RESEARCH PERFORMANCE PROGRESS REPORT

SUBMITTED TO:

U. S. Department of Energy
National Energy Technology Laboratory

WORK PERFORMED UNDER AGREEMENT: DE-FE0029020

PROJECT TITLE:

Smart Methane Emission Detection System Development

SUBMITTED BY:

Maria Araujo, PI
maria.araujo@swri.org
(210) 522-3730

SUBMISSION DATE: April 28, 2017

DUNS NUMBER: 007936842

RECIPIENT ORGANIZATION:

Southwest Research Institute
6220 Culebra Road
San Antonio, TX 78238

PROJECT/GRANT PERIOD:

October 1, 2016 through September 30, 2017

REPORTING PERIOD END DATE:

March 31, 2017

REPORT TERM OR FREQUENCY: Quarterly

SIGNATURE OF SUBMITTING OFFICIAL:

Maria S. Araujo

ACCOMPLISHMENTS

What was done? What was learned?

As anticipated, and defined in the Project Management Plan (PMP), activities during this quarter focused on performing simulated methane release tests, acquiring data and commencing algorithm development. Testing activity began in earnest during the second month of Quarter 1 (Q1); equipment needed to start execution of technical tasks arrived on the first week of December 2016.

- **What are the major goals of the project?** The major objective of this DOE research project is to develop an autonomous, real-time methane leak detection technology, the Smart Methane Leak Detection System (SLED), which applies machine learning techniques to passive optical sensing modalities to mitigate emissions through early detection. The goal during Phase 1 is to develop the prototype methane detection system with integrated optical sensors and the embedded processing unit. The goal for Phase 2 will be to integrate and field-test the prototype system, and then demonstrate the capabilities to DOE.

  To accomplish these goals, SwRI has identified a comprehensive schedule with milestone dates for important activities that will evidence progress on the project. The milestone schedule, with actual completion dates, is shown below.

Phase	Milestone Description	Verification Method	Planned Completion	Completion Date or Percentage Completed
1	Prepare and Submit the PMP	Delivery to DOE	10/29/16	10/29/2016
1	Update PMP with DOE Comments	Delivery to DOE	12/2/16	11/16/2016
1	Update the Data Management Plan	Delivery to DOE	12/16/16	12/16/2016
1	Develop the Algorithm	Assessment Results	6/19/17	
1	Develop and Assemble Prototype	Testing Results	8/29/17	
2	Integrate and Test Prototype	Testing Results	4/23/18	
2	Demonstrate the System to DOE	Demonstration	8/21/18	

  There have been no significant changes in approach or methods from the approved PMP.

- **What was accomplished under these goals?**

  Controlled Tests

  - Once the equipment was received, SwRI began setting up, configuring, and calibrating the cameras, as shown in Figure 1. The Mid-Wave Infrared (MWIR) cameras are being utilized as the transducers to capture frames in search of methane gases. The cameras are configured and calibrated to effectively capture the environment under varying illumination, weather conditions, and distances.
  - SwRI performed twenty-five (25) separate methane release tests under realistic conditions to establish a baseline database containing methane leaks of various concentrations, distances, and scenarios. A portable rig was constructed to allow

for gas discharges through various leak geometries while controlling pressure and leak rate. The test conditions included an initial set of varying ambient temperature conditions, cloud cover, presence and lack of obstacles (such as piping), and varying wind (including stagnant) conditions. Figure 2 through Figure 5 show pictures from some of the tests conducted during the months of January and February. Twenty-two of the releases were methane and three were carbon dioxide (to train the algorithm for false positives). The range of conditions for the testing were:

- Leak rates of 1-8 scfm
- Line pressures of 30-210 psig
- Orifice sizes ranging from 1/32" to 1/8"
- Leak geometries including open nozzles, diffuse tubing, and leaking joints

Figure 1: Niatros™ and FLIR MWIR Cameras

Figure 2: Niatros™ and FLIR MWIR Cameras Acquiring Data During a Supervised Methane Release

