Acquisition Directorate
Research & Development Center

**Report No**. CG-D-07-22

# Freshwater In-situ Oil Burning Air Monitoring

Distribution Statement A: Approved for public release; distribution is unlimited.

September 2022

Homeland Security

# NOTICE

M. J. Lewandowski
Environment & Waterways Branch Chief
United States Coast Guard
Research & Development Center
1 Chelsea Street
New London, CT 06320

Technical Report Documentation Page

| | | | |
|---|---|---|---|
| **1. Report No.**<br>CG-D-07-22 | **2. Government Accession Number** | **3. Recipient's Catalog No.** | |
| **4. Title and Subtitle**<br>Freshwater In-Situ Oil Burning Air Monitoring | | **5. Report Date**<br>September 2022 | |
| | | **6. Performing Organization Code**<br>Project No. 47041 | |
| **7. Author(s)**<br>Adewale, B. S., Balsley, A., Wurl, M. A., Booker, B., Aurell, J., Gullett, B.K | | **8. Performing Report No.**<br>R&DC UDI 1903 | |
| **9. Performing Organization Name and Address**<br>U.S. Coast Guard<br>Research and Development Center<br>1 Chelsea Street<br>New London, CT 06320 | | **10. Work Unit No. (TRAIS)** | |
| | | **11. Contract or Grant No.**<br>EPA GLNPO IAA DW-070-95926401-0 | |
| **12. Sponsoring Organization Name and Address**<br>Commander (dr)<br>Ninth Coast Guard District<br>1240 E 9th Street<br>Cleveland, OH 44199-2001<br><br>U.S. Environmental Protection Agency<br>Great Lakes National Program Office<br>77 West Jackson Blvd<br>Chicago, IL 60604-3507 | | **13. Type of Report & Period Covered**<br>Final | |
| | | **14. Sponsoring Agency Code**<br>CGD NINE (dr)<br>EPA/GLNPO | |
| **15. Supplementary Notes**<br>The R&D Center's technical point of contact is Dr. Benedette Adewale, 860-271-2849, Email: Benedette.S.Adewale@uscg.mil | | | |
| **16. Abstract (MAXIMUM 200 WORDS)**<br>This report documents the background, planning, preparation for a series of in-situ burning (ISB) tests using Alaskan North Slope (ANS) crude oil in fresh water. This study assessed the use of a small, unmanned aerial system (sUAS) with gas monitoring equipment to track the chemical compositions and particulate spread of a smoke plume during an ISB event. The Special Monitoring of Applied Response Technologies (SMART) protocol methodology currently recommends downwind personnel deployment of ground-based DustTrak sensors to assess potential exposure to gases and soot from the plume. Ground-mounted terrestrial Light Detection and Ranging (LIDAR) equipment was also used to assess the density and particle size of the smoke plume during testing.<br><br>The sUAS monitoring system, SMART protocol DustTrak sensors, and LIDAR were compared to assess their efficacy for monitoring ISB smoke plumes, assessing risk, and improving the safety of responders and localized populations. The U. S. Coast Guard Research and Development Center (RDC) conducted this work with material and technical support from the U. S. Army Cold Regions Research and Engineering Lab, the U.S. Coast Guard National Strike Force and the U.S Environmental Protection Agency. The intent is to provide responders with information to consider in deciding whether ISB is a feasible action to mitigate the threat of spill in a freshwater environment. | | | |
| **17. Key Words**<br>In-situ Burning (ISB), Freshwater Oil Spill Response, Great Lakes, DustTrak, Burn Efficiency, Remote Air Monitoring, small-uncrewed aerial system (sUAS), Special Monitoring of Applied Response Technology (SMART) protocol. | **18. Distribution Statement**<br>Distribution Statement A: Approved for public release; distribution is unlimited. | | |
| **19. Security Class (This Report)**<br>UNCLAS\\Public | **20. Security Class (This Page)**<br>UNCLAS\\Public | **21. No of Pages**<br>56 | **22. Price** |

**(This page intentionally left blank.)**

## EXECUTIVE SUMMARY

In-situ burning (ISB) is an applied response technology to minimize adverse environmental effects of oil spilled on water. The overall objectives of this research are to:

1) Evaluate the suitability of remote air monitoring through a small-unmanned aircraft system (sUAS) to replace U.S. Coast Guard (USCG) downwind personnel deployment of ground-based DustTrak sensors to satisfy the SMART protocol, which monitors response technologies during an oil spill,

2) Evaluate the capability of remote sensing through high definition light detection and ranging (LIDAR) to satisfy SMART protocol and/or augment sUAS data,

3) Measure the toxicity of the smoke plume in terms of particulate and emissions concentrations, and

4) Calculate the average burn efficiency of the test-oil in fresh water and assess the relationship of efficiency to emissions.

The USCG Research and Development Center (RDC) designed a series of ISB tests and conducted eight oil burns at U.S. Army Engineer Research and Development Center (ERDC), Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, NH from October 25th to October 27th, 2021. RDC used Alaskan North Slope (ANS) crude oil for the experiments, a medium crude oil similar to the crude oils transported through fresh water- and Great Lakes regions.

Oil spilled into freshwater environments poses a significant risk to their ecosystems and must be recovered or removed quickly and effectively to minimize ecological damage and to avoid potential health risks to inhabited areas and responders. This effort measured emissions from a three-day campaign of oil burns on water at the U.S. Army Corps of Engineers CRREL. The objective of this study is to evaluate the feasibility of remote air monitoring via sUAS to and to compare sUAS monitoring with USCG downwind deployment of ground-based DustTrak sensors, which the SMART protocol currently recommends. The study also derives emission factors[1] from oil burns on fresh water and evaluates the relationship between emissions and burn efficiency. Concentration values determined from the SMART protocol measurements and co-located EPA sensors were compared to those determined in the plume by the sUAS. Lastly, the efficacy of low-cost particulate monitors was assessed for use in the SMART protocol. This report follows the work presented in “Freshwater In-situ Oil Burning” (Murphy, 2021).

---

[1] Emission factor is the ratio of the mass of particulate matter to the mass of oil burned.

**(This page intentionally left blank.)**

# TABLE OF CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

# LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS

| | |
|---|---|
| °C | Degree(s) Celsius |
| °F | Degree(s) Fahrenheit |
| µg | Microgram(s) |
| µm | Micron/micrometer |
| ANS | Alaska North Slope |
| AST | Atlantic Strike Team |
| AVE | Average |
| CEMM | Center for Environmental Measurements and Monitoring |
| CG-MER | Coast Guard Office of Marine Environmental Response Policy |
| cm | Centimeter(s) |
| CO | Carbon monoxide |
| $CO_2$ | Carbon dioxide |
| cP | Centipoise |
| CRREL | Cold Regions Research and Engineering Laboratory |
| DAS | Data Acquisition System |
| DRAT | District Response Advisory Team |
| EC | Elemental carbon |
| EF | Emission Factors |
| EPA | Environmental Protection Agency |
| ERDC | Engineer Research and Development Center |
| FAA | Federal Aviation Administration |
| FOSC | Federal On-scene Coordinator |
| ft | Feet (imperial measurement) |
| GLRI | Great Lakes Restoration Initiative |
| GRF | Geophysical Research Facility |
| GST | Gulf Strike Team |
| h | Hour(s) |
| $H_20$ | Water |
| HRR | Heat release rate |
| IAA | Interagency Agreement |
| IARC | International Agency for Research on Cancer |
| i.e. | "Id est"/in other words |
| in | Inch(es) |
| IR | Infrared |
| ISB | In-situ burning |
| kg | Kilogram(s) |
| kW | Kilowatt(s) |
| LiDAR | Light Detection and Ranging |
| LOC | Level of Concern |
| m | Meter(s) |
| $m^3$ | Cubic meter |

# LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS (Cont'd)

| | |
|---|---|
| MAX | Maximum |
| $MCE_T$ | Modified combustion efficiency |
| mg | Milligram(s) |
| min | Minute(s) |
| ml | Milliliter(s) |
| mm | Millimeter(s) |
| MIN | Minimum |
| MSD | Mass selective detector |
| MW | Megawatt |
| n | Normal (i.e., n-alkane) |
| n/a | Not applicable |
| ND | Not determined |
| NDAA | National Defense Authorization Act |
| No. | Number |
| NOAA | National Oceanic and Atmospheric Administration |
| NRC | Nuclear Regulatory Commission |
| NRL | Naval Research Laboratory |
| NRT | National Response Team |
| OC | Organic carbon |
| ORD | Office of Research and Development |
| $\rho$ | Density |
| PAHs | Polycyclic aromatic hydrocarbons |
| PCDD | Polychlorinated dibenzo-*para*-dioxin |
| PCDF | Polychlorinated dibenzofuran |
| PM | Particulate matter |
| $PM_{1.0}$ | Particulates less than one micrometer in diameter |
| $PM_{2.5}$ | Particulates less than 2.5 micrometers in diameter |
| $PM_{4.0}$ | Particulates less than four micrometers in diameter |
| $PM_{10}$ | Particulates less than ten micrometers in diameter |
| R&D | Research and development |
| RDC | Research and Development Center |
| RH | Relative humidity |
| RRT | Regional Response Team |
| s | Second(s) |
| SG | Specific gravity |
| SMART | Special Monitoring of Applied Response Technologies |
| SOP | Standard operating procedure(s) |
| SSC | Scientific Support Coordinator |
| sUAS | Small unmanned aerial system |
| T | Time |
| TC | Total carbon |

## LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS (Cont'd)

| | |
|---|---|
| TC tree | Thermocouple tree |
| TPH | Total petroleum hydrocarbons |
| USACE | United States Army Corp of Engineers |
| USCG | U.S. Coast Guard |
| VOC | Volatile organic compound(s) |

# 1 INTRODUCTION

In-situ burning (ISB) is a response technology used to minimize the adverse environmental effects of oil spilled on water. It constitutes controlled burning at the spill site for rapid removal of oil from the surface of water (NOAA, 2019). ISB is already a generally accepted option for offshore oil spill response, but Great Lakes stakeholders are uncertain about the potential effect of smoke plumes on public health since most nearshore population centers could potentially be exposed. There is also limited data about emissions from these burns, which adds to the uncertainty.

As domestic production of crude oil in the United States and Canada increases, the Great Lakes Region has experienced an increase in oil transportation by pipeline, rails, and vessels (Great Lakes Commission 2018). This has drawn recent attention to the potential threat of a substantial oil spill and the environmental, economic, and public health risk this poses. Regional decision-makers need access to unbiased information to properly weigh the risks against the rewards of large-scale transportation of crude oil in this region. Performing mesoscale ISB experiments in fresh water will provide the information needed by stakeholders to consider the safety and efficacy of ISB as a spill response approach in the Great Lakes region.

In the early phase of this project, the USCG Research and Development Center (RDC) project team consulted with USCG District Nine (D9) representatives and the National Oceanic and Atmospheric Administration (NOAA) Great Lakes Scientific Support Coordinator (SSC) to better understand Great Lakes region research priorities for ISB response technologies and techniques. The measurement of air quality dynamics through remote air monitoring was identified by the team as research priority. The Special Monitoring of Applied Response Technologies (SMART) protocol currently recommends downwind deployment of ground-based DustTrak sensors to assess potential exposure to gases and soot from the plume. These sensors are stationary and typically set up at ground level whenever an ISB is planned. This limits their ability to monitor the air pollution generated from the event.

In response to this identified need, RDC partnered with the Environmental Protection Agency (EPA) Office of Research and Development (ORD) and the United States Army Corp of Engineers (USACE) Engineering Research and Development Center's (ERDC) Cold Regions Research and Engineering Laboratory (CRREL) to carry out ISB tests with synoptic measurements to characterize freshwater ISB plumes. RDC also coordinated with the National Strike Force (NSF) to use their ground-based monitoring equipment while EPA would use a gas monitoring system mounted on a small, unmanned aircraft system (sUAS) to characterize the smoke plume during each ISB test.

CRREL provided a Light Detection and Ranging (LiDAR) device to assess the potential for monitoring particle density and size distribution in the ISB plume. This data would be compared to that of EPA's sensor suite and USCG NSF's DustTrak sensors. The goal of the project was to determine each technology's feasibility and better understand how they can work individually or in concert to assess the risks associated with ISB plumes. The verification of these systems will aid first responders in oil spill cleanup efforts in freshwater environments and provide information for concerned stakeholders in the Great Lakes region. In addition to the principal goal, other test objectives of the project included:

1. Determine the burn behavior, including ignitability, burn rate, and burn efficiency, of medium to heavy oil spilled in fresh water.
2. Quantify emissions from freshwater, in-situ oil burns using a sUAS.

3. Compare emissions quantity to the combustion efficiency.
4. Compare sUAS-based aerial measurements with SMART measurements.
5. Compare SMART measurements with other low-cost particulate matter sensor measurements.
6. Provide information for decision makers related to near shore, freshwater environment (e.g., Great Lakes).

RDC designed a series of ISB tests to analyze these criteria. This report includes a discussion of the procedures followed in these tests, the results from the test data, findings, and conclusions regarding smoke plume air monitoring analysis during freshwater ISB research.

# 2 BACKGROUND

Oil spills can occur in any environment and leave devastating ecological impacts. Response and recovery technologies have been extensively studied for both marine and freshwater environments to determine the most effective methods for spill response. In-situ burning (ISB) of spilled crude oil is an effective response technique that attempts to rapidly aerosolize a large portion of the oil to reduce the potentially harsh effects on marine and freshwater ecosystems (National Oceanic and Atmospheric Administration 2019). Aerosolizing the lighter molecular weight portion of the oil, such as the polycyclic aromatic hydrocarbons (PAHs), reduces its toxicity to humans and wildlife that may contact the oil. However, smoke plumes that ISBs create pose concerns about potential negative impact on public health.

ISB has been extensively researched for marine environments; however, there have been few studies that investigate their impact in freshwater systems. Freshwater systems often contain a rich diversity of aquatic and semi-aquatic species in close proximity to one another making rapid recovery and removal of any spilled oil critical to reducing detrimental ecological impact. ISB is a promising oil removal method for these systems given their rapid reduction in oil volume. Freshwater systems are often close to densely populated areas, therefore the response community needs to determine the full range of potential health risks of this response option.

The SMART protocol is a collaborative document that establishes a monitoring system for rapid collection and reporting of real-time, scientifically based information, in order to assist the Unified Command with decision-making during in-situ burning or dispersant operations (USCG, 2006). It is a living document that is continuously adapted to include changing technologies and operational improvements (USCG, 2006; Parscal, et al., 2014). As the frequency of hazardous events increases and a variety of environments are impacted, the SMART protocol needs to be continuously assessed and improved to ensure that it can aid first responders in every situation and is up to date following the latest technologies (USCG, 2014).

Current methods of measuring potential exposure risk from ISB require placing a limited number of downwind samplers in the estimated direction of the smoke plume. This method is documented in the SMART protocol and is used by emergency responders including the USCG NSF. The protocol also requires potential personnel exposure to the plume during placement and monitoring of the sensors. Use of sUAS may improve plume tracking when wind direction changes and ensure that important data is collected and analyzed. Another challenge that responders face is the minimal number of instruments available for monitoring due to their relatively high cost. The current availability of low cost sensors that can be deployed in an array shows promise for better area coverage provided larger numbers of sensors can be used for a lower cost.

# 3 EXPERIMENT EXECUTION AND EMISSION MEASUREMENTS RESULTS

## 3.1 Experimental Methods

### 3.1.1 Facility and Experimental Setup

This study was executed on CRREL's campus in Hanover, NH. The testing facility was CRREL's Geophysical Research Facility (GRF), an 18.3 m x 7.6 m x 2.1 m basin filled with fresh water (Figure 1). Testing was conducted from October 25th to October 27th, 2021. The fuel used in these experiments was Alaskan North Slope (ANS) crude oil, a medium crude oil, which is similar to the crude oils transported through the Great Lakes region. For each ISB, a 4 cm oil slick was created in a 1.5 m x 1.0 m burn pan made of 15 cm iron flat stock placed on a frame that held the burn pan at the water surface (Figure 2). The oil was added using a spill plate to reduce its velocity when entering the water and the potential for oil to slip under the edge of the burn pan and into the surrounding water.

Figure 1. USACE-ERDC Cold Regions Research and Engineering Laboratory, Geophysical Research Facility (GRF).

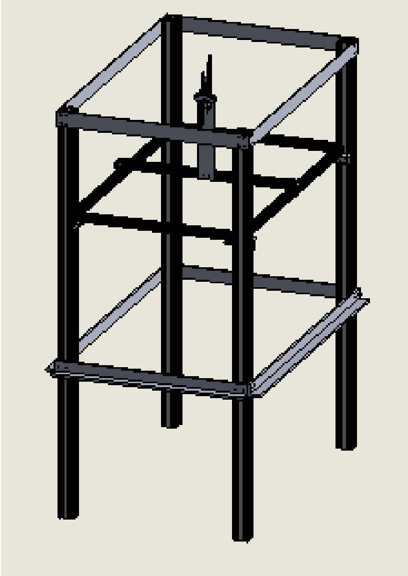


Figure 2. ISB burn pan with dimensions. A thermocouple tree is found in the center of the burn pan.

### 3.1.2 Burn Pan Instrumentation

The project team collected all relevant meteorological data from the CRREL weather station. These data were monitored and recorded using a Campbell Scientific Automatic Weather Station. The project team used nine “K-type” thermocouples (TCs) to measure flame, oil, and water temperatures at varying heights (Figure 3). The TCs were constructed with Omega type K fiberglass insulated thermocouples (Omega Scientific, Tarzana, California), encased in high-temperature ceramic tubes (McMaster Carr, Elmhurst, Illinois) to reduce fire damage with ~1 cm tip exposed and fused using a fine-wire welder.

#### 3.1.2.1 *Thermocouple Tree (TC)*

Figure 3. Thermocouple tree in the burn pan before ISB testing.

One TC "tree" held nine TCs in the center of the burn pan (Figure 3). The TCs were placed at 4 cm below the water surface, at the oil-water interface, 2 cm above the oil-water interface, 4 cm above the oil-water interface, 6 cm above the oil-water interface, 8 cm above the oil-water interface, 10 cm above the oil-water interface, and at 15 cm above the oil-water interface (Figure 4). The TC tree measured the temperature profiles of the flame, oil-layer, and water-sublayer. CRREL team fabricated the TC tree using a custom slotted clamp to allow for fine adjustment of the TCs once mounted.

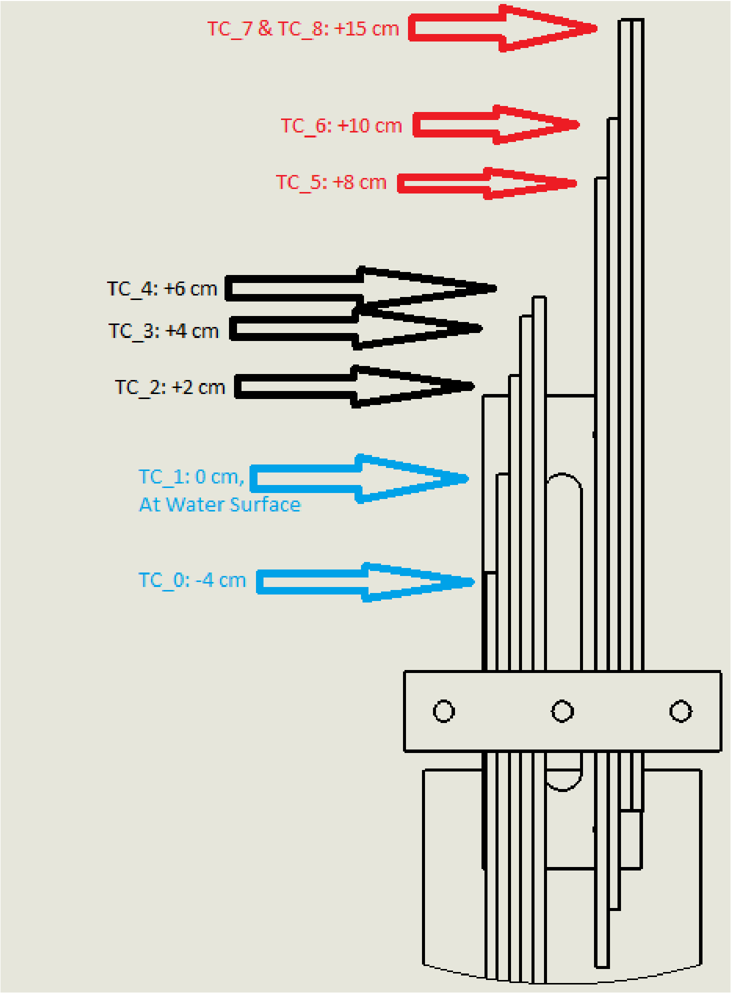


Figure 4. Thermocouple tree showing underwater TCs (blue), TCs expected to be in the oil slick (black), and TC located in the ISB (red).

### 3.1.3 Air Monitoring Sensors

The experiment used sensors to determine plume chemistry and plume particulates. Particulate Matter (PM) and gases (CO, $CO_2$) are of concern in a smoke plume during an ISB. It is important to measure these smoke emissions when discharged into the atmosphere. PM measure ranges from 1 to 10µm. The most crucial of all the PMs is $PM_{2.5}$ (and smaller), due to the ability to enter the lungs, damage the function of the lungs, and cause respiratory problems (WHO). Figure 5 shows locations of air-monitoring sensors for the experiment.

