U.S. DEPARTMENT OF ENERGY

Crude Oil Characterization Research Study

Report to Congress
April 2020

United States Department of Energy
Washington, DC 20585

Message from the Secretary

As set forth in Section 7309 of the Fixing America's Surface Transportation Act (FAST Act), I am pleased to submit the enclosed report titled, Crude Oil Characterization Research Study Report to Congress. The report was prepared by the Department of Energy in cooperation with the Department of Transportation and summarizes the progress being made in this important area of research. Pursuant to statutory requirements, this report is being provided to the following Members of Congress:

- **The Honorable Michael R. Pence**
  President of the Senate

- **The Honorable Mitch McConnell**
  Senate Majority Leader

- **The Honorable Nancy Pelosi**
  Speaker of the House of Representatives

- **The Honorable Lisa Murkowski**
  Chairwoman, Senate Committee on Energy and Natural Resources

- **The Honorable Joe Manchin**
  Ranking Member, Senate Committee on Energy and Natural Resources

- **The Honorable Eddie Bernice Johnson**
  Chairwoman, House Committee on Science, Space and Technology

- **The Honorable Frank Lucas**
  Ranking Member, House Committee on Science, Space and Technology

- **The Honorable Frank Pallone**
  Chairman, House Committee on Energy and Commerce

- **The Honorable Greg Walden**
  Ranking Member, House Committee on Energy and Commerce

- **The Honorable Bobby Rush**
  Chairman, Subcommittee on Energy
  House Committee on Energy and Commerce

- **The Honorable Fred Upton**
  Ranking Member, Subcommittee on Energy
  House Committee on Energy and Commerce

- **The Honorable Richard Shelby**
  Chairman, Senate Committee on Appropriations

- **The Honorable Patrick Leahy**
  Vice Chairman, Senate Committee on Appropriations

- **The Honorable Lamar Alexander**
  Chairman, Subcommittee on Energy and Water Development
  Senate Committee on Appropriations

- **The Honorable Dianne Feinstein**
  Ranking Member, Subcommittee on Energy and Water Development
  Senate Committee on Appropriations

- **The Honorable Susan Collins**
  Chairman, Subcommittee on Transportation, Housing and Urban Development,
  and Related Agencies
  Senate Committee on Appropriations

- **The Honorable Jack Reed**
  Ranking Member, Subcommittee on Transportation, Housing and Urban Development,
  and Related Agencies
  Senate Committee on Appropriations

- **The Honorable Nita M. Lowey**
  Chairwoman, House Committee on Appropriations

- **The Honorable Kay Granger**
  Ranking Member, House Committee on Appropriations

- **The Honorable Marcy Kaptur**
  Chairwoman, Subcommittee on Energy and Water Development
  House Committee on Appropriations

- **The Honorable Mike Simpson**
  Ranking Member, Subcommittee on Energy and Water Development
  House Committee on Appropriations

- **The Honorable David Price**
  Chairman, Subcommittee on Transportation, Housing and Urban Development,
  and Related Agencies
  House Committee on Appropriations

- **The Honorable Mario Diaz-Balart**
  Chairman, Subcommittee on Transportation, Housing and Urban Development,
  and Related Agencies
  House Committee on Appropriations

- **The Honorable Roger Wicker**
  Chairman, Senate Committee on Commerce, Science and Transportation

- **The Honorable Maria Cantwell**
  Ranking Member, Senate Committee on Commerce, Science and Transportation

- **The Honorable Deb Fischer**
  Chairwoman, Subcommittee on Transportation and Safety
  Senate Committee on Commerce, Science and Transportation

- **The Honorable Tammy Duckworth**
  Ranking Member, Subcommittee on Transportation and Safety
  Senate Committee on Commerce, Science and Transportation

- **The Honorable Peter DeFazio**
  Chairman, House Committee on Transportation and Infrastructure

- **The Honorable Sam Graves**
  Ranking Member, House Committee on Transportation and Infrastructure

- **The Honorable Daniel Lipinski**
  Chairman, Subcommittee on Railroads, Pipelines, and Hazardous Materials
  House Committee on Transportation and Infrastructure

- **The Honorable Rick Crawford**
  Ranking Member, Subcommittee on Railroads, Pipelines, and Hazardous Materials
  House Committee on Transportation and Infrastructure

If you have any questions or need additional information, please contact me or Ms. Katie Donley, Deputy Director of External Affairs, Office of the Chief Financial Officer, at (202) 586-0176, Mr. Shawn Affolter, Deputy Assistant Secretary for Senate Affairs or Mr. Christopher Morris, Deputy Assistant Secretary for House Affairs, Office of Congressional and Intergovernmental Affairs, at (202) 586-5450.

Sincerely,

Dan Brouillette

Executive Summary

The U.S. Department of Energy, Office of Fossil Energy (DOE/FE), the U.S. Department of Transportation, Pipeline and Hazardous Materials Safety Administration (DOT/PHMSA), and Transport Canada, Transport of Dangerous Goods Directorate (TC/TDG) commissioned a research study by Sandia National Laboratories to investigate whether crude oils currently transported in North America, including those produced from tight formations, exhibit physical or chemical properties that are distinct from conventional crudes, and further how these properties associate with combustion hazards that may be realized during transportation and handling. The research identified crude oil sampling and analysis methods that accurately characterized crude oil properties and then applied the methods to characterize oils burned in large-scale pool fire and fireball experiments. The oils tested spanned a range of vapor pressure and light ends content observed among domestic conventional and tight (non-conventional) crudes. Results were put into context with combustion properties of common liquid hydrocarbon fuels that both overlap and well-exceed the vapor pressures of the crude oils tested here.

The key findings from the research include the following:

- The comparison of several commercially available, industry standard sampling and analysis methods to a baseline instrument system from the U.S. Strategic Petroleum Reserve indicated that several combinations of methods are sufficiently accurate for evaluating crude oil vapor pressure and pressurized whole oil composition. Thus, they were appropriate for use in characterizing the oils used in the combustion experiments.
- The similarity of pool fire and fireball burn characteristics pertinent to thermal hazard distances of the three oils studied indicate that vapor pressure is not a statistically significant factor in affecting these outcomes. Thus, the results from this work do not support creating a distinction for crude oils based on vapor pressure with regard to these combustion events.
- Based on comparison to combustion data from public literature on common liquid fuels, primarily commercial grade propane and butane, the results of this study are considered to be pertinent to crude oils and most hydrocarbon liquids that exceed the vapor pressures of the crude oils tested here.

Based on the results of the Study, which assessed vapor pressure as it affects the thermal hazards from the combustion events studied; the Department of Energy and the Department of Transportation find that no further regulations by the Secretary of Transportation or the Secretary of Energy or further legislation is necessary to improve the safe transport of crude oil with specific regard to vapor pressure.

CRUDE OIL CHARACTERIZATION RESEARCH STUDY

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I. Legislative Language

This report responds to legislative language set forth in H.R. 22 "Fixing America's Surface Transportation Act" ("FAST Act") (Public Law 114-94). Section 7309 of the FAST Act directs the Secretary of Energy, in cooperation with the Secretary of Transportation, to submit a report to Congress based on a comprehensive study of crude oil characteristics with recommendations for regulations and legislation to improve the safe transport of crude oil.

SEC. 7309. REPORT ON CRUDE OIL CHARACTERISTICS RESEARCH STUDY.

Not later than 180 days after the research completion of the comprehensive Crude Oil Characteristics Research Sampling, Analysis, and Experiment Plan study at Sandia National Laboratories, the Secretary of Energy, in cooperation with the Secretary of Transportation, shall submit a report to the Committee on Commerce, Science, and Transportation of the Senate, the Committee on Energy and Natural Resources of the Senate, the Committee on Transportation and Infrastructure of the House of Representatives, and the Committee on Energy and Commerce of the House of Representatives that contains—

(1) the results of the comprehensive Crude Oil Characteristics Research Sampling, Analysis, and Experiment Plan study; and

(2) recommendations, based on the findings of the study, for—

(A) regulations by the Secretary of Transportation or the Secretary of Energy to improve the safe transport of crude oil; and

(B) legislation to improve the safe transport of crude oil.

Enacted December 4, 2015.

II. Motivation and Study Design

North America witnessed a number of high-profile accidents in 2013-2014 involving movement of crude by rail (PHMSA 2014; Stancil 2014). Photos from two prominent accidents in Canada and the U.S. are shown in Figure 1. These events coincided with a peak in crude by rail volume and significant growth in tight oil production, as illustrated in Figure 2. These incidents, as well as others, raised questions at many levels about the safety of transporting large quantities of crude by rail. In response, the U.S. Department of Energy, Office of Fossil Energy (DOE/FE), the U.S. Department of Transportation, Pipeline and Hazardous Materials Safety Administration (DOT/PHMSA), and Transport Canada, Transport of Dangerous Goods Directorate (TC/TDG) commissioned a research study by Sandia National Laboratories[1] (Sandia) to investigate the physical, chemical, and combustion properties of crude oils, and in particular the so-called "tight oils," like Bakken crude, that comprised the majority of crude oil rail shipments in the U.S. at the time (AAR 2018). Tight or "unconventional" oils are produced from relatively impermeable reservoir rock that must be stimulated by hydraulic fracturing to increase permeability to a level that supports oil production rates that are economically feasible. In contrast, "conventional" oils, which comprised the majority of material that moved through the supply chain for many decades prior, are produced from formations that have the right combination of permeability and fluid characteristics to permit the oil to flow to the wellbore.

