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: October 30, 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, 2018

REPORTING PERIOD END DATE:

September 30, 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 additional data and continuing the development and refinement of the detection algorithm. The design and development of the embedded software was another major focus during this quarter. Finally, the design of the Smart Methane Leak Detection System (SLED) mechanical enclosure was also a focus of this quarter,

- **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 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
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	9/15/17 (revised per PMP submitted on 6/13/17)	9/15/17
1	Develop and Assemble Prototype	Testing Results	9/22/17 (revised per PMP submitted on 6/13/17)	9/22/17
2	Integrate and Test Prototype	Testing Results	4/23/18	
2	Demonstrate the System to DOE	Demonstration	8/21/18	

On June 13, 2017, a revised PMP was submitted to account for the higher level of complexity of the problem and the level of algorithm tuning required. However, there is no anticipated cost impact to the project related to these date changes nor any delay to overall project schedule.

- Revision of delivery dates and project schedule to reflect new planned dates for:
  - Initial Leak Detection Algorithm: from 6/13/17 to 9/15/17.
  - Embedded Software Executable and Source Code: from 7/31/17 to 9/22/17.
  - Develop and Assemble Prototype: from 6/13/17 to 9/22/17.

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

Controlled Tests

- SwRI continued to perform several methane release tests under realistic conditions to continue to increase the 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. This was captured on video. The test conditions included varying ambient temperature conditions, cloud cover, presence and lack of obstacles (such as piping), and varying wind (including stagnant) conditions.

Algorithm Development

- This task encompasses further development and refinement of the detection algorithm. This includes detection of the methane plume as well as rejection of false positives. The chosen algorithmic approach uses three separate steps.
  - First, preprocessing is used to make the methane more apparent in the MWIR imagery.
  - Second, the preprocessed frames are classified using a segmentation neural network.
  - Third, the output of the neural network is interpreted by a clustering algorithm that implements a clean tunable threshold for setting the sensitivity of the alarm reporting.
  - Figure 1 shows the high-level data flow of the algorithm.

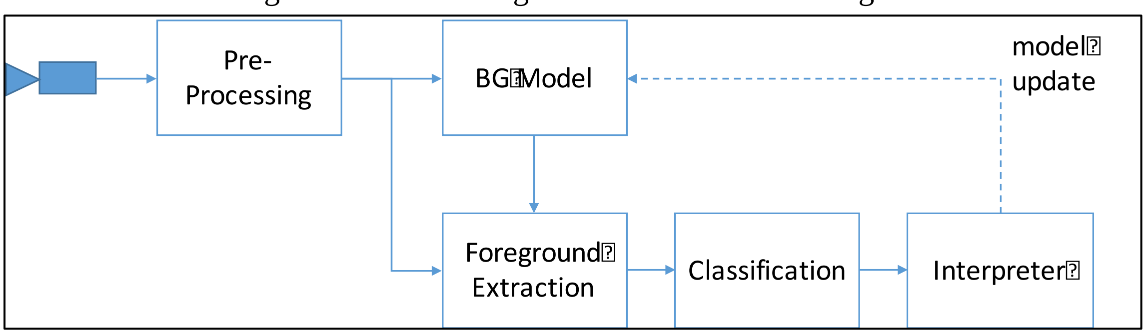

Figure 1: A Flow Chart Depicting the Data Path From Camera Acquisition to the Reporting Mechanism

- During this quarter, the following algorithm refinements were made:
  - SwRI performed further data collection in order to diversify the training sets for both methane imagery and false positives.

- Multiple new potential sources of false positives have been identified and were incorporated into the model training in order to improve rejection. These false positives include certain scales of persons (Figure 2), dust clouds (Figure 3), and other sources of gas which absorb in the MWIR spectrum (Figure 4).

Figure 2: An example of a person being falsely classified. The original training dataset included very few examples of persons. Data has been collected and added to the training set in order to mitigate this behavior.

Figure 3: A dust cloud kicked up by a passing vehicle. The algorithm tries to classify some of the less opaque areas of the dust cloud that look like a plume.