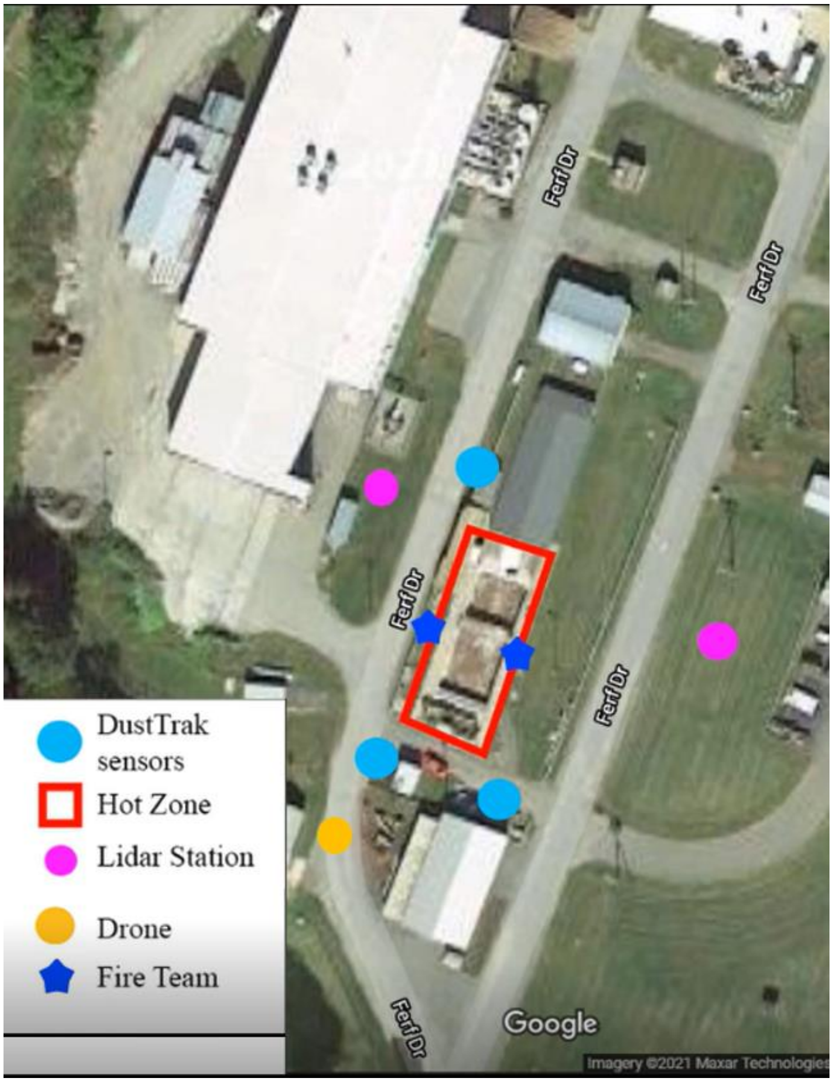


Figure 5. Locations of the emission monitoring instruments.

#### 3.1.3.1 *Kolibri Sampling Package*

The experiment used EPA ORD's small, lightweight "Kolibri" aerial emission sampling package. Kolibri has three configurations, primarily relating to the different sizes of the pumps needed for specific analytes. For this study, the Kolibri was configured to sample carbon monoxide (CO), carbon dioxide (CO$_2$), total hydrocarbons (THC), volatile organic compounds (VOC), relative humidity (RH), and particulates less than 2.5 micrometers in diameter (PM$_{2.5}$)(batch and continuous). Table 1 describes the three sampling package components and total weight.

The Kolibri's data acquisition system (DAS) consists of an onboard Teensy USB-based microcontroller board running an Arduino-based data acquisition and control program called "TeensyDAQ". The main assignment for the TeensyDAQ is power regulation, data logging, and data transmission. The power control circuit on the Teensy board provides a regulated voltage for all the electrical components in the sensor package. Also included in the DAS is a ground-based computer which is running "KolibriDAQ", a Labview generated data acquisition and control program, which is used to view live data and run/control the onboard TeensyDAQ via a XBee wireless network (Xbee S1B, Digi International, Inc., Minnetonka, MN, USA).

KolibriDAQ is capable of plotting real-time $CO_2$ and CO data, display sampling time, and VOC sampling volume. Table 2 shows a summary of the parameters measured in this study, sampling methods, and instrumentation used in this study.

Table 1. Sampling platform and designated sampling package (EPA QAPP 2021).

| Sampling Package | Component | Weight (gram) |
|---|---|---|
| Kolibri: Forseti | $CO_2$, CO, $PM_{2.5}$, VOC, RH, Temperature, SidePak | 3648g total weight, 2988 g no SidePak, |
| Kolibri: Alvis | $CO_2$, CO, $PM_{2.5}$, Temperature | 2392g total weight |
| Kolibri: Balder | $CO_2$, CO, THC, 4x$PM_{2.5}$, RH, Temperature, SidePak | 4088 g total weight, 3376 g no SidePak |

Table 2. Measured parameters, sampling instruments, methods, and flow/sampling rates (EPA QAPP 2021).

| Measured Parameter | Instrument/Equipment | Method | Flow Rate/ Sampling Rate |
|---|---|---|---|
| $CO_2$ | $CO_2$ Engine® K30 | Non-dispersive infrared | 0.5-1.0 L/min, 1 Hz |
| CO | EC4-500-CO | Electrochemical cell | 0.5 L/min, 1 Hz |
| THC | MiniPID2 | Electrochemical cell | 0.5 L/min, 1 Hz |
| VOC | CarboTrap 300 | Thermal desorption | 200 mL/min, Batch |
| $PM_{2.5}$ | SKC Personal Modular Impactor (PMI) | 37 mm Teflon filter/ gravimetric | 3 L/min, Batch |
| $PM_{2.5}$ | SKC Personal Environmental Monitor (PEM) Impactor | 37 mm Teflon filter/ gravimetric | 10 L/min, Batch |
| $PM_{2.5}$ | PurpleAir | Optical light scattering | 100 mL/min, 5 sec reporting rate, of a 120sec average |
| TC/OC/EC | SKC Personal Modular Impactor (PMI) | Quartz filter/thermal-optical analyses | 3 L/min, Batch |
| PM by size | SidePak™ AM520 | 90° Light scattering | 1.5 L/min, 1 Hz |
| PM by size | DustTrak DRX 8534, 8533 | 90° Light scattering | 3 L/min, 1 Hz |

The aerial sampling was conducted using a sUAS operated at a height of less than 400 feet above ground level. The sUAS, a Freefly Alta X 4-rotor quadcopter (Figure 6) has a weight of 10.4 kg and a maximum payload of 15.9 kg. The maximum flight time with payload is 25 minutes. The sUAS is radio controlled using a 5.8GHz controller. By monitoring the real-time $CO_2$ and CO readings from the sUAS sensor package, the pilot could keep the sUAS directly in the plume.

Figure 6. sUAS Freefly Alta X and Kolibri sampling equipment.

#### 3.1.3.2 *SidePak*

This instrument measures light scattering by aerosols as they intercept a laser diode and has the capability of real-time measurements every second of $PM_1$, $PM_{2.5}$, $PM_4$, $PM_{10}$ or total PM. In this study, EPA used the SidePak$^{TM}$ AM250, (TSI, Shoreview, MN, USA) (Figure 7) to sample continuous $PM_{2.5}$. EPA configured the instrument with a $PM_{2.5}$ inlet to measure $PM_{2.5}$. The sampling flow rate is user adjustable and set to 1.5 L/min.

#### 3.1.3.3 *DustTrak*

This instrument measures light scattering by aerosols as they intercept a laser diode and has the capability of simultaneous real-time measurements (every second) of $PM_1$, $PM_{2.5}$, $PM_4$, $PM_{10}$ or total PM. The DustTrak DRX 8534 and 8533 (TSI, Shoreview, MN, USA) is an alternative to the SidePak. The aerosol concentration range for the DustTrak DRX 8534/8533 is 0.001-150 mg/$m^3$ with a resolution of ± 0.1% reading. The USCG National Strike Force (NSF) used the DustTrak/AreaRae equipment to record ground-based air quality data.

#### 3.1.3.4 *PurpleAir*

This instrument is a sensor reporting continuous concentrations of $PM_1$, $PM_{2.5}$, $PM_{10}$ in µg/$m^3$. The sensor is equipped with PMS5003 and PMS1003 laser particle counters counting suspended particles in the sizes 0.3, 1.0, 2.5, 5.0 and 10µm. The PurpleAir is able to report its data to an online platform continuously every 2 minutes (this feature was not functional during this study).

Ground-based sampling instruments were collocated. (Figure 7).

Figure 7. SMART protocol’s DustTrak DRX 8533EP (mounted on tripod) and EPA’s SidePak,(orange square) and PurpleAir (yellow square).

#### 3.1.3.5 *Light Detection and Ranging (LiDAR):*

This instrument uses fast pulses of laser light to measure distances from the sensor to an object. It can measure an entire plume as opposed to point measurements that are susceptible to changing precipitation of particulate matter and gas concentrations with variable wind and other atmospheric conditions. In a real world response, LiDAR could evaluate safe distancing from a smoke plume. In this study, the smoke plume was monitored using a tripod mounted Riegl VZ 400i and VZ-2000i Terrestrial Laser Scanner (Figure 8) LiDAR system.

Figure 8. Tripod mounted Riegl VZ 400i and VZ-2000i Terrestrial Laser Scanner.

### 3.1.4 Experimental Matrix

The RDC, CRREL and EPA project team conducted eight replicate burns. All burns were sampled for emissions. Table 3 describes the detail of the experimental matrix.

Table 3. Test burn matrix including initial oil slick thickness and mean meteorological conditions during the test.

| Test # | Date | Initial Oil Slick Thickness (cm) | Weather | | |
|---|---|---|---|---|---|
| | | | Wind Speed (m/s) | Direction (From – To) | Rain (mm) |
| 1 | 10/25/21 | 4.17 | 0.384 | NW – SE | 0 |
| 2 | 10/26/21 | 4.28 | 0.864 | SW – NE | |
| 3 | 10/27/21 | 4.16 | 2.583 | SW – NE | 1.811 |
| 4 | 10/27/21 | 4.15 | 2.705 | SW – NE | 1.783 |
| 5 | 10/27/21 | 4.15 | 1.617 | NW – SE | 0 |
| 6 | 10/27/21 | 4.15 | 2.809 | NW – SE | |
| 7 | 10/27/21 | 4.15 | 3.044 | SW – NE | |
| 8 | 10/27/21 | 4.15 | 0.530 | NE – SW | |

The first set of experiments, burns # 1-4, were conducted with drone data collection downwind from the smoke plume. The second set of experiments, burns # 5-8, were conducted with drone data collection in the center of the smoke plume. The initial mass of oil added to the containment area and residue recovered after the ISB were measured to calculate burn removal efficiency. The burns were manually timed to determine the burn rate. Table 4 shows the physical characteristics of the ANS crude oil used in the test. Appendix A contains specification sheets for the oil.

Table 4. Test oil physical properties.

| Test Oil | Density (ρ) at 15ºC (kg/m$^3$) | API Gravity at 15.5ºC (ºC) | Viscosity (cP) | Flash Point (°C) | Pour Point (°C) |
|---|---|---|---|---|---|
| Alaska North Slope (ANS) Crude Oil | 817.1 | 41.6 | 93.48 | <40 | <-30 |

### 3.1.5 Burn time, Burn Efficiency, and Burn Rate

The average burn duration was 15.6 minutes, and the average burn rate was 2.67 mm/min. To determine residual oil mass (unconsumed oil), the team used pre-weighed sorbent pads.

#### 3.1.5.1 *Burn time*

Each ISB was recorded with a video camera to determine when the fire (1) was started with a propane torch (Figure 9), (2) fully engulfed the oil in the burn pan, and (3) extinguished. Burn times were used to calculate the burn rate using the initial slick thickness and assuming a very thin slick remained after the ISB extinguished itself. For each ISB test, enough oil was added to create a 4 cm oil slick, this provided an approximate 15 minute burn time to allow for burn conditions replicative of field response efforts.

Figure 9. Propane torch ignition of ANS, ~4 cm thickness for all the test burns.

#### 3.1.5.2 *Burn Efficiency and Burn rate*

Burn efficiency is the percent of oil removed from the water surface during burning. Each ISB test had a burn efficiency above 90% with an average burn efficiency of 93±1.7% (Table 5 ). This is expected for fresh ANS which is classified as a medium-grade oil. The mean burn rate was ~2.70±0.78 % mm/min (Table 6).

The mass of ANS added to the burn pan was recorded before each test. After each burn, oil residues were recovered using oleophilic pads. Oil residues collected from inside and outside the pan were recorded separately to determine the amount of oil that splashed out of the burn pan during the ISB. Oil absorbents were placed in an enclosed space with a dehumidifier for 7 days to remove any excess water. Once the pads were dry, the oil residue mass was measured. This data was compared to the mass of initial oil for the ISB to calculate the burn efficiency for each burn test.

Researchers calculated the burn rate and burn efficiency for all tests using Equations 1 and 2.

Equation 1. *Burn rate*

Burn rate is the regression of slick thickness over time:

$$Burn\ Rate\ (mm/min) = \frac{Oil\ Slick\ Thickness}{Burn\ Time}$$

Equation 2. *Burn efficiency*

Burn efficiency is the ratio of the mass of oil burned to the initial oil mass:

$$Burn\ Efficiency\ (\%) = \left[\frac{Inital\ Oil\ Mass - Residue\ Mass}{Initial\ Oil\ Mass}\right] \times 100$$

Table 5. Mass in and out for each ISB test and the burn efficiency.

| Test # | Initial Mass Oil (Kg) | Residue Mass (Kg) | | Burn Efficiency (%) |
|---|---|---|---|---|
| | | Inside the Pan | Outside the Pan | |
| 1 | 50.87 | 1.29 | 1.03 | 95.4 |
| 2 | 52.19 | 2.06 | 3.77 | 88.8 |
| 3 | 50.61 | 1.02 | 3.26 | 91.5 |
| 4 | 50.55 | 2.44 | 2.08 | 91.1 |
| 5 | 50.48 | 2.36 | 1.63 | 92.1 |
| 6 | 50.58 | 1.25 | 1.33 | 94.9 |
| 7 | 50.59 | 1.77 | 1.76 | 93.0 |
| 8 | 54.16 | 1.60 | 2.14 | 93.1 |

Table 6. The initial slick thickness, burn time, and burn rate for each ISB test.

| Test # | Oil Slick Thickness (mm) | Burn Time (minutes) | Burn Rate (mm/min) |
|---|---|---|---|
| 1 | 41.7 | 16.0 | 2.61 |
| 2 | 42.8 | 16.0 | 2.68 |
| 3 | 41.6 | 16.1 | 2.60 |
| 4 | 41.5 | 15.5 | 2.76 |
| 5 | 41.5 | 15.3 | 2.59 |
| 6 | 41.5 | 15.4 | 2.59 |
| 7 | 41.5 | 15.0 | 2.77 |
| 8 | 41.5 | 15.0 | 2.77 |

#### 3.1.5.3 *ISB Temperature and Heat Flux*

Each ISB followed a similar temperature profile of climbing to the maximum temperature, maintaining a steady-state, then reducing significantly as it extinguished. The steady-state of an ISB occurs when there is sufficient oxygen and fuel to grow and reach fully engulfed state. At this time, there will be an abundance of heat generated at the oil-air interface and it will rise rapidly. **When all thermocouples located at or above the oil-air interface show increasing temperature moving higher up the tree, the ISB is considered to be at a steady-state.** Temperature profiles for the steady-state of ISB tests are represented as temperature averaged over 60-sec intervals for each TC. Results for ISB tests 1 and 2 are displayed in (Figure 10 and Figure 11). The temperature profile data for burn tests 3-8 are found in Appendix B. Assessing the rate at which the burn reached and maintained steady-state allows for a comparison with the gas monitoring and LiDAR systems to understand when the ISB is expected to reach its highest combustion efficiency.

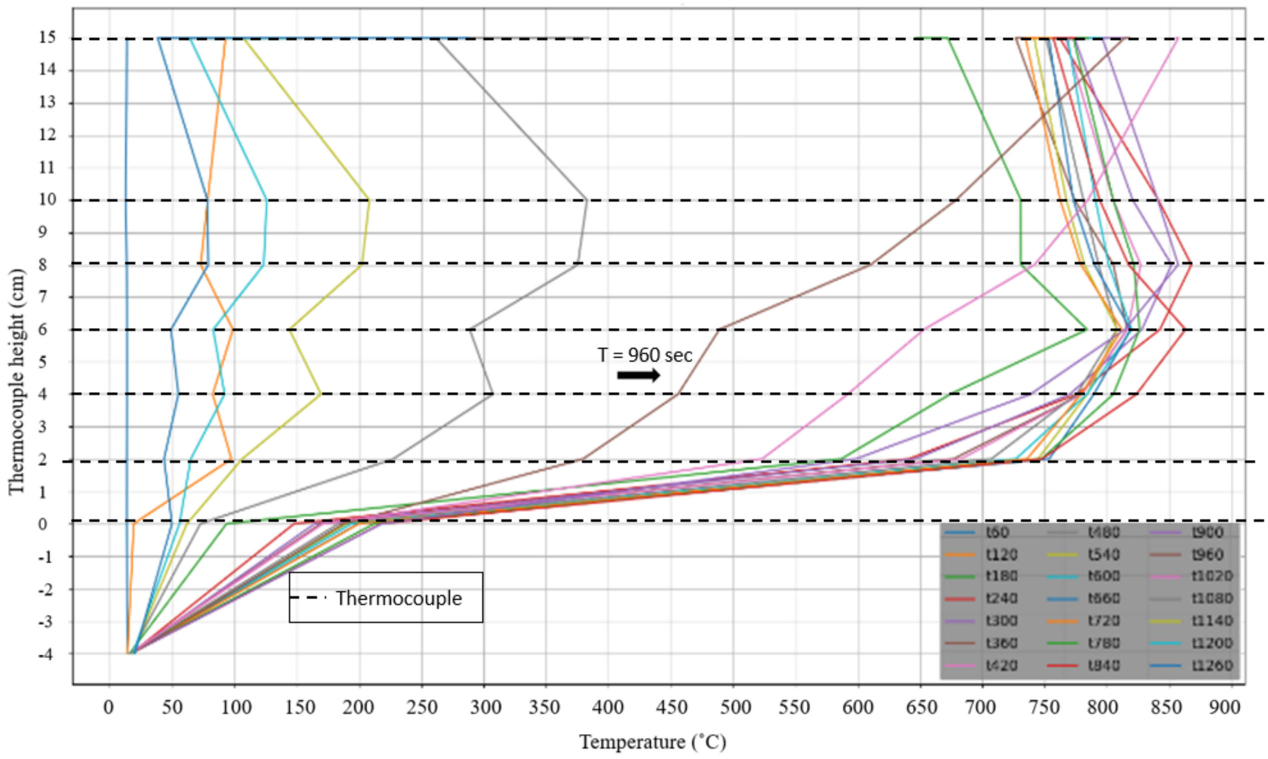


Figure 10. Steady-state data from the thermocouple tree from ISB Test 1.

The plots display the thermocouple temperature (x-axis) as a function of its location in the tree (y-axis). Each colored line represents a 60 sec block of time and the arrow indicates the time-line when the ISB is at a steady state.

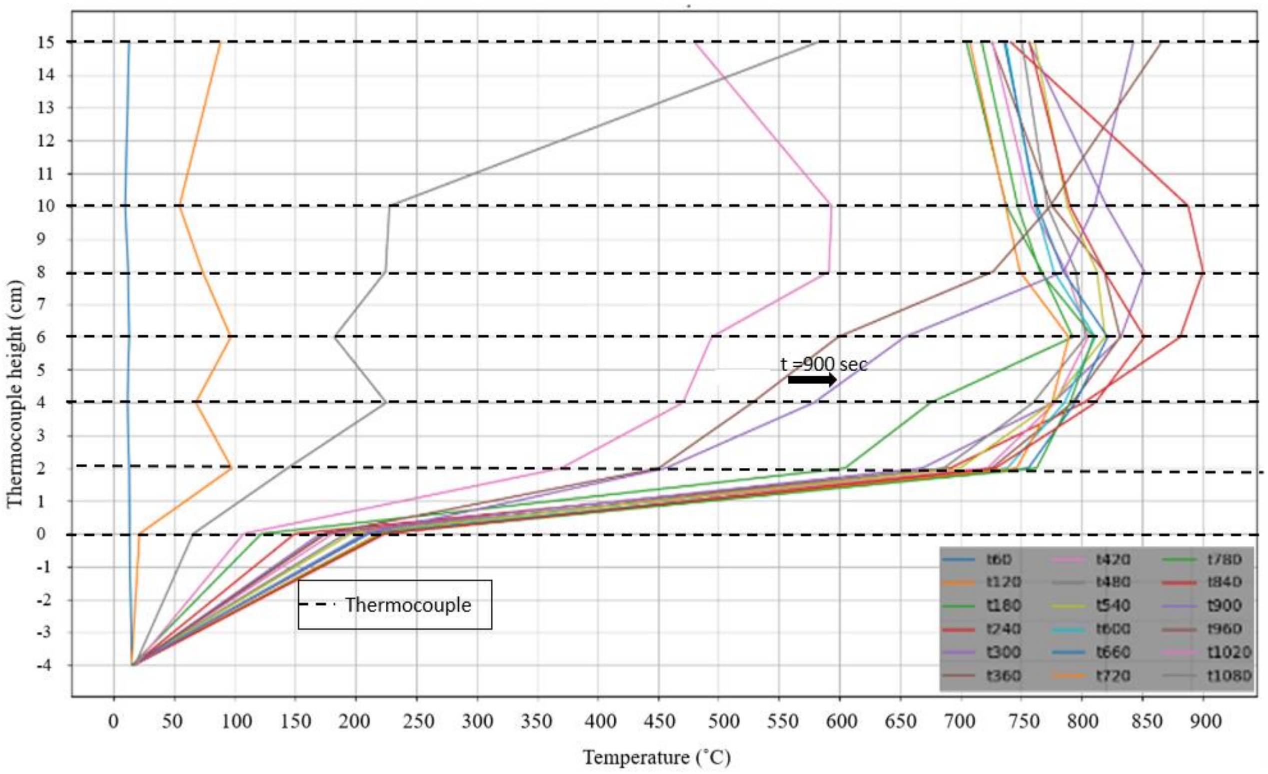


Figure 11. Steady-state data from the thermocouple tree from ISB Test 2.

