EPA Public Access

Author manuscript

Fire Technol. Author manuscript; available in PMC 2018 November 07.

About author manuscripts

Submit a manuscript

Published in final edited form as:

Fire Technol. 2017 November 7; 53(6): 2023–2038. doi:10.1007/s10694-017-0670-2.

Characterization of Emissions from Liquid Fuel and Propane Open Burns

Johanna Aurell¹, David Hubble², Brian K. Gullett^{*3}, Amara Holder³, Ephraim Washburn⁴, and Dennis Tabor³

¹University of Dayton Research Institute, 300 College Park, Dayton, OH 45469, USA

²Naval Surface Warfare Center Dahlgren Division, Dahlgren, VA 22485, USA

³U.S. Environmental Protection Agency, Office of Research and Development, National Risk Management Research Laboratory, Research Triangle Park, NC 27711, USA

⁴Naval Air Warfare Center Weapons Division, China Lake, CA 93555, USA

Abstract

The effect of accidental fires are simulated to understand the response of items such as vehicles, fuel tanks, and military ordnance and to remediate the effects through re-design of the items or changes in operational procedures. The comparative combustion emissions of using jet propellant (JP-5) liquid fuel pools or a propane manifold grid to simulate the effects of accidental fires was investigated. A helium-filled tethered aerostat was used to maneuver an instrument package into the open fire plumes to measure CO, CO₂, fine particulate matter (PM_{2.5}), polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs), and elemental/organic/total carbon (EC/OC/TC). The results showed that all emissions except CO₂ were significantly higher from JP-5 burns than from propane. The major portion of the PM mass from fires of both fuels was less than 1 µm in diameter and differed in carbon content. The PM_{2.5} emission factor from JP-5 burns (129 ± 23 g/kg Fuel_c) was approximately 150 times higher than the PM_{2.5} emission factor from propane burns (0.89 ± 0.21 g/kg Fuel_c). The PAH emissions as well as some VOCs were more than one hundred times higher for the JP-5 burns than the propane burns. Using the propane test method to study flammability responses, the environmental impact of PM_{2.5}, PAHs, and VOCs would be reduced by 2300, 700, and 100 times per test, respectively.

1 INTRODUCTION

Open fires are used to test the behavior of items such as vehicles and fuel tanks in response to a high heat flux accident environment. For example, the military conducts these tests to understand the response of ordnance to fire accidents such as might occur on an aircraft carrier deck. Current practice is to place the test item over a large pool of a liquid hydrocarbon fuel such as kerosene or jet fuel. After ignition, the test item is engulfed in flame and the response of the item to the fire is determined. Responses can include detonations, burns, or no reaction at all. From this information, the item design can be

*Corresponding author: gullett.brian@epa.gov; phone (919) 541-1534; fax (919) 541-0554.

changed to improve the outcome of accidental exposure to fire. This testing practice is referred to as “Fast Cook-Off” or FCO, and is an international standard test that is determined by United Nations (UN) and North Atlantic Treaty Organization (NATO) specifications [1–3]. FCO tests require liquid hydrocarbon fuels. The fuels are usually kerosene-based fuels such as jet propellant 4 (JP-4), JP-5, JP-8, Jet-A, aviation carrier turbine fuel (AVCAT), or commercial kerosene. A common fuel used by the U.S. Navy for FCO is the JP-5 which is a kerosene-based fuel commonly used for aircraft. An undesirable effect of burning liquid jet fuel pools is the production of vast quantities of black smoke. This black smoke is a natural result of insufficient air mixing, resulting in partial combustion and formation of large quantities of black, carbonaceous soot. Pool fires have been studied for burning rate and heat transfer [4; 5] simulating hydrocarbon spills and other industrial accidents, but very little data are available on emissions with the possible exception of work by Frederickson et al. [6; 7], which focused only on small molecules. An alternative fuel source for FCO is gaseous propane that appears to burn without copious pollutants [8; 9]. Other incentives for alternative fuel sources/methods include the high cost of the fuel, long set-up times, ease to extinguish, and difficulties working around smelly, soot-covered facilities resulting from liquid hydrocarbon burns [9]. Various system designs for propane use have been proposed to ensure that a sufficient heat flux and uniform thermal exposure to the test item can result, including a sand bed burner [10] and a steel pipe manifold grid [8]. Testing on the latter showed that the manifold grid using a propane fuel met resulted in comparable temperatures and heat transfer rates to those of JP-5 pool fires [11].

In the work reported here, a propane burner method was tested at the Naval Surface Warfare Center Dahlgren Division (NSWCDD) along with a separate test bed for the traditional JP-5 liquid pool fire. For both applications emissions were measured for comparison of their environmental consequences. The difficulty of accurately and representatively sampling large, open fires was met by using a helium-filled, tethered aerostat, or balloon, to loft an instrument package into the plumes from each source. The instrument package contained various emission monitors and samplers to characterize and quantify emission factors from the fires.