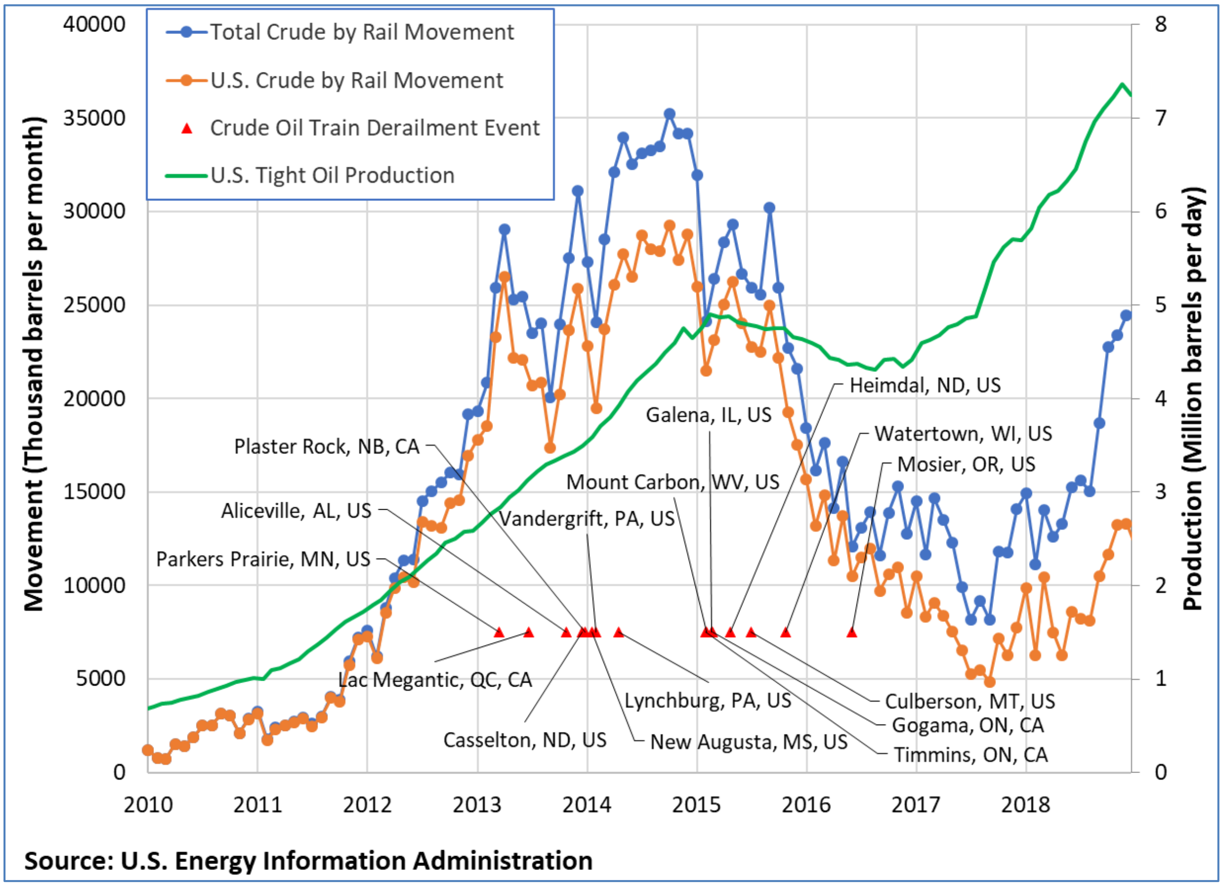
Figure 1. Photos from two prominent crude oil train accidents: (a) aftermath of a 7/6/2013 derailment and fire in Lac-Mégantic, Canada, resulting in 47 fatalities and destruction of 40 buildings and 53 vehicles (TSBC 2014); (b) fireball from a 12/30/2013 derailment in Casselton, North Dakota, with estimated damage at $13.5M and no reported injuries (NTSB 2017a).

At DOE/DOT/TC direction, Sandia focused its research on oil properties and their role in influencing the severity of combustion events in crude by rail accidents. Vapor pressure is an indication of volatility, which is the propensity of a substance to produce vapors. Among crude oil properties, vapor pressure is at the center of national debate around crude by rail safety. As evidence of this, several U.S. states, including North Dakota, New York, and Washington, either

[1] Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

enacted state law (NDIC 2014; RCW 2019) or petitioned for federal rulemaking (NYAG 2015) on setting upper limits on crude oil vapor pressure in the interest of reducing fire risk in crude by rail accidents.

Figure 2. Monthly movements of crude by rail in North America with U.S. tight oil production from 2010-2019. Major crude oil train derailment events are overlaid by date and identified by location.



As a first step, Sandia conducted a literature survey released in March 2015 on crude oil properties relevant to handling and fire safety in transport (Lord, Luketa et al. 2015) that established a record of the current state of knowledge in this area and identified important gaps. The literature survey concluded that there is a lack of uniformity in sampling and analysis methods for measures of crude oil volatility (i.e., vapor pressure) and thus meaningful comparison among oils is very difficult and must be heavily caveated. Identifying sampling and analysis methods that could accurately measure vapor pressure and composition of crude oil as it exists in relevant segments of the midstream (truck, pipeline, terminal, rail, marine) oil transportation system was therefore identified as a crucial first step of this research project. It was also concluded from the literature survey that the vast majority of train accidents provide enough kinetic energy to result in ignition from sparks or hot fragments from damaged railcars regardless of the crude oil type; thus, ignitability was not included within these research efforts.

Based on the findings of the literature survey, a sampling, analysis, and experimental plan (SAP) (USDOE 2015) was released in June 2015. The 2015 SAP outlined six tasks, the first four of which were authorized and funded in a joint project titled the Crude Oil Characterization Research Study (COCRS) overseen by DOE/FE, DOT/PHMSA, and TC/TDG. The COCRS was additionally supported by DOT's Volpe Research Center and Federal Railroad Administration (FRA).

At a high level, the four authorized tasks included:

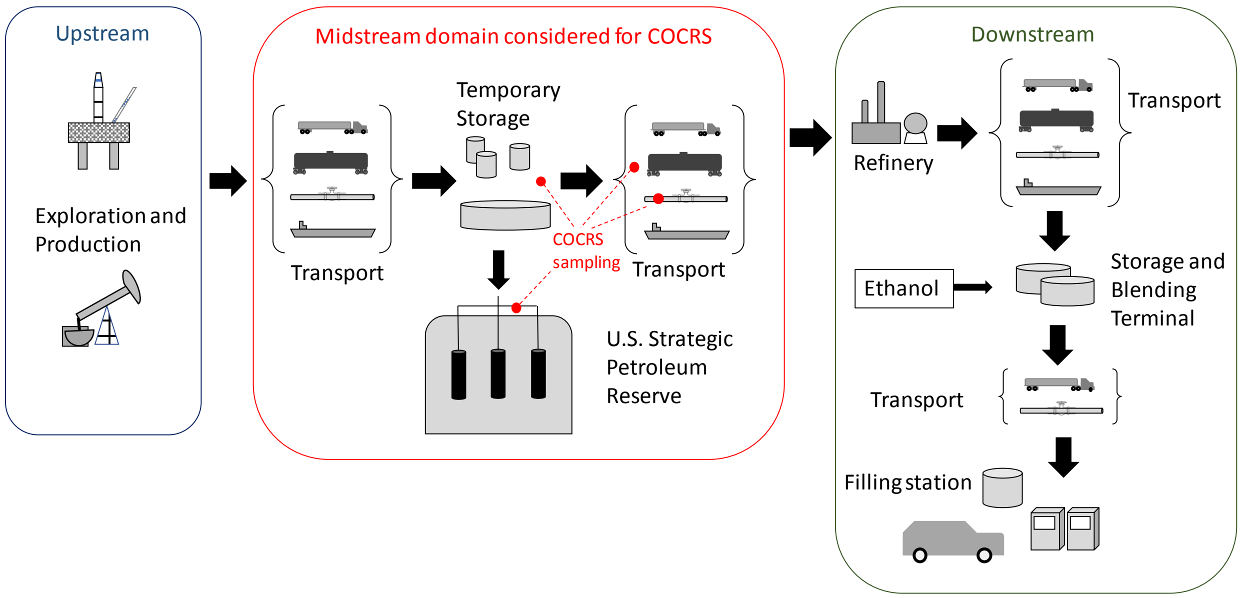
- Task 1: Project Administration and Outreach
    - Project management
    - Communication of study findings with government, sponsors, technical associations, interest groups, and the public
- Task 2: Sampling & Analysis Methods Evaluation
    - Identify commercial crude oil sampling and analysis methods that could accurately characterize crude oil properties such as vapor pressure and composition
- Task 3: Combustion Experiments
    - Perform pool fire and fireball experiments to determine if vapor pressure affects thermal hazard distances
    - Compare measured combustion parameters to others fuels from data available in the literature
- Task 4: Tight vs. Conventional Characterization (tentative)
    - Generate a comprehensive data set of properties on multiple crude types to provide a better understanding of which types are associated with higher versus lower thermal hazards for pool fires and fireballs

Note that the requirement for Task 4 was predicated on the outcome of Task 3. Since the results from Task 3 indicated that thermal hazards are independent of vapor pressure, additional Task 4 data were not required.

Completion of Tasks 2 and 3 resulted in publication of three Unclassified, Unlimited Release technical reports by Sandia on Task 2 (Lord, Allen et al. 2017), Task 2A with additional winter sampling (Lord, Allen et al. 2018), and Task 3 (Luketa, Blanchat et al. 2019). This report to Congress represents a high-level summary of the findings outlined in the three Sandia National Laboratories reports (also referred to as SAND reports), which are all publicly available in their complete and original forms at www.OSTI.gov.

A conceptual drawing of the U.S. crude oil supply chain as related to the current COCRS Tasks 2 and 3 work is illustrated in Figure 3. More comprehensive supply chain descriptions are given elsewhere (API 2012; EIA 2013). COCRS focused on properties of crude oil in the "midstream" segment where the aforementioned rail accidents occurred. The midstream segment essentially connects the "upstream" production facilities with the "downstream" refineries through a network of transportation and temporary storage facilities. Crude oil samples for Tasks 2 and 3 were acquired from midstream sources associated with tank storage, pipeline, rail, and the U.S. Strategic Petroleum Reserve (USSPR).

Figure 3. Conceptual drawing of the U.S. crude oil supply chain from exploration and production to one end use as a motor fuel. All COCRS samples were taken from midstream facilities.



III. Crude Oil Sampling and Analysis Methods Evaluation

Task 2 Baseline and Alternative Characterization Methods

Safety issues raised during increased tight oil production brought renewed interest in how exactly to measure vapor pressure for crude oil and what the results mean in the context of transportation safety. Crude oils are characterized routinely for selected properties (flashpoint and initial boiling point) under Federal law in the U.S. and Canada governing transportation of hazardous materials. These properties, in turn, delineate hazard class and packing group that ultimately determine specifications for the transport container and associated placarding (PHMSA 2014). While Federal law requires such testing prior to transportation, questions were raised in related technical literature as to the adequacy of those procedures to accurately quantify the properties of interest, especially when considering the effects of volatile components (ANSI/API 2014; Auers, Couture et al. 2014; GPAC 2014).

In consideration of this work, the U.S. Department of Energy's Energy Information Administration (EIA) defines crude oil as: a mixture of hydrocarbons that exists in liquid phase in natural underground reservoirs and remains liquid at atmospheric pressure after passing through surface separating facilities (EIA 2019).