### 3.1.6 Burn Test Summary

For this study, eight replicate ISB tests were conducted to accommodate synoptic sampling for the USCG NSF ground gas monitoring system, the EPA's gas monitoring system, and CRREL terrestrial LiDAR scanning. The mean slick thickness across each burn was 4.1 cm, which provided a mean burn time of 15.6 min and a mean burn rate of 2.65 mm/min. The mean burn efficiency of ANS crude oil was about 93%. This is very high burn efficiency, which can be attributed to the chemical properties of ANS and the calm environmental conditions for each burn (e.g., no wave action or heavy rain). Each ISB test reached steady state at approximately 13-15 minutes where combustion efficiency is expected to be the highest during this time.

## 3.2 Emission Measurements: sUAS Air Monitoring

Ground observers were stationed in the specific locations and orthogonal to the sUAS pilot station. The ground observers monitored and directed the pilot via radio on how to position the sUAS to ensure both safe operating position and effective flight position for data gathering in the outskirts of the smoke plume. A ground observer monitored carbon monoxide and temperature data transmitted in real-time via telemetry from the sUAS mounted sensor package to ensure safe and effective positioning. Remote sUAS monitoring pilots remained in constant radio communication with the ground-based lookout and the aerial imagery pilot.

### 3.2.1 sUAS Air Monitoring Execution and Test Results

Aerial measurements were conducted with the EPA's Kolibri, which provided time- resolved CO, $CO_2$, and Particulate Matter 2.5 ($PM_{2.5}$) as well as batch measurements of Organic Carbon/Elemental Carbon/Total Carbon (OC/EC/TC) and $PM_{2.5}$.

CO and $CO_2$ emission factors (Table 7, Figure 12) as a function of the total modified combustion efficiency, ($MCE_{t)}$.are based on both gas phase and solid phase carbon measurements, and the latter derived from analysis of the captured particles' carbon content.

Table 7. CO, $CO_2$, and $MCE_t$ values for the seven burns.

| | $CO_2$ (g/kg fuel) | CO (g/kg fuel) | MCEt Fraction |
|---|---|---|---|
| Average | 3044 | 47 | 0.88 |
| Standard Deviation | 18 | 11 | 0.031 |
| Relative Standard Deviation | 0.58% | 24.30% | 3.55% |

The typical trend exhibited is that the CO emission factor decreases as $MCE_t$ improves (gets higher) and the opposite is observed for $CO_2$. $CO_2$ emission factor increases as the burn gets a higher MCEt. While the burns were replicates, MCEt ranged 9% lower than when compared to similar burn conditions (Murphy et al., 2021)

In Figure 12, there are more data points than burns, as some burns had two filter samples.

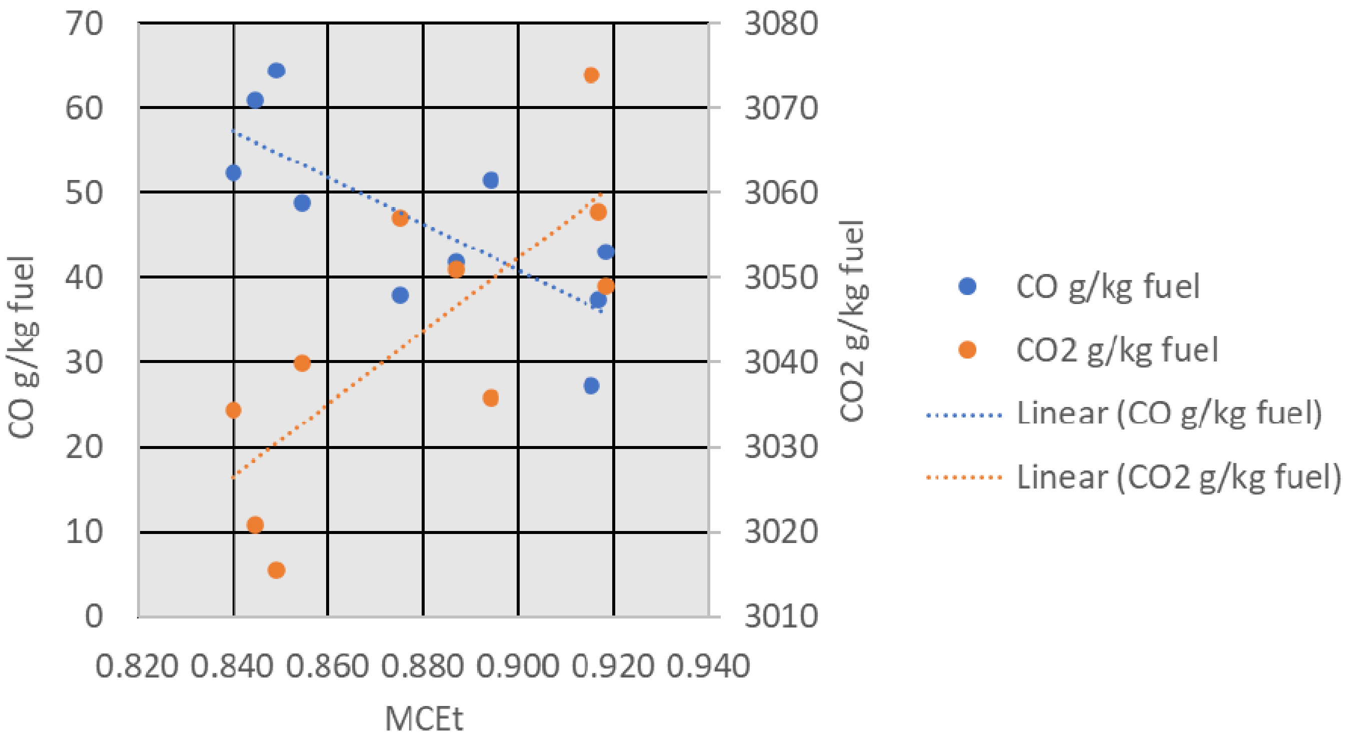


Figure 12. CO and $CO_2$ emission factors compared to the MCEt.

The $PM_{2.5}$ emission factors (Table 8, Figure 13) decrease with increasing combustion efficiency, MCEt. As with the $CO/CO_2$ measurements, some burns had more than one $PM_{2.5}$ filter collected, resulting in more data points than the number of ISBs. The data indicate a three-fold range of $PM_{2.5}$ emission factors despite similar oil burn conditions.

Table 8. $PM_{2.5}$ emission factors and $MCE_t$ values.

| | EF $PM_{2.5}$ (g/kg oil) | MCEt Fraction |
|---|---|---|
| Average | 154 | 0.88 |
| Standard Deviation | 70 | 0.031 |
| Relative Standard Deviation | 45.63% | 3.55% |

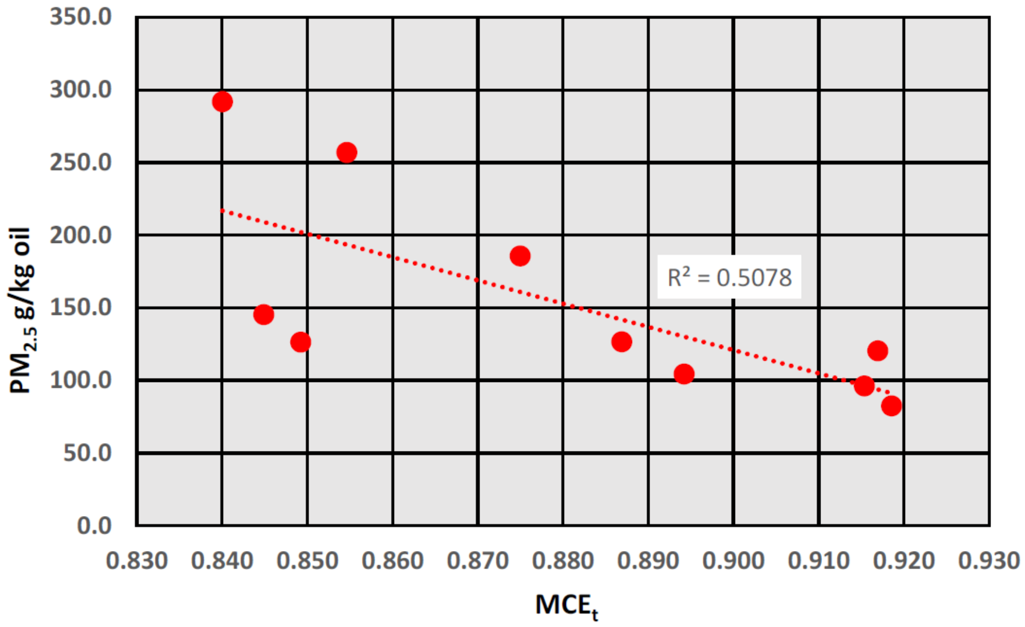


Figure 13. A comparison of the PM2.5 emission factors (EF) as a function of MCEt.

Figure 14 shows $PM_{2.5}$ emission factors as a function of total modified combustion efficiency in terms of near source and far source sUAS/Kolibri measurements. Downwind sUAS transects of the plume returned similar emission factors as those sUAS flights in the thick part of the plume indicating that emission factors are spatially consistent no matter where the measurement is made in the plume.

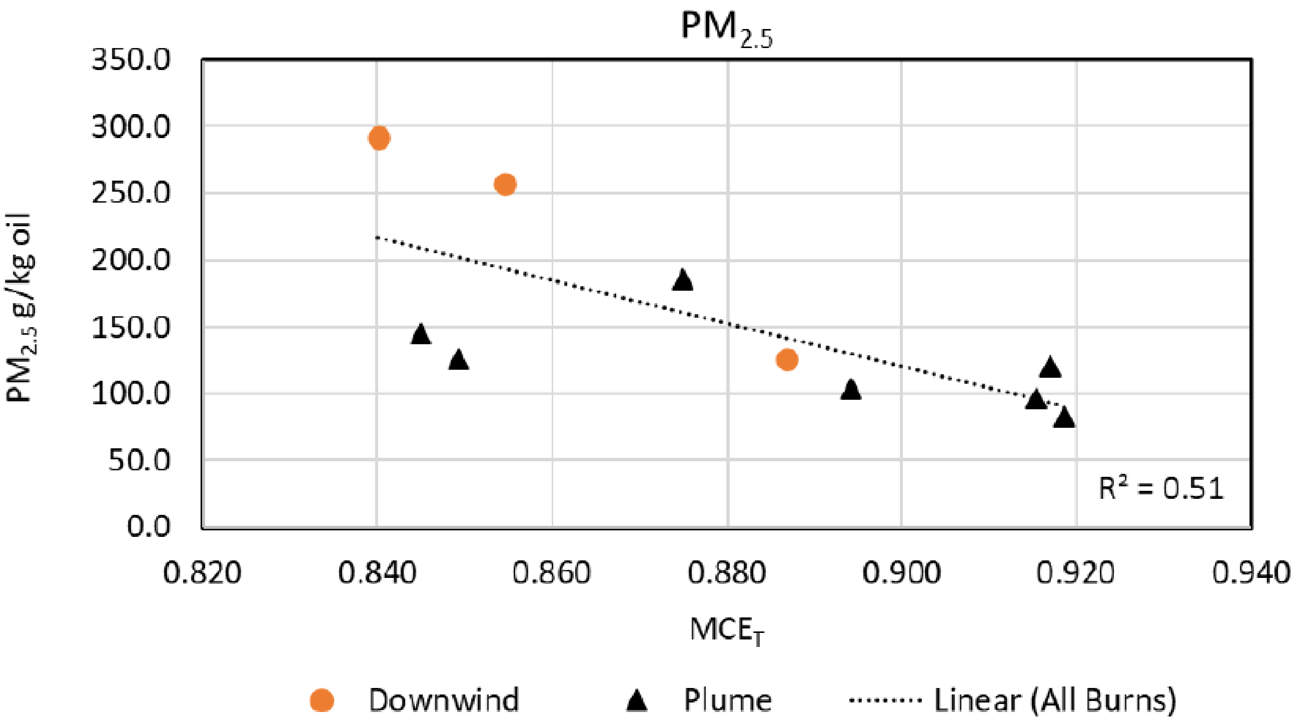


Figure 14. Comparison of PM2.5 emission factors collected in the near source plume and the far source (downwind) plume.

Previous observations by Aurell and group reported that there is no apparent relationship between combustion efficiency (MCEt) and the amount of oil consumed. Figure 15 shows the plot of Non-methane hydrocarbon emission factors as a function of total modified combustion efficiency with a $R^2$=0.5886. This also shows no relationship with the combustion efficiency (MCEt) (Aurell et al., 2021). It is important for tests to verify this finding. Particular attention should be placed on the recovery of the oily residue, as this procedure is difficult and may lead to miscalculation of the amount of oil burned. The amount of oil consumed by the fire and the total modified combustion efficiency comparison is shown in Figure 16.

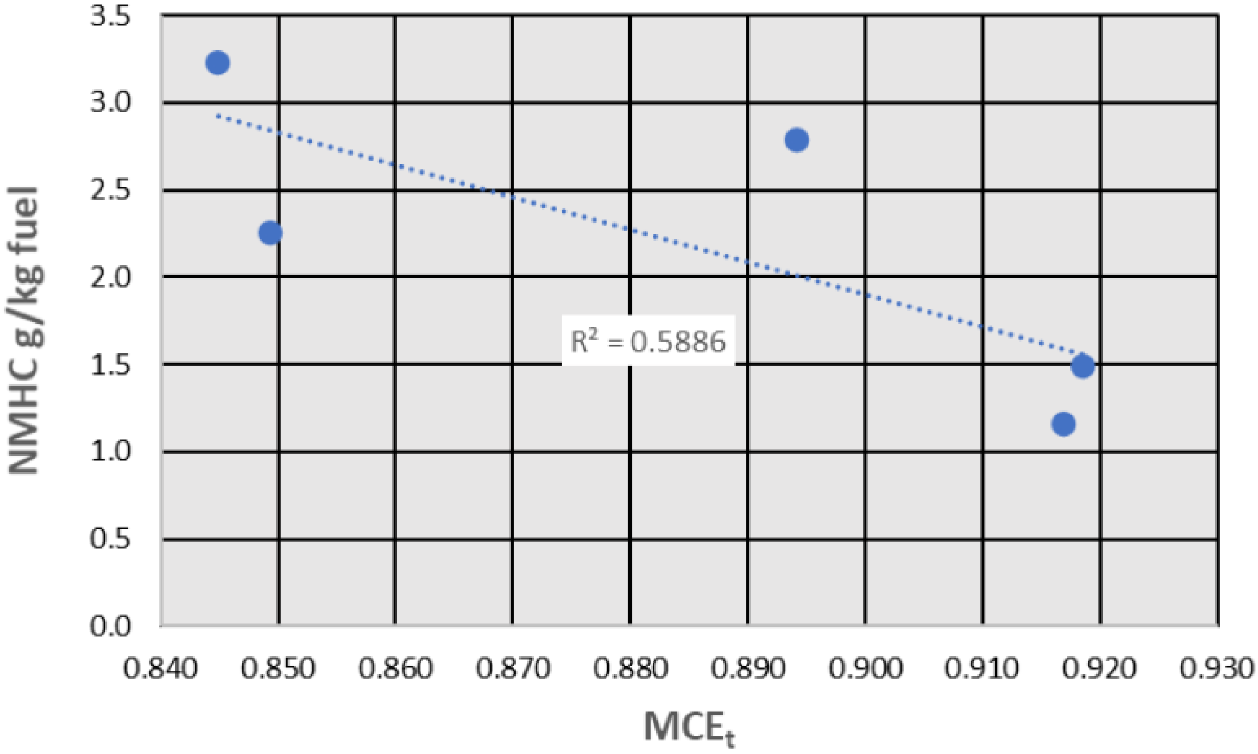


Figure 15. Non-methane hydrocarbon emission factors versus total modified combustion efficiency.

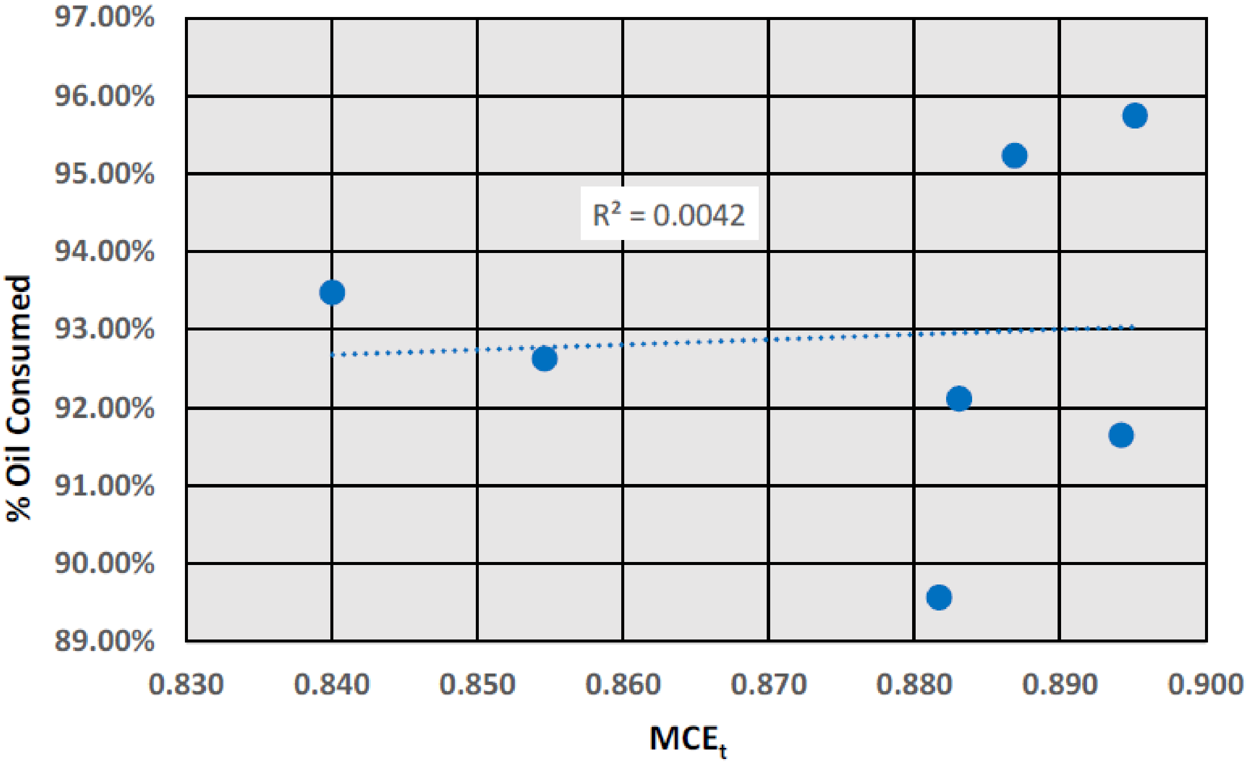


Figure 16. A comparison of the amount of oil consumed by the fire and the total modified combustion efficiency.

The *real time* PM2.5 instruments used in this work use optical measurements to calculate particle size distribution by mass. Since optical measurements depend on the characteristics of the particles in question, calibration of the instruments to an integrated filter mass measurement is required.

In this work, the sUAS/Kolibri held both the optical SidePak as well as a filter-based PM2.5 particle measurement. The filter mass was a primary standard whose value was then used to calibrate the corresponding SidePak optical data. The filter-mass-corrected SidePak data were then compared to the EPA DRX DustTrak results shown in Figure 17. This figure reports 2-min average concentrations that correspond to the time periods for data reported by the PurpleAir sensors. The PurpleAir sensors report 2-min averaged concentrations so for each burn of about 10 minutes duration there are five data points of the same color. In the graph, areas where color points are lacking indicates that the burn plume didn't impinge the sensors or the data points are too clustered to distinguish.

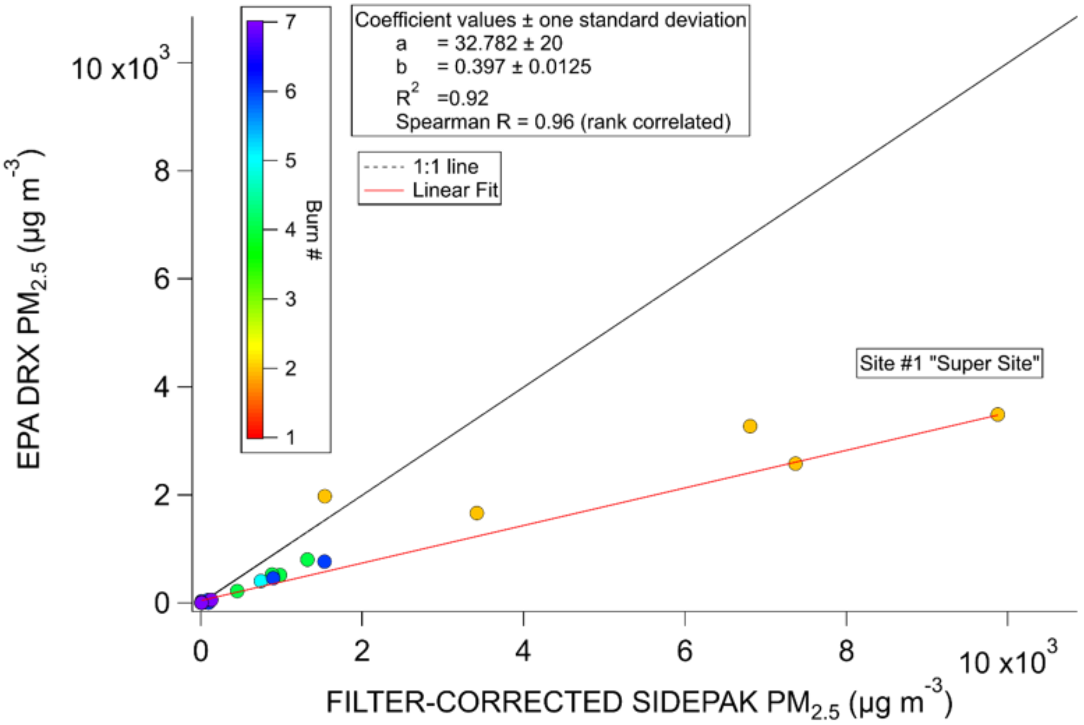


Figure 17. Comparison of uncorrected EPA DRX DustTrak with filter-corrected SidePak.