2 MATERIALS AND METHODS

2.1 Sampling instrumentation

An instrumentation package named the “Flyer” was used to sample emissions from open burns of JP-5 and propane. This instrument package has been described in detail elsewhere [12]. Briefly, this light-weight instrument package includes multiple sampling instruments and an onboard computer running a data acquisition (FlyerDAQ) control program enabling sampling instruments to be turned on using user-set carbon dioxide (CO₂) level triggers. For this effort, a ground-based computer was equipped with a data acquisition and control program (GroundDAQ), which was used to view live data and run/control the onboard FlyerDAQ via a XBee wireless network (XBee S1B, Digi International, Inc., Minnetonka, MN, USA).

Target compounds included carbon monoxide (CO), CO₂, particulate matter with an aerodynamic diameter equal to and less than 2.5 μm (PM_{2.5}), polycyclic aromatic

hydrocarbons (PAHs), volatile organic compounds (VOCs), carbonyl compounds, and elemental/organic carbon/total carbon (EC/OC/TC). Targeted emission constituents and their sampling methods are listed in Table 1. Three replicate samples of each target compound and fuel were collected. An ambient background sample for each of the target compounds was also collected as well as trip blanks for PAHs and carbonyls.

The CO₂ and CO sensors were pre-test calibrated and post-test drift-checked on a daily basis using National Institute of Standards and Technology (NIST)-traceable standards in accordance with U.S. EPA Method 3A [14]. PAHs and PM_{2.5} were sampled using Leland Legacy pumps (SKC Inc., USA) and EC/OC/TC and carbonyls were sampled using Gilian 5000 pumps (Sensidyne LP, St. Petersburg, FL, USA). These pumps were calibrated before sampling using a Gilibrator Air Flow Calibration System (Sensidyne LP, St. Petersburg, FL, USA).

2.2 Fuel

2.2.1 Liquid fuel burn—The liquid fuel burns consisted of JP-5 and were performed in a 3.66 m square, 0.305 m deep pan. The pan consisted of approximately 0.050 m of water to provide a level surface for the fuel to float on and to keep the pan cool during testing. JP-5 (1.9 m³) was used for each liquid pool test. Ignition was initiated by the use of 38 L of gasoline, half of which was added in two diagonal corners of the burn pan. The gasoline was ignited by two thermite grenades that were remotely detonated using electronic squib ignitors. Two liquid fuel burns were conducted during test day one and one liquid fuel burn during test day two. A cool-down time of four hours was required between liquid pool burns.

2.2.2 Propane burn—The propane burner is described in detail elsewhere [8]. Briefly, the propane burner consists of 26 parallel burner tubes within a 3.66 m × 3.66 m burn box. The burner tubes are made from nominal 0.05 m schedule 40 galvanized steel pipe. Each burner tube contains 26 vertically-oriented, 2 mm diameter holes, located 0.127 m apart. Liquid propane is supplied to the burner through a flow regulating valve that maintains a constant fuel flow rate for a range of supply pressures. The fuel flow rate for the propane burner is approximately 51 L/min, and each burn lasts for approximately 25 min. Ignition is accomplished with a simple pilot flame that is remotely ignited by an electric spark. The main burner is then initiated by opening the remotely operated primary fuel valve that supplies the full fuel flowrate to the 26 burner tubes. For these tests, three propane burns were conducted during test day two.

2.3 Test set-up

A 4.9 m-diameter helium-filled tethered aerostat was used to maneuver the payload/Flyer into the plume of the JP-5/propane burns (Fig. 1). The aerostat was attached to a tether line spooled on a trailer-mounted winch. The Flyer sampling package was attached to a 244 m payload suspension line to ensure that the aerostat was clear of the plume. The aerostat was pre-positioned downwind of the JP-5/propane burn pan, and the aerostat altitude was adjusted as needed to place the Flyer between 40 and 120 m above the JP-5/propane flame to ensure sufficient capture of the combustion products while ensuring the safety of all equipment from the flames. The Flyer was maneuvered into the plume with the help of three

handling lines, manually operated for optimal sample collection (CO_2 concentrations above ambient background levels). All personnel were located outside the required safety stand-off distance.

2.4 Data and Sample Analysis

Emission factors, in terms of pollutant mass per mass of fuel consumed (mass/mass Fuel_c), were derived using the carbon mass balance approach [21]. This method co-samples the pollutant of interest with the fire-emitted carbon and applies this ratio to the total carbon in the fuel, assuming complete carbon release from the fire. For batch-collected pollutants (Table 1) the sampling period is matched to the simultaneous, time-resolved carbon values to determine emission factors. The emitted carbon is calculated from species such as CO_2 , CO, methane (CH_4), hydrocarbons, and PM while accounting for background levels of the same. Often many of these carbon sources are negligible and can be omitted from the calculation without significant loss of accuracy in the emission factor. JP-5 as jet fuel exists in several grades, and the molecular formula can range from $\text{C}_{12}\text{H}_{26}$ to $\text{C}_{15}\text{H}_{32}$ resulting in a carbon fraction of 0.85. Propane has a molecular formula of C_3H_8 , resulting in a carbon fraction of 0.82.