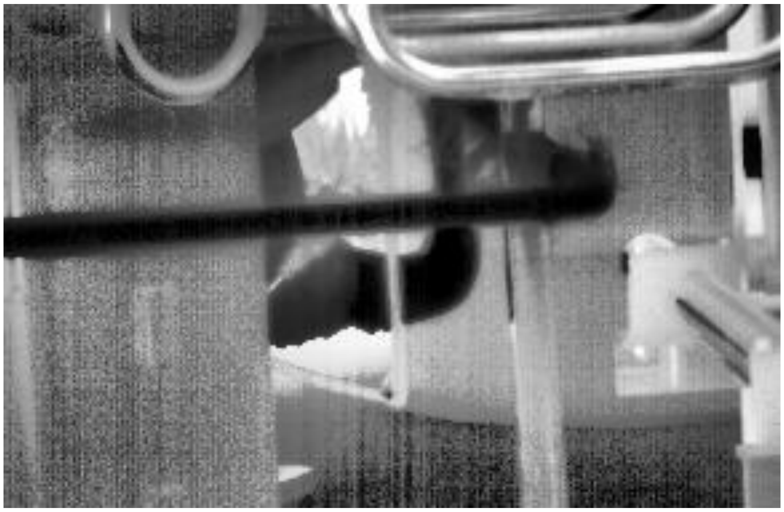

Figure 4: An example of water vapor condensing around a liquid nitrogen carrying line. The algorithm successfully rejected this as non-methane.

- Results from the classifier continue to improve with each period of performance. Figure 5 illustrates an example of new testing results. This image is from a live stream of the system performing classifications on real-time video on the Tegra board.
- In the next quarter, the algorithm will continue to undergo testing and refinement using live, field-collected data as training feedback.

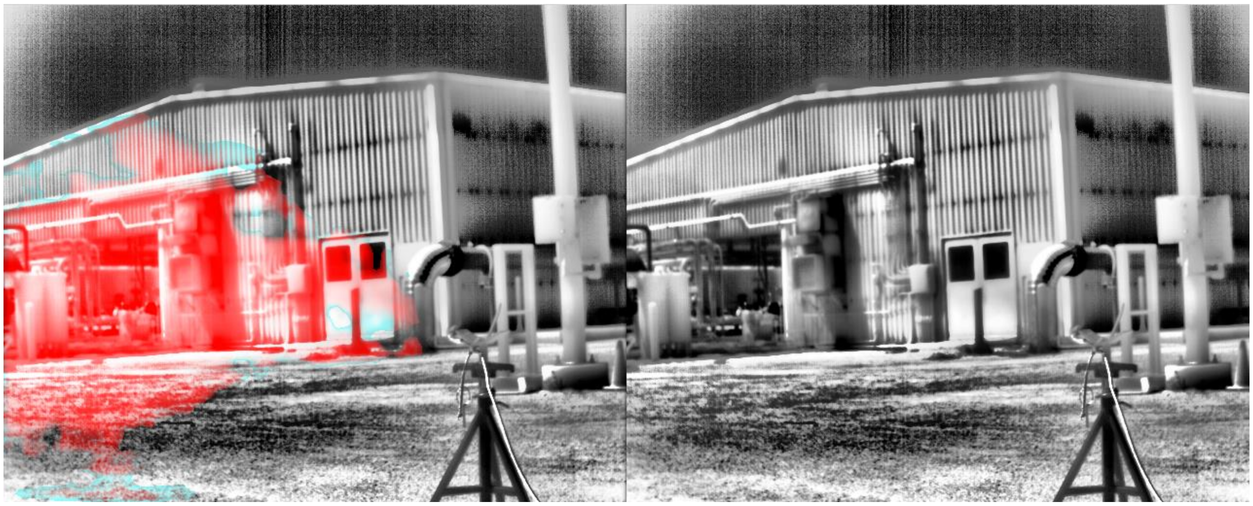

Figure 5: A live methane plume detection using the embedded SLED/M algorithm on a very noisy background.

<u>Embedded Processor Code Development</u>

- This task encompasses porting the algorithm detection to an embedded system in a deployed platform. 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, progress in the last quarter includes:
    - Completion of the integration of detection algorithm.
    - Creation of a functional software baseline (current version is v1.4, tagged as “2017_0914_1550_sled-m”).
    - Continued integration and testing of user interface software.
- As a reference, the refined system architecture is seen in Figure 6, and a set of figures showing v1.4 of the SLED/M system in deployment is shown in Figure 7 and Figure 8.