Figure reference: Color indicates ISB number. Data are 2-min averaged. The red line is a linear fit line. Linear regression coefficient are given as a and b where y=bx+a

These results indicate that the uncorrected EPA DRX DustTrak reported PM2.5 concentrations that were potentially a factor of three lower than the filter-corrected SidePak values. This underscores the need to calibrate the instruments with appropriate correction factors particular to the particle optical properties.

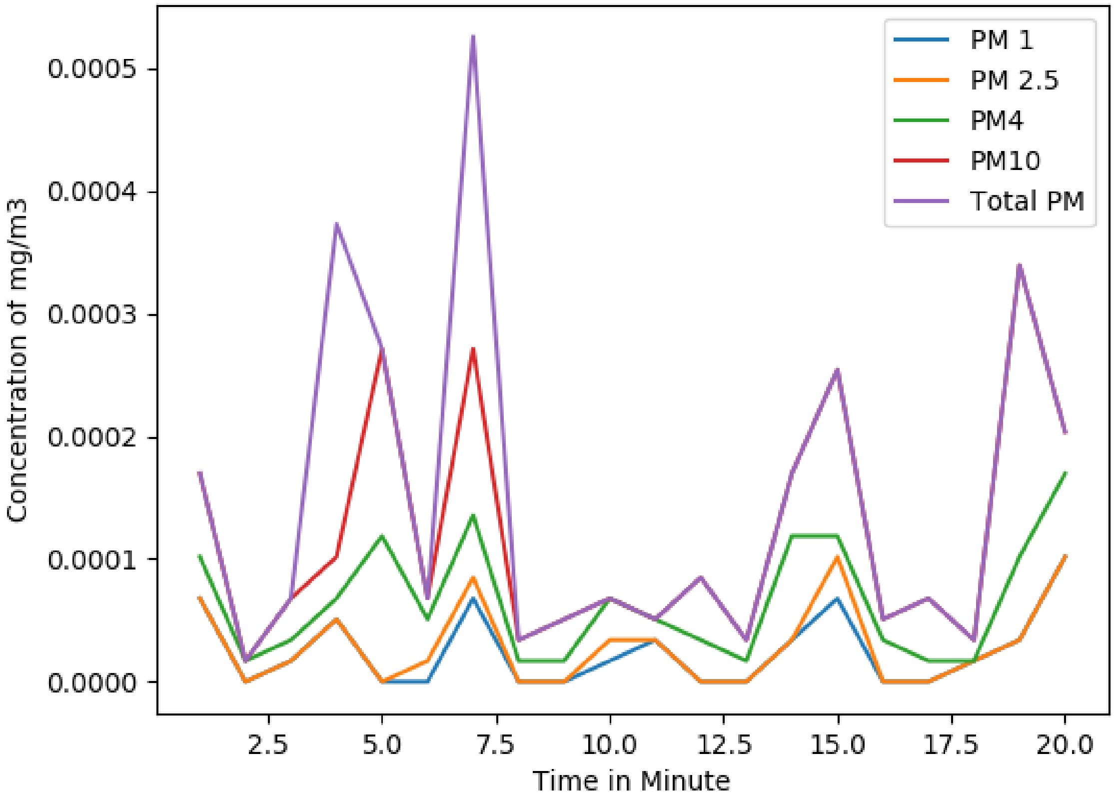


Figure 18. Figure of particulate concentrations verses Time.

## 3.3 Emission Measurements: Ground Monitoring

The USCG Gulf and Atlantic Strike Team performed air sampling during ISB of ANS using a Dust track DRX 8533EP and AreaRAE pro. The instrument collected real-time measurement every second of $PM_1$, $PM_{2.5}$, $PM_4$, $PM_{10}$ and total PM (up to 15µm) in diameter from three different locations around the Geophysical Research Facility (GFR). Figure 18 shows the different concentration readings of particulate matter as a function of time (minutes) measured with the ground-monitoring instruments. The strike team distributed three DustTraks and three AreaRae Pro, which measures the gas meter reading ($O_2$ and $H_2S$) in different locations. The first location was northwest of the GRF; the second was southeast of the GRF and the third was located at the southwest corner of the GRF.

### 3.3.1 Ground Monitoring Execution and Test Results

For all test iterations, the USCG NSF team collected ground-based air quality data using DustTrak/AreaRae equipment in accordance with the SMART protocol. Ground sampling was conducted by the USCG Strike Team using the SMART protocol (USCG No. CG-D-08-14, 2014), which consisted of TSI DustTraks for $PM_{2.5}$ in three locations and several AreaRae samplers or $H_2S$, CO, and VOCs. Up to eight PurpleAir PM sensors were deployed by ORD at each of the three Strike Team locations and at other sites deemed to be impinged by the plume. At one“Super Site” collocated samplers consisted of the Strike Team’s DustTrak, the ORD PurpleAir sensor, an ORD DRX DustTrak and ORD’s backup Kolibri.

Figure 19 compares uncorrected EPA DRX DustTrak with the USCG SMART DRX DustTrak, both instruments underreported the actual concentration of $PM_{2.5}$ values by about 3-fold. The uncorrected

PurpleAir data was also under-reported to approximately 8-fold lower (Figure 20). The correction of the EPA DRX DustTrak data with the filter-corrected SidePak data shows good agreement ($R_2$ =0.92).[2] Corrected PurpleAir data with the filter-corrected SidePak data (Figure 21) are encouraging, with $R^2$ =0.93 and a slope of approximately 1 (b=0.9).

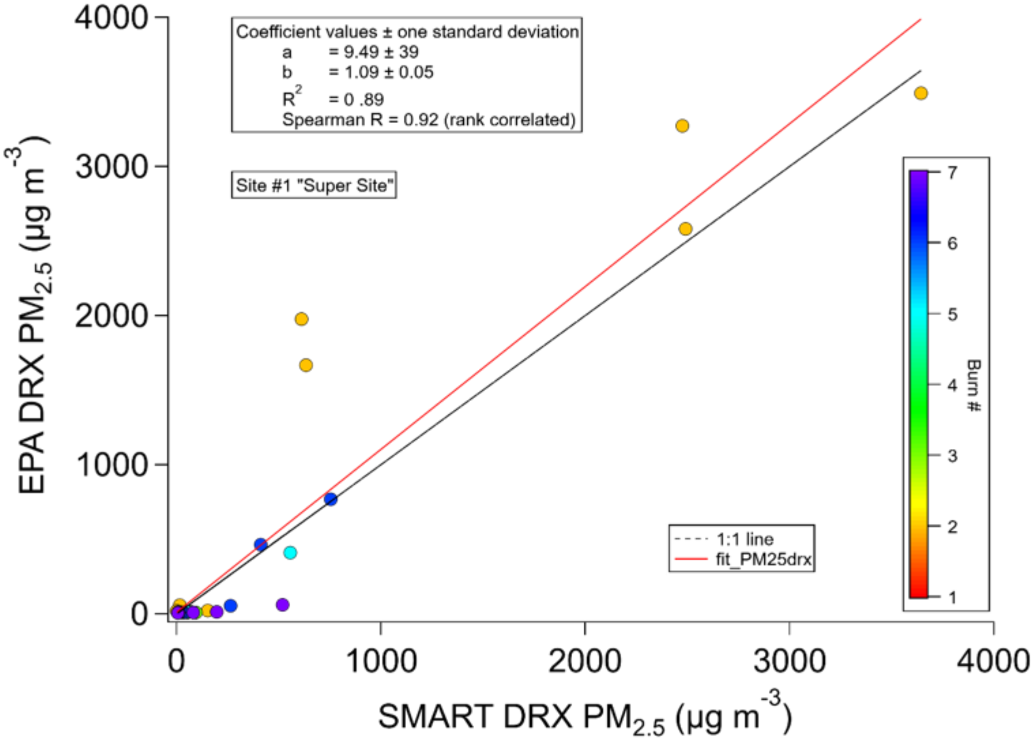


Figure 19. Comparison of uncorrected EPA DRX DustTrak with uncorrected USCG SMART DRX DustTrak.

Figure reference: Color indicates ISB number. Data are 2-min averaged. Linear regression coefficients are given as *a* and *b* where y = bx + a.

---

[2] Correction factors are applied *after* the experiment because they require a filter weight obtained during the sampling, measured gravimetrically, compared to the "photometric" (electro-optical) measurements of the DustTrak, PurpleAir, and SidePak.

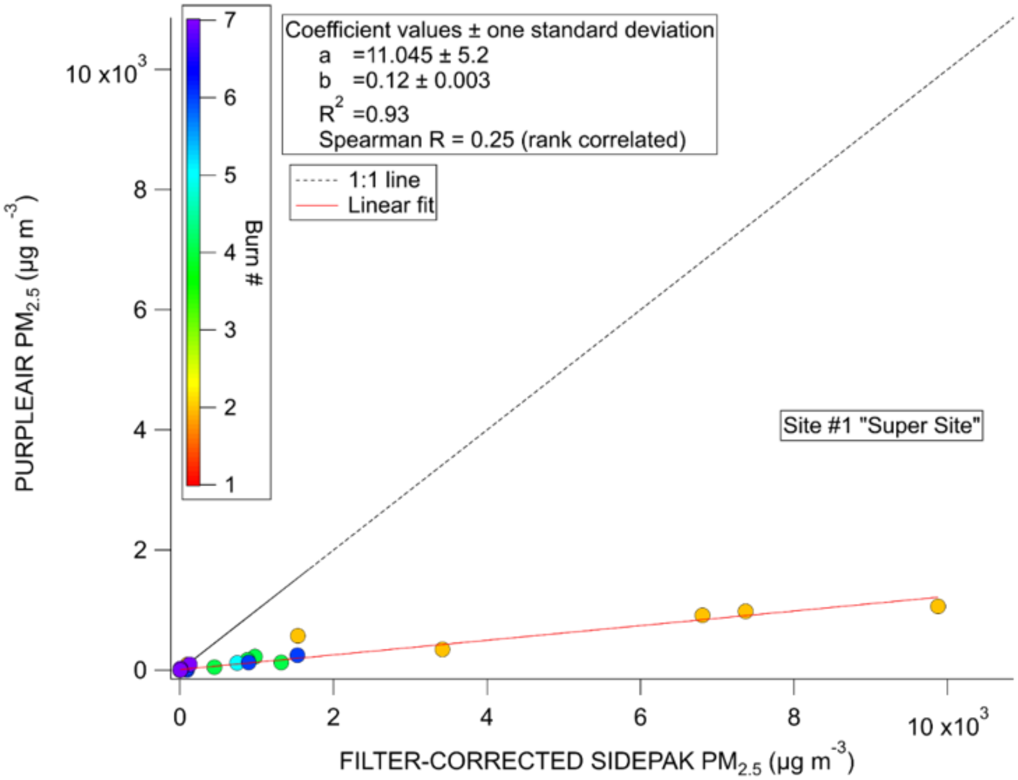


Figure 20. Uncorrected PurpleAir sensor versus filter-corrected SidePak.

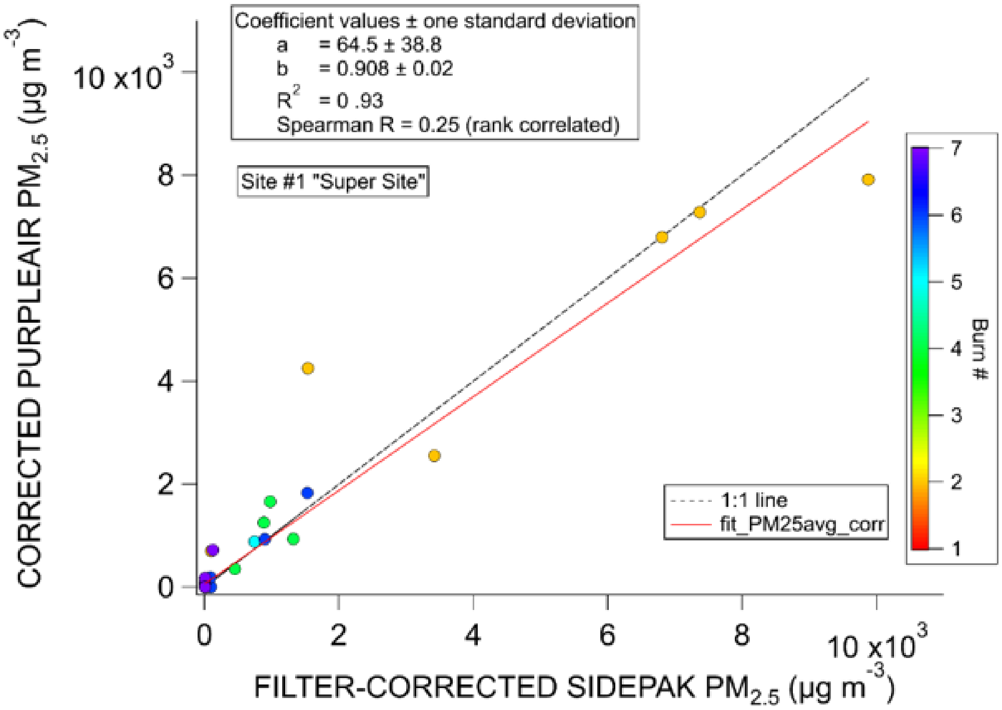


Figure 21. Corrected PurpleAir results versus filter-corrected Side Pak.

## 3.4 Remote Sensing via LiDAR

RDC collaborated with CRREL to execute the hyper-temporal terrestrial laser scanning of the smoke plumes using sensors Riegl VZ-400i (SN2222190) and Riegl VZ-2000i (H2223747) to image the ISB in three dimensions. Scanning began with ignition of the oil slick and was repeated approximately every 30 seconds until the flame ceased. The first scanner VZ-400i was used for the entire duration of the experiments (Tests #1-8) while the second scanner VZ-2000i was used for Tests #5-8. The scanner configuration (Appendix C) lists the parameters and specifications of each individual ISB.

During the ISB tests, technicians used the LiDAR to conduct real-time monitoring of smoke yield (mass of smoke generated per mass of fuel consumed) to evaluate continuous feedback about progression and safety of the burns.

### 3.4.1 Remote Sensing via LiDAR Execution and Test Results

For each ISB, the LiDAR scan data were used to produce three voxel[3] classes of 5 $cm^3$, 10 $cm^3$, and 25 $cm^3$. First, the background point clouds were removed from the dataset leaving only point counts (Figure 20) generated by the plume. A lower limit of 3 reflectance counts was used to qualify each voxel. For these analyses, the 10 $cm^3$ voxel data were used as they provide the best resolution and were mostly limited to the plume directly above the ISB and did not represent the less dense portions as the plume height increased. The point count should represent distinct units of returned reflectance from the plume. Theoretically, it should have a correlation to the density of particulate matter (PM) in the plume. The relationship should be positively monotonic and linear, meaning as the density of the PM in the plume increase, the amount of reflectance and density of the point cloud from the LiDAR scan should increase. During an ISB the overall combustion efficiency is negatively correlated to PM concentrations. As combustion efficiency increases and the hydrocarbons in the fuel combust completely and generate CO and $CO_2$, the PM in the plume should be reduced.

The ISBs were scanned every 30 seconds with LiDAR. ISB Test #1-4 were scanned with a Riegl VZ-400i from the east side of the ISB. ISB Tests #5-8 were scanned with the same system as well as a Riegl VZ-2000i from the west side of the ISB. For this analysis, the data (Figure 22) are presented as the total point count from the plume, the mean and standard deviation of the point counts as a function of the 10 $cm^3$ voxels, and the mean reflectance as a function of the 10 $cm^3$ voxels. For the Riegl VZ400i scans, there was a positive temporal relationship between total point counts for each burn. Although there was a good temporal relationship for both the mean point count and the mean reflectance, they are neither positive nor negative. This suggests that these analysis methods may not be following the dynamics of the ISB PM generation.

---

[3] A voxel is a unit of graphic information that defines a point in three-dimensional space.

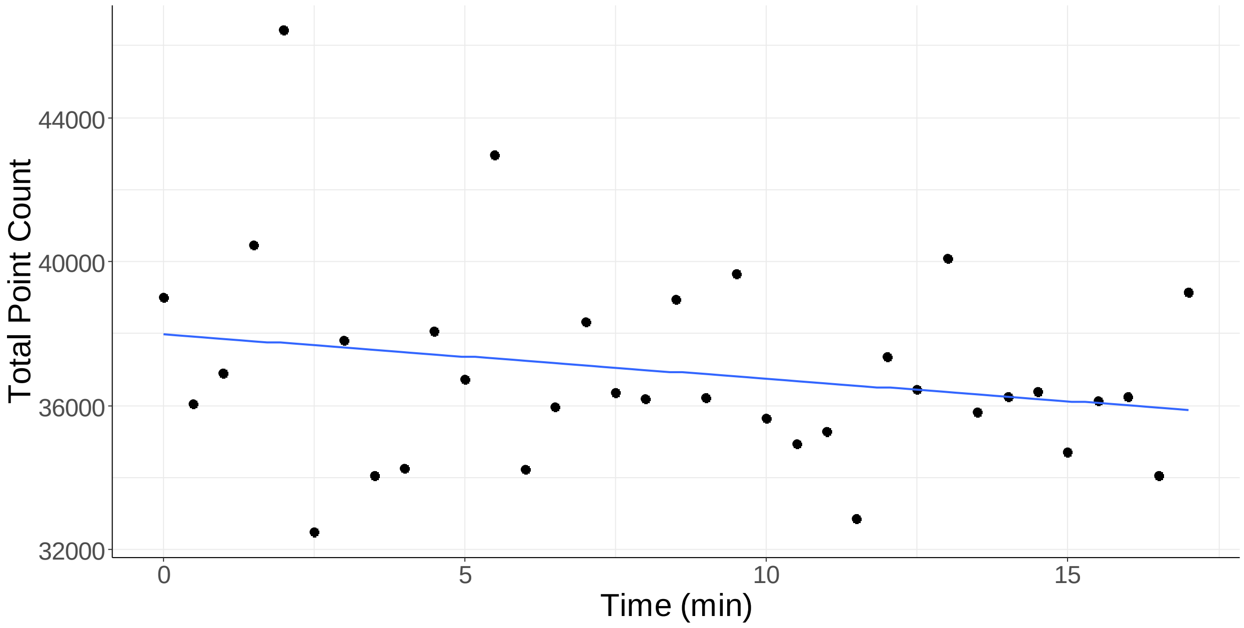


Figure 22. ISB Test #6 West: Total point count.

*Data is 10cm$^3$ voxel with point counts and reflectance values*

For ISB test # 6 (Figure ) scans using the Riegl VZ-2000i from the west, there is a negative temporal correlation for the total point counts. This phenomenon is likely related to the expected increasing combustion efficiency of the ISB. This was not observed in the mean point counts or reflectance which may be attributed to inadequacies of the analysis methods.

Figure 23 depicts (A) all points, (B) 5cm$^3$ Voxels, (C) 10cm$^3$ Voxels, (D) 25cm$^3$ Voxels. All depictions indicate reflectance by color: (yellow, orange, magenta, blue; highest to lowest reflectance).

Figure 24, also ISB test #6 viewed from the west, provides relative point density.