The modified combustion efficiency (MCE) was calculated ($\text{CO}_2/(\text{CO}_2 + \text{CO})$) for each of the burns [22]. While calculation of combustion efficiency using MCE often considers only gas phase CO and CO_2 , the high particle emission factor and high carbon content of the particles requires inclusion of the unburnt carbon emissions in the calculations. We also calculated MCE including the carbon mass in the $\text{PM}_{2.5}$ ($\text{C}_{\text{PM}_{2.5}}$) in the denominator. Use of the $\text{C}_{\text{PM}_{2.5}}$ term is a more accurate reflection on the combustion performance of the two different fuels.

As per manufacturer recommendations, a custom correction factor was derived for the DustTrak DRX 8533 by dividing the average continuous $\text{PM}_{2.5}$ concentration by the $\text{PM}_{2.5}$ batch filter concentration collected in the same time period. The average correction factor for JP-5 and propane was 1.28 ± 0.11 and 0.45 ± 0.22 , respectively.

PAHs and carbonyl compounds were analyzed as described by Gullett et al. [23]. The PAH toxic equivalent (TEQ) emission factors were determined using toxic equivalent factor (TEF) values relative to benzo-[a]-pyrene (B[a]P-TEQs) by Larsen and Larsen [24]. The VOC concentrations were background-corrected.

To determine any differences in air pollution emissions between the JP-5 and propane burns a single factor one-way analysis of variance (ANOVA) with a level of significance $\alpha = 0.05$ was used. To establish significant difference, the F/F_{crit} value has to be greater than 1.0 and the ANOVA-returned p value (significant value) has to be less than the level of significance (0.05) [25].

3 RESULTS AND DISCUSSION

A total of 35 different emission samples were collected from six burns during two test days. The duration of the three liquid fuel burns, was approximately 26, 26, and 38 min burns with

wind speeds of 2-3 m/s, 1.5-3 m/s, and no wind, respectively. The propane burns were conducted during the same day with constant wind speeds, 1.5 m/s, and the three burns lasted for 26, 25, and 28 min.

3.1 Gaseous Carbon Emissions

The background-corrected CO₂ and CO emission factors were higher for the JP-5 burns (20 g CO/kg fuel_c, 3,085 g CO₂/kg fuel_c) than the propane burns (2.4 g CO/kg fuel_c, 3,003 g CO₂/kg fuel_c) (Table 2). The literature reports 3,084 g CO₂/kg jet fuel [26] and 2,948-2,995 g CO₂/kg propane [26; 27], both values almost identical to those found in this study. The emission factors presented here also compare to surface oil burns at 18-58 g CO/kg oil_c and 2,810-3,023 CO₂/kg oil_c [21; 23; 28; 29]. The MCE calculated with gas phase carbon showed almost complete combustion for propane burns (0.993±0.001) and relatively high values for the JP-5 burns (0.959±0.002). However, including the PM carbon mass (C_{PM2.5}) in the MCE calculations resulted in a large decrease in the MCE from 0.959 to 0.847 for the JP-5 and a no effect for propane, 0.993 to 0.992. This differential effect is due to the large amount of carbon-containing soot emitted from the JP-5 fires. No CH₄ was detected from either JP-5 or propane burns.

3.2 PM

The average PM_{2.5} emission factor from JP-5 burns (129 ± 23 g/kg Fuel_c) was approximately 150 times higher than from propane burns (0.89 ± 0.21 g/kg Fuel_c) (Fig. 2, Table 2), resulting in a statistically significant ($F/F_{crit} = 12$, $p = 0.0006$) difference between the fuels. Fig. 2 shows an approximately 10% decrease in the PM_{2.5} emission factor for the JP-5 burns when the PM carbon mass (C_{PM2.5}) is included in the emission factor calculations; the propane burn (Table 2) shows little such effect.

The PM_{2.5} emission factor for propane is higher than the reported literature values combusting propane in boilers, 0.17 g Total PM/kg propane [27]. This was expected as the propane burner was designed to produce an optically thick flame to get similar radiative heat transfer in the flame as the jet fuel pool fire. Therefore, the burner was not optimized for combustion efficiency as a boiler would be. The JP-5 PM_{2.5} emission factor is more than two times larger than emissions from surface burns of crude oil (58 ± 14 g/kg oil consumed) [23]. The PM size distribution showed that 82% and 97% of the PM from the JP-5 and propane burns, respectively, were PM₁ and less (Fig. 3). Emission factor results for PM₁, PM_{2.5}, PM₄, PM₁₀ and Total PM as well as the accompanying MCE are summarized in Table 3.

