from the National Wind Technology Center.[14] Respondents are allowed full latitude in positioning the components of their monitoring system on, or outside of, the site. Details about the model site and additional criteria will be provided in the instructions for Full Applications.

3. REDUCTION CRITERION

Although the property of primary interest for gas sensors is concentration, design of the entire system is needed to determine the required sensitivity of the sensors. For example, a single high-sensitivity sensor may be replaced with an array of lower cost, lower sensitivity sensors. Similarly, sensors for use in mobile sensing (from ground vehicles, airplanes, UAVs, etc.) may require high sensitivity but may be able to tolerate higher sensor costs since the system allows measurement of multiple sites. This diversity of approaches makes it impractical to establish sensitivity criteria for sensors *a priori*. Instead, ARPA-E has established a system goal of reducing methane leakage from the model site by 90%. The base case assumes that site inspections are performed on an annual basis. Statistically, it is also assumed that leaks that occur between the annual inspections are evenly distributed throughout the year. For simplicity, it is assumed that any leak that is detected by a monitoring system is repaired instantly. Therefore, when a leak is detected (and repaired) before the next annual inspection, a reduction in leakage is achieved.

[14] http://www.nrel.gov/midc/nwtc_m2/

Respondents who submit Full Applications will be required to document the expected performance of their system, including calculation of the lower detection limit required for their sensors. Additional instructions on performance modeling will be provided in the instructions for submitting a Full Application.

Quantifying system performance will require an estimate of the natural gas savings that can be facilitated by a particular measurement system; this requires assumptions about maintenance and repair practices. For the purpose of this FOA, it is assumed that:

1. An annual leak inspection will be conducted and would detect any leaks (above the 6 scfh threshold) at the site. It is assumed that all leaks at or above 6 scfh will be detected and repaired at the time of the annual inspection.

2. A leak can occur at any time between annual inspections.

3. The initiation times of leaks are evenly distributed throughout the year; thus, the starting time of the "average" (mean and median are the same in this case) leak occurs at the midpoint of the year. This implies that the average leak would persist for 365/2 = 182.5 days. Consequently, a 90% reduction in average leakage requires detection of a leak within 10% of the time between its start and the annual inspection, so within 18.25 days on average.

4. If a leak is detected, it is "instantly" considered repaired.[15]

5. The "gas saved" is the amount of gas that would have otherwise been emitted between detection and the annual inspection.

4. COST AND ENHANCED FUNCTIONALITY

The primary goal of this FOA is for early detection of methane or natural gas leakage and establishes a cost metric of $3,000 / site / year for basic functionality, i.e. the ability to measure methane within a time period (18.25 days) sufficient to produce a 90% reduction of methane loss from leakage. However, there are other considerations which can increase or reduce the value of the system, and can therefore influence the allowable annual cost of measurement. Additional capabilities of interest include:

1. Methane selectivity: Defined as a system that has the ability to discriminate between methane and longer chain hydrocarbons.

2. Speciation capability: Similar to methane selectivity, but with additional ability to quantify the primary constituents of the natural gas stream.

3. Thermogenic / biogenic differentiation: Defined as a system that can differentiate between methane from thermogenic sources (i.e., natural gas) and methane from biogenic sources (i.e. cattle, landfills, wastewater treatment, etc.). This could include, but is not limited to, analysis of higher hydrocarbons, carbon isotope analysis, and hydrogen isotope analysis.

4. Continuous measurement: Defined as a system that continuously measures methane (or natural gas) concentration at a site. A system will be deemed to make continuous measurements if it measures the concentration at least once every 10 minutes.

5. Enhanced stability: The increasing concerns about atmospheric levels of methane suggest the need for sensing systems that may have higher precision and stability than required for leak detection. These sensors could be deployed for long-term ambient baseline studies, for "ground verification" of satellite or aerial imaging, or for scientific studies of methane emissions from sources as varied as tundra and alpine lakes.

[15] The unrealistically optimistic assumption of maintenance practice is acknowledged. Detecting a leak is only the first step in repairing it. An inspection and repair crew must be mobilized; with mobilization assumed to be prioritized by the magnitude of the leak. Although many leaks can be quickly fixed while the system is pressurized, others may require "blowdown" of piping components.

6. Other functionality: Other enhanced functionality may be of interest. Applications for systems with other enhanced functionality should describe the expected capabilities.

Enhanced functionality is generally expected to allow additional cost. The number of combinations and permutations prevents a prescriptive specification cost for each of these capabilities and/or combination of capabilities. It is unlikely that applications for systems with a cost of over $10,000 / year would be competitive, even if they combine multiple categories of enhanced functionality as described above. Applications for systems with enhanced capabilities should document the expected cost of the system; in cases where the enhanced functionality is additive to the system (rather than built into the basic structure of the system and therefore inseparable), it may be useful to describe the costs with and without the enhanced capability.