After reviewing procedures to quantify crude oil properties of interest, Sandia determined that additional rigor and measurements were needed for delineating critical material properties among crude oils in the current research study. The COCRS decided to leverage existing knowledge, instrumentation, and methods developed out of the USSPR program to help establish a property baseline that could be used to compare/contrast subject oils for important material properties that could, in turn, be associated with fire testing. Under Federal law, the USSPR located in Louisiana and Texas holds reserves of crude oil in underground salt domes to offset major disruptions in oil supply to the U.S. The USSPR vapor pressure measurement system, known as the TVP-95, is a mobile laboratory instrument system that was developed for volatility measurements on midstream crude oils that exhibit moderate to low volatility and that have been handled and stored at the USSPR facility over the last 25 years. The TVP-95 was developed to help the program comply with Occupational Safety and Health Administration and regional emissions requirements associated with its statutory function to quickly deliver large amounts of oil to markets. The system could quantify vapor pressure and dissolved gas concentrations that were generally below detection limits of 1990's era industry standard methods designed mainly for highly volatile oils in upstream operations. The midstream oils evaluated for the COCRS are difficult to measure for volatility, as this property exists at or below the lower detection limits of typical instruments designed for the upstream segment of the supply chain. The TVP-95 system was therefore well suited to analyze these midstream oils within this research.

The DOE, DOT, and TC sponsors also expressed an interest in employing commercially available methods to obtain this property baseline that would have wider applicability than the methods specifically used at the USSPR, so the test matrix included a number of comparison methods from a variety of vendors in the U.S. and Canada that were all ultimately evaluated against the performance of the USSPR system.

Many industry advances in sampling and measurement capabilities since the 1990s have created a number of commercially available alternatives to the TVP-95. The important common theme in all these methods is that the sample handling and analysis prevents contact between the oil sample and air, thus preserving all volatiles in the original sample from the point of capture in the supply chain to the point of analysis in the laboratory. Such samples must also be reconstituted to a single liquid phase when introduced into the analytical instruments so that any property or compositional measurements are made on the whole, original sample. These methods are referred to as “closed” sampling and “pressurized” analysis methods in the industry.

Critical for the current work was the industry development of a new measurement standard for vapor pressure of crude, method ASTM D6377 for $VPCR_x(T)$, originally released in 1999 and revised six times to its current form published in 2016 (ASTM 2016). $VPCR_x(T)$ is a method that measures equilibrium vapor pressure of crude oil at a user-defined vapor/liquid ratio quantified by the subscript “x” and at a controlled temperature “T.” The new $VPCR_x(T)$ method implemented several improvements over the traditional Reid Vapor Pressure method, which was originally developed for testing gasoline in 1930 and was adapted to widespread use on crude oils over the next century. First, the $VPCR_x(T)$ method allowed for a user-defined vapor/liquid ratio (x=V/L). The volume of vapor space over a multi-component liquid like crude oil has a direct impact on the observed vapor pressure. Having the ability to adjust “x” to a value relevant to the configurations found in transportation and storage is an improvement over the Reid method, which has a set vapor:liquid volume ratio of 4:1. Actual vapor:liquid volume ratio in railcars is closer to the statutory limit of 0.01:1 (ANSI/API 2014), which is a 400 times smaller vapor space than measured in the Reid method. Second, the current ASTM D6377 method requires closed sampling for supplying VPCR measurements at V/L < 1.0. Alternatively, the Reid method permits “open” sampling, which allows for exchange of volatiles between the sample and the atmosphere. This exchange has the potential to fundamentally change the composition of volatiles and ultimately the measured vapor pressure for a crude oil sample, misrepresenting the properties of the oil as it existed at the point of collection.

Also important to the current work was the industry development and implementation of commercially viable gas chromatography-based analytical methods to characterize the critical components that drive vapor pressure and overall volatility in midstream oils with accuracy and reproducibility similar to that of the TVP-95 system.

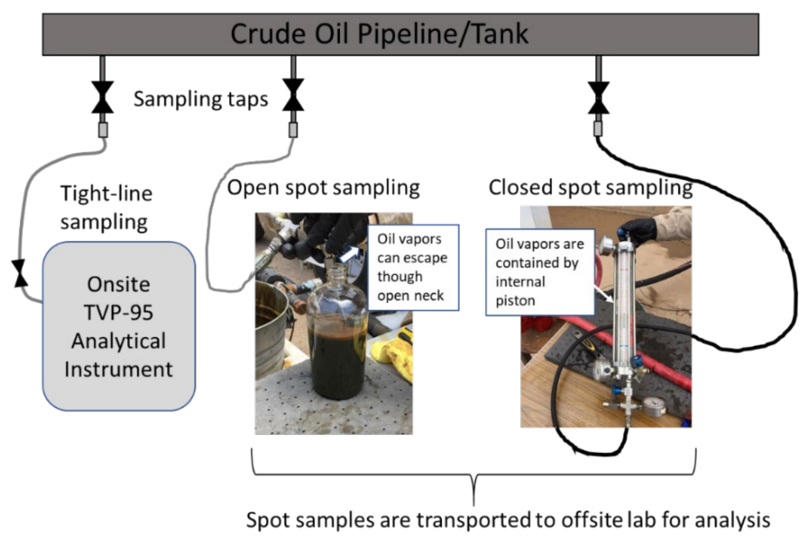
Task 2 Methods Comparison using Bakken and Eagle Ford Crudes

Sandia arranged with crude oil midstream operators in 2016-2017 to obtain Bakken crude from North Dakota and Eagle Ford crude from Texas. The oils were subjected to a range of commercially available industry standard analysis methods at service laboratories contracted by Sandia, and the findings were compared back to those from the baseline TVP-95 system used at the USSPR to evaluate method performance. The TVP-95 uses a “tight-line” sampling configuration where the pressurized liquid oil sample is piped directly from the source to the analytical instrument on-site for analysis. The alternative spot sampling methods subdivided into "open" and "closed" collected samples from the same source into specialized liter-scale containers that are transported to an offsite lab for analysis. Open sampling methods allow for direct contact between air and the liquid oil samples while closed sampling prevents air contact. A high-level conceptual test matrix for the Task 2 effort is given in Table 1. A schematic comparing the tight-line, open, and closed sampling methods is given in Figure 4.

Table 1. Conceptual test matrix for evaluating new commercially available sampling and analysis methods against the TVP-95 baseline.

Sampling Method	Vapor Pressure Method	Compositional Method
Tight-line TVP-95	TVP-95 separator pressure	TVP-95 separator gas chromatography
Open spot sampling (two variants)	$VPCR_x(T)$	Pressurized gas chromatography (four variants)
Closed spot sampling (three variants)	$VPCR_x(T)$	Pressurized gas chromatography (four variants)

Figure 4. Conceptual drawing of basic tight line, open, and closed spot sampling configurations connected to sampling taps from a common source oil pipeline or tank.



In summary, several combinations of commercial sampling and analysis methods returned comparable performance to the baseline TVP-95. Sampling performance in this context did not appear to depend on winter versus summer sampling conditions, as investigated in the Task 2A work. Some specific Task 2/2A findings include:

- Both open and closed industry standard sampling methods yielded comparable results for vapor pressure of crude oil [$VPCR_x(T)$] and hydrocarbon content against the tight-line TVP-95 system for oils that were tested. An important condition, however, is that the oils tested in Task 2 had likely equilibrated to local ambient pressure and temperature conditions prior to sampling by Sandia. As such, there is no basis in the current work for extending the findings on comparable performance for open and closed sampling to highly volatile oils that visibly boil when handled in open containers.

- Open and closed methods were not able to deliver equivalent samples for vapor pressure measurements at conditions of low vapor/liquid ratio (V/L < 1). Closed sampling must be used for supplying VPCR measurements where V/L < 1.
- The selection of vapor/liquid ratio (V/L) used in the $VPCR_x(T)$ measurement has important implications for reproducibility and sensitivity to small amounts of dissolved gas. The Task 2 study was unable to generate reproducible measurements of VPCR for V/L = 0.02 and 0.05, though it showed high reproducibility for V/L= 1.5 and 4. Also, for the oils tested, $VPCR_{0.2}$(100°F) correlated closely with the bubble-point pressures for the same crudes as measured by the TVP-95.
- Three commercially available methods of pressurized compositional analysis were determined to provide equivalent results to the baseline TVP-95 system for yielding "whole oil" compositions.

Burn Sample Acquisition and Characterization for Task 3

Based on the information gathered in the Task 2 methods evaluation, Sandia developed a sampling and analysis plan for characterizing the Task 3 large-scale combustion samples. At a high level, this included utilizing:

- Closed sampling methods compliant with specific published industry standards to evaluate vapor pressure [$VPCR_x(T)$] and composition that were sensitive to loss of volatiles.
- ASTM D6377 $VPCR_x(T)$ for all vapor pressure measurements. Minimum V/L was set to 0.1 to enable sufficient measurement reproducibility. V/L = 4.0 was included to facilitate comparison with public data.
- Pressurized compositional analysis method GPA 2103-M for generating whole oil compositions. This method retains and quantifies all light hydrocarbons and dissolved gases present in the oil that control volatility.
- For all other crude oil properties (total sulfur, viscosity, metals, water content and others), applicable industry standard methods were used as listed in the Task 3 final report (Luketa, Blanchat et al. 2019).

The crude oils burned in the Task 3 combustion experiments were selected to span a measurable range of vapor pressure and light ends content that may be observed among domestic conventional and tight (unconventional) crudes. Several constraints, including operator willingness to allow Sandia direct access to their facility, permission for Sandia to release oil property data to the public, and ability to implement a purchase agreement for the oil also factored into the sample selection. The following three crude oils were selected for burn testing:

1. A light, sweet[2] crude obtained from a regional Bakken terminal upstream of a rail loading facility in North Dakota (Tight 1– Bakken).
2. A light, sour crude obtained from a production sales point in the Permian region of Texas that handles tight shale production (Tight 2 – TX Shale).
3. A medium, sour, stabilized conventional crude obtained from a USSPR storage facility in Louisiana that also weathered at Sandia while in unpressurized storage (SPR).

Tanker-Scale Sample Acquisition

An important feature of the test series was maintaining the composition and volatility characteristics of the oil as obtained from the supply chain. Thus, the tight oils were transported in a Sandia-designed tanker that prevented loss of volatiles and prevented air contact. Allowing the oil samples uncontrolled exposure to the atmosphere during loading, transport, and storage over the months required to complete the Task 3 testing would have resulted in a convergence to a very stable, weathered state that (i) may not represent the properties applicable to hydrocarbon fluids that are loaded into railcars or pipelines on their way from the production facility to the refinery, and (ii) possibly result in small or indistinct differences in properties, particularly vapor pressure, among test fluids that were once distinct when they entered the transportation supply chain.