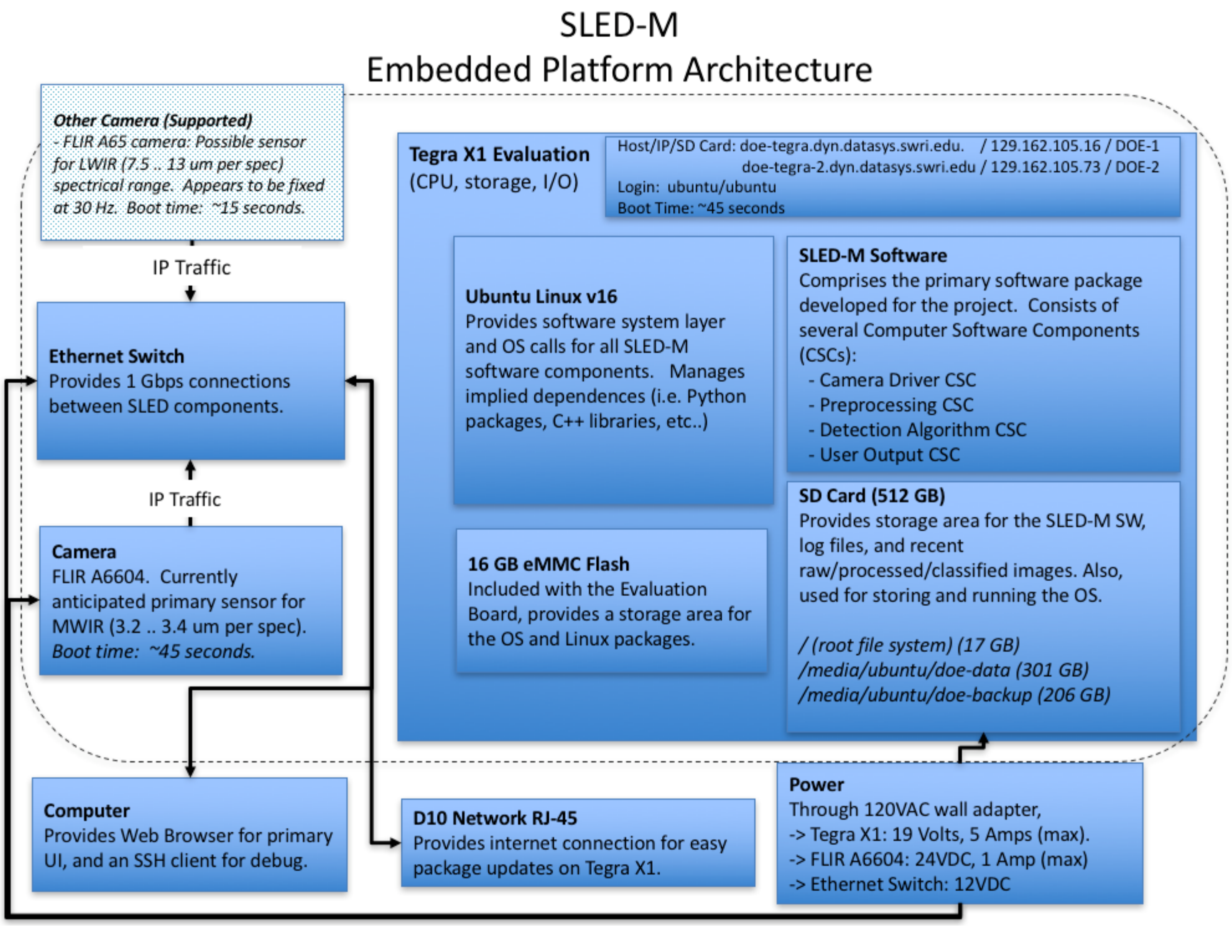

Figure 6: SLED/M Embedded Platform Architecture

Figure 7: Test Setup for 9/13/17 Methane Release against SLED-M Software v1.4

Figure 8: Methane Leak Detection against SLED-M Software v1.4

- Next steps on this task include:
  - Completion of integration and testing of user interface software, with focus on:
    - Minimizing false positives, and,
    - Updates (if any) resulting from integrated mechanical testing.

Mechanical and Electrical Design

- For this task, progress in the last quarter includes:
  - Completion of Mechanical Design. Figure 9 shows the top-level mechanical sketch for the SLED/M enclosure and internal components.
  - Procurement of mechanical components and parts.