C. TECHNICAL CATEGORIES OF INTEREST

FOA Applicants must convincingly demonstrate that the proposed system has the potential to meet the detection, measurement, and cost metrics required for widespread deployment. ARPA-E is primarily interested in applications that propose *complete systems* that combine methane detection and measurement with data analytics in order to estimate methane emission rates and location of leaks; the systems should also include provisions for data quality control and digital communication. ARPA-E will also consider for awards transformational *partial solutions* that demonstrate promising new approaches to sensing, but are too early in their development to warrant incorporation into a complete system.

CATEGORY 1: COMPLETE MEASUREMENT SYSTEMS

The primary focus of this FOA is the development of *complete methane measurement systems*, which will include 1) methane emission sensing, 2) methane leakage characterization and data analytics in order to estimate the leakage rates and approximate location of leaks, 3) provisions for data quality control, 4) digital communication, and 5) enhanced functionality.

Technologies of Interest

ARPA-E is particularly interested in applications that incorporate one or more of the following technological advances into their systems solution:

- Reduced-cost TLDAS systems that incorporate either an internal absorption path or an external absorption path;
- Reduced-cost long-path spectroscopic approaches which are configured to provide sensing along one side or potentially around the entire perimeter of a site of interest;
- Hyperspectral approaches with an ambient thermal radiation infrared source;
- Absorption approaches in which the sun or sky provide the reference source;
- Low-cost approaches to mid-infrared (IR) detectors, particularly uncooled detectors;
- Reduced cost and/or increased resolution methane imaging systems, particularly with non-cryogenic detectors;
- Single-point sensors or imaging systems using plasmonic detectors, with particular interest in uncooled plasmonic detectors;
- LIDAR or laser backscatter approaches;
- Mobile sensing from dedicated and non-dedicated ground vehicles and aerial vehicles;
- Highly automated deployment of unmanned aerial vehicles (UAVs), using any combination of single-point, open-path, or imaging detectors;

- Multiple UAVs with long-path sensing, or combinations involving ground-based and aerial sensing;
- Low-cost approaches to mid-IR lasers, including quantum cascade lasers(QCLs), inter-sub-band gap lasers (ISBs), vertical cavity surface emission lasers (VCSELs), or other novel/emerging concepts;
- Other novel concepts and technologies that would be enabling for low-cost gas monitoring; and
- Advanced data analytics that aggregate localized methane measurement with wider area atmospheric and dispersion models in order to estimate regional flux rates, including, but not limited to: 1) GIS integration, 2) reinforcement learning, 3) inversion modeling, 4) micro-climate modeling, and 5) site flux apportionment.

CATEGORY 2: PARTIAL MEASUREMENT SOLUTIONS

The second category of interest is the development of *partial measurement solutions*. Although ARPA-E is primarily interested in applications for complete sensing systems, it is understood that some nascent technologies may be too early in the development process for incorporation into a complete sensing systems. ARPA-E will support the development of such potentially transformational new technologies that could significantly contribute to progress towards the system level objectives in this FOA. Partial solutions are primarily envisioned as advances in detector technology or data analytics.

Technologies of Interest

ARPA-E is particularly interested in partial solutions that include:

- Novel spectrometers;
- Novel electrochemical sensors;
- Critical sensor components, such as reduced cost mid-infrared lasers or detectors;
- Advanced dispersion models;
- Data-processing algorithms; and
- Other technologies that would be enabling for low-cost gas monitoring.

D. TECHNICAL PERFORMANCE TARGETS

As discussed in Section IV.A, this FOA will use a two-stage application approach: 1) Concept Paper Stage and 2) Full Application Stage. After a review of the Concept Papers, Applicants will either be “encouraged” or “not encouraged” to submit a Full Application. Concept papers are expected to provide a description of a system that would be “reasonably expected” to meet the technical performance targets in this section, but are not required to provide detailed supporting analysis. Full Applications will be expected to include a sufficient level of analysis to document that the system can achieve the system level goals of:

- Detecting a leak of 6 SCFH (1 ton/year) on a 10 m x 10 m well pad, within a time period that will allow a 90% reduction of leakage, with a 90% confidence level;
- Validating the data so that the rate of “false positive” indications is no more than 1 per year; as an alternative to a binary indication of “leak” or “no leak”, the system can also choose to report the probability that a leak of a given size exists;
- Estimating the mass flow rate of each leak, to within 20% error;

- Estimating the location of each leak to within 1 meter;
- Communicating the results wirelessly to a remote receiver;
- Total system cost (amortized capital cost + operating cost) is less than $3,000 / year for basic functionality; additional cost is allowed for enhanced functionality.
- Finally, if a system with enhanced functionality is proposed, the enhanced functionality must be documented.