Two specialized tankers (one shown in Figure 5) were designed and built to satisfy these technical requirements for ~3,000-gallon samples of crude necessary to fuel the burn tests. The tanker used water as a piston and eliminated direct contact between air and the oil and could operate at sufficiently high pressure to maintain the oil in a single liquid phase and deliver it to test apparatus in this state. The tanker design was modeled after liter-scale water displacement closed sampling methods that were identified from Task 2 as acceptable for this work.

The SPR crude oil was transported and maintained in a standard unpressurized crude oil hauler that did not prevent loss of volatiles. Any further weathering would offer the advantage of widening the range of vapor pressure among the oils. The end result was that the SPR source oil started at a lower vapor pressure than the tight oils and was further allowed to "weather", that is, the volatile components in the crude naturally dissipated to the atmosphere during the testing sequence. The SPR oil thus served as the low vapor pressure end-member while the two tight oils served as the higher vapor pressure samples of the test oil set. From an experimental design standpoint, the SPR oil did not need to be maintained at its source vapor pressure. Rather, it needed to be well quantified for every test and be maintained as the low-volatility end-member of the test set.

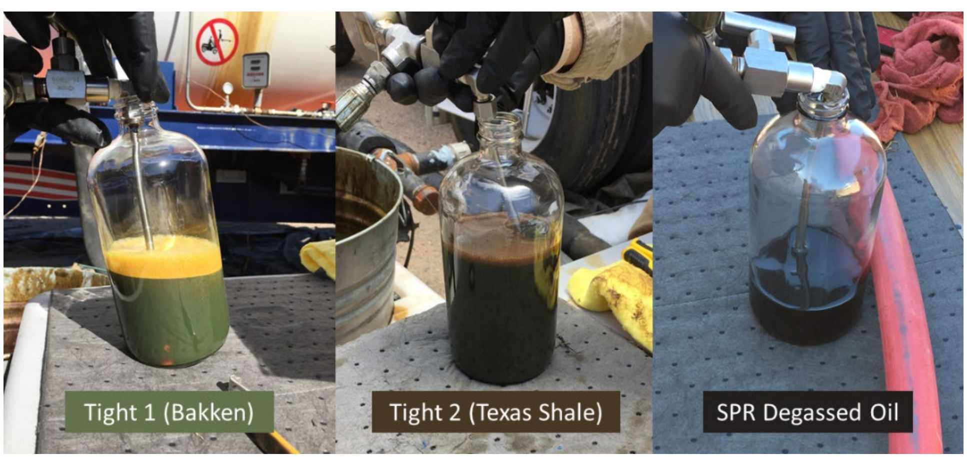
[2] "Sweet" and "sour" terms refer to the sulfur content present in the crude. The USSPR definition of "sweet" indicates that total weight % sulfur is less than 0.5%, while "sour" contains greater than 0.5% but less than 2%.

Figure 5. Custom tanker-trailer designed to collect the ~3,000-gallon samples of tight crude and isolate them from air by using water as a piston.

Property Comparison: Tight 1 (Bakken) vs. Tight 2 (TX Shale) vs. SPR

For property evaluation, liter-scale subsamples were pulled from each tanker upon loading in the field in ND, TX, and LA, and again in close association with each fire test at Sandia. A visual comparison of the three test oils based on subsamples collected into glass jars is shown in Figure 6. The visible differences indicate compositional and property differences that were quantified by comprehensive analyses performed on each oil multiple times during custody at Sandia.

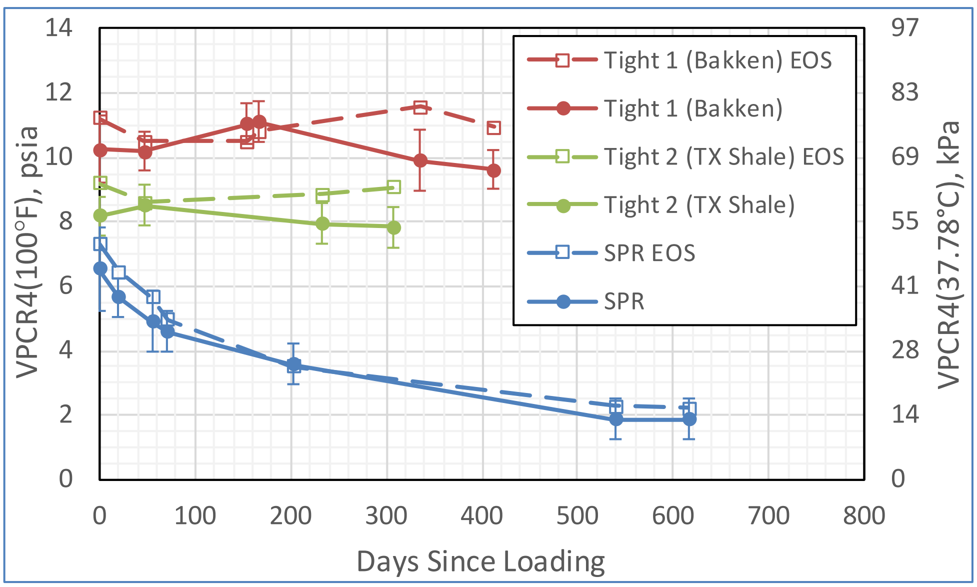
Figure 6. Photos of the crude oil samples taken by open bottle sampling method the week of July 16, 2018 (oil temperature 75-80°F, ambient pressure ~11 psia @ ~7,000 ft elevation).



An example plot showing measured and simulated vapor pressures by $VPCR_4$(100°F) for each oil by storage time at Sandia is given in Figure 7. Each oil VPCR is quantified in two ways: (i) by direct measurement (solid symbols), and (ii) by equation of state model (EOS) simulation based on compositional analysis (open symbols). Key takeaways include: (i) $VPCR_4$(100°F) for the tight oils in pressurized containment was relatively stable with time, within the limits of accuracy of the methods; (ii) EOS modeled and directly-measured $VPCR_4$(100°F) correlate closely for each oil, providing high confidence that the key light components that drive vapor pressure are known and well quantified in each sample; and (iii) the $VPCR_4$(100°F) of the SPR oil dropped conspicuously over the 600+ days in storage as volatile components were dissipated due to weathering.

The range of vapor pressure ($VPCR_{0.2}$(100°F) and $VPCR_4$(100°F) by ASTM D6377) and light components[3] (mass% < C6 by GPA 2103-M) for the three oils as tested in association with the 2-m diameter pool fires, 5-m diameter pool fires, and fireballs are given in Table 2. By these measures, Tight 1 (Bakken) was the most volatile (highest $VPCR_{0.2}$(100°F), $VPCR_4$(100°F) and < C6 content), Tight 2 (TX Shale) was in the middle, and SPR was the least volatile of the test oils. Regarding the two measures of vapor pressure for each oil, $VPCR_{0.2}$(100°F) better represents the vapor pressure that would be observed in a nearly liquid-filled transport container, while $VPCR_4$(100°F) exhibits higher measurement reproduciblity (Lord, Allen et al. 2018) and has widespread use in industry and regulatory space so results here can be easily compared with crude oil data in the public domain.

Figure 7. Measured and simulated (EOS) vapor pressures by $VPCR_4$ of Tight 1 (Bakken), Tight 2 (TX Shale), and SPR oils through time while in storage at Sandia.



[3] Light components in this work are defined as those with six or fewer carbon atoms that control the volatility and vapor pressures observed at ambient temperature.

Table 2. Average vapor pressures and < C6 content for the crude oil samples tested.

Oil Type	$VPCR_{0.2}$(100°F), psia	$VPCR_4$(100°F), psia	< C6 Content, mass%
2-m diameter pool fires			
SPR (hot)	11.0 ± 2.9	4.9 ± 0.6	3.18
SPR (cold)	12.9 ± 2.9	5.7 ± 0.6	3.70
5-m diameter pool fires			
Tight 1 (Bakken)	19.3 ± 2.9	10.2 ± 0.6	5.99
Tight 2 (TX Shale)	15.7 ± 2.9	8.5 ± 0.6	4.03 ± 0.07
SPR	9.0 ± 2.9	3.6 ± 0.6	2.07
SPR (hot)	11.4 ± 2.9	4.6 ± 0.6	3.09
Fireballs			
Tight 1 (Bakken)	18.0 ± 2.9	9.6 ± 0.6	6.21 ± 0.04
Tight 2 (TX Shale)	15.8 ± 2.9	7.8 ± 0.6	4.20 ± 0.05
SPR	6.7 ± 2.9	1.9 ± 0.6	1.40 ± 0.02

IV. Combustion Testing Experimental Results

The experiments for Task 3 focused on combustion events most likely to arise from a severe rail accident, namely, pool fires and fireballs. Details of the experiments, results, and discussion can be found in the Task 3 report (Luketa, Blanchat et al. 2019). The main objective was to determine if vapor pressure affects thermal hazard distances, which demark regions of thermal injury and damage from radiant heat exposure from a fire. To address this objective, a series of pool fire and fireball experiments using the previously discussed oils were conducted measuring combustion parameters appropriate for use in common solid flame models that predict thermal hazard distances. The following describes these experiments and results for the measured parameters.

Pool Fires

The pool fire tests involved indoor and outdoor testing in which measurements were taken to evaluate burn rate, flame height, and surface emissive power (SEP), which is the radiant heat emitted at the flame's surface per unit time per unit area. These parameters were then used to evaluate thermal hazard distances. Heat flux to an object engulfed in the fire was also collected, though this measurement is not required for thermal hazard distance evaluation. Instrumentation included radiometers, infrared and real-time cameras, liquid-level sensors, calorimeter, thermocouples within the pool, and directional flame thermometers. The test matrix for the pool fire experiments is provided in Table 3.

Table 3. Pool Fire Test Matrix.

Test	Gallons burned	Fuel Temperature (°C)	Oil
2-m diameter indoor pool fires			
1	150	6.9 ± 0.4	SPR (cold)
2	150	59.5 ± 4.5	SPR (hot)
5-m diameter outdoor pool fires			
3	600	54 ± 2.7	SPR (hot)
4	600	27 ± 0.0	SPR
5	600	22 ± 2.7	Tight 1 (Bakken)
6	600	20 ± 1.1	Tight 2 (TX Shale)

The 2-m diameter pool fires (Figure 8) were conducted indoors and served as exploratory tests, while the 5-m diameter pool fires (Figure 9) were conducted outdoors and provided the data used for the thermal hazard evaluation. Since oil contained within a rail car experiences seasonal changes in temperature, the effect of crude oil temperature was investigated using the SPR oil for both the indoor and outdoor tests and indicated that crude oil supply temperature does not have a significant effect on the measured parameters. Thus, the effect of crude oil supply temperature was not investigated for subsequent tests.