Figure 3: Controlled Methane Release Valves

Figure 4: Controlled Methane Release Test Apparatus

Figure 5: Methane Tank with Release Valves

Algorithm Development

- SwRI performed data collection and cataloguing.
- For this task, a set of comprehensive image processing and convolutional neural network (deep learning) techniques are being applied to evaluate the captured baseline database containing various methane leaks to extract significant spectral, spatial, and temporal information unique to methane gas.
- The MWIR data collected during the controlled releases was catalogued according to different descriptive features in the imagery and stored. A routine cleansing of the data was performed in order to eliminate poor quality images resulting from noise and certain unrealistic operating conditions (excessive sun glare, for example). From this cleansed data set, the imagery was divided such that 80% of the data would be used during algorithm development for training, and the remaining 20% would be used for validation.
- The raw data is scaled differently than images typically visible to the human eye. A preprocessing step was needed before attempting to establish ground truth so that meaningful features could be established within the images, as seen in Figure 6. Even with this processing, in a still image it is still difficult to verify where there is methane present. A further processing step was applied to extract features within in the images that roughly correspond to the methane plume's flow rate and concentration, as seen in Figure 7. With this information, ground truth was established by labeling these changing pixels that could be verified to be either of class "methane" or "other".

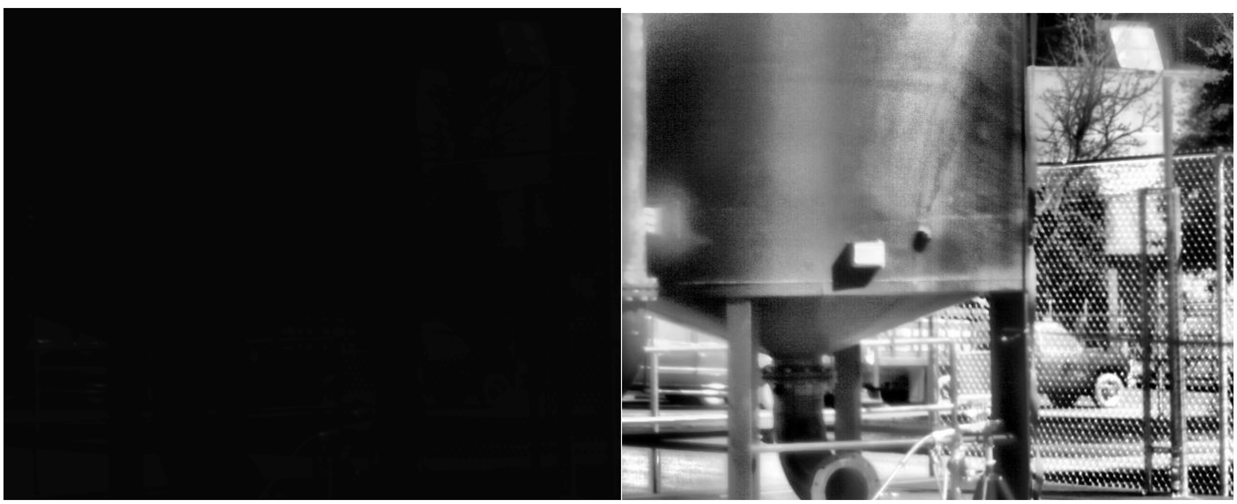

Figure 6: Raw and Processed MWIR Images

In a raw image (left), the contrast is insufficient for identifying any useful features. After processing (right), a human can more easily pick out the methane plume and verify the correct ground truth.

Figure 7: Additional Processing for Methane Identification
An image with methane (left); however, the methane is still difficult to spot with the human eye. Further processing (right) reveals where the methane is in the image.