The JP-5 PM_{2.5} emission factors from each burn were compared to their respective fuel consumption rate. The result showed a significant difference between JP-5 emissions and fuel consumption rate ($F/F_{crit} = 12.6$, $p = 0.00060$), suggesting that faster JP-5 consumption rates produce less PM_{2.5} emissions, albeit still significantly higher than with propane.

3.3 EC, OC, and TC

The majority of the PM_{2.5} was carbonaceous for both the JP-5 (TC/PM_{2.5} = 0.86) and the propane burns (0.54). The carbonaceous PM_{2.5} from the JP-5 burns was almost entirely EC

($EC/PM_{2.5} = 0.82 \pm 0.022$), unlike from the propane burns where EC accounted for only a minor fraction of the $PM_{2.5}$ ($EC/PM_{2.5} = 0.11 \pm 0.11$). The large EC fraction for the JP-5 and the $PM_{2.5}$ emission factors resulted in highly visible black smoke from the JP-5 burns. The $EC/PM_{2.5}$ of the JP-5 is the same as the $EC/PM_{2.5}$ from surface burns of crude oil ($EC/PM_{2.5} = 0.82 \pm 0.062$) [23]. The composition of $PM_{2.5}$ from the propane burns is similar to the composition of $PM_{2.5}$ from natural gas fired appliances ($EC/PM_{2.5} = 0.063$ to 0.13) [30].

3.4 VOCs

The most abundant VOCs in the plumes were benzene and propene for JP-5 and propane burns, respectively (Table 4). Fig. 4 summarizes some of the most abundant VOCs, all of which are on EPA's list of hazardous air pollutants [31]. Benzene, formaldehyde, 1,3-butadiene, and acetaldehyde are known to be human carcinogens, and acrolein and toluene are considered toxic. The VOC emissions from JP-5 burns compared similar to open burning of crude oil, e.g. benzene and acrolein levels were $1,249 \pm 629$ and 82 ± 54 mg/kg Fuel_c, respectively from JP-5 and $1,574 \pm 372$ and 82 ± 32 mg/kg Fuel_c, respectively from crude oil burns [23].

3.5 PAHs

PAH compounds are products of incomplete combustion. The propane burns, which had a high MCE of 0.993, resulted in detectable levels of only five of the sixteen toxic PAHs. With a lower MCE for JP-5 (MCE 0.959 or MCE $C_{PM_{2.5}}$ 0.847), PAH emissions were more than one hundred times higher than from the propane burns (Table 5). The PAH results showed a statistically significant difference (F/F_{crit} 4.0, $p = 0.0051$) between the propane (1.16 ± 0.14 mg/kg Fuel_c) and JP-5 (189 ± 59 mg/kg Fuel_c) emission factors. The most abundant PAHs varied slightly between the fuels with naphthalene, phenanthrene, fluoranthene, and pyrene having the highest concentrations for JP-5 and naphthalene, phenanthrene, and anthracene having the highest concentrations for propane. The PAH emissions from JP-5 burns (189 ± 59 mg/kg Fuel_c) compared low to crude oil burns (980 ± 157 mg/kg Fuel_c) [23].

Comparing the PAH emission factor from each burn with its fuel consumption rate showed that there was a significant difference between JP-5 emissions and fuel consumption rate (F/F_{crit} 4.0, $p = 0.0051$), suggesting that faster JP-5 consumption rates produce lower PAH emissions.

3.6 Total Amount Emissions Emitted per Test

For a FCO test, it is not practical to insert additional fuel during the test. Therefore, an excess of liquid fuel is used during the FCO test to ensure sufficient duration of the simulation. Additionally, it is not practical to extinguish the pool fire once it has started, so there is always excess fuel that is burned. The propane burner is able to cease the flow of fuel to the burner once the item has reacted and therefore the excess of burnt fuel is prevented. With this ability to shut off the propane flow during the test, approximately 280 kg of propane are used for a typical FCO test while approximately 4500 kg of JP-5 are used in an equivalent test. Table 6 shows the total amount of emissions emitted per test for JP-5 and propane. These data show that use of the propane burner instead of the traditional JP-5

FCO test could decrease the environmental impact substantially, e.g., the PM_{2.5} emissions would be reduced 2000-fold per test.

4 CONCLUSIONS

A comparative emission investigation was carried out to understand the air emission characteristics as well as the environmental consequence of a traditional “Fast Cook-Off” test using JP-5 pool fires and an alternative fuel source test using a propane manifold grid for simulating accidental fires. The differences in emission levels between JP-5 and propane burns were significant. The following was concluded from this study:

- 100-fold higher PM_{2.5}, PAH, VOC, EC, TC emissions were emitted from JP-5 than from propane on an equal fuel mass basis.
- MCE was lower from JP-5 fuel burns (0.847) than propane burns (0.992).
- The higher emission factors from the JP-5 fuel burns are a consequence of incomplete burn out as reflected by the lower MCE value for JP-5 when the carbonaceous soot is taken into consideration.
- Most of the PM emitted from both types of fire was one micrometer or less, 98% for propane and 82% for JP-5.
- The PM_{2.5} from JP-5 burns was comprised primarily of EC and was the same as from surface burns of crude oil.
- The VOC, CO, and CO₂ emission levels from JP-5 burns were similar to surface burns of crude oil.
- The JP-5 PM_{2.5} emissions were more than two times larger than emissions from surface burns of crude oil.
- The JP-5 PAH emissions were five times lower than emissions from surface burns of crude oil.