Applicants that receive funding under this FOA will be held to development-specific technical milestones and objectives throughout the course of their project, generally established to be reviewed on a quarterly basis. However, three annual evaluations are also proposed. By the end of Year 1, the performer is expected to demonstrate the performance of all system components. By the end of Year 2, the performer is expected to demonstrate the performance of a complete system. By the end of Year 3, the performer is expected to demonstrate the performance of a mature system that can operate over an extended period. of time and meet the performance targets listed above. The three stages are designed to evaluate system performance under progressively more realistic conditions and are described in the following sections.

- The Year 1 evaluation will take place at the performer's site (or a site of their choosing) and is expected to demonstrate performance of individual system components (sensor, data analytics, communications system, etc.)
- The Year 2 evaluation will take place at an outdoor site approved by ARPA-E and is expected to demonstrate performance of the entire system against quantitative targets approved by ARPA-E. It is expected that the Year 2 targets will reflect substantial progress towards the performance targets established above.
- The Year 3 end-of-project evaluation will take place at an outdoor site approved by ARPA-E and is expected to demonstrate performance of the entire system against quantitative targets approved by ARPA-E. It is expected that the Year 3 targets will largely reflect achievement of the performance targets established above.

It is possible that a common test site or sites may be established and/or selected by ARPA-E. If a common test site is established, the choice of testing at the common site or at an alternative site will be agreed to between the performer team and ARPA-E. In either case, sufficient budget should be identified to support the Year 2 and Year 3 demonstrations.

Not every project will fit into the proposed annual evaluation framework. Some may be able to demonstrate system performance more rapidly while others may require more time to develop individual component technologies. Performance milestones will be proposed by the Applicant and reviewed with the Program Director during the negotiation process. Category 2 Partial Solutions may not fit into the proposed evaluation framework; again, milestones should be proposed by the Applicant and will be reviewed with the Program Director during the negotiation process.

E. INSTRUCTIONS FOR CONCEPT PAPERS

CATEGORY 1: COMPLETE MEASUREMENT SYSTEMS

Concept Papers must show a well-justified, realistic potential for a novel technology to meet the technical performance targets summarized in the previous section. In the Concept Paper, applications for Category of Interest 1 (Complete Measurement System) should describe their concept, including all of the following elements:

1. A system level diagram that includes all major system components and displays how they would be deployed on the well site;
2. A discussion of the value of the technology compared to state-of-the-art
3. A description of technical maturity of the concept, highlighting novel and high-risk elements
4. A description of the gas sensing technology, including any novel features, sensitivity, and selectivity;
5. A table which estimates the annual operating cost of the system. This should include a breakdown of the system's capital cost, annual operating cost, and system life; these should then be combined to estimate the annual cost of measurement.

In the Concept Paper, applications for Category of Interest 1 (Complete Measurement System) should also include all of the following elements, if relevant to the proposed measurement system:

6. A description of any other sensors required (wind speed, wind direction, etc.), including a description of any novel features.
7. A description of the data analytics approach to estimate the leakage rate and approximate location of the leak.
8. A description of the approach to data quality control, with the intent of maximizing detection while minimizing reporting of false positive alarms.
9. A description of the approach to wireless digital communication of results to a remote receiver.
10. A description of the approach to any “enhanced capability”, which may include: methane selectivity, speciation capability, thermogenic / biogenic differentiation, continuous measurement, enhanced stability, etc.

CATEGORY 2: PARTIAL MEASUREMENT SYSTEMS

In the Concept Paper, applications for Category of Interest 2 (Partial Measurement Solutions) should describe their partial solution, including the following elements:

1. A description of the partial solution proposed;
2. A discussion of how the partial solution would be enabling to the overall goals of the MONITOR program;
3. A discussion of the value of the technology compared to state-of-the-art;
4. A description of technical maturity of the concept, highlighting novel and high-risk elements;
5. A table that estimates the annual operating cost of a complete system that utilizes the partial solution; this will require specification of a hypothetical complete system that takes advantage of the partial solution. This should include a breakdown of the system’s capital cost, annual operating cost, and system life; these should then be combined to estimate the annual cost of measurement. If a partial solution does not support this direct cost estimation, the benefits and their potential impact on the cost of measurement should be discussed as completely as possible; and
6. A discussion of any “enhanced capability” that the solution would provide to a measurement system.