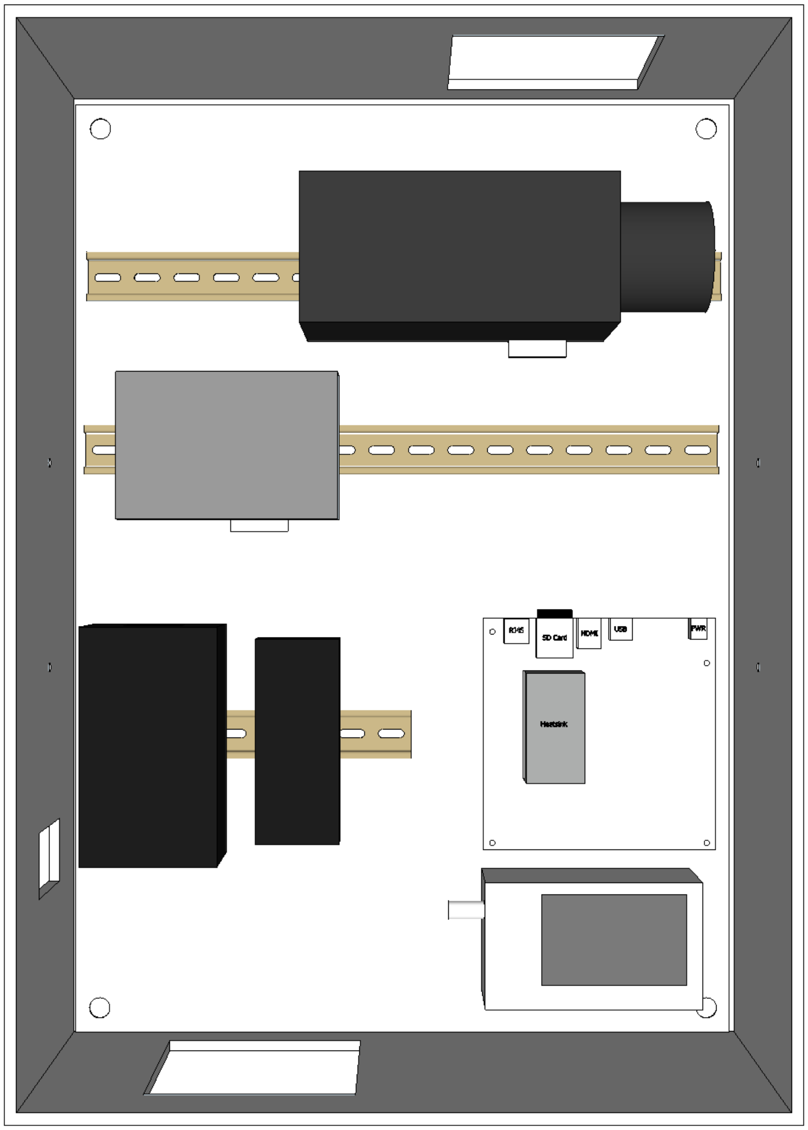

Figure 9: SLED/M System Enclosure and Mechanical Layout Sketch

- Next steps on this task include:
  - Assembly of SLED/M system.
  - Integrated testing of the SLED/M system.

- **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 presented 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."

    - Team plans on presenting at the Pipeline and Energy Expo in Tulsa, OK in April 2018 with a presentation titled "Automated Leak Detection Using Machine Learning and Multi-Platform Remote Sensing."
    - Team plans on presenting at the World Gas Conference (June 2018) and the American Gas Association Conference (June 2018). Abstracts were submitted to both conferences.
  - The team is also looking at additional conferences/venues to divulge this work.
  - Additionally, several high-level articles regarding the work being done on this project were published and aired on television. Some references are noted below:
    - https://pgjonline.com/2017/10/02/teaching-technology-solution-finds-small-pipeline-leaks/
    - https://www.talkingiotinenergy.com/single-post/2017/06/08/Machine-learning-improves-oil-and-gas-monitoring
    - https://www.asme.org/engineering-topics/articles/energy/machine-learning-applies-pipeline-leaks
    - 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
    - https://www.ksat.com/news/swri-working-on-oil-and-gas-leak-detection

- **What does SwRI plan to do during the next reporting period to accomplish the goals?**

  During the next reporting period, SwRI will:

  - Continue fine-tuning algorithm performance. This will include incorporating more training data from the collection stage, searching through the classifier's settings to find the optimal conditions, and modifying the network structure to improve the feature learning.
  - Refine the embedded processor code development.
  - Finalize building the prototype system.
  - Perform field testing.