The results show that using the propane burner for testing flammability effects instead of the traditional FCO test would reduce the PM_{2.5}, PAH, and VOC emissions 2300-, 700- and 100-fold, respectively, significantly reducing the environmental consequence per test. The significant improvements in emissions and the comparability of temperatures and rates of heat transfer to that of the JP-5 pool fires [11], suggest use of the propane grid to simulate and assess the effects of accidental fires.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

References

1. STANAG 4240 Edition2. NATO Liquid Fuel/External Fire, Munition Test Procedures. April 2003.
2. Department of Defense Test Method Standard MIL-STD-2105D. Hazard Assessment Tests for Non-Nuclear Munitions. April 2011.

3. TB 700-2 NAVSEAINST 8020.5C, 11A-1-47, DLAR 8220.1. Joint Technical Bulletin, Department of Defense Ammunition and Explosives Hazard Classification Procedures. May 2004.
4. Jiang CM, Li YT, Huang H, Zhao JL, Wang Z, Zhang JZ. Experimental study of burning rate in large-scale rectangular pool fire. *J Fire Sci.* 2016; 34:323–334.
5. Sikanen T, Hostikka S. Modeling and simulation of liquid pool fires with in-depth radiation absorption and heat transfer. *Fire Safety Journal.* 2016; 80:95–109.
6. Frederickson K, Kearney SP, Grasser TW. Laser-induced incandescence measurements of soot in turbulent pool fires. *Applied Optics.* 2011; 50:A49–A59. [PubMed: 21283220]
7. Frederickson K, Kearney SP, Luketa A, Hewson JC, Grasser TW. Dual-Pump CARS Measurements of Temperature and Oxygen in a Turbulent Methanol-Fueled Pool Fire. *Combust Sci Technol.* 2010; 182:941–959.
8. Hubble, D., Yagla, J., Washburn, E., Ford, K. Development and characterization of a propane fueled fast cook-off burner. Insensitive Munitions and Energetic Materials Technology Symposium; Rome, Italy. 2015. <http://imemg.org/wp-content/uploads/2015/06/7B2-17109-Development-and-Characterization-of-a-Propane-Fueled-Fast-Cookoff-burner.pdf>. Accessed December 29 2016
9. Toreheim, J., Jansson, A., Connedahl, K. Pimp my flames – How to create a hot environment. Insensitive Munitions and Energetic Materials Technology Symposium; Rome, Italy. 2015. <http://imemg.org/wp-content/uploads/2015/06/7B1-17194-Pimp-my-Flames-How-to-Create-a-Hot-Environment.pdf>. Accessed December 29 2016
10. Toreheim, J., Evers, B., Möllerström, P. The sand bed burner and the adiabatic surface temperature probe – The future equipment for fast cook off testing. Insensitive Munitions and Energetic Materials Technology Symposium; San Diego, USA. 2013.
11. Yagla, J., Griffiths, D., Busic, J. Heat Flux and Thermal Response Measurements for Designing a Propane Fuel Fast Cook-Off Test Apparatus. Insensitive Munitions and Energetic Materials Technology Symposium; Las Vegas. 2012.
12. Aurell J, Gullett BK, Yamamoto D. Emissions from Open Burning of Simulated Military Waste from Forward Operating Bases. *Enviro Sci Technol.* 2012; 46:11004–11012.
13. US EPA Method 10A. Determination of carbon monoxide emissions in certifying continuous emission monitoring systems at petroleum refineries. <https://www3.epa.gov/ttnemc01/promgate/m-10a.pdf> Accessed July 25, 2016
14. US EPA Method 3A. Determination of oxygen and carbon dioxide concentrations in emissions from stationary sources (instrumental analyzer procedure). 1989. <http://www.epa.gov/ttn/emc/promgate/m-03a.pdf> Accessed May 5, 2014
15. 40 CFR Part 50, Appendix L. Reference method for the determination of particulate matter as PM_{2.5} in the Atmosphere. 1987. <https://www.gpo.gov/fdsys/pkg/CFR-2014-title40-vol2/pdf/CFR-2014-title40-vol2-part50-appL.pdf> Accessed November 22, 2016
16. US EPA Method TO-13A. Determination of polycyclic aromatic hydrocarbons (PAHs) in ambient air using gas chromatography/mass spectrometry (GC/MS). 1999. <http://www.epa.gov/ttnamti1/files/ambient/airtox/to-13arr.pdf> Accessed January 26, 2017
17. US EPA Compendium Method TO-15. Determination of volatile organic compounds (VOCs) in air collected in specially-prepared canisters and analyzed by gas chromatography/mass spectrometry (GC/MS). 1999. <http://www.epa.gov/ttnamti1/files/ambient/airtox/to-15r.pdf> Accessed November 10, 2015
18. US EPA Method 25C. Determination of nonmethane organic compounds (NMOC) in landfill gases. <http://www.epa.gov/ttn/emc/promgate/m-25c.pdf> Accessed May 11, 2016
19. Khan B, Hays MD, Geron C, Jetter J. Differences in the OC/EC Ratios that Characterize Ambient and Source Aerosols due to Thermal-Optical Analysis. *Aerosol Sci Technol.* 2012; 46:127–137.
20. US EPA Compendium Method TO-11A. Determination of Formaldehyde in Ambient Air Using Adsorbent Cartridge Followed by High Performance Liquid Chromatography (HPLC). 1999. <https://www3.epa.gov/ttnamti1/files/ambient/airtox/to-11ar.pdf> Accessed July 25, 2016
21. Laursen KK, Ferek R, Hobbs P, Rasmussen RA. Emission factors for particles, elemental carbon, and trace gases from the Kuwait oil fires. *J Geophys Res.* 1992; 97:14491–14497.