Table 4 provides a summary of results, which are averages, determined over periods of steady-state. The SEP indicates heat flux to objects external to the fire, while the calorimeter indicates heat flux to an object engulfed in the fire. For reference regarding heat flux levels, on a warm summer day a person is exposed to a heat flux of about 1 kW/m^2 from solar radiation.

Figure 8. Indoor 2-m diameter pool fire tests: (a) SPR (cold) and (b) SPR (hot).

(a) **(b)**

Figure 9. Outdoor 5-m diameter pool fire tests: (a) SPR (hot), (b) SPR, (c) Bakken, and (d) TX Shale.

(a) **(b)** **(c)** **(d)**

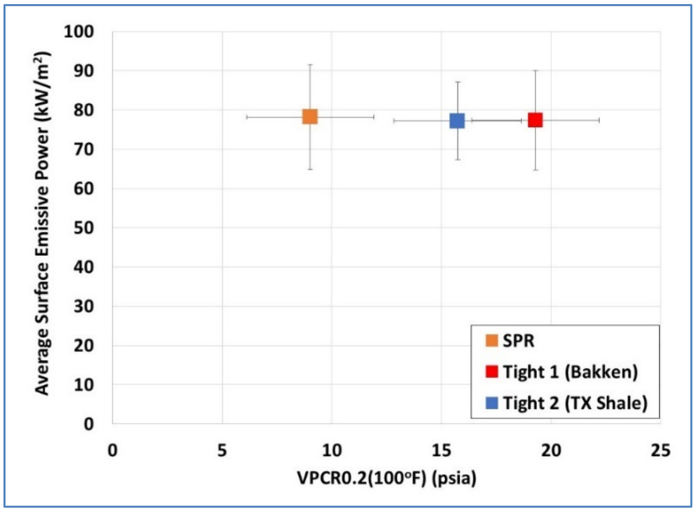
Table 4. Summary of results for pool fire experiments.

Oil	Fuel Supply Temperature (°C)	Average Burn rate (mm/min)	Average Flame Height (m)	Average Surface Emissive Power (kW/m²)	Average heat flux to calorimeter (kW/m²)
2-m diameter indoor pool fires					
SPR	6.9 ±0.35	2.12 ±0.01	5.0 ±2.0	47.4 ±17.7*	74.3 ±2.6
SPR	59.5 ±4.5	1.95 ±0.02	2.9 ±1.6**	48.1 ±13.7*	103.2 ±5.9***
5-m diameter outdoor pool fires					
SPR	54 ±2.7	3.0 ±0.5	5.6 ±3.1	na †	89.6 ±34.4
SPR	27 ±0.0	2.7 ±0.1	4.9 ±3.1	78.2 ±13.4	90.0 ±33.8
Tight 1 (Bakken)	22 ±2.7	4.6 ±0.1	4.5 ±3.9	77.4 ±12.7	70.5 ±25.8
Tight 2 (TX Shale)	20 ±1.1	2.7 ±0.3††	5.5 ±3.9	77.2 ±9.9	78.3 ±18.0

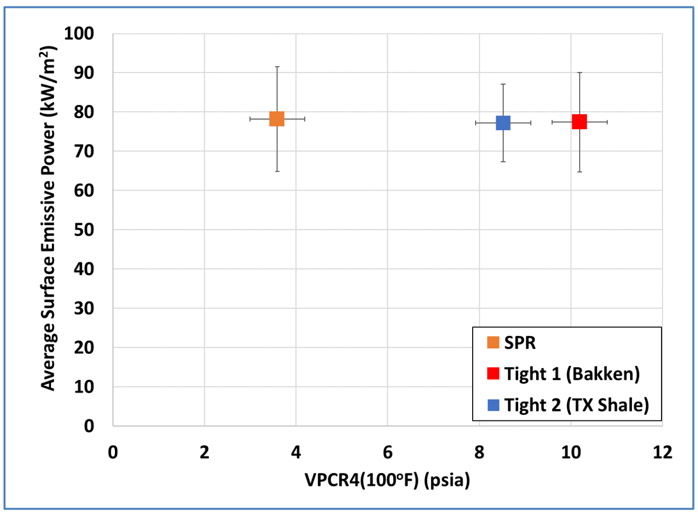
(*from narrow-angle radiometers with focal diameter of about 0.8 m), (** pan lip increased from 4" to 12"), (*** averaged over all thermocouples and over time. Calorimeter was about 0.5" lower in elevation within flame for the 'hot' fuel test.), († IR cameras not used for this test. Radiometers measured similar range of heat fluxes to SPR test with an ambient fuel supply temperature.), (†† estimated).

Figure 10 shows the measured average surface emissive power versus $VPCR_{0.2}$(100°F), $VPCR_4$(100°F) (psia) and mass% of whole oil <C6 content for the 5-m diameter pool fire tests. The average SEP is not affected by wind conditions and thus is provided here for conciseness since it does not require additional discussion for interpretation of the results compared to the other parameters. The SEP is also the dominant parameter affecting thermal hazard distances for large-scale pool fires due to smoke obscuration. The comparison indicates that the average surface emissive power was nearly constant for all three oils, thus no variation with oil properties $VPCR_{0.2}$, $VPCR_4$, or mass% whole oil < C6 was observed. Recall the subscripts 0.2 and 4.0 on VPCR represent the ratio of vapor volume to liquid volume (V/L) when the vapor pressure was evaluated. While V/L = 0.2 is more relevant to an actual transportation or storage configuration, the majority of VPCR data from the public record were measured at 4.0, so this allows for comparison of the current property data to oils used in other studies. See the full Task 3 report (Luketa, Blanchat et al. 2019) for additional discussion on this.

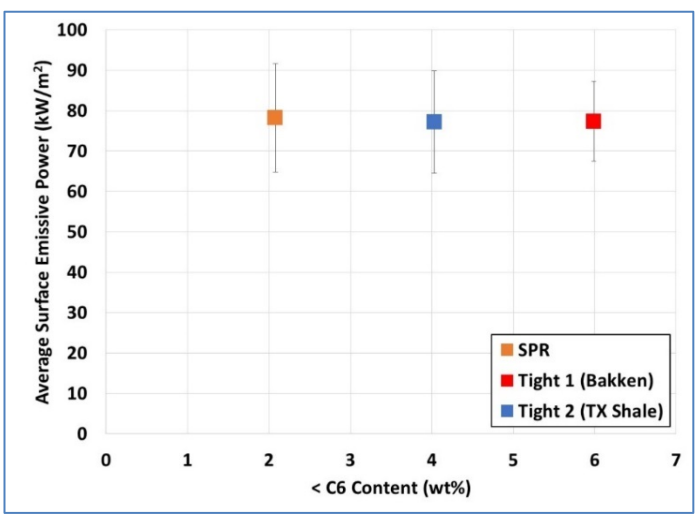
Figure 10. Pool fire average surface emissive power versus (a) $VPCR_{0.2}$(100°F) (psia), (b) $VPCR_4$(100°F) (psia), and (c) <C6 content (mass%).



(a)



(b)



(c)

Fireball Testing

The fireball experiments involved releasing and igniting oil from a heated, pressurized 1,000-gallon vessel containing 400-gallons of oil for each test. The pressure vessel was designed to 1) allow control of the oil's temperature and pressure, 2) prevent air contact within the vessel, and 3) control time of release. The thermodynamic state was chosen to maximize the probability that the entire mass of the oil contributed to the fireball, which was successfully achieved. Measurements were taken to evaluate the fireball's maximum diameter, rise height, duration, and SEP, which were then used to evaluate thermal hazard distances. Instrumentation included infrared spectral imaging cameras, radiometers, and high-speed and real-time cameras. To facilitate the design of the vessel and ensure quality data, a preliminary set of experiments with a smaller 100-gallon vessel were initially performed. The test matrix is provided in Table 5 and illustrates a summary of the results. For a reference point regarding energy levels listed in Table 6, the average energy consumption per capita in the U.S. is about 900 MJ per day (EIA 2020).

Table 5. Fireball Test Matrix.

Test	Vessel Size (gallons)	Oil Description
1	100	Water
2	100	50/50 mix Jet-A and gasoline
3	100	Jet-A
4	1000	Tight 1 (Bakken)
5	1000	Tight 2 (TX Shale)
6	1000	SPR

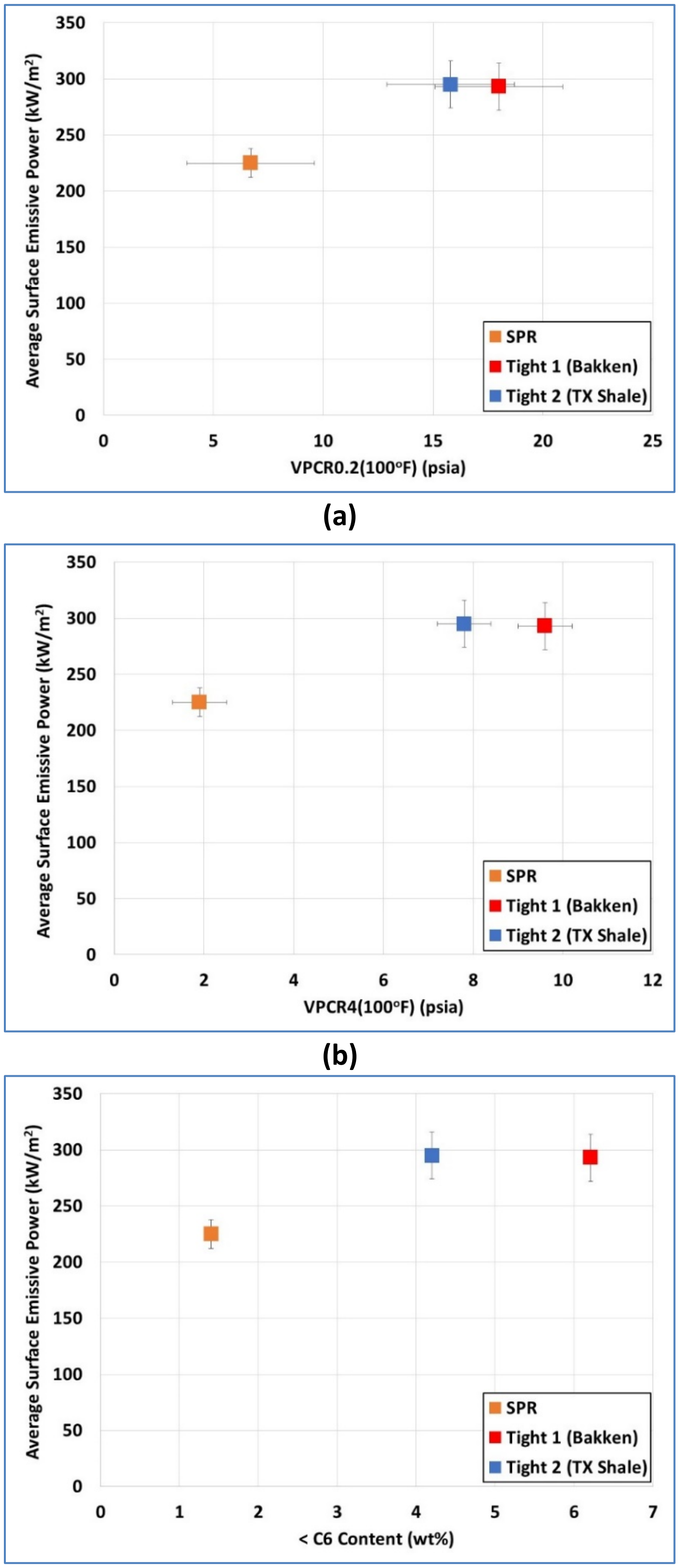
Table 6. Summary of results for fireball experiments.