PRODUCTS

What has the project produced?

- **Publications, conference papers, and presentations:**
  - **Journal publications -**
    - Teaching Technology: Solution Finds Small Pipeline Leaks, Pipeline and Gas Journal. October 2017, Vol. 244, No. 10.
    - Machine Learning Applies to Pipeline Leaks, American Society of Mechanical Engineers (ASME). August 2017.
    - Machine learning improves oil and gas monitoring, Talking IoT in Energy, June 2017.
  - **Books or other non-periodical, one-time publications** - Nothing to Report During This Period.
  - **Other publications, conference papers and presentations -**
    - Maria Araujo presented 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."
    - Team plans on presenting at the Pipeline and Energy Expo in Tulsa, OK in April 2018 with a presentation titled "Automated Leak Detection Using Machine Learning and Multi-Platform Remote Sensing."
    - Team plans on presenting at the World Gas Conference (June 2018) and the American Gas Association Conference (June 2018). Abstracts were submitted to both conferences.
  - **Website(s) or other Internet site(s)** –
    - https://pgjonline.com/2017/10/02/teaching-technology-solution-finds-small-pipeline-leaks/
    - https://www.talkingiotinenergy.com/single-post/2017/06/08/Machine-learning-improves-oil-and-gas-monitoring
    - https://www.asme.org/engineering-topics/articles/energy/machine-learning-applies-pipeline-leaks
    - 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
    - https://www.ksat.com/news/swri-working-on-oil-and-gas-leak-detection
- **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 reporting 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:** Daniel Davila
   a. **Project Role:** Developer
   b. **Nearest person month worked:** 3
   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
3. **Name:** Scott Miller
   a. **Project Role:** Developer
   b. **Nearest person month worked:** 2
   c. **Contribution to Project:** Mr. Miller led the embedded software 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:** Samantha Blaisdell
   a. **Project Role:** Developer
   b. **Nearest person month worked:** 2
   c. **Contribution to Project:** Ms. Blaisdell 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
5. **Name:** Christopher Jelesnianski
    a. **Project Role:** Developer
    b. **Nearest person month worked:** 2
    c. **Contribution to Project:** Mr. Jelesnianski assisted with embedded software 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
6. **Name:** Kirk Busche
    a. **Project Role:** Developer
    b. **Nearest person month worked:** 2
    c. **Contribution to Project:** Mr. Busche 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

- **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?**

  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 impacts have been realized or quantified. However, with the approval of the DOE, the team has already been engaging in conversations with oil and gas companies about how the SLED/M technology could potentially improve their efficiency and safety.

- **What is the impact on the development of the principal discipline(s) of the project?**

  The development of the SLED/M technology allows for mitigation of fugitive emissions via the early detection of methane leaks. The technology is real-time and autonomous, thus allowing for facilities to be monitored with minimal human resource involvement and, therefore, reducing the overall monitoring costs and improving the reliability of detections.

- **What is the impact on other disciplines?**

  The technology being developed in this project has a variety of applications beyond methane emissions monitoring, such as carbon monoxide monitoring; agricultural land use analysis and crop prediction; water management and soil moisture analysis; natural hazards monitoring and prediction; and ecosystem monitoring and conservation.

- **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?**

  The byproducts of this project will allow for more effective mitigation of methane emissions, which are a major greenhouse effect contributor. By reducing fugitive methane emissions, climate change impacts caused by greenhouse gas emissions are also reduced.

- **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 –**

  Nothing to report during this reporting period.

- **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	$128,947	$138,793	$151,515	$290,308	$169,138	$459,446								$459,446
Non-Federal Share	$2,461	$2,461	$32,237	$34,698	$37,879	$72,577	$42,284	$114,862								$114,862
Total Incurred Costs	$12,307	$12,307	$161,184	$173,491	$189,394	$362,886	$211,422	$574,308								$574,308
Variance																
Federal Share	$39,154	$39,154	$31,053	$70,207	$13,485	$83,692	-$25,731	$57,961								$168,950
Non-Federal Share	$36,884	$36,884	$7,108	$43,992	$1,466	$45,458	-$2,939	$42,518								$42,518
Total Variance	$76,038	$76,038	$38,161	$114,199	$14,951	$129,149	-$28,670	$100,479								$211,468

The variance for Q4 is shown above.