22. Ward, DE., Hao, WM. Projections of emissions from burning of biomass for use in studies of global climate and atmospheric chemistry; Air Waste Manag Assoc. Jun 16–21. 1991 p. 91-128. https://www.fs.fed.us/rm/pubs_journals/1991/rmrs_1991_ward_d001.pdf Accessed June 1 2017
23. Gullett BK, Aurell J, Holder A, Mitchell W, Greenwell D, Hays M, Conmy R, Tabor D, Preston W, George I, Abrahamson JP, Vander Wal R, Holder E. Characterization of Emissions and Residues from Simulations of the Deepwater Horizon Surface Oil Burns. *Mar Poll Bull.* 2016; 117:392–405.
24. Larsen, JCL. Air pollution and health. Cambridge, UK: The Royal Society of Chemistry; 1998. P.B. Chemical carcinogens; p. 33-56.
25. Seltman, HJ. Experimental Design and Analysis. Carnegie Mellon University. 2015 <http://www.stat.cmu.edu/~hseltman/309/Book/Book.pdf>. Accessed Jun 5 2017
26. U.S. Department of Energy. Carbon dioxide emissions coefficients by fuel. U.S. Energy Information Administration; https://www.eia.gov/environment/emissions/co2_vol_mass.cfm Accessed July 28, 2016
27. US EPA AP-42. Liquefied petroleum gas combustion. 1993. <https://www3.epa.gov/ttnchie1/ap42/ch01/bgdocs/b01s05.pdf>, Accessed July 28, 2016
28. Middlebrook AM, Murphy DM, Ahmadov R, Atlas EL, Bahreini R, Blake DR, Brioude J, de Gouw JA, Fehsenfeld FC, Frost GJ, Holloway JS, Lack DA, Langridge JM, Lueb RA, McKeen SA, Meagher JF, Meinardi S, Neuman JA, Nowak JB, Parrish DD, Peischl J, Perring AE, Pollack IB, Roberts JM, Ryerson TB, Schwarz JP, Spackman JR, Warneke C, Ravishankara AR. Air quality implications of the Deepwater Horizon oil spill. *P Natl Acad Sci USA.* 2012; 109:20280–20285.
29. Perring AE, Schwarz JP, Spackman JR, Bahreini R, de Gouw JA, Gao RS, Holloway JS, Lack DA, Langridge JM, Peischl J, Middlebrook AM, Ryerson TB, Warneke C, Watts LA, Fahey DW. Characteristics of black carbon aerosol from a surface oil burn during the Deepwater Horizon oil spill. *Geophys Res Lett.* 2011; 38:5.
30. Chow JC, Watson JG, Lowenthal DH, Chen LWA, Motallebi N. PM_{2.5} source profiles for black and organic carbon emission inventories. *Atmos Environ.* 2011; 45:5407–5414.
31. US EPA Hazardous Air Pollution List. Clean Air Act: Title 42 - The public health and welfare. U.S. Government Printing Office; 2008. <http://www.gpo.gov/fdsys/pkg/USCODE-2008-title42/pdf/USCODE-2008-title42-chap85.pdf> Accessed May 5 2014

Fig. 1. Schematic of test set-up, not to scale. Note: Liquid and propane burns were conducted in separate facilities.

Fig. 2.

PM_{2.5} emission factors from JP-5 and propane burns. Modified combustion efficiency (MCE) was determined during collection of PM_{2.5} batch emissions. C_{PM2.5} values include PM-bound carbon in the calculation.

Fig. 3. PM size distribution. Note: PM_x equals particulate matter with a median aerodynamic diameter equal to and less than $x \mu\text{m}$ ($x = 1, 2.5, 4$ or $10 \mu\text{m}$).