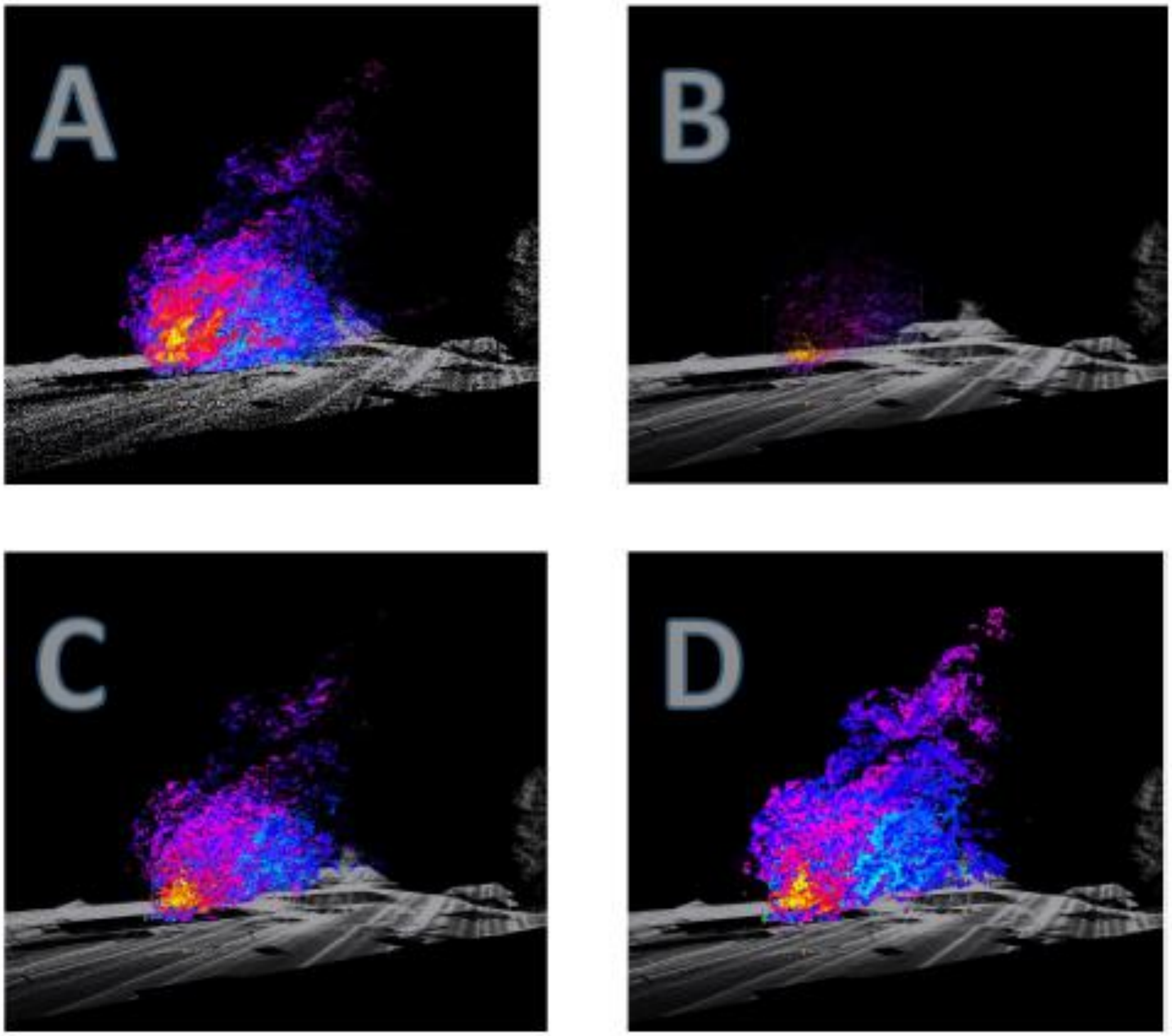


Figure 23. ISB Test #6 West. LiDAR imagery depicting reflectance by color

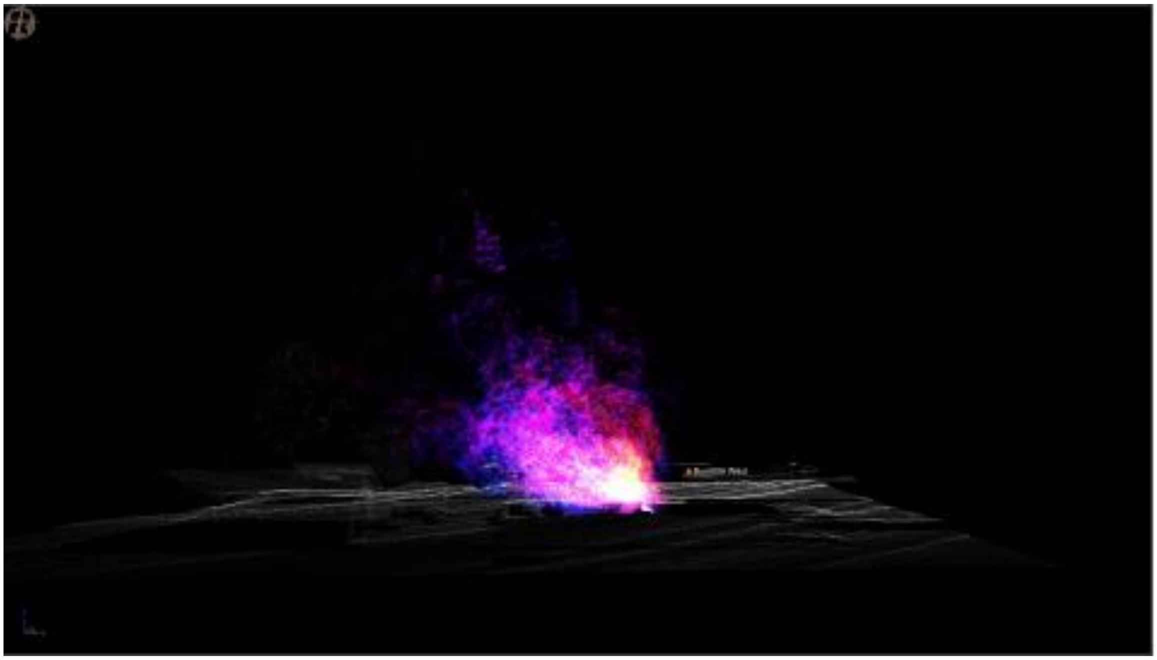


Figure 24. ISB Test #6 West “3-dimensional” view (visualizes relative point density).

### 3.4.2 Remote Sensing via LiDAR

With additional processing of the Riegl VZ-2000i data, there may be an opportunity to develop a methodology using the LiDAR scan to assess PM concentrations in ISB plumes. Further assessments of this technology is necessary.

# 4 CONCLUSIONS

For this study, eight replicate ISB tests were conducted to allow synoptic sampling for the USCG National Strike Force ground monitoring system (DustTraks and Area Rae Pro), the EPA’s sUAS gas monitoring system, and CRREL terrestrial LiDAR scanning. The mean slick thickness across each burn was 4.1 cm which provided a mean burn time of 15.6 min and a mean burn rate of 0.265 cm/min. A sUAS-borne sensor/sampler system was flown into the ISB plume to sample the emissions. Concurrent ground measurements were made using various particle and gas sampling devices to compare aerial and ground measurements. The EPA also deployed an array of low cost particle sensors to compare with the Strike Team’s Special Monitoring of Applied Response Technologies (SMART) protocol.

## 4.1 Burn Efficiency

As noted earlier, the mean burn efficiency of ANS crude oil was approximately 93%. This very high burn efficiency can be attributed to the chemical properties of ANS and the calm environmental condition for each burn (e.g., no wave action or heavy rain). (An efficiency greater than 90% can be expected in calm conditions in an open water system.)

## 4.2 Emission Measurements

The emission factors from ISB were determined with the Kolibri sensor/sampler system onboard a multicopter sUAS. The remotely piloted sUAS was easily positioned within the plume for sampling emissions. There is no discernable difference in emission values between sample locations. The deployment of an array of ground-based sampler equipment accompanied the sUAS/Kolibri measurements. A sUAS-mounted optical particle sampler was corrected using a co-located $PM_{2.5}$ impactor whose mass value provided a correction factor, specific to the optical properties of ISB smoke. When this correction was applied to the ground-based EPA DRX DustTrak and EPA Purple Air sensors and compared to the primary standard[4], there was good inter-agreement ($R^2 > 0.9$). However, the raw, uncorrected data from the DustTraks were three times lower than the actual concentrations, emphasizing the critical need to calibrate the optical measurements with the actual source particulate matter mass (collected using an integrated filter capture method). Up to eight PurpleAir $PM_{2.5}$ sensors were used, three of which were deployed in common locations with the DustTraks and up to five others were positioned at other upwind and downwind locations. The uncorrected PurpleAir sensors under-reported concentrations compared to the primary standard even more than the DustTraks, by about a factor of eight. However, the PurpleAir results, like the DRX DustTrak, when calibrated with the appropriate factor, had an $R^2 > 0.9$ when compared with the filter-corrected SidePak (the primary standard for this test program).

The mobility of a sUAS-mounted system assures data collection without concern for wind direction and ground-based sensor placement. The spatial freedom of the system allows the operators to sample upwind from the source, presenting considerable personnel safety advantages over ground-based system placement. The responsiveness of the sUAS also allows adjustments to be made for wind shifts as well as for thermally lofted plumes which may later cool and descend. One disadvantage of the sUAS systems is that they have wind speed and precipitation limits for safe operation.

# 5 RECOMMENDATIONS

With the NSF SMART protocol, the operator must place ground-based equipment based on the predicted plume direction so there is a risk that limited or no data may be collected on a plume due to changes in wind direction during the ISB. Deployment of ground-based systems requires good judgement regarding downwind placement of sensors. Arrayed sensors, numbers of which are promoted by lower cost, have a greater chance of capturing ISB smoke plumes. These systems can also be networked together, even working with a sUAS-based system, to provide real time data over a wide area for the on-scene coordinator. These real time data would prove more reliable for health hazards and plume direction during emergency responses. RDC recommends further experimentation, trial, and comparison of lower-cost, arrayed sensors to determine potential ground-based alternatives to the present SMART measurement protocols.

Comparing sUAS-based aerial measurements with SMART measurements, the sUAS derived measurements were consistent as could be expected with the spatial orientation. In addition, emission factors for $PM_{2.5}$ calculated from the sUAS system measurements, accurately correlated decreasing $PM_{2.5}$ value to improved oil combustion efficiencies over time.

---

[4] Primary standards are reagents of high purity, representative of the number of moles the substance contains, and easily weighed.

RDC recommends future sUAS experimentation for ISB plume monitoring based on operations-based concerns. Use-scenarios and documenting how a Federal On Scene Coordinator or Regional Response Team would apply sUAS-gathered information must be included in any experimentation plan to determine how best to incorporate sUAS in ISB monitoring and measurement.

As the LiDAR data from this study provided rudimentary datasets to assess this technology for ISB plume assessment, RDC recommends further testing to determine efficacy of LiDAR use in plume mapping and characterization.

# 6 REFERENCES

Aurell, J., et al. Analysis of emissions and residue from methods to improve efficiency of at-sea, in situ oil spill burns, Marine Poll. Bull. 173 (2021), 113016, https://doi.org/10.1016/j.marpolbul.2021.113016.

Great Lakes Commission. 2018. Oil Transportation in the Great Lakes – St. Lawrence River Region: Project Archive. July. https://www.glc.org/work/oil-transportation.

Gullett, Brian. 2021. Quality Assurance Project Plan for Freshwater In-Situ Burn Air Monitoring: USCGQAPP ID: 0033370-QP-1-0 U.S. Environmental Protection Agency, Office of Research and Development, Center for Environmental Measurement and Modeling.

Murphy, E. A., Adewale, B. S., Pham, H. V., Aurell, J., Gullett, B. K., Arsava, K. S., Lamie,. N.J., Wurl, M.A., Cisternelli, M.M., Fitzpatrick, M. (2021). Freshwater In-situ Oil Burning. CG-D-01-21, Washington, DC: United States Coast Guard.

National Oceanic and Atmospheric Administration. 2019. In Situ Burning. February 8. https://response.restoration.noaa.gov/oil-and-chemical-spills/oil-spills/resources/in-situ-burning.html.

Parscal, Brian, Robert Young, and Richard Barone. 2014. Modernization of Special Monitoring of Applied Response Technologies (SMART) Technology and Methods. CG-D-08-14, Washington, DC: United States Coast Guard.

United States Coast Guard. 2006. Special Monitoring of Applied Response Technologies. Seattle, Washington: National Oceanic and Atmospheric Administration.

# APPENDIX A. TEST OIL SPECIFICATION SHEETS

## A.1 Alaska North Slope (ANS) Crude Oil

ConocoPhillips
Alaska

### SAFETY DATA SHEET

### SECTION 1 : IDENTIFICATION

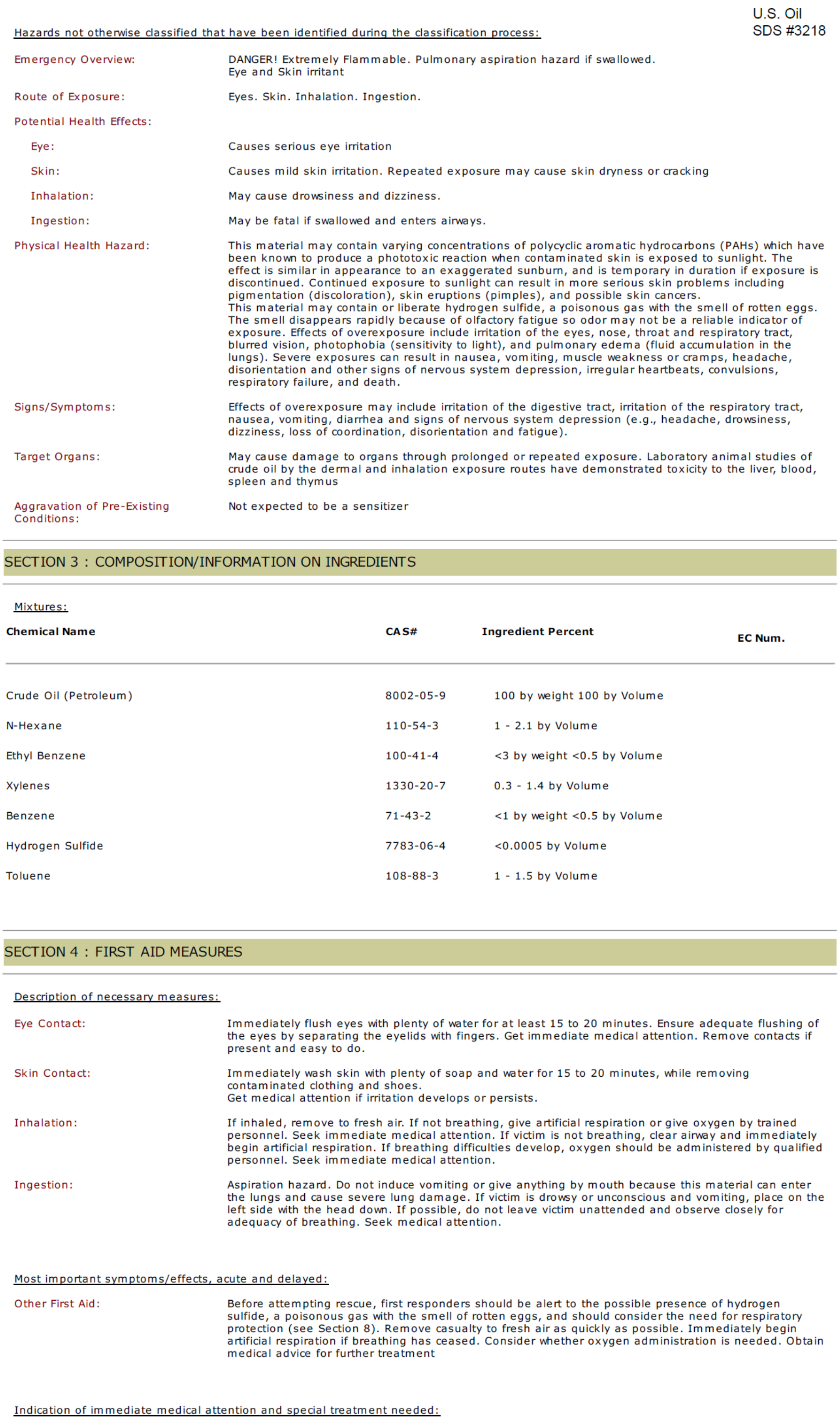
| | |
|---|---|
| Product identifier used on the label: | |
| Product Name: | **Alaska North Slope Crude Oil** |
| SDS Manufacturer Number: | 791002 |
| Other means of identification: | |
| Synonyms: | ANS Crude, Alaska North Slope (ANS) Crude Oil, Crude Oil (ANS Type), Earth Oil, Petroleum Oil, Rock Oil |
| Recommended use of the chemical and restrictions on use: | |
| Chemical manufacturer address and telephone number: | |
| Manufacturer Name: | ConocoPhillips Alaska, Inc. |
| Address: | A Subsidiary of ConocoPhillips<br>P.O. Box 100360 700 G. Street<br>Anchorage, Alaska 99510-0360<br>USA |
| Website: | www.conocophillips.com |
| Customer Service Phone Number: | 907-659-7812 |
| Health Issues Information: | 855-244-0762 |
| Technical Product Information: | 907-659-7812 |
| Emergency phone number: | |
| Emergency Phone Number: | Chemtrec: 800-424-9300 (24 Hours) |

### SECTION 2 : HAZARD(S) IDENTIFICATION

| | |
|---|---|
| Classification of the chemical in accordance with CFR 1910.1200(d)(f): | |
| GHS Pictograms: | |
| Signal Word: | DANGER. |
| GHS Class: | Flammable Liquid. Category 1.<br>Aspiration Hazard. Category 1.<br>Carcinogenicity. Category 1A.<br>Germ cell mutagenicity. Category 1B.<br>Specific Target Organ Toxicity -STOT Repeated exposure RE. Category 2 (Inhalation, liver, brain & central nervous system).<br>Reproductive toxicity. Category 2.<br>Skin Irritation. Category 2. |
| Hazard Statements: | H224 - Extremely flammable liquid and vapor<br>H304 - May be fatal if swallowed and enters airways.<br>H350 - May cause cancer.<br>H340 - May cause genetic defects.<br>H373 - May cause damage to organs through prolonged or repeated exposure.<br>H361 - Suspected of damaging fertility or the unborn child.<br>H315 - Causes skin irritation. |
| Precautionary Statements: | P201 - Obtain special instructions before use.<br>P202 - Do not handle until all safety precautions have been read and understood.<br>P210 - Keep away from heat/sparks/open flames/hotsurfaces. — No smoking.<br>P233 - Keep container tightly closed.<br>P240 - Ground/Bond container and receiving equipment.<br>P241 - Use explosion-proof electrical/ventilating/lighting equipment.<br>P242 - Use only non-sparking tools.<br>P243 - Take precautionary measures against static discharge.<br>P260 - Do not breathe dust/fume/gas/mist/vapours/spray.<br>P264 - Wash hands thoroughly after handling.<br>P280 - Wear protective gloves/protective clothing/eye protection/face protection.<br>P301+P310 - IF SWALLOWED: Immediately call a POISON CENTER or doctor/physician<br>P302+P352 - IF ON SKIN: Wash with plenty of water.<br>P303+P361+P353 - IF ON SKIN (or hair): Remove/Take off immediately all contaminated clothing. Rinse skin with water/shower.<br>P308+P313 - IF exposed or concerned: Get medical advice/attention.<br>P314 - Get medical advice/attention if you feel unwell.<br>P321 - Specific treatment (see ... on this label).<br>P331 - Do not induce vomiting.<br>P332+P313 - If skin irritation occurs: Get medical advice/attention.<br>P362+P364 - Take off contaminated clothing and wash it before reuse.<br>P370+P378 - In case of fire: Use dry chemical, carbon dioxide to extinguish small fires. Use water for large fires.<br>P403+P235 - Store in a well-ventilated place. Keep cool.<br>P405 - Store locked up.<br>P501 - Dispose of contents/container in accordance with Local, State, Federal and Provincial regulations. |

Alaska North Slope Crude Oil
Revision:: 11/20/2015

Product Code: 791002



U.S. Oil
SDS #3218

Hazards not otherwise classified that have been identified during the classification process:

| | |
|---|---|
| Emergency Overview: | DANGER! Extremely Flammable. Pulmonary aspiration hazard if swallowed.<br>Eye and Skin irritant |
| Route of Exposure: | Eyes. Skin. Inhalation. Ingestion. |
| Potential Health Effects: | |
| Eye: | Causes serious eye irritation |
| Skin: | Causes mild skin irritation. Repeated exposure may cause skin dryness or cracking |
| Inhalation: | May cause drowsiness and dizziness. |
| Ingestion: | May be fatal if swallowed and enters airways. |
| Physical Health Hazard: | This material may contain varying concentrations of polycyclic aromatic hydrocarbons (PAHs) which have been known to produce a phototoxic reaction when contaminated skin is exposed to sunlight. The effect is similar in appearance to an exaggerated sunburn, and is temporary in duration if exposure is discontinued. Continued exposure to sunlight can result in more serious skin problems including pigmentation (discoloration), skin eruptions (pimples), and possible skin cancers.<br>This material may contain or liberate hydrogen sulfide, a poisonous gas with the smell of rotten eggs. The smell disappears rapidly because of olfactory fatigue so odor may not be a reliable indicator of exposure. Effects of overexposure include irritation of the eyes, nose, throat and respiratory tract, blurred vision, photophobia (sensitivity to light), and pulmonary edema (fluid accumulation in the lungs). Severe exposures can result in nausea, vomiting, muscle weakness or cramps, headache, disorientation and other signs of nervous system depression, irregular heartbeats, convulsions, respiratory failure, and death. |
| Signs/Symptoms: | Effects of overexposure may include irritation of the digestive tract, irritation of the respiratory tract, nausea, vomiting, diarrhea and signs of nervous system depression (e.g., headache, drowsiness, dizziness, loss of coordination, disorientation and fatigue). |
| Target Organs: | May cause damage to organs through prolonged or repeated exposure. Laboratory animal studies of crude oil by the dermal and inhalation exposure routes have demonstrated toxicity to the liver, blood, spleen and thymus |
| Aggravation of Pre-Existing Conditions: | Not expected to be a sensitizer |

## SECTION 3 : COMPOSITION/INFORMATION ON INGREDIENTS

Mixtures:

| Chemical Name | CAS# | Ingredient Percent | EC Num. |
|---|---|---|---|
| Crude Oil (Petroleum) | 8002-05-9 | 100 by weight 100 by Volume | |
| N-Hexane | 110-54-3 | 1 - 2.1 by Volume | |
| Ethyl Benzene | 100-41-4 | <3 by weight <0.5 by Volume | |
| Xylenes | 1330-20-7 | 0.3 - 1.4 by Volume | |
| Benzene | 71-43-2 | <1 by weight <0.5 by Volume | |
| Hydrogen Sulfide | 7783-06-4 | <0.0005 by Volume | |
| Toluene | 108-88-3 | 1 - 1.5 by Volume | |

## SECTION 4 : FIRST AID MEASURES

Description of necessary measures:

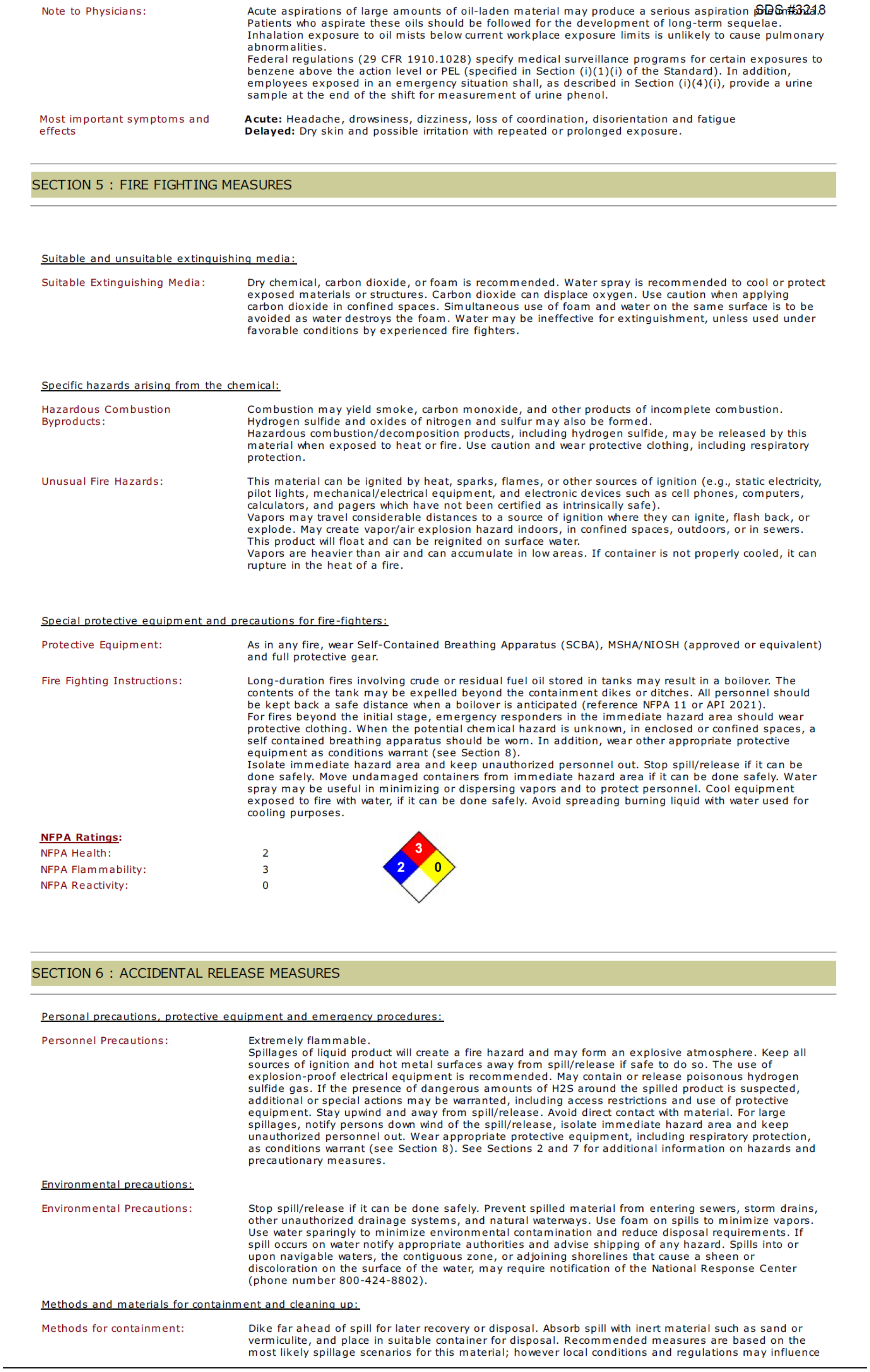
| | |
|---|---|
| Eye Contact: | Immediately flush eyes with plenty of water for at least 15 to 20 minutes. Ensure adequate flushing of the eyes by separating the eyelids with fingers. Get immediate medical attention. Remove contacts if present and easy to do. |
| Skin Contact: | Immediately wash skin with plenty of soap and water for 15 to 20 minutes, while removing contaminated clothing and shoes.<br>Get medical attention if irritation develops or persists. |
| Inhalation: | If inhaled, remove to fresh air. If not breathing, give artificial respiration or give oxygen by trained personnel. Seek immediate medical attention. If victim is not breathing, clear airway and immediately begin artificial respiration. If breathing difficulties develop, oxygen should be administered by qualified personnel. Seek immediate medical attention. |
| Ingestion: | Aspiration hazard. Do not induce vomiting or give anything by mouth because this material can enter the lungs and cause severe lung damage. If victim is drowsy or unconscious and vomiting, place on the left side with the head down. If possible, do not leave victim unattended and observe closely for adequacy of breathing. Seek medical attention. |

Most important symptoms/effects, acute and delayed:

| | |
|---|---|
| Other First Aid: | Before attempting rescue, first responders should be alert to the possible presence of hydrogen sulfide, a poisonous gas with the smell of rotten eggs, and should consider the need for respiratory protection (see Section 8). Remove casualty to fresh air as quickly as possible. Immediately begin artificial respiration if breathing has ceased. Consider whether oxygen administration is needed. Obtain medical advice for further treatment |

Indication of immediate medical attention and special treatment needed:

U.S. Oil
SDS #3218



| | |
|---|---|
| Note to Physicians: | Acute aspirations of large amounts of oil-laden material may produce a serious aspiration pneumonia.<br>Patients who aspirate these oils should be followed for the development of long-term sequelae.<br>Inhalation exposure to oil mists below current workplace exposure limits is unlikely to cause pulmonary abnormalities.<br>Federal regulations (29 CFR 1910.1028) specify medical surveillance programs for certain exposures to benzene above the action level or PEL (specified in Section (i)(1)(i) of the Standard). In addition, employees exposed in an emergency situation shall, as described in Section (i)(4)(i), provide a urine sample at the end of the shift for measurement of urine phenol. |
| Most important symptoms and effects | **Acute:** Headache, drowsiness, dizziness, loss of coordination, disorientation and fatigue<br>**Delayed:** Dry skin and possible irritation with repeated or prolonged exposure. |

## SECTION 5 : FIRE FIGHTING MEASURES

Suitable and unsuitable extinguishing media:

| | |
|---|---|
| Suitable Extinguishing Media: | Dry chemical, carbon dioxide, or foam is recommended. Water spray is recommended to cool or protect exposed materials or structures. Carbon dioxide can displace oxygen. Use caution when applying carbon dioxide in confined spaces. Simultaneous use of foam and water on the same surface is to be avoided as water destroys the foam. Water may be ineffective for extinguishment, unless used under favorable conditions by experienced fire fighters. |

Specific hazards arising from the chemical:

| | |
|---|---|
| Hazardous Combustion Byproducts: | Combustion may yield smoke, carbon monoxide, and other products of incomplete combustion.<br>Hydrogen sulfide and oxides of nitrogen and sulfur may also be formed.<br>Hazardous combustion/decomposition products, including hydrogen sulfide, may be released by this material when exposed to heat or fire. Use caution and wear protective clothing, including respiratory protection. |
| Unusual Fire Hazards: | This material can be ignited by heat, sparks, flames, or other sources of ignition (e.g., static electricity, pilot lights, mechanical/electrical equipment, and electronic devices such as cell phones, computers, calculators, and pagers which have not been certified as intrinsically safe).<br>Vapors may travel considerable distances to a source of ignition where they can ignite, flash back, or explode. May create vapor/air explosion hazard indoors, in confined spaces, outdoors, or in sewers.<br>This product will float and can be reignited on surface water.<br>Vapors are heavier than air and can accumulate in low areas. If container is not properly cooled, it can rupture in the heat of a fire. |

Special protective equipment and precautions for fire-fighters:

| | |
|---|---|
| Protective Equipment: | As in any fire, wear Self-Contained Breathing Apparatus (SCBA), MSHA/NIOSH (approved or equivalent) and full protective gear. |
| Fire Fighting Instructions: | Long-duration fires involving crude or residual fuel oil stored in tanks may result in a boilover. The contents of the tank may be expelled beyond the containment dikes or ditches. All personnel should be kept back a safe distance when a boilover is anticipated (reference NFPA 11 or API 2021).<br>For fires beyond the initial stage, emergency responders in the immediate hazard area should wear protective clothing. When the potential chemical hazard is unknown, in enclosed or confined spaces, a self contained breathing apparatus should be worn. In addition, wear other appropriate protective equipment as conditions warrant (see Section 8).<br>Isolate immediate hazard area and keep unauthorized personnel out. Stop spill/release if it can be done safely. Move undamaged containers from immediate hazard area if it can be done safely. Water spray may be useful in minimizing or dispersing vapors and to protect personnel. Cool equipment exposed to fire with water, if it can be done safely. Avoid spreading burning liquid with water used for cooling purposes. |

**NFPA Ratings:**

| | |
|---|---|
| NFPA Health: | 2 |
| NFPA Flammability: | 3 |
| NFPA Reactivity: | 0 |

## SECTION 6 : ACCIDENTAL RELEASE MEASURES

Personal precautions, protective equipment and emergency procedures:

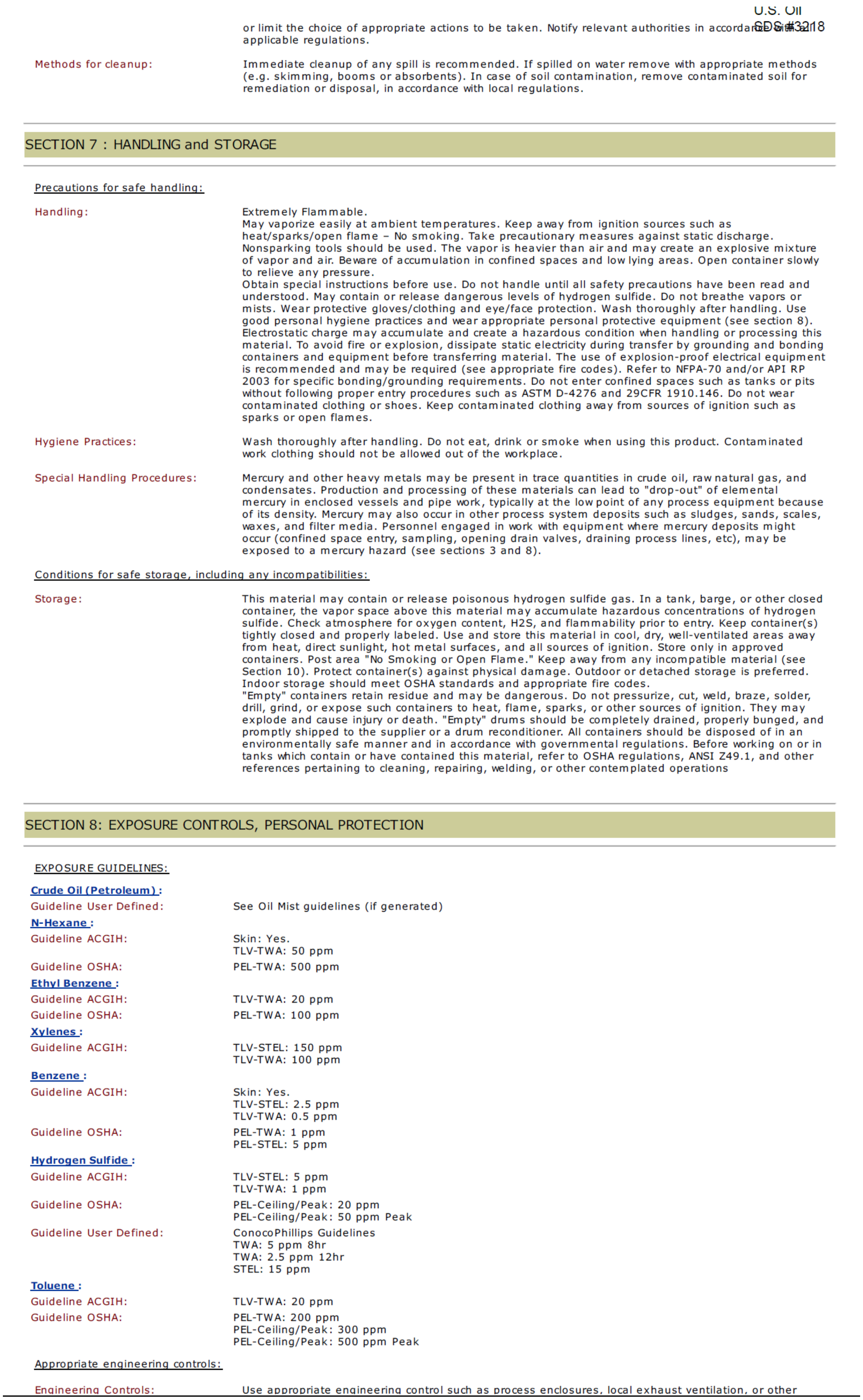
| | |
|---|---|
| Personnel Precautions: | Extremely flammable.<br>Spillages of liquid product will create a fire hazard and may form an explosive atmosphere. Keep all sources of ignition and hot metal surfaces away from spill/release if safe to do so. The use of explosion-proof electrical equipment is recommended. May contain or release poisonous hydrogen sulfide gas. If the presence of dangerous amounts of H2S around the spilled product is suspected, additional or special actions may be warranted, including access restrictions and use of protective equipment. Stay upwind and away from spill/release. Avoid direct contact with material. For large spillages, notify persons down wind of the spill/release, isolate immediate hazard area and keep unauthorized personnel out. Wear appropriate protective equipment, including respiratory protection, as conditions warrant (see Section 8). See Sections 2 and 7 for additional information on hazards and precautionary measures. |

Environmental precautions:

| | |
|---|---|
| Environmental Precautions: | Stop spill/release if it can be done safely. Prevent spilled material from entering sewers, storm drains, other unauthorized drainage systems, and natural waterways. Use foam on spills to minimize vapors. Use water sparingly to minimize environmental contamination and reduce disposal requirements. If spill occurs on water notify appropriate authorities and advise shipping of any hazard. Spills into or upon navigable waters, the contiguous zone, or adjoining shorelines that cause a sheen or discoloration on the surface of the water, may require notification of the National Response Center (phone number 800-424-8802). |

Methods and materials for containment and cleaning up:

| | |
|---|---|
| Methods for containment: | Dike far ahead of spill for later recovery or disposal. Absorb spill with inert material such as sand or vermiculite, and place in suitable container for disposal. Recommended measures are based on the most likely spillage scenarios for this material; however local conditions and regulations may influence |



|  |  |
|---|---|
|  | or limit the choice of appropriate actions to be taken. Notify relevant authorities in accordance with all applicable regulations. |
| Methods for cleanup: | Immediate cleanup of any spill is recommended. If spilled on water remove with appropriate methods (e.g. skimming, booms or absorbents). In case of soil contamination, remove contaminated soil for remediation or disposal, in accordance with local regulations. |

## SECTION 7 : HANDLING and STORAGE

Precautions for safe handling:

|  |  |
|---|---|
| Handling: | Extremely Flammable.<br>May vaporize easily at ambient temperatures. Keep away from ignition sources such as heat/sparks/open flame – No smoking. Take precautionary measures against static discharge. Nonsparking tools should be used. The vapor is heavier than air and may create an explosive mixture of vapor and air. Beware of accumulation in confined spaces and low lying areas. Open container slowly to relieve any pressure.<br>Obtain special instructions before use. Do not handle until all safety precautions have been read and understood. May contain or release dangerous levels of hydrogen sulfide. Do not breathe vapors or mists. Wear protective gloves/clothing and eye/face protection. Wash thoroughly after handling. Use good personal hygiene practices and wear appropriate personal protective equipment (see section 8).<br>Electrostatic charge may accumulate and create a hazardous condition when handling or processing this material. To avoid fire or explosion, dissipate static electricity during transfer by grounding and bonding containers and equipment before transferring material. The use of explosion-proof electrical equipment is recommended and may be required (see appropriate fire codes). Refer to NFPA-70 and/or API RP 2003 for specific bonding/grounding requirements. Do not enter confined spaces such as tanks or pits without following proper entry procedures such as ASTM D-4276 and 29CFR 1910.146. Do not wear contaminated clothing or shoes. Keep contaminated clothing away from sources of ignition such as sparks or open flames. |
| Hygiene Practices: | Wash thoroughly after handling. Do not eat, drink or smoke when using this product. Contaminated work clothing should not be allowed out of the workplace. |
| Special Handling Procedures: | Mercury and other heavy metals may be present in trace quantities in crude oil, raw natural gas, and condensates. Production and processing of these materials can lead to "drop-out" of elemental mercury in enclosed vessels and pipe work, typically at the low point of any process equipment because of its density. Mercury may also occur in other process system deposits such as sludges, sands, scales, waxes, and filter media. Personnel engaged in work with equipment where mercury deposits might occur (confined space entry, sampling, opening drain valves, draining process lines, etc), may be exposed to a mercury hazard (see sections 3 and 8). |

Conditions for safe storage, including any incompatibilities:

|  |  |
|---|---|
| Storage: | This material may contain or release poisonous hydrogen sulfide gas. In a tank, barge, or other closed container, the vapor space above this material may accumulate hazardous concentrations of hydrogen sulfide. Check atmosphere for oxygen content, H2S, and flammability prior to entry. Keep container(s) tightly closed and properly labeled. Use and store this material in cool, dry, well-ventilated areas away from heat, direct sunlight, hot metal surfaces, and all sources of ignition. Store only in approved containers. Post area "No Smoking or Open Flame." Keep away from any incompatible material (see Section 10). Protect container(s) against physical damage. Outdoor or detached storage is preferred. Indoor storage should meet OSHA standards and appropriate fire codes.<br>"Empty" containers retain residue and may be dangerous. Do not pressurize, cut, weld, braze, solder, drill, grind, or expose such containers to heat, flame, sparks, or other sources of ignition. They may explode and cause injury or death. "Empty" drums should be completely drained, properly bunged, and promptly shipped to the supplier or a drum reconditioner. All containers should be disposed of in an environmentally safe manner and in accordance with governmental regulations. Before working on or in tanks which contain or have contained this material, refer to OSHA regulations, ANSI Z49.1, and other references pertaining to cleaning, repairing, welding, or other contemplated operations |

## SECTION 8: EXPOSURE CONTROLS, PERSONAL PROTECTION

EXPOSURE GUIDELINES:

|  |  |
|---|---|
| **Crude Oil (Petroleum) :** |  |
| Guideline User Defined: | See Oil Mist guidelines (if generated) |
| **N-Hexane :** |  |
| Guideline ACGIH: | Skin: Yes.<br>TLV-TWA: 50 ppm |
| Guideline OSHA: | PEL-TWA: 500 ppm |
| **Ethyl Benzene :** |  |
| Guideline ACGIH: | TLV-TWA: 20 ppm |
| Guideline OSHA: | PEL-TWA: 100 ppm |
| **Xylenes :** |  |
| Guideline ACGIH: | TLV-STEL: 150 ppm<br>TLV-TWA: 100 ppm |
| **Benzene :** |  |
| Guideline ACGIH: | Skin: Yes.<br>TLV-STEL: 2.5 ppm<br>TLV-TWA: 0.5 ppm |
| Guideline OSHA: | PEL-TWA: 1 ppm<br>PEL-STEL: 5 ppm |
| **Hydrogen Sulfide :** |  |
| Guideline ACGIH: | TLV-STEL: 5 ppm<br>TLV-TWA: 1 ppm |
| Guideline OSHA: | PEL-Ceiling/Peak: 20 ppm<br>PEL-Ceiling/Peak: 50 ppm Peak |
| Guideline User Defined: | ConocoPhillips Guidelines<br>TWA: 5 ppm 8hr<br>TWA: 2.5 ppm 12hr<br>STEL: 15 ppm |
| **Toluene :** |  |
| Guideline ACGIH: | TLV-TWA: 20 ppm |
| Guideline OSHA: | PEL-TWA: 200 ppm<br>PEL-Ceiling/Peak: 300 ppm<br>PEL-Ceiling/Peak: 500 ppm Peak |

Appropriate engineering controls:

|  |  |
|---|---|
| Engineering Controls: | Use appropriate engineering control such as process enclosures, local exhaust ventilation, or other |

# APPENDIX B. ISB TEMPERATURE RESULTS

## B.1 Steady-state Data for ISB Tests 3-8

Assessing the rate at which the burn reached and maintained steady-state allows for a comparison with the gas monitoring and LiDAR systems to understand when the ISB reached its highest combustion efficiency. . In all figures, the arrow represents the time at which the in-situ burn reached steady state as defined in section 3.

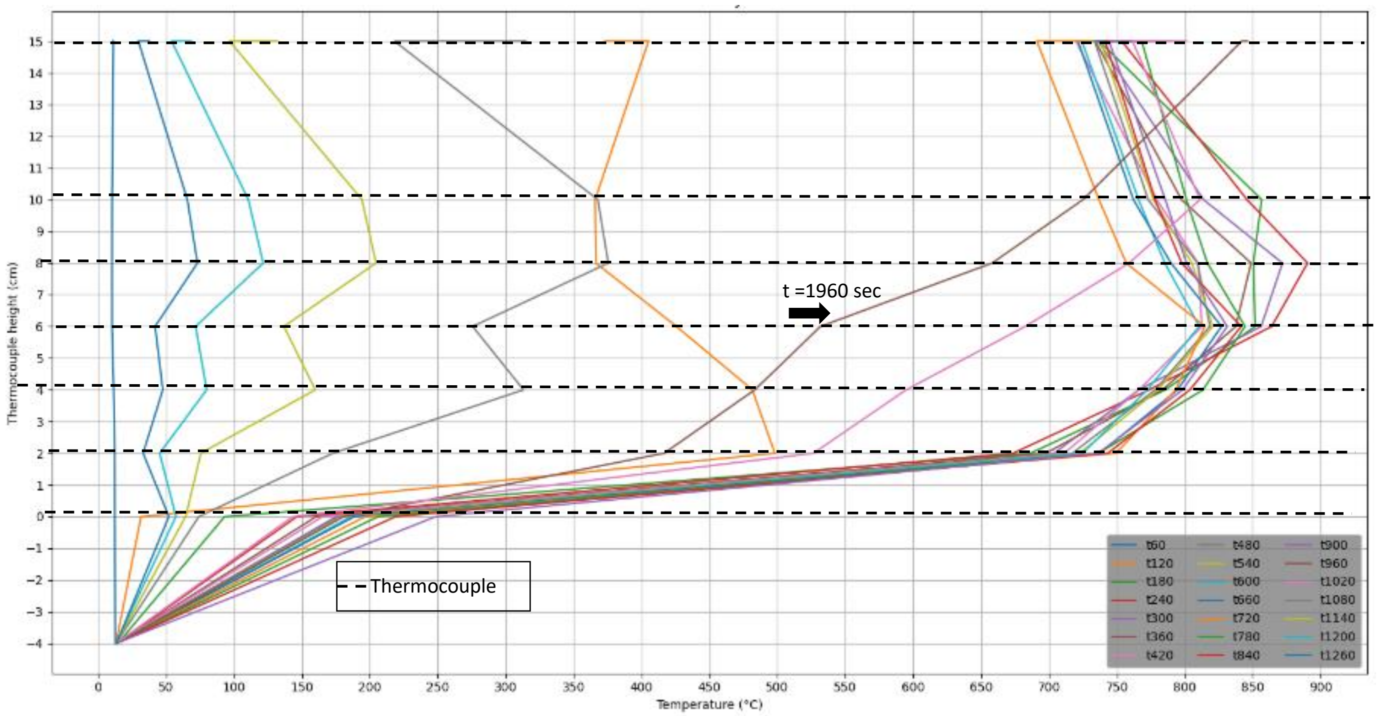


Figure B-1. Steady-state data from the thermocouple tree from ISB Test 3.