Fuel	Mass (kg)	Diameter* (m)	Height*† (m)	Duration** (s)	Average Surface Emissive Power*** (kW/m²)	Maximum Power**† (MW)	Energy**† (MJ)
Jet-A	116	23 ±1	15 ±1	3.2 ±0.2	287 ±17	117 ±14	162 ±19
Tight 1 (Bakken)	1229	58 ±4	55 ±4	10.0 ±1	293 ±22	764 ±119	1823 ±285
Tight 2 (TX Shale)	1269	54 ±4	52 ±4	10.0 ±1	295 ±22	686 ±107	1515 ±236
SPR	1303	61 ±4	81 ±5	11.0 ±1	225 ±14	665 ±82	1491 ±184

(*effective diameter based on projected area measurements at time of maximum power), (*†distance from ground to fireball center at time of maximum power), (**time until visible thermal radiation ceases), (***spatially averaged and at time of maximum power), (**† average of X6900 IR cameras over 3.3 seconds).

Figure 11 shows the measured average SEP versus vapor pressure by $VPCR_{0.2}$(100°F), $VPCR_4$(100°F) (psia) and mass% of whole oil <C6 content for crude oil fireball tests. The average SEP for both the tight oils was about 30% greater than for the SPR oil. Implications of this difference with regards to thermal hazard distance is discussed in Section V.

Figure 11. Fireball average surface emissive power versus (a) $VPCR_{0.2}$(100°F) (psia), (b) $VPCR_4$(100°F) (psia), and (c) <C6 content (mass%).



(a)

(b)

(c)

V. Thermal Hazard Distance Evaluation

Thermal hazard distances resulting from pool fires and fireballs were assessed using a solid flame model, which predicts heat flux as a function of distance external to the fire. For the pool fires, the distance demarking a heat flux level of 5 kW/m^2 was evaluated for all oils. This heat flux level causes 2nd degree burns to bare skin after about 30 seconds of exposure. For the fireballs, the distance demarking a thermal dose unit (TDU) of 240 $(kW/m^2)^{4/3}s$ was evaluated for all oils. This level will result in 2nd degree burns when exposed over the duration of the fireball.

The following sections provide the results of this evaluation for pool fires and fireballs for each oil tested. The results are for comparison purposes only and are not meant to be used to identify exclusion zones for emergency responders. Historic accidents have demonstrated that hazards can exceed the distances calculated in this work due to the thermal damage arising from numerous railcars leading to significant amounts of oil contributing to a fire, which can then propagate to surrounding fuels sources, such as wooden structures, vegetation, and other hydrocarbons. In practice, evacuation areas encompassing up to a ~1600 m (1 mi.) have been enforced by emergency personnel for historic accidents as reported in several National Transportation Safety Board (NTSB) reports (NTSB 2017b; NTSB 2018).

The findings presented in this section support the first general conclusion of the Task 3 research, which states the following:

> *The similarity of pool fire and fireball burn characteristics pertinent to thermal hazard distances of the three oils studied indicate that vapor pressure is not a statistically significant factor in affecting these outcomes. Thus, the results from this work do not support creating a distinction for crude oils based on vapor pressure with regards to these combustion events.*

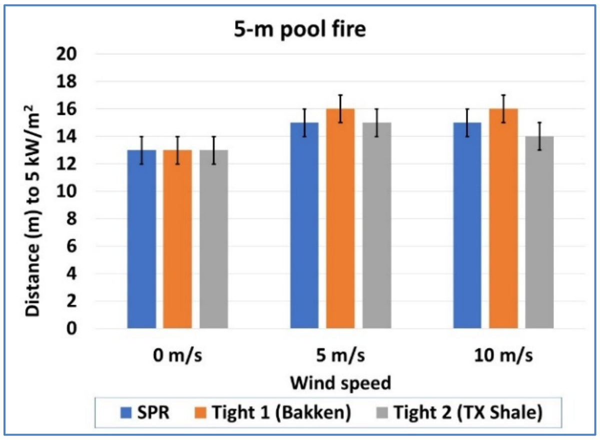
Pool Fires

For the uncontained or spreading pools the comparison assumes a spill rate of 0.1 m^3/s which corresponds to 1,584 gal/min. A breached rail car carrying 30,000 gallons of oil would deplete within about 19 minutes at this spill rate. A spill rate providing depletion on the order of minutes was chosen since this is likely more reflective of an accident scenario, rather than a spill lasting on the order of hours or an instantaneous release. During the spill, the spreading pool will attain a maximum diameter when the burn rate matches the spill rate. The results indicate that the pool diameter for Tight 1 (Bakken) is smaller than the other oils due to its higher burn rate (Figure 13). Due to the smaller pool, the distances to 5 kW/m^2 are as much as 27% lower compared to the other oils. In the presence of wind, this difference reduces to about 16% due to tilt and changes in flame length.

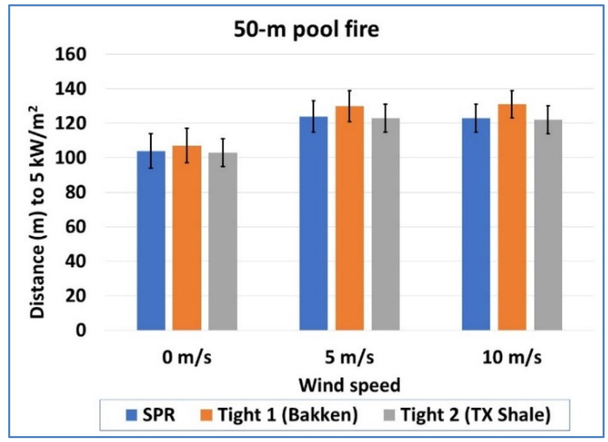
Given potential variation in accident scenarios, atmospheric conditions, and parameter input uncertainty, what should be concluded is that thermal hazard distances do not differ greatly and should be treated equivalently by emergency responders.

Given potential variation in accident scenarios, atmospheric conditions, and parameter input uncertainty, what should be concluded is that thermal hazard distances do not differ greatly and should be treated equivalently by emergency responders.

Figure 12. Comparison of distances to 5 kW/m² for (a) 5-m diameter, and (b) 50-m diameter pool fires for various wind speeds based on model predictions.

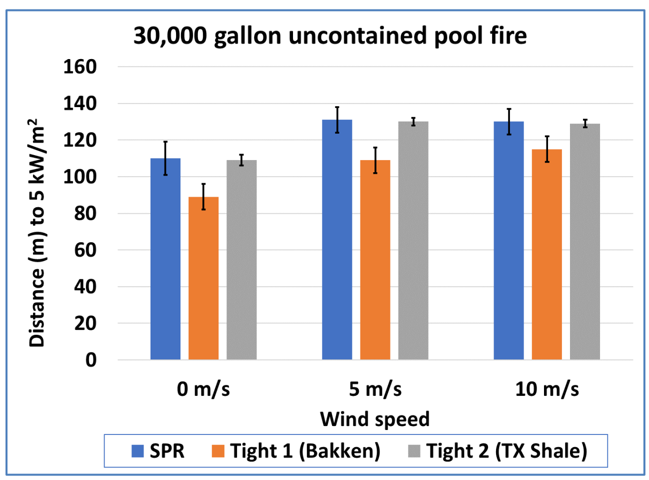


(a)



(b)

Figure 13. Comparison of distances to 5 kW/m² for spreading pool fire for various wind speeds based on model predictions, assuming a spill rate of 0.1 m³/s.



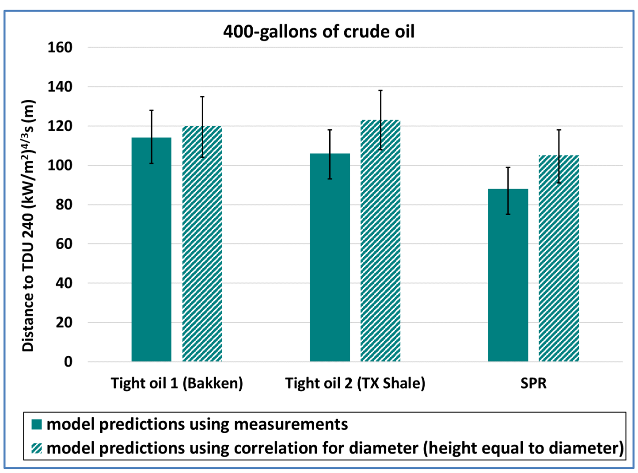
Fireballs

Three sets of model predictions were performed for each oil. The first is of the 400-gallon tests using experimental values of spatially-averaged SEP, effective diameter, and rise height at the time of maximum power. The second is of the 400-gallon tests that uses the same experimental SEP values as the first comparison but uses a correlation (Roberts 1982) to predict diameter and an assumption that the rise height is equivalent to the diameter. This second set of comparisons was performed because it was used for predicting larger releases and allowed for evaluation of the performance of the correlation against the predictions using experimental parameters. The final set of model predictions using this approach was then performed for a release volume representative of that expected from a railcar.