Fig. 4. VOC emission factors. * = VOC on U.S. EPA's list of hazardous air pollutants [31].

Table 1

Target compounds and sampling methods.

Analyte	Instrument/Technique	Frequency	Method Reference
CO ₂	LICOR-820 ^a , NDIR	Continuous – 1 Hz	U.S. EPA Method 10A [13]. U.S. EPA Method 3A calibration [14]
CO	e2V EC4-500-CO ^b , Electrochemical cell	Continuous – 1 Hz	U.S. EPA Method 10A [13]. Method 3A calibration [14]
PM _{2.5}	SKC Impactor ^c with a 47 mm Teflon filter with 2 micron pore size	Batch – 10 L/min	40 CFR Part 50, Appendix L [15]
PM ₁ , PM _{2.5} , PM ₄ , PM ₁₀ , Total PM	TSI DustTrak DRX 8533 ^d	Continuous – 1 Hz	Factory calibration to respirable fraction. Custom correction factor using batch PM _{2.5} sample.
PAHs	Quartz filter PUF/XAD-2/PUF, LRGC/LRMS ^e	Batch – 5 L/min	Modified U.S. EPA Method TO-13A [16]
VOCs	6 L SUMMA canister, GC/LRMS, GC/FID ^f	Batch – 2 L/min, 0.3 L/min	U.S. EPA Method TO-15 [17] with modified U.S. EPA Method 25C [18] (CO, CO ₂ , CH ₄)
EC/OC/TC	SKC Impactor ^c with a 47 mm quartz filter	Batch – 3 L/min	Modified NIOSH Method 5040 as described in Khan et al. [19]
Carbonyls	DNPH cartridge ^h	Batch – 1 L/min	U.S. EPA Method TO-11A [20]

^a LI-COR Biosciences, Lincoln, Nebraska, USA. NDIR – Non-dispersive infrared detection.^b SGX Sensortech, Essex, UK.^c SKC Inc., USA.^d TSI Incorporated, Shoreview, MN, USA.^e LRGC/LRMS - Low Resolution GC/Low Resolution MS.^f FID – Flame ionization detector.^g AethLabs, San Francisco, CA, USA.^h 2,4-Dinitrophenylhydrazine, Sigma-Aldrich, PN 505323, Dorset, UK.

Table 2

Results.^a

Pollutant	Unit	JP-5		Propane	
		Average	Stand. Dev.	Average	Stand. Dev.
CO ₂	g/kg Fuel _c	3,085	7.0	3,003	0.34
CO	g/kg Fuel _c	20	4.4	2.4	0.22
CO ₂	g C/kg Fuel _c	841	1.9	819	0.10
CO	g C/kg Fuel _c	7.8	2.1	1.0	0.10
CH ₄	g/kg Fuel _c	ND		ND	
MCE ^b	Ratio	0.959	0.029	0.993	0.0055
MCE C _{PM2.5} ^b	Ratio	0.847	0.015	0.992	0.0058
PM _{2.5}	g/kg Fuel _c	129	23	0.892	0.206
PM _{2.5} C _{PM2.5}	g/kg Fuel _c	114	18	0.891	0.205
EC	g/kg Fuel _c	105	17	0.10	0.090
OC	g/kg Fuel _c	6.4	2.7	0.37	0.15
TC	g/kg Fuel _c	111	16	0.48	0.23
OC/EC	Ratio	0.063	0.031	9.4	10.5
EC/PM _{2.5}	Ratio	0.82	0.022	0.11	0.11
Σ VOCs ^c	mg/kg Fuel _c	1,764	568	236	167
Σ PAH ₁₆	mg/kg Fuel _c	189	59	4.3	1.2
Σ PAH - TEQ	mg B[a]P _{eq} /kg Fuel _c	1.2	0.14	0.0010	0.00021
Fuel Consumption Rate	m ³ /min	0.065	0.013	0.051	0

^aUnits in mass of pollutant per mass of fuel consumed (Fuel_c). NS = No sample, Stand. Dev. = Standard deviation. ND = not detected.^bMCE = modified combustion efficiency from the entire burn.^cSum of 77 VOCs analyzed via U.S. EPA Method TO-15 [17] and TO-11A [20].^dAbsolute difference.

Table 3

PM emission factors derived from optical measurements.