- Once the datasets were sufficiently labeled, they were used to start training a fully convolutional neural network (FCNN) in order to detect at a per-pixel level the presence of methane. Preliminary results are summarized in **Figure 8** and **Figure 9**. On one validation set, it can be seen that the algorithm is learning to detect the methane plume but further training and fine-tuning is required in order to eliminate some common sources of false positives, such as highly reflective surfaces. In other tests, it was found that the algorithm still needs further training in order to account for noise and other variances introduced by changes in ambient lighting conditions.

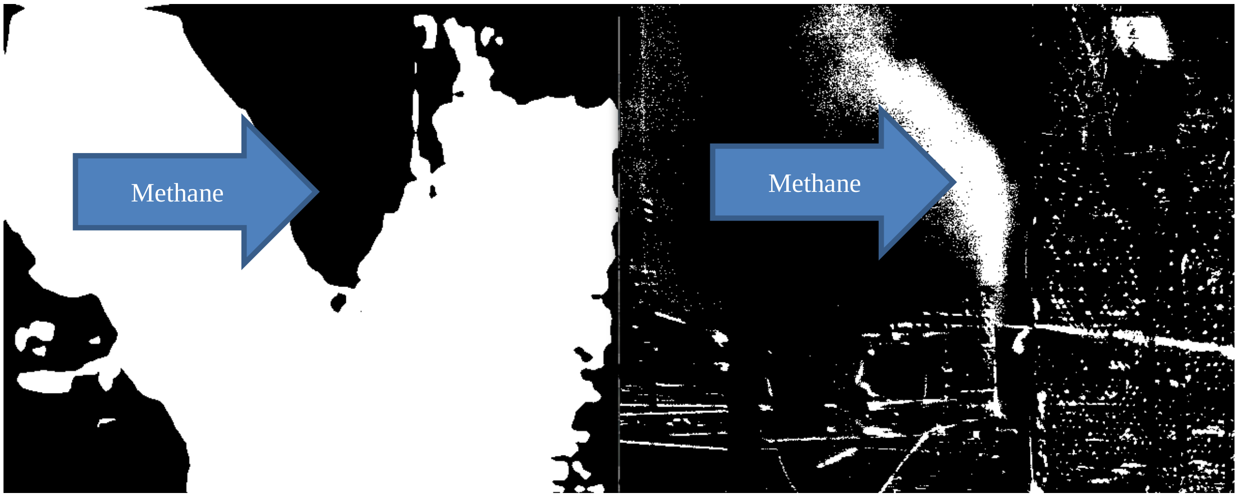

Figure 8: Neural Network Initial Output – Positive Identification
The output of the detection network (left) compared with a visualization of the raw methane plume imagery (right). In the detection image, black pixels represent a methane detection. The algorithm is detecting more methane plume than what is immediately apparent in the image that is used for easy human verification. However, noise still exists, particularly around the edges. These issues are currently being addressed.