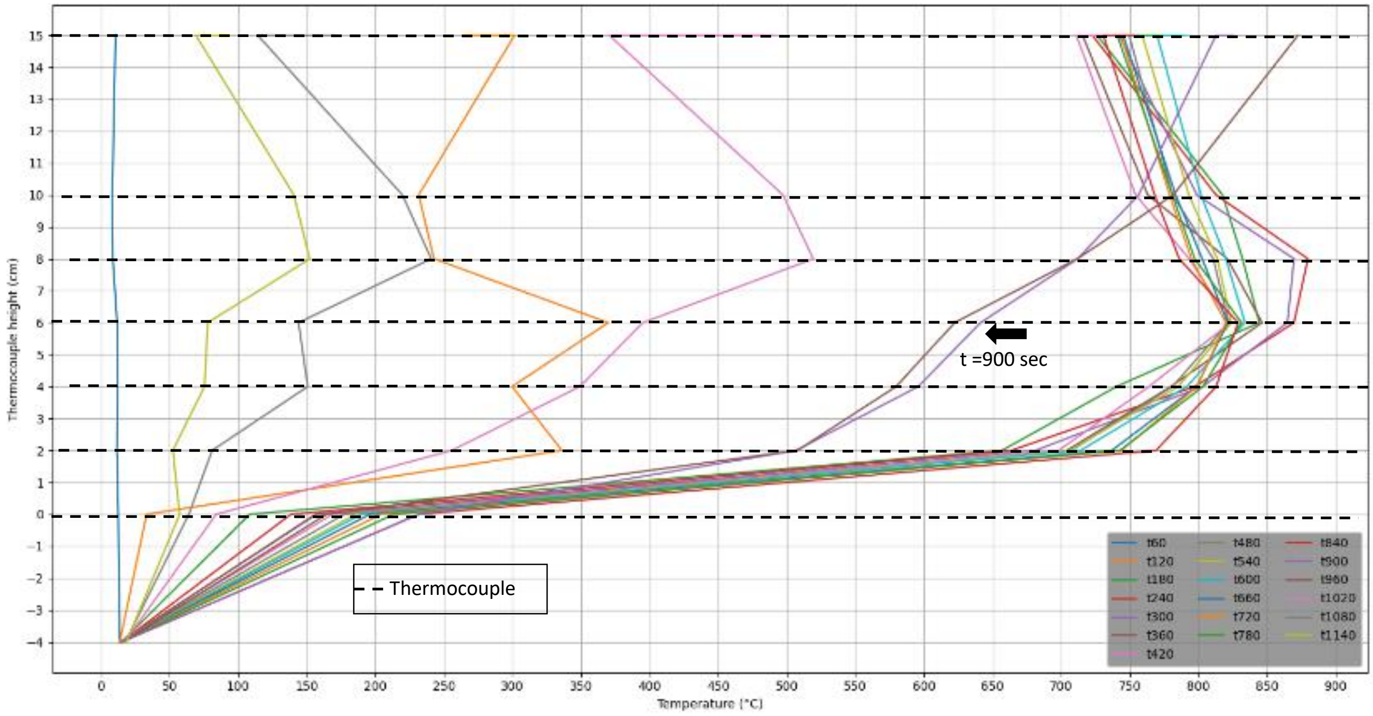


Figure B-2. Steady-state data from the thermocouple tree from ISB Test 4.

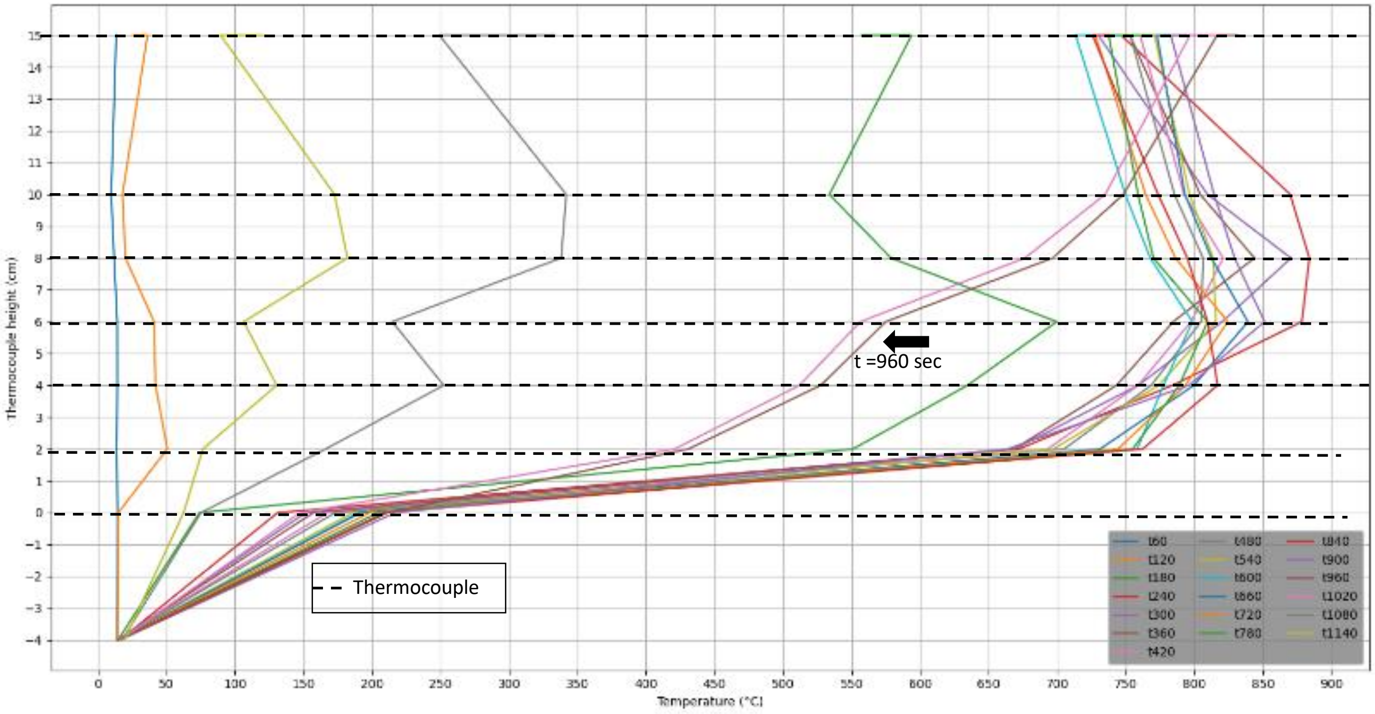


Figure B-3. Steady-state data from the thermocouple tree from ISB Test 5.

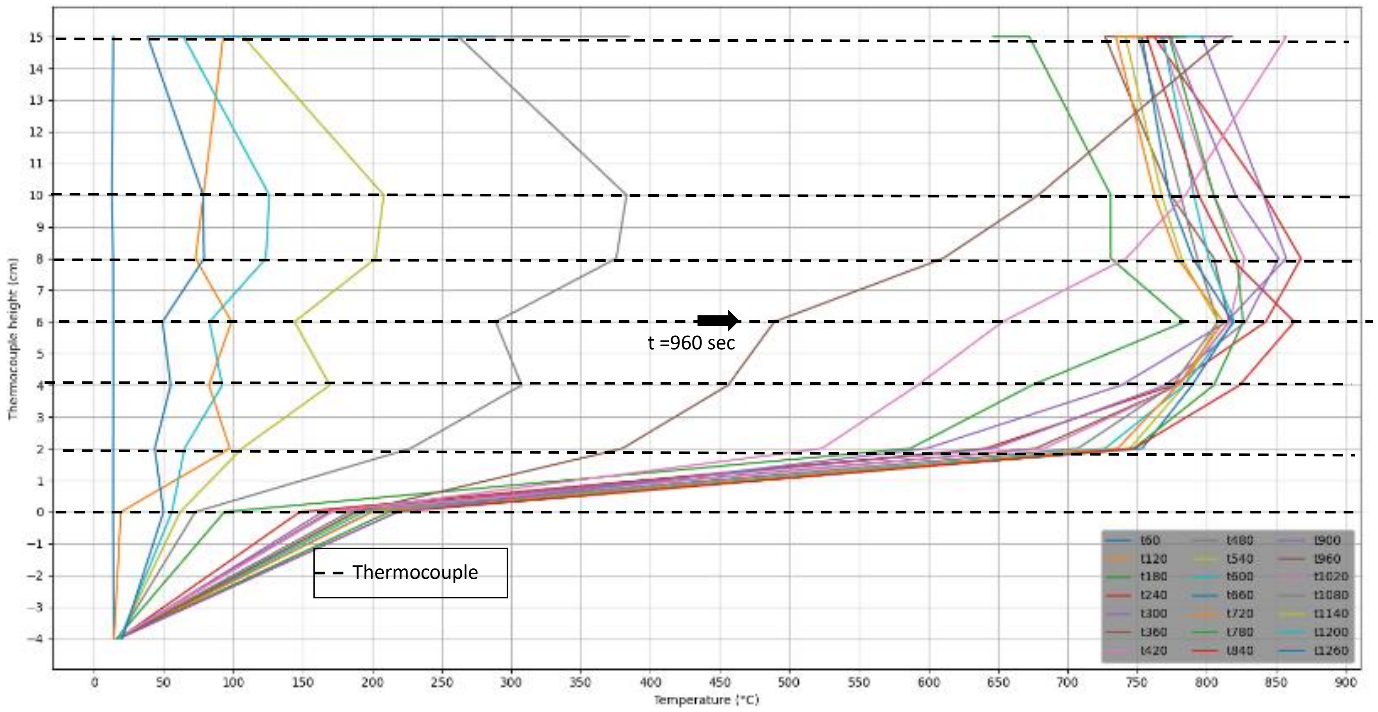


Figure B-4. Steady-state data from the thermocouple tree from ISB Test 6.

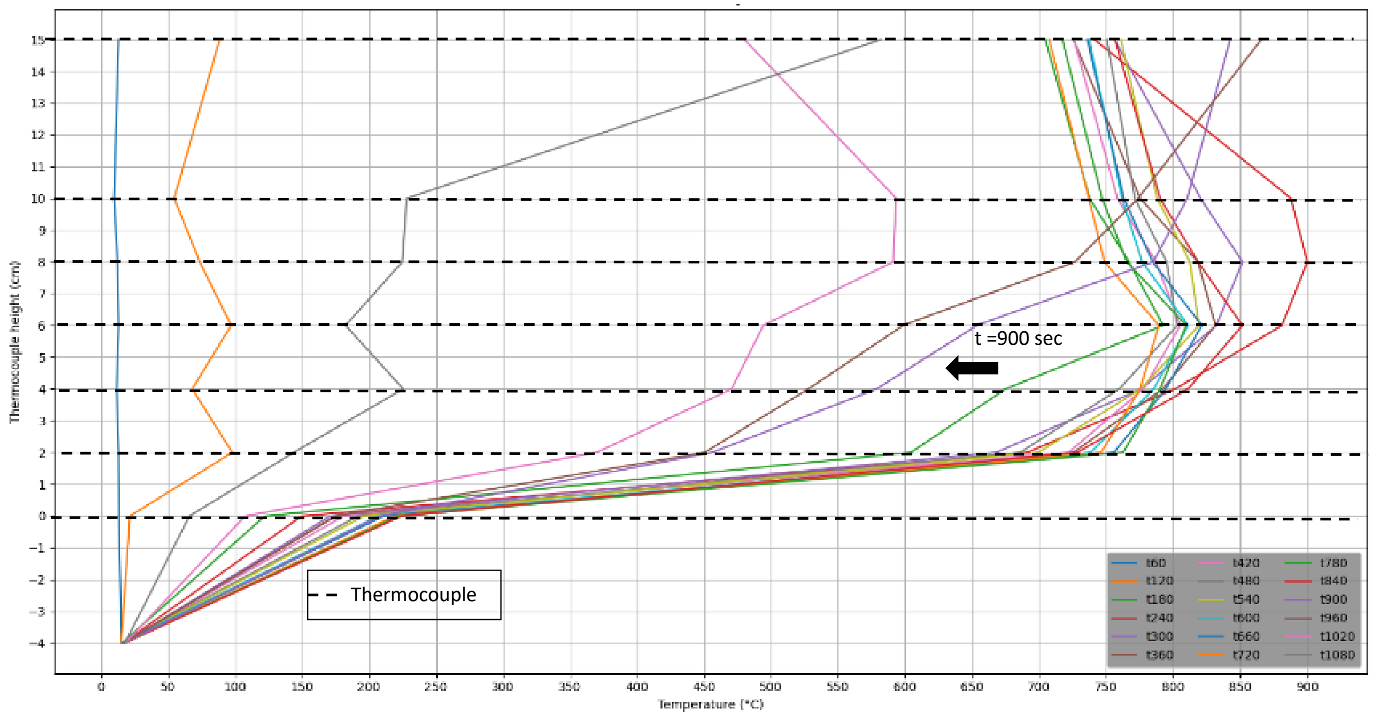


Figure B-5. Steady-state data from the thermocouple tree from ISB Test 7

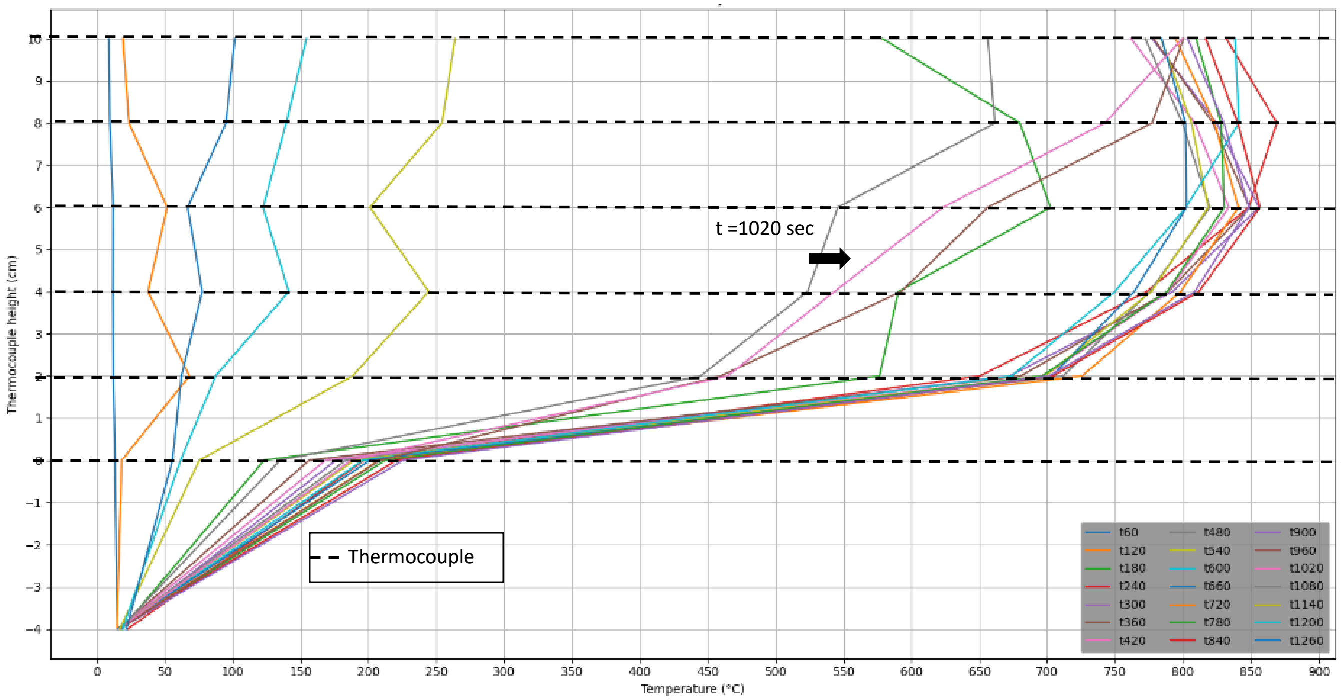


Figure B-6. Steady-state data from the thermocouple tree from ISB Test 8.

# APPENDIX C. LIGHT DETECTION AND RANGING (LIDAR) LASER SCANNING REPORT

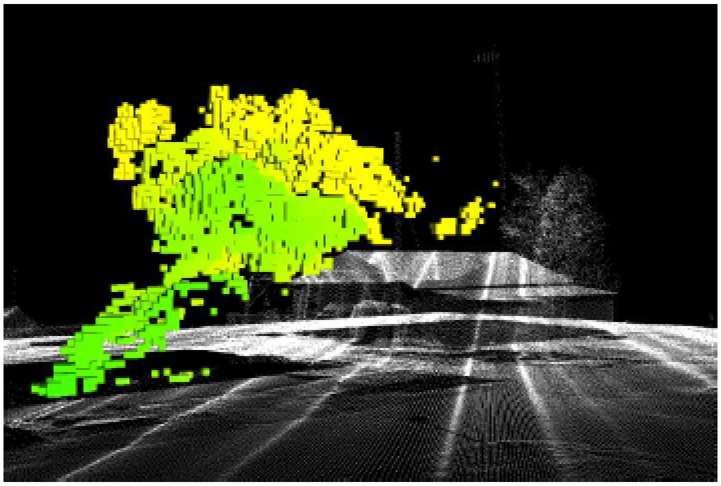
United States Army Corps of Engineers
Cold Regions Research & Engineering Laboratory
Remote Sensing and GIS Center of Expertise
Hanover, NH

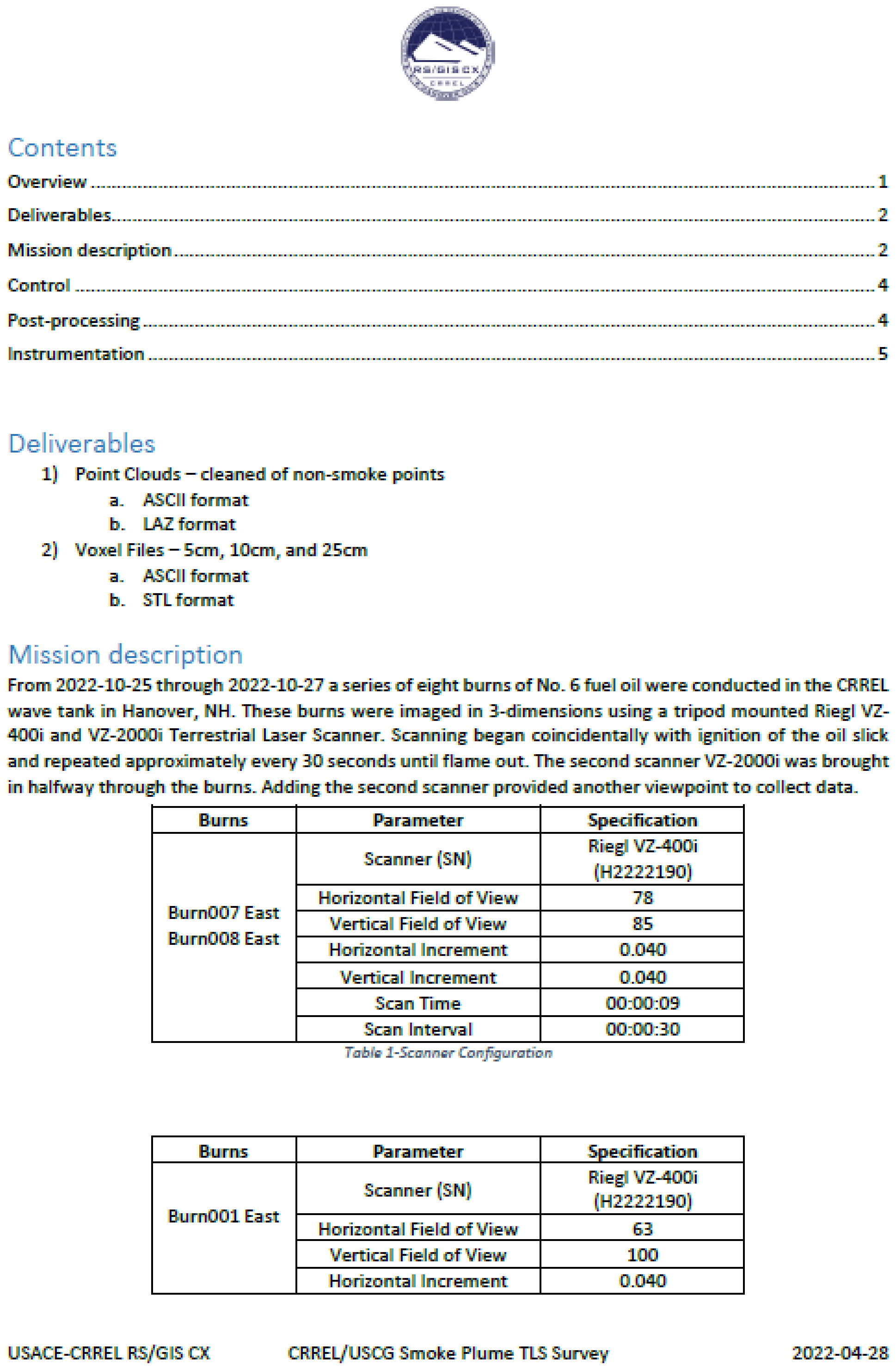
## Hyper-temporal Terrestrial Laser Scanning of Smoke Plumes from burning Alaskan North Slope oil