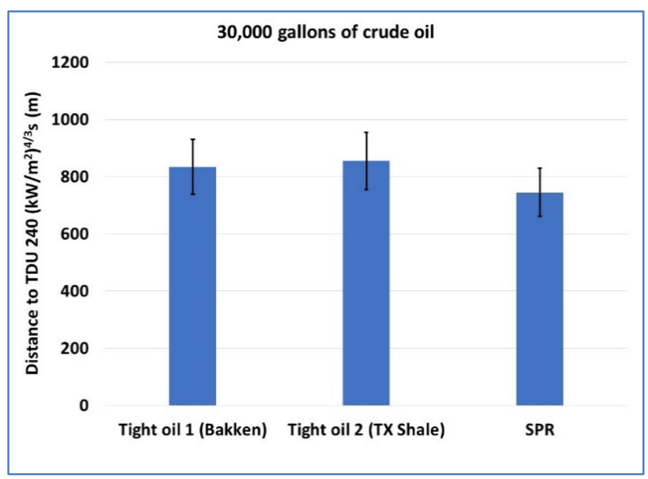
Figure 14a provides predicted distances to a thermal dose unit (TDU) of 240 $(kW/m^2)^{4/3}s$ using the measured parameters at maximum power and also that using the correlation. The comparison indicates that when measurements are used, the Tight 1 (Bakken) resulted in the furthest distance, while the SPR resulted in the lowest. The range between these crude oils is a difference of about 30% and the difference between Tight 2 (TX Shale) and SPR is about 20%. The error bars are based on experimental uncertainty in the measurements of fireball diameter, height, and SEP. Considering that the range of uncertainties overlap and the inherent variation (~20%) of repeat fireball tests as demonstrated by other researchers, this difference is not considered to be significant.

Figure 14b provides the results for 30,000-gallon fireballs for all three oils using the correlation. The results indicate that the distances for the Tight oils are similar and have greater hazard distances than the SPR oil by about 12%. Since the range of uncertainties overlap, these results indicate that the Tight oils are not statistically different than the SPR oil with regard to thermal hazard distances.

Figure 14. Comparison of predicted distances to TDU of 240 $(kW/m^2)^{4/3}s$ for (a) 400-gallon release fireball, and (b) 30,000-gallon release fireball.



(a)



(b)

VI. Comparison of Combustion Parameters

Task 3 also involved comparing the measured combustion parameters from the pool fire and fireball crude oil experiments to other fuels, which were taken from data available in the literature. Datasets that provided measurements most similar to the crude oil data and were of field scale were selected. The results provided in this section provide support for the second general conclusion from the Task 3 research, which states the following:

> *Based on comparison to combustion data from public literature on common liquid fuels (primarily commercial grade propane and butane), the results of this study are considered to be pertinent to crude oils and most hydrocarbon liquids that exceed the vapor pressures of the crude oils tested here.*

The following provides the results of the comparison of all combustion parameters for both pool fires and fireballs to other fuels.

Pool Fires

The comparison of measured burn rates to several types of fuels indicated none of the tested crude oils displayed outlier behavior compared to the other hydrocarbons (Task 3 tested crude oils circled in Figure 15). With regard to flame height or length, there is very limited reported data for pool diameters of 5-m. The most complete reporting of flame length performed at a similar scale involved gasoline and diesel pool fire experiments testing pool diameters of 1.5, 3, 4, and 6-m (Munoz, Arnaldos et al., 2004) and was used for comparison. Even though a 5-m diameter pool was not tested, a best-fit correlation was determined in (Munoz, Arnaldos et al., 2004) that allowed for a comparison at a pool diameter of 5-m shown in Figure 16. The comparison indicates good agreement given the uncertainty introduced by testing in outdoor conditions with time-varying wind speeds and directions.

Figure 15. Comparison of burn rate with other fuels (1 – (Blanchat, Helmick et al. 2010), 2 – (Mizner and Eyre 1982), 3 – (Blinov and Khudiakov 1961), 4 – (Munoz, Arnaldos et al. 2004), 5 – (Evans, Mulholland et al. 2001), 6 – (Sjostrom, Amon et al. 2015), 7 – (Koseki and Iwata 2000), 8 – (Blanchat, Sundberg et al. 2006), 9 – (Suo-Anttila and Gritzo 2001), 10 – (Koseki 1989)).

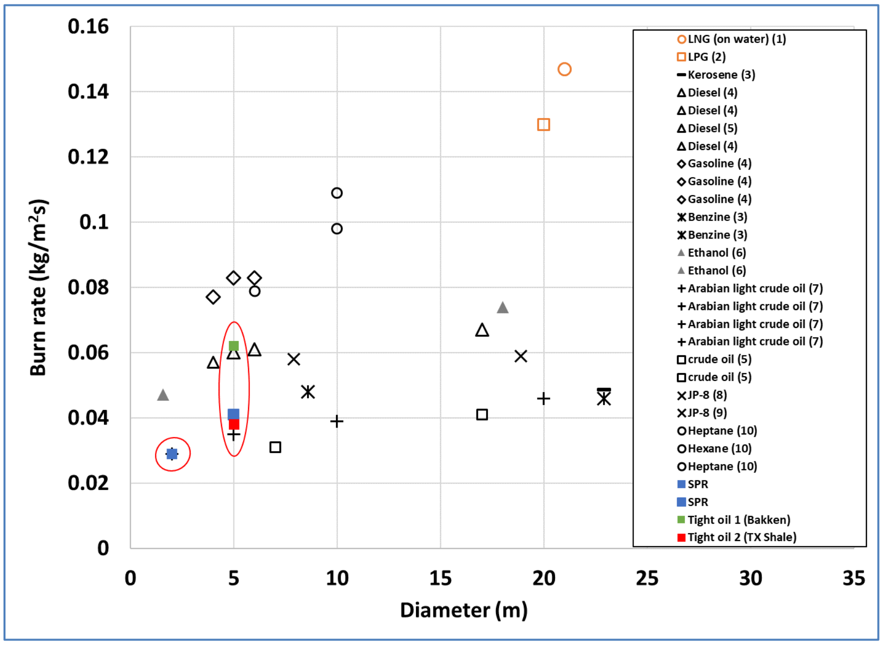
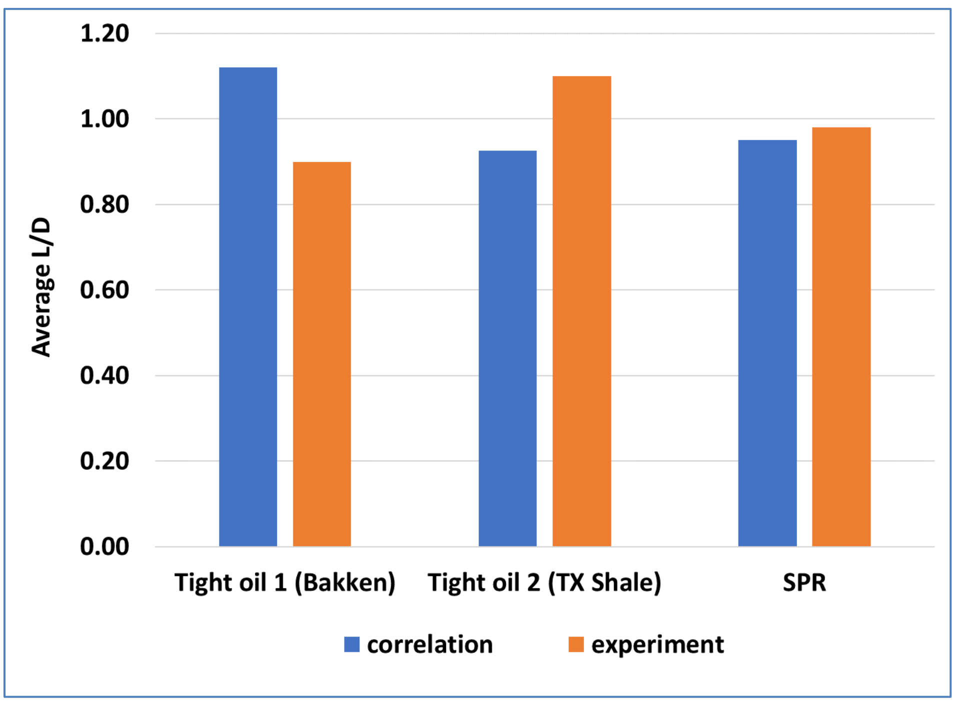
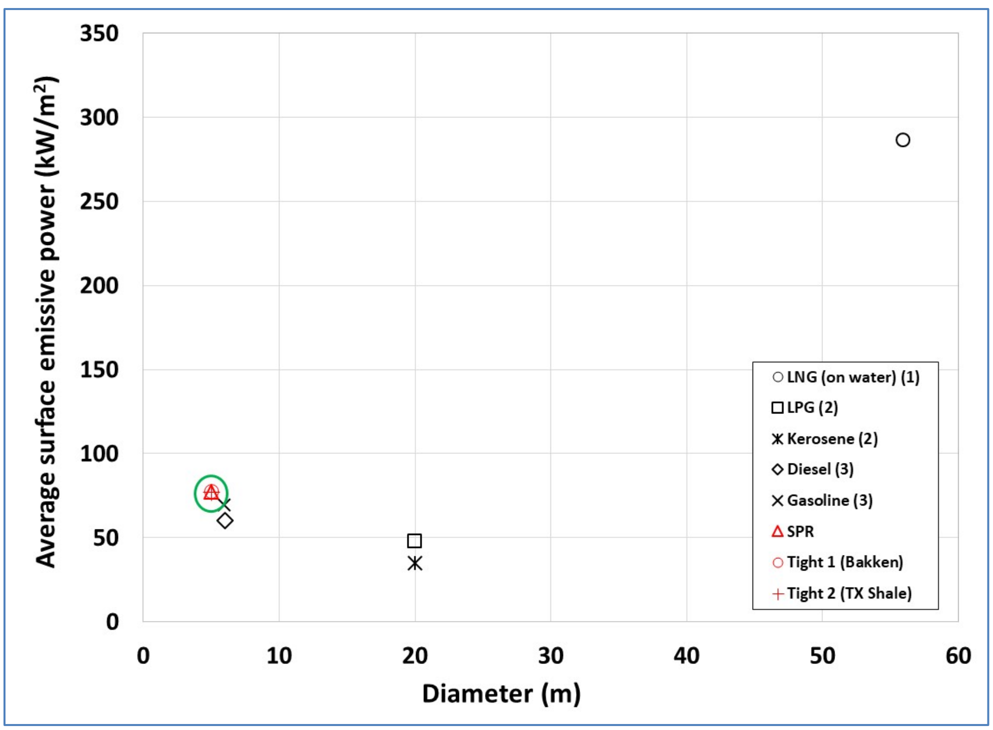


Figure 16. Comparison of average L/D (length/diameter) with correlation and crude oil data.