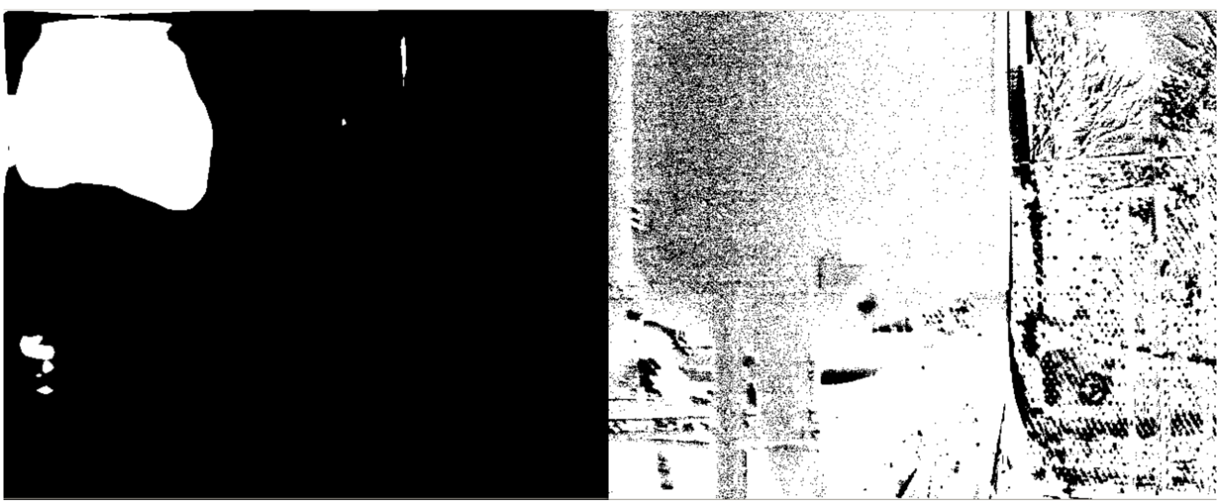

Figure 9: Neural Network Initial Output – Failed Identification
A failed detection image (left) compared with a visualization of the raw methane plume imagery (right). As can be seen in the visualization on the right, even with processing it is difficult to distinguish the methane plume in static imagery. Algorithm development is continuing to address these types of issues.

- Algorithm development is continuing to improve detections and reduce false alarms.

Embedded Processor Code Development

- This task encompasses porting the algorithm detection to an embedded system. The embedded system will support the camera interface, execute the detection algorithm, and provide a user interface for system monitoring and event triggering.
- For this task, the system and software architecture has been refined, the Tegra X1 evaluation board has been set up, and work on design/implementation/testing of each Computer Software Component (CSC) has begun. The refined system architecture is seen in **Figure 10**, and the software architecture defined in **Figure 11**.