Final report

### Overview

- Collection date: 2021-10-25 to 2021-10-27
- Location: CRREL Campus, Hanover, NH
- Collection type: Terrestrial
- Sensor: Riegl VZ-400i (SN2222190), Riegl VZ-2000i (H2223747)
- Delivered on: 2022-04-28
- Point of contact: Andrew E. Pohl
- Delivery point of contact: Brandon Booker, Nate Lamie
- Spatial reference system: NAD83(2011)/ UTM Zone 18N / Geoid 12BUS
    - Heights: Orthometric
    - Units: Meters





## Contents

## Deliverables

1) Point Clouds – cleaned of non-smoke points
    a. ASCII format
    b. LAZ format
2) Voxel Files – 5cm, 10cm, and 25cm
    a. ASCII format
    b. STL format

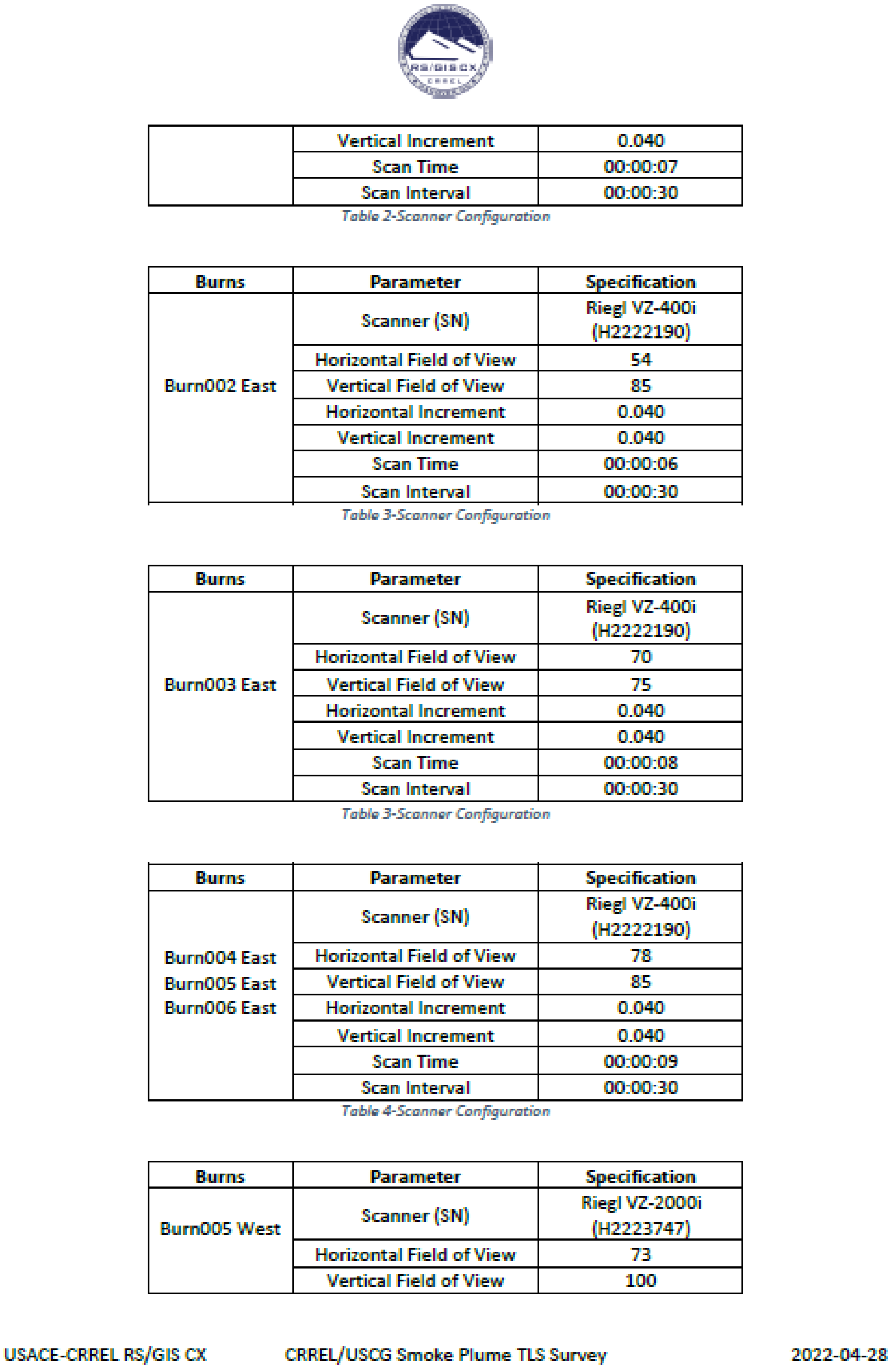
## Mission description

From 2022-10-25 through 2022-10-27 a series of eight burns of No. 6 fuel oil were conducted in the CRREL wave tank in Hanover, NH. These burns were imaged in 3-dimensions using a tripod mounted Riegl VZ-400i and VZ-2000i Terrestrial Laser Scanner. Scanning began coincidentally with ignition of the oil slick and repeated approximately every 30 seconds until flame out. The second scanner VZ-2000i was brought in halfway through the burns. Adding the second scanner provided another viewpoint to collect data.

| Burns | Parameter | Specification |
|---|---|---|
| Burn007 East<br>Burn008 East | Scanner (SN) | Riegl VZ-400i (H2222190) |
| | Horizontal Field of View | 78 |
| | Vertical Field of View | 85 |
| | Horizontal Increment | 0.040 |
| | Vertical Increment | 0.040 |
| | Scan Time | 00:00:09 |
| | Scan Interval | 00:00:30 |

*Table 1-Scanner Configuration*

| Burns | Parameter | Specification |
|---|---|---|
| Burn001 East | Scanner (SN) | Riegl VZ-400i (H2222190) |
| | Horizontal Field of View | 63 |
| | Vertical Field of View | 100 |
| | Horizontal Increment | 0.040 |



| | | |
|---|---|---|
| | Vertical Increment | 0.040 |
| | Scan Time | 00:00:07 |
| | Scan Interval | 00:00:30 |

*Table 2-Scanner Configuration*

| Burns | Parameter | Specification |
|---|---|---|
| Burn002 East | Scanner (SN) | Riegl VZ-400i<br>(H2222190) |
| | Horizontal Field of View | 54 |
| | Vertical Field of View | 85 |
| | Horizontal Increment | 0.040 |
| | Vertical Increment | 0.040 |
| | Scan Time | 00:00:06 |
| | Scan Interval | 00:00:30 |

*Table 3-Scanner Configuration*

| Burns | Parameter | Specification |
|---|---|---|
| Burn003 East | Scanner (SN) | Riegl VZ-400i<br>(H2222190) |
| | Horizontal Field of View | 70 |
| | Vertical Field of View | 75 |
| | Horizontal Increment | 0.040 |
| | Vertical Increment | 0.040 |
| | Scan Time | 00:00:08 |
| | Scan Interval | 00:00:30 |

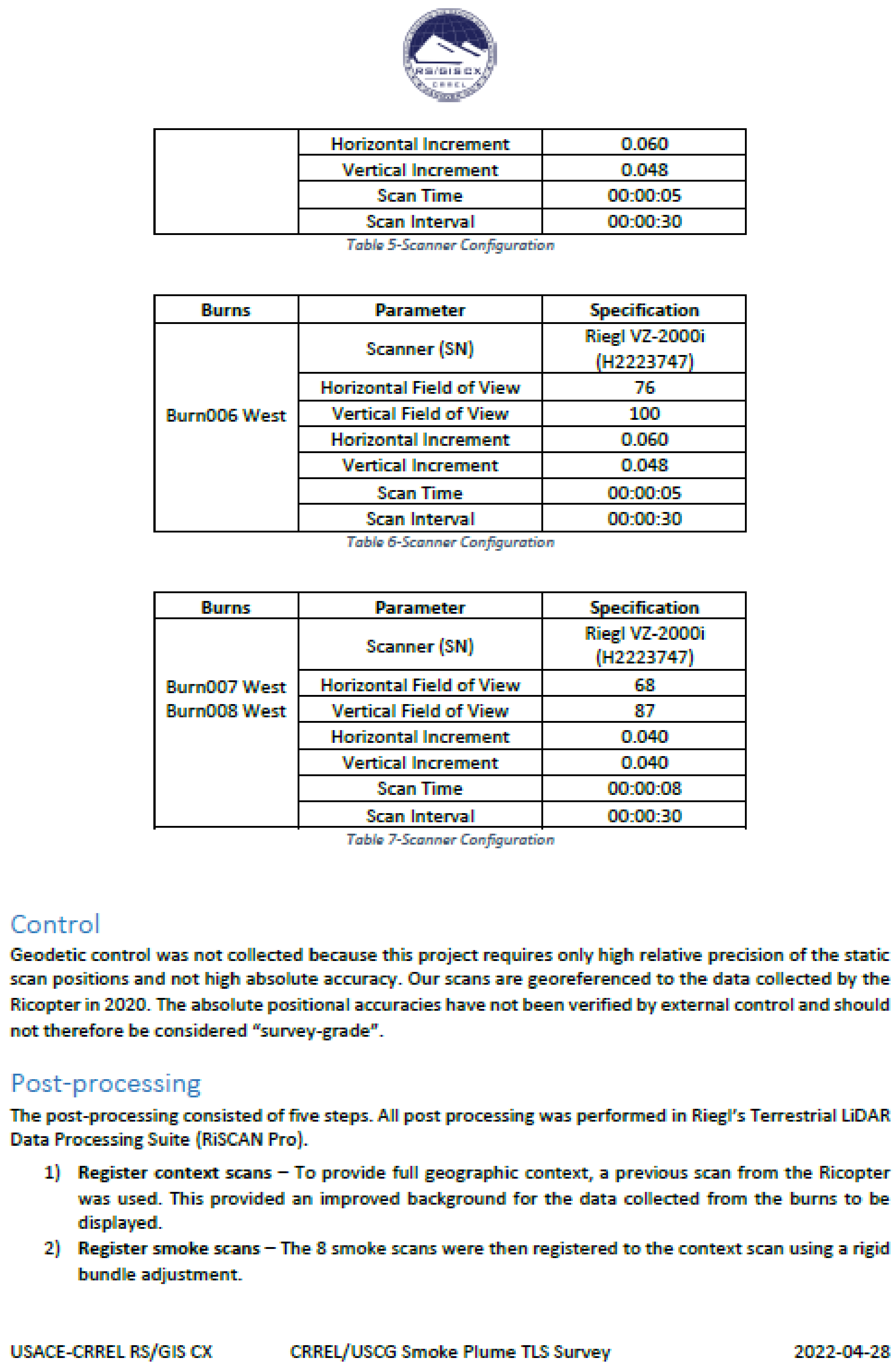
*Table 3-Scanner Configuration*

| Burns | Parameter | Specification |
|---|---|---|
| Burn004 East<br>Burn005 East<br>Burn006 East | Scanner (SN) | Riegl VZ-400i<br>(H2222190) |
| | Horizontal Field of View | 78 |
| | Vertical Field of View | 85 |
| | Horizontal Increment | 0.040 |
| | Vertical Increment | 0.040 |
| | Scan Time | 00:00:09 |
| | Scan Interval | 00:00:30 |

*Table 4-Scanner Configuration*

| Burns | Parameter | Specification |
|---|---|---|
| Burn005 West | Scanner (SN) | Riegl VZ-2000i<br>(H2223747) |
| | Horizontal Field of View | 73 |
| | Vertical Field of View | 100 |

USACE-CRREL RS/GIS CX CRREL/USCG Smoke Plume TLS Survey 2022-04-28



| | | |
|---|---|---|
| | Horizontal Increment | 0.060 |
| | Vertical Increment | 0.048 |
| | Scan Time | 00:00:05 |
| | Scan Interval | 00:00:30 |

*Table 5-Scanner Configuration*

| Burns | Parameter | Specification |
|---|---|---|
| Burn006 West | Scanner (SN) | Riegl VZ-2000i (H2223747) |
| | Horizontal Field of View | 76 |
| | Vertical Field of View | 100 |
| | Horizontal Increment | 0.060 |
| | Vertical Increment | 0.048 |
| | Scan Time | 00:00:05 |
| | Scan Interval | 00:00:30 |

*Table 6-Scanner Configuration*

| Burns | Parameter | Specification |
|---|---|---|
| Burn007 West<br>Burn008 West | Scanner (SN) | Riegl VZ-2000i (H2223747) |
| | Horizontal Field of View | 68 |
| | Vertical Field of View | 87 |
| | Horizontal Increment | 0.040 |
| | Vertical Increment | 0.040 |
| | Scan Time | 00:00:08 |
| | Scan Interval | 00:00:30 |

*Table 7-Scanner Configuration*

## Control

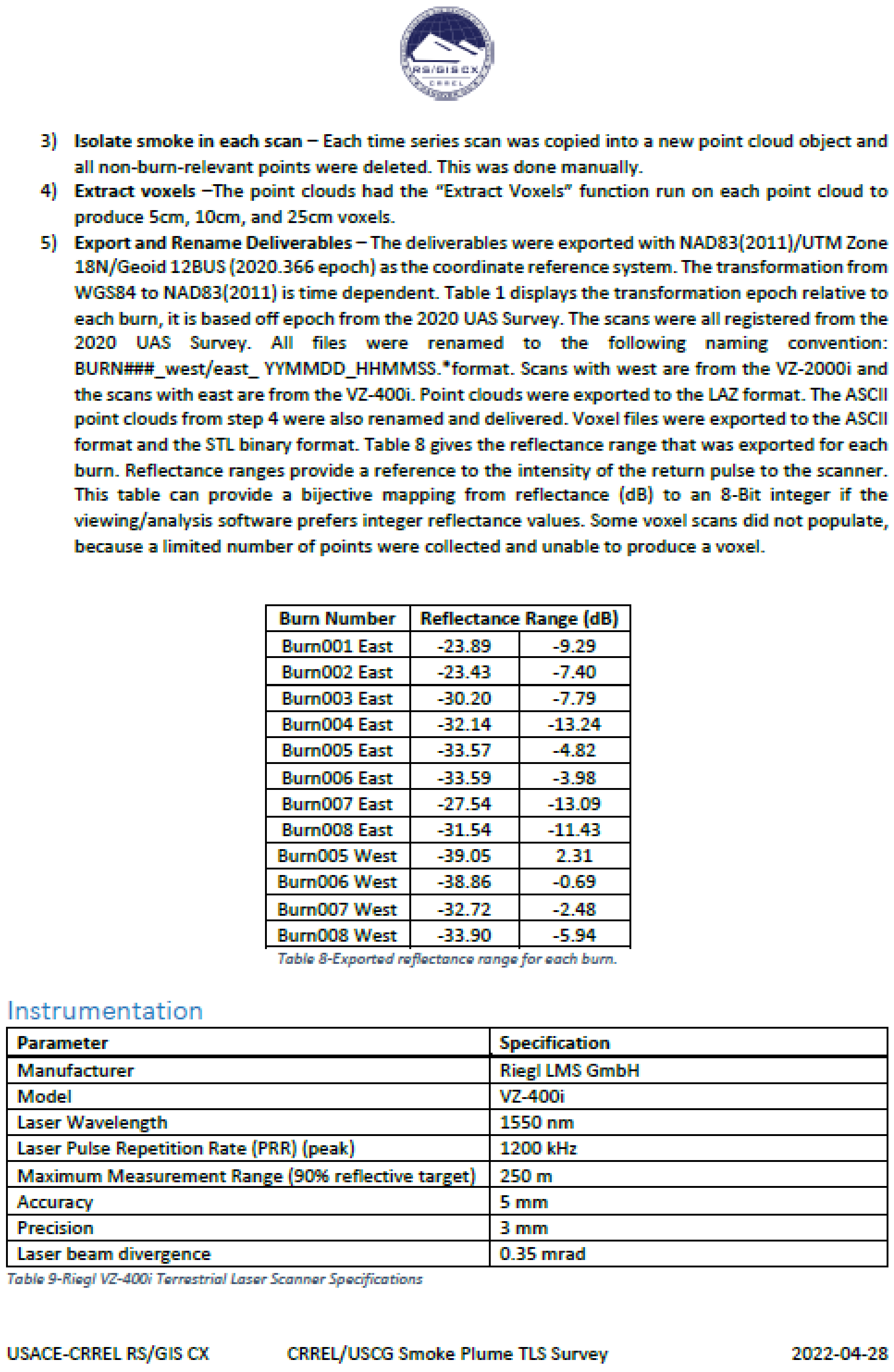
Geodetic control was not collected because this project requires only high relative precision of the static scan positions and not high absolute accuracy. Our scans are georeferenced to the data collected by the Ricopter in 2020. The absolute positional accuracies have not been verified by external control and should not therefore be considered "survey-grade".

## Post-processing

The post-processing consisted of five steps. All post processing was performed in Riegl's Terrestrial LiDAR Data Processing Suite (RiSCAN Pro).

1) **Register context scans** – To provide full geographic context, a previous scan from the Ricopter was used. This provided an improved background for the data collected from the burns to be displayed.
2) **Register smoke scans** – The 8 smoke scans were then registered to the context scan using a rigid bundle adjustment.

USACE-CRREL RS/GIS CX CRREL/USCG Smoke Plume TLS Survey 2022-04-28



3) **Isolate smoke in each scan** – Each time series scan was copied into a new point cloud object and all non-burn-relevant points were deleted. This was done manually.
4) **Extract voxels** –The point clouds had the "Extract Voxels" function run on each point cloud to produce 5cm, 10cm, and 25cm voxels.
5) **Export and Rename Deliverables** – The deliverables were exported with NAD83(2011)/UTM Zone 18N/Geoid 12BUS (2020.366 epoch) as the coordinate reference system. The transformation from WGS84 to NAD83(2011) is time dependent. Table 1 displays the transformation epoch relative to each burn, it is based off epoch from the 2020 UAS Survey. The scans were all registered from the 2020 UAS Survey. All files were renamed to the following naming convention: BURN###_west/east_ YYMMDD_HHMMSS.*format. Scans with west are from the VZ-2000i and the scans with east are from the VZ-400i. Point clouds were exported to the LAZ format. The ASCII point clouds from step 4 were also renamed and delivered. Voxel files were exported to the ASCII format and the STL binary format. Table 8 gives the reflectance range that was exported for each burn. Reflectance ranges provide a reference to the intensity of the return pulse to the scanner. This table can provide a bijective mapping from reflectance (dB) to an 8-Bit integer if the viewing/analysis software prefers integer reflectance values. Some voxel scans did not populate, because a limited number of points were collected and unable to produce a voxel.

| Burn Number | Reflectance Range (dB) | |
|---|---|---|
| Burn001 East | -23.89 | -9.29 |
| Burn002 East | -23.43 | -7.40 |
| Burn003 East | -30.20 | -7.79 |
| Burn004 East | -32.14 | -13.24 |
| Burn005 East | -33.57 | -4.82 |
| Burn006 East | -33.59 | -3.98 |
| Burn007 East | -27.54 | -13.09 |
| Burn008 East | -31.54 | -11.43 |
| Burn005 West | -39.05 | 2.31 |
| Burn006 West | -38.86 | -0.69 |
| Burn007 West | -32.72 | -2.48 |
| Burn008 West | -33.90 | -5.94 |

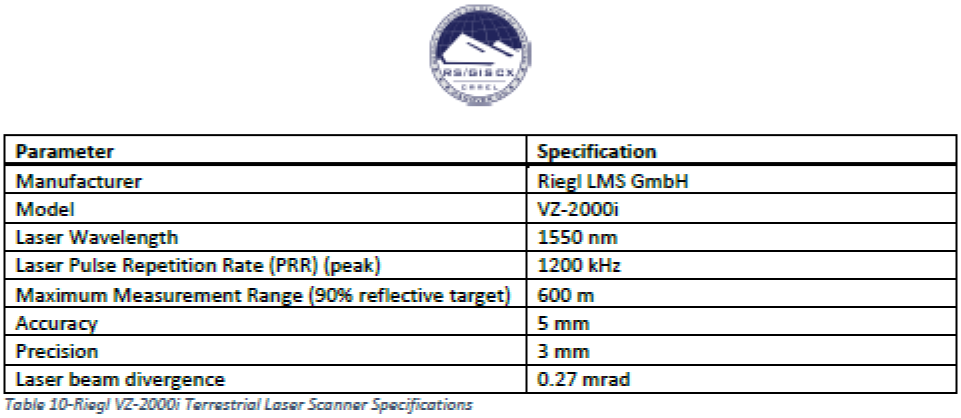
*Table 8-Exported reflectance range for each burn.*

## Instrumentation

| Parameter | Specification |
|---|---|
| Manufacturer | Riegl LMS GmbH |
| Model | VZ-400i |
| Laser Wavelength | 1550 nm |
| Laser Pulse Repetition Rate (PRR) (peak) | 1200 kHz |
| Maximum Measurement Range (90% reflective target) | 250 m |
| Accuracy | 5 mm |
| Precision | 3 mm |
| Laser beam divergence | 0.35 mrad |

*Table 9-Riegl VZ-400i Terrestrial Laser Scanner Specifications*

USACE-CRREL RS/GIS CX CRREL/USCG Smoke Plume TLS Survey 2022-04-28



| Parameter | Specification |
|---|---|
| Manufacturer | Riegl LMS GmbH |
| Model | VZ-2000i |
| Laser Wavelength | 1550 nm |
| Laser Pulse Repetition Rate (PRR) (peak) | 1200 kHz |
| Maximum Measurement Range (90% reflective target) | 600 m |
| Accuracy | 5 mm |
| Precision | 3 mm |
| Laser beam divergence | 0.27 mrad |

*Table 10-Riegl VZ-2000i Terrestrial Laser Scanner Specifications*