Size	Unit	JP-5	Propane
PM ₁	g/kg Fuel	149 ± 9.6	1.51 ± 0.48
PM _{2.5}	g/kg Fuel	152 ± 9.7	1.51 ± 0.48
PM ₄	g/kg Fuel	161 ± 11.2	1.51 ± 0.48
PM ₁₀	g/kg Fuel	178 ± 14.5	1.52 ± 0.48
Total PM	g/kg Fuel	182 ± 14.3	1.54 ± 0.48
MCE	Fraction	0.959 ± 0.029	0.993 ± 0.006

Table 4VOC emission factors.^a

	JP-5	Propane
	mg/kg Fuel _c	
Benzene ^b	1,249 ± 629	2.5 ± 2.1
Formaldehyde ^{b, c}	322 ± 209	42 ± 12
Propene	98 ± 70	101 ± 77
Ethanol	96 ± 20	68
Acetaldehyde ^{b, c}	93 ± 82	17 ± 2.8
Acrolein ^b	82 ± 54	9.6 ± 6.9
Benzaldehyde ^c	81 ± 59	ND
Acetone ^c	77 ± 124	4.8 ± 5.9
Toluene ^b	71 ± 20	5.1 ± 4.3 ^d
1,3-Butadiene ^b	42 ± 28	ND
Styrene ^b	41 ± 25	ND
Ethyl Acetate	39 ± 35 ^d	12
<i>m,p</i> -Xylenes ^b	22 ± 12 ^d	4.6
1,2,4-Trimethylbenzene	16 ± 10	ND
Carbon Disulfide ^b	14 ± 22	5.5 ± 10 ^d
<i>n</i> -Hexane	13 ± 14	4.5
2-Butanone (MEK)	13 ± 4.5	3.8 ± 1.4
<i>o</i> -Xylene ^a	9.7 ± 5.1	ND
Ethylbenzene	9.2 ± 5.7	ND

^aRange of data one standard deviation if nothing else is mentioned. The VOCs shown here were selected based on the number of samples detectable above three times the detection limit and their relevance to the EPA's list of hazardous air pollutants list and their role as greenhouse gas/ozone precursors. Full list of the 87 analyzed VOCs and their emission factors are presented in SI Table S1.

^bOn EPA's list of hazardous air pollutants (HAP list) [31].

^cSampled and analyzed by U.S. EPA Method 11A [20].

^dAbsolute difference.

Table 5PAH Emission Factors.^a

PAHs	JP-5		Propane	
	mg/kg Fuel _c	mg B[a]P _{eq} /kg Fuel _c	mg/kg Fuel _c	mg B[a]P _{eq} /kg Fuel _c
Naphthalene	9.31E+01 ± 2.6E+01	NA	8.58E-01 ± 8.4E-02	NA
Acenaphthylene	2.24E+01 ± 1.5E+01	NA	ND	NA
Acenaphthene	ND	NA	ND	NA
Fluorene	2.40E+00 ± 7.5E-01	NA	ND	NA
Phenanthrene	2.28E+01 ± 5.8E+00	1.14E-02 ± 2.9E-03	2.20E-01 ± 5.9E-02	1.10E-04 ± 2.9E-05
Anthracene	2.60E+00 ± 7.3E-01	1.30E-03 ± 3.6E-04	5.67E-02 ± 4.2E-02	2.84E-05 ± 2.1E-05
Fluoranthene	1.47E+01 ± 3.8E+00	7.36E-01 ± 1.9E-01	1.70E-02 ± 3.4E-03	8.48E-04 ± 1.7E-04
Pyrene	1.47E+01 ± 3.9E+00	1.47E-02 ± 3.9E-03	1.09E-02 ± 1.7E-03	1.09E-05 ± 1.7E-06
Benzo(a)anthracene	1.28E+00 ± 2.8E-01	6.40E-03 ± 1.1E-03	ND	ND
Chrysene	1.97E+00 ± 4.8E-01	5.92E-02 ± 1.2E-02	ND	ND
Benzo(b)fluoranthene	2.09E+00 ± 5.9E-01	2.09E-01 ± 5.9E-02	ND	ND
Benzo(k)fluoranthene	2.30E+00 ± 4.7E-01	1.15E-01 ± 2.3E-02	ND	ND
Benzo(a)pyrene	2.90E+00 ± 8.6E-01	2.90E+00 ± 8.6E-01	ND	ND
Indeno(1,2,3-cd)pyrene	2.19E+00 ± 4.6E-01	2.19E-01 ± 4.6E-02	ND	ND
Dibenz(a,h)anthracene	ND	ND	ND	ND
Benzo(ghi)perylene	3.61E+00 ± 9.6E-01	7.21E-02 ± 1.9E-02	ND	ND
SUM PAH₁₆	1.89E+02 ± 5.9E+01	4.34E+00 ± 1.2E+00	1.16E+00 ± 1.4E-01	9.97E-04 ± 2.1E-04

^aNA – not applicable, compounds do not have assigned TEF values. Range of data represents 1 standard deviation. All PAHs are on EPA's list of hazardous pollutants [31].

Table 6

Total Amount Emissions Emitted per Test.

	JP-5 kg	Propane kg
PM _{2.5}	580	0.25
CO ₂	13,882	841
CO	91	0.67
Sum PAH ₁₆	0.85	0.0012
Sum VOCs ^a	7.9	0.066
EC	473	0.028
OC	29	0.10
TC	500	0.13

^aSum of 77 VOCs analyzed via U.S. EPA Method TO-15 [17] and TO-11A [20]