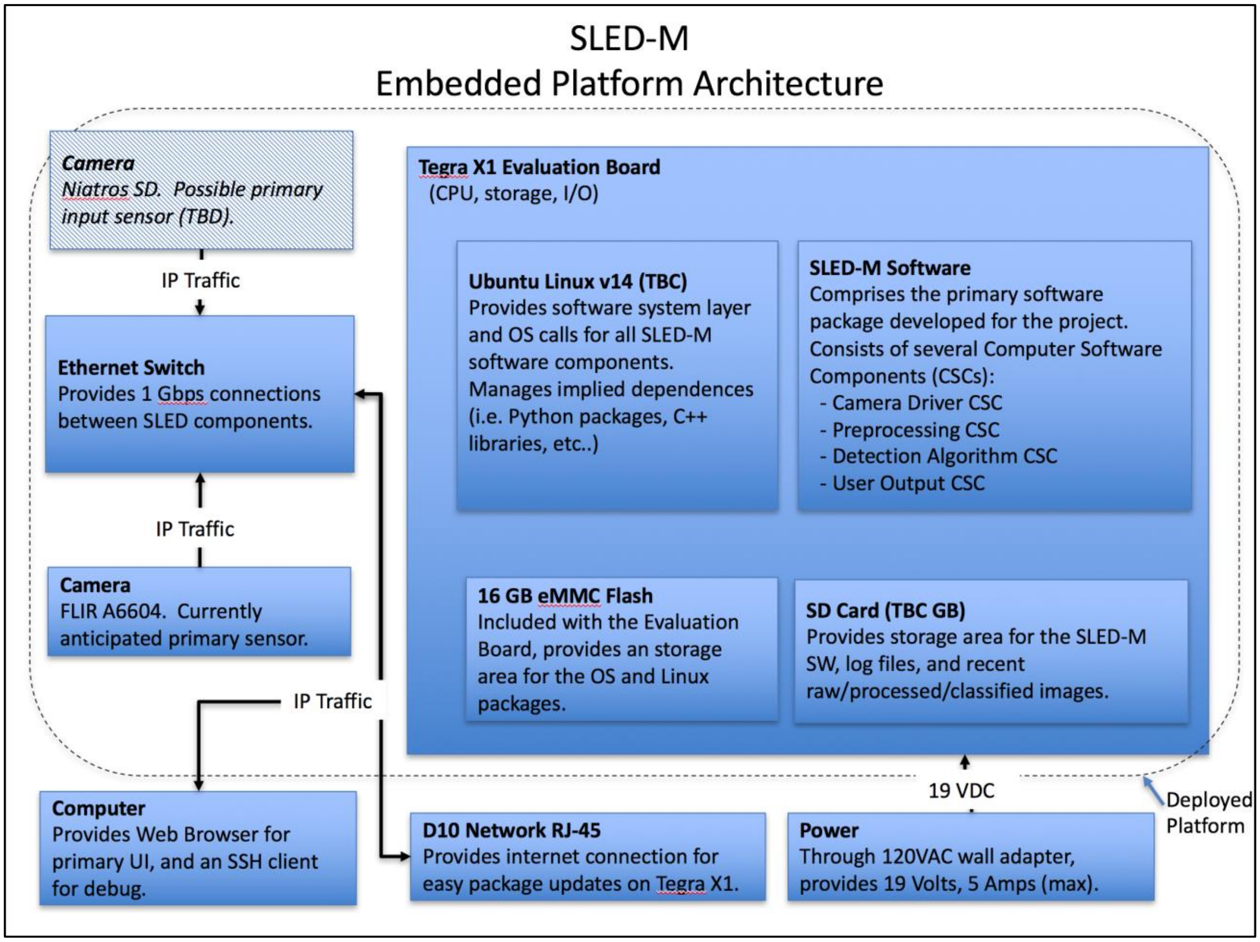

Figure 10: SLED/M Embedded Platform Architecture

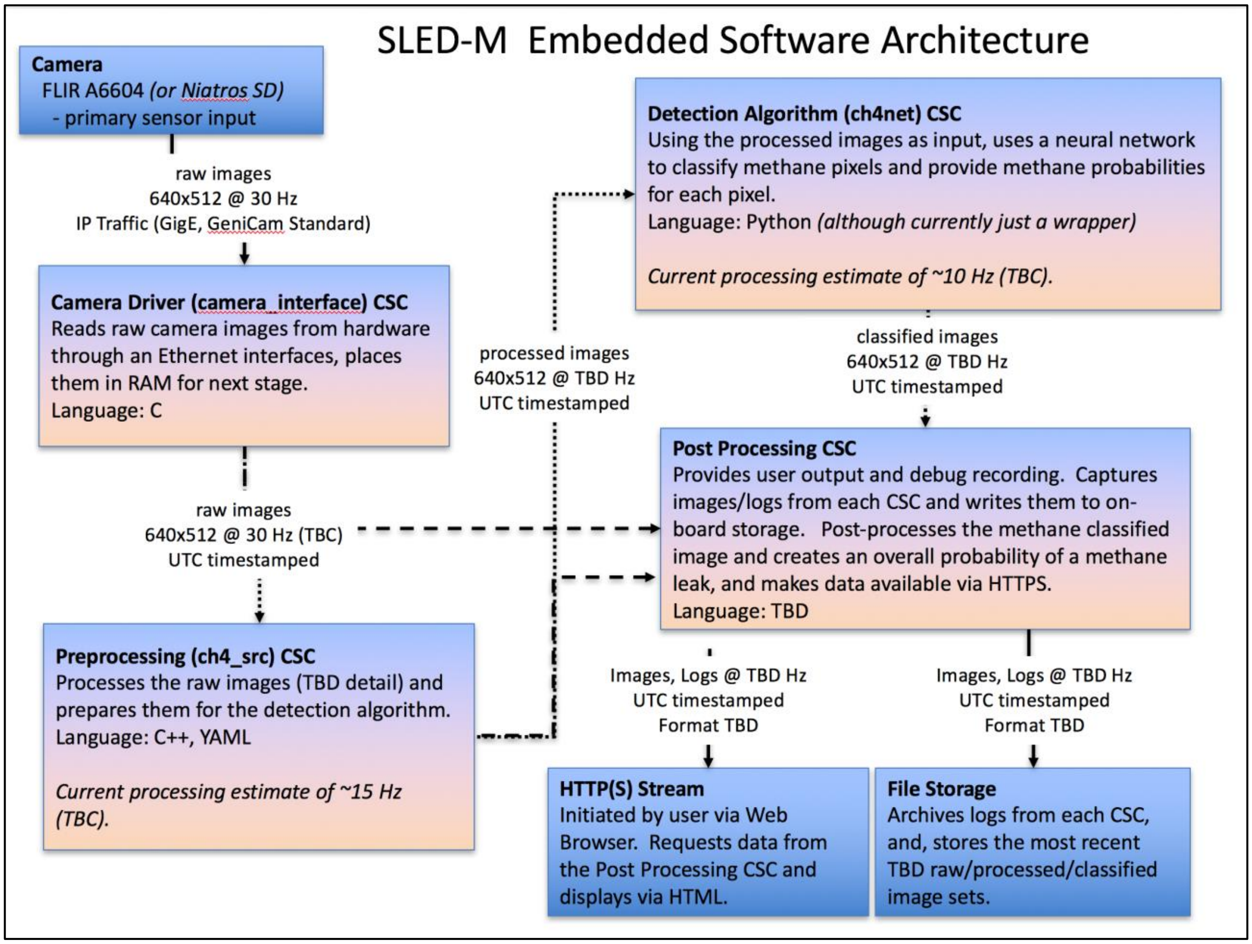

Figure 11: SLED/M Embedded Software Architecture

- Next steps on this task include:
  - Documenting detailed interfaces between CSCs
  - Each CSC going through an implementation/review/testing process, and final integration testing on the embedded platform

- **What opportunities for training and professional development has the project provided?** Nothing to report during this reporting period.

- **How have the results been disseminated to communities of interest?**
  - With the concurrence of the DOE PM, Mr. Joseph Renk III, Maria Araujo will be presenting at the Western Regional Gas Conference in San Diego, CA on August 30, 2017, with a presentation titled “Bringing Smarts to Methane Emissions Detection: An Update on the DOE Smart Methane Emissions Project”.
  - High-level articles regarding the award and description of the work being done were published. Some references are noted below:
    - http://www.naturalgasintel.com/articles/108067-texas-laboratory-developing-methane-leak-detection-system-for-doe
    - http://www.rigzone.com/iPhone/article.asp?a_id=147295

    - http://www.klrn.org/blogs/station-news/swri-developing-smart-technology-to-detect-methane-leaks/
    - http://www.oilandgaslawyerblog.com/2017/02/high-tech-detect-pipeline-leaks.html

- **What does SwRI plan to do during the next reporting period to accomplish the goals?**
  During the next reporting period, SwRI will:
    - Continue to perform the data collection and cataloguing as needed, and continue to work on the feature extraction and analysis.
    - Continue algorithm development. For this task, a set of comprehensive image processing and convolutional neural networks (deep learning) techniques will continue to be applied to evaluate the captured baseline database containing various methane leaks to extract significant spectral, spatial, and temporal information unique to methane gas.
    - Continue embedded processor code development.

PRODUCTS

What has the project produced?

- **Publications, conference papers, and presentations**
    - **Journal publications -** Nothing to Report During This Period.
    - **Books or other non-periodical, one-time publications -** Nothing to Report During This Period.
    - **Other publications, conference papers and presentations -** Nothing to Report During This Period. Maria Araujo will be presenting at the Western Regional Gas Conference in San Diego, CA on August 30, 2017, with a presentation titled "Bringing Smarts to Methane Emissions Detection: An Update on the DOE Smart Methane Emissions Project".
    - **Website(s) or other Internet site(s) -** Nothing to Report During This Period.
- **Technologies or techniques –** A technique for autonomously detecting methane using MWIR cameras and machine learning is currently under development, with promising results.
- **Inventions, patent applications, and/or licenses –** Assuming successful results and with DOE's concurrence, SwRI plans on filing an invention disclosure of the technique for autonomously detecting methane using MWIR cameras and machine learning.
- **Other products -** Nothing to Report During This Period.

PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS (optional)

Who has been involved?

- **What individuals have worked on the project?**

The following individuals were the main contributors to this project during this reporting period:

1. **Name:** Maria Araujo
    a. **Project Role:** PI
    b. **Nearest person month worked:** 1
    c. **Contribution to Project:** Ms. Araujo oversees the project and technical direction. She participated on the simulated tests and holds weekly meetings with the project team.
    d. **Funding Support:** N/A
    e. **Collaborated with individual in foreign country:** No
    f. **Country(ies) of foreign collaborator:** N/A
    g. **Travelled to foreign country:** No
    h. **If traveled to foreign country(ies), duration of stay:** N/A
2. **Name:** Edmond DuPont
    a. **Project Role:** Co-PI
    b. **Nearest person month worked:** 1
    c. **Contribution to Project:** Dr. DuPont assisted with tests performed and algorithm development during this reporting period.
    d. **Funding Support:** N/A
    e. **Collaborated with individual in foreign country:** No
    f. **Country(ies) of foreign collaborator:** N/A
    g. **Travelled to foreign country:** No
    h. **If traveled to foreign country(ies), duration of stay:** N/A
3. **Name:** Daniel Davila
    a. **Project Role:** Developer
    b. **Nearest person month worked:** 1
    c. **Contribution to Project:** Mr. Davila assisted with tests performed and algorithm development during this reporting period
    d. **Funding Support:** N/A
    e. **Collaborated with individual in foreign country:** No
    f. **Country(ies) of foreign collaborator:** N/A
    g. **Travelled to foreign country:** No
    h. **If traveled to foreign country(ies), duration of stay:** N/A
4. **Name:** Matthew Weatherston
    a. **Project Role:** Developer
    b. **Nearest person month worked:** 1
    c. **Contribution to Project:** Mr. Weatherston assisted with algorithm development during this reporting period.
    d. **Funding Support:** N/A
    e. **Collaborated with individual in foreign country:** No
    f. **Country(ies) of foreign collaborator:** N/A
    g. **Travelled to foreign country:** No
    h. **If traveled to foreign country(ies), duration of stay:** N/A
5. **Name:** Shane Siebenaler
    a. **Project Role:** Co-I
    b. **Nearest person month worked:** 1

c. **Contribution to Project:** Mr. Siebenaler oversaw methane release tests performed during this reporting period.
d. **Funding Support:** N/A
e. **Collaborated with individual in foreign country:** No
f. **Country(ies) of foreign collaborator:** N/A
g. **Travelled to foreign country:** Yes
h. **If traveled to foreign country(ies), duration of stay:** 1 week

6. **Name:** John Edlebeck
   a. **Project Role:** Test Engineer
   b. **Nearest person month worked:** 1
   c. **Contribution to Project:** Mr. Edlebeck assisted methane release tests performed during this reporting period.
   d. **Funding Support:** N/A
   e. **Collaborated with individual in foreign country:** No
   f. **Country(ies) of foreign collaborator:** N/A
   g. **Travelled to foreign country:** No
   h. **If traveled to foreign country(ies), duration of stay:** N/A

- **What other organizations have been involved as partners?** There are no other planned partner organizations besides the cost share partners.

- **Have other collaborators or contacts been involved?** Although this is planned, no other collaborators or contacts have yet been involved.

IMPACT (optional)

What is the impact of the project? How has it contributed?

Although SwRI fully expects this project to provide significant impacts that benefit the nation, development is not yet to a point where any impacts can be noted.

- **What is the impact on the development of the principal discipline(s) of the project?** Nothing to Report
- **What is the impact on other disciplines?** Nothing to Report
- **What is the impact on the development of human resources?** Nothing to Report
- **What is the impact on physical, institutional, and information resources that form infrastructure?** Nothing to Report
- **What is the impact on technology transfer?** Nothing to Report
- **What is the impact on society beyond science and technology?** Nothing to Report
- **What dollar amount of the award's budget is being spent in foreign country(ies)?** Nothing to Report

CHANGES/PROBLEMS

SwRI does not anticipate any significant changes in the project or its direction. If this should occur, SwRI is fully aware of its responsibility to provide all relevant details, and to obtain prior written approval from the Contracting Officer.

- **Changes in approach and reasons for change -** Nothing to report during this reporting period.
- **Actual or anticipated problems or delays and actions or plans to resolve them –** Algorithm development and embedded software development is underway. However, due to the complexity of the problem and the level of algorithm tuning required, there is a chance additional time might be needed to reach a good level of performance, past the dates noted below, which are documented in the PMP. We do not anticipate any cost impacts in the event a small delay happens.

Number	Task/Subtask	Deliverables	Completion Date
Pd4	2.0	Initial Leak Detection Algorithm	6/16/17
Pd5	3.0	Embedded Software Executable and Source Code	7/31/17

If delays occur related to these two tasks, we still anticipate them being completed by August/September 2017. By May 15, 2017, Maria Araujo will contact Joseph Renk III in the vent that a delay may indeed occur.

- **Changes that have a significant impact on expenditures -** Nothing to report during this reporting period.
- **Significant changes in use or care of human subjects, vertebrate animals, and/or biohazards -** Nothing to report during this reporting period.
- **Change of primary performance site location from that originally proposed -** Nothing to report during this reporting period.

SPECIAL REPORTING REQUIREMENTS

SwRI is not aware of any special reporting requirements in the award terms and conditions.

BUDGETARY INFORMATION

The cost status is provided on the next page. It identifies the baseline cost plan, actual incurred costs, and variance.

Budget Reporting Quarter	Budget Period 1								Budget Period 2							
	Q1		Q2		Q3		Q4		Q1		Q2		Q3		Q4	
	10/1-16 - 12/31/16		1/1/17 - 3/31/17		4/1/17 - 6/30/17		7/1/17 - 9/30/17		10/1-17 - 12/31/17		1/1/18 - 3/31/18		4/1/18 - 6/30/18		7/1/18 - 9/30/18	
	Q1	Cumulative Total	Q2	Cumulative Total	Q3	Cumulative Total	Q4	Cumulative Total	Q1	Cumulative Total	Q2	Cumulative Total	Q3	Cumulative Total	Q4	Cumulative Total
Budget Cost Plan																
Federal Share	$49,000	$49,000	$160,000	$209,000	$165,000	$374,000	$143,407	$517,407	$27,748	$545,155	$27,747	$572,902	$27,747	$600,649	$27,747	$628,396
Non-Federal Share	$39,345	$39,345	$39,345	$78,690	$39,345	$118,035	$39,345	$157,380	$0	$157,380	$0	$157,380	$0	$157,380	$0	$157,380
Total Planned	$88,345	$88,345	$199,345	$287,690	$204,345	$492,035	$182,752	$674,787	$27,748	$702,535	$27,747	$730,282	$27,747	$758,029	$27,747	$785,776
Actual Incurred Cost																
Federal Share	$9,846	$9,846	$91,674	$101,520												$101,520
Non-Federal Share	$2,461	$2,461	$22,918	$25,380												$25,380
Total Incurred Costs	$12,307	$12,307	$114,592	$126,900												$126,900
Variance																
Federal Share	$39,154	$39,154	$68,326	$107,480												$526,876
Non-Federal Share	$36,884	$36,884	$16,427	$53,310												$132,000
Total Variance	$76,038	$76,038	$84,753	$160,790												$658,876

The variance for Q2 is shown above. Project expenditures have been below the original plan, but SwRI expects to make up much of this variance during Q3.