The comparison of average SEP to other fuels (Figure 17) indicated that the Task 3 tested crude oils (circled) are similar to diesel fuel and gasoline. Liquefied natural gas (LNG) is plotted as an example of an outlier which is discussed in (Luketa 2011). Of importance to note is that the 20-m diameter tests for kerosene and for liquefied petroleum gas (LPG), comprised of propane, have similar average SEP values that are lower than the 5-6 m diameter pool fires. Due to increasing smoke production, the average SEP decreases with increasing pool diameter. Large hydrocarbon fires on the order of 10s of meters or greater will generate copious quantities of smoke that will shroud a fire. A sufficient layer of black smoke will absorb a sizable portion of the radiation emitted from the flame, resulting in a much lower effective SEP to the surroundings and hence reduced thermal hazard distances. Open-source video coverage of railcar accidents involving Tight 1 (Bakken) crude oil confirms that a substantial amount of smoke is produced and heavily shrouds the fire. Thus, the SEP for the tested crude oils will decrease with increasing diameter and is anticipated to be of a similar value to the 20-m diameter tests for LPG and kerosene shown in Figure 17. Of the measured parameters, the SEP will dominate thermal hazard distances for pool diameters greater than 10s of meters due to smoke production. The visible flame height will be controlled by the level of smoke shrouding and not the burn rate at large scales. The importance of burn rate at large scales is its effect on pool size for an uncontained fuel and time to depletion. Fuels with higher burn rates will result in smaller pools, which will reduce thermal hazard distances.

Figure 17. Comparison of average surface emissive power with other fuels (1 – (Blanchat, Helmick et al. 2010), 2 – (Mizner and Eyre 1982), 3 – (Munoz, Arnaldos et al. 2004)).



Fireballs

A comparison of measured maximum rise height to several types of fuel indicated that the heights of the tested crude oils are much higher than those of the other fuels (crude oils circled in Figure 18). This can be attributed to differences in test configuration. For the crude oil tests, the fuel was directed only in the upward vertical direction, whereas the other fuels had a release that allowed for the fuel to be released horizontally as well as vertically near the ground. This type of configuration results in the fireball first expanding along the ground and then lifting off to form a spherical shape. In the latter configuration, lower rise heights result since a portion of the energy is distributed in the horizontal and downward vertical direction. Observation of crude oil railcar accidents indicate that the oil is released in the upward vertical direction issuing from a thermal tear along the topside of the railcar. Thus, the configuration used in the crude oil test series is more applicable to observed railcar accidents.

A comparison of duration until extinction to other fuels indicated that the crude oil fireballs have longer durations until extinction than the other fuels (crude oils circled in Figure 19). Note, however, as found from other researchers the results in duration can differ by up to 50% among repeat tests (Johnson and Pritchard 1990). Also, note that for the Task 3 tested crude oils, radiometers recorded measurements up to about 9 to 10 seconds that were significant. Thus, only minor regions of burning, lasting an additional 1 to 2 seconds, were observed beyond that time. Given the inherent stochastic nature of fireball tests and the different test configurations, the results for the crude oils tests are not considered to be outliers compared to the other fuels with regard to duration.

Figure 18. Comparison of maximum rise height versus fuel mass (1 – (Johnson and Pritchard 1990), 2 – (Betteridge and Phillips 2015)).

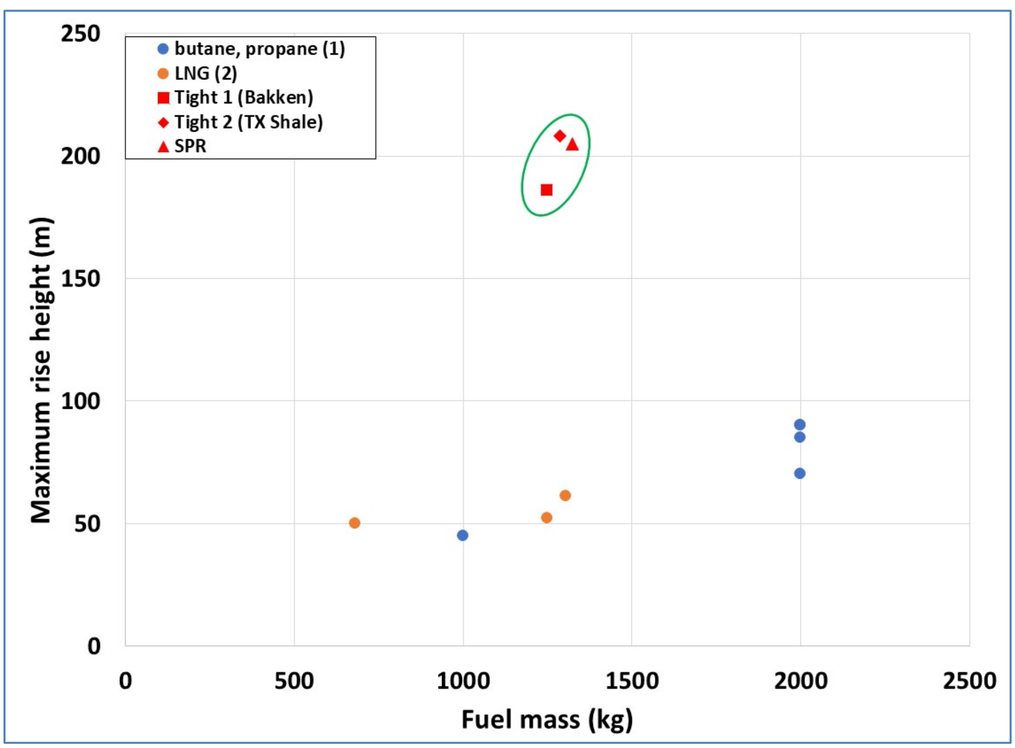
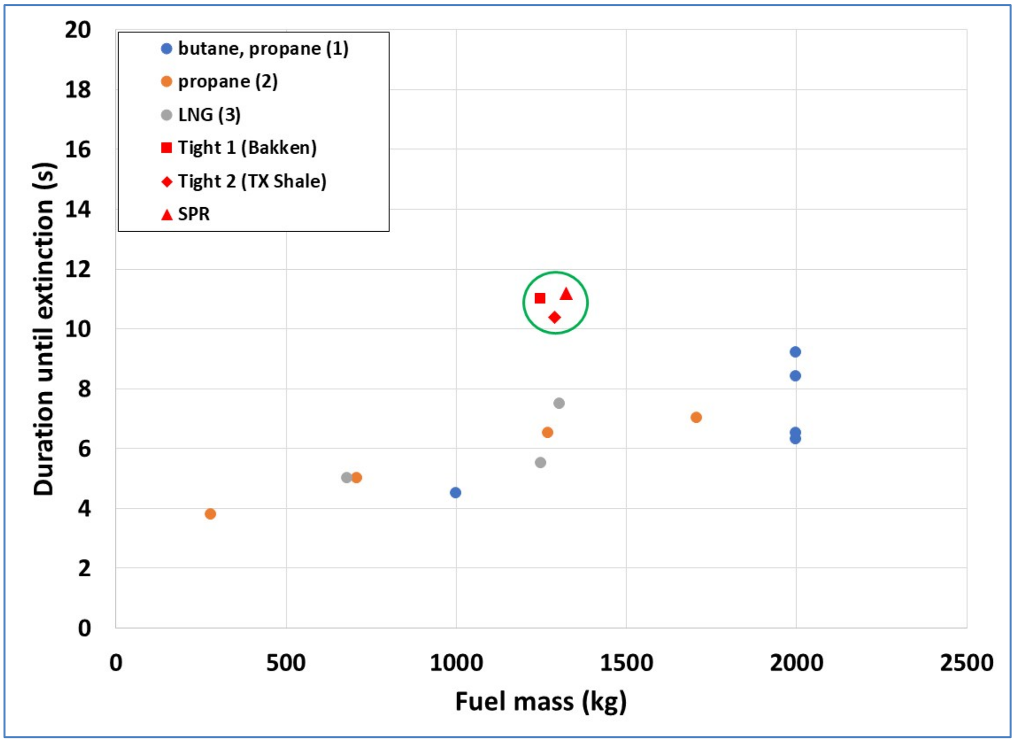
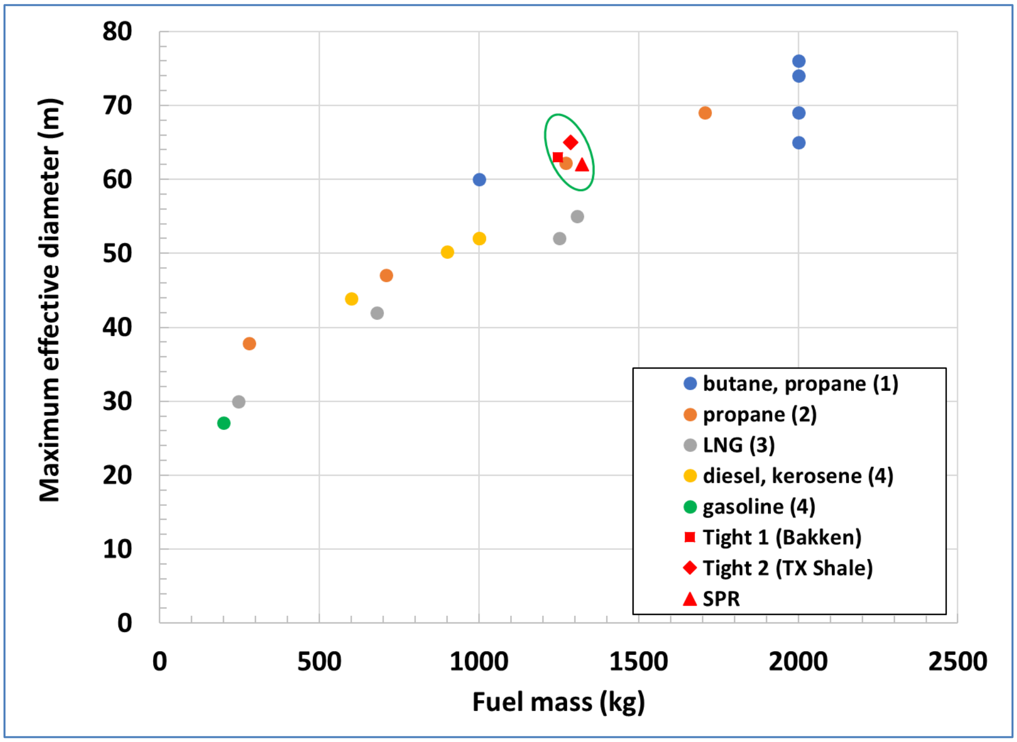


Figure 19. Comparison of duration until extinction versus fuel mass (1 – (Johnson and Pritchard 1990), 2 – (Roberts, Gosse et al. 2000), 3 – (Betteridge and Phillips 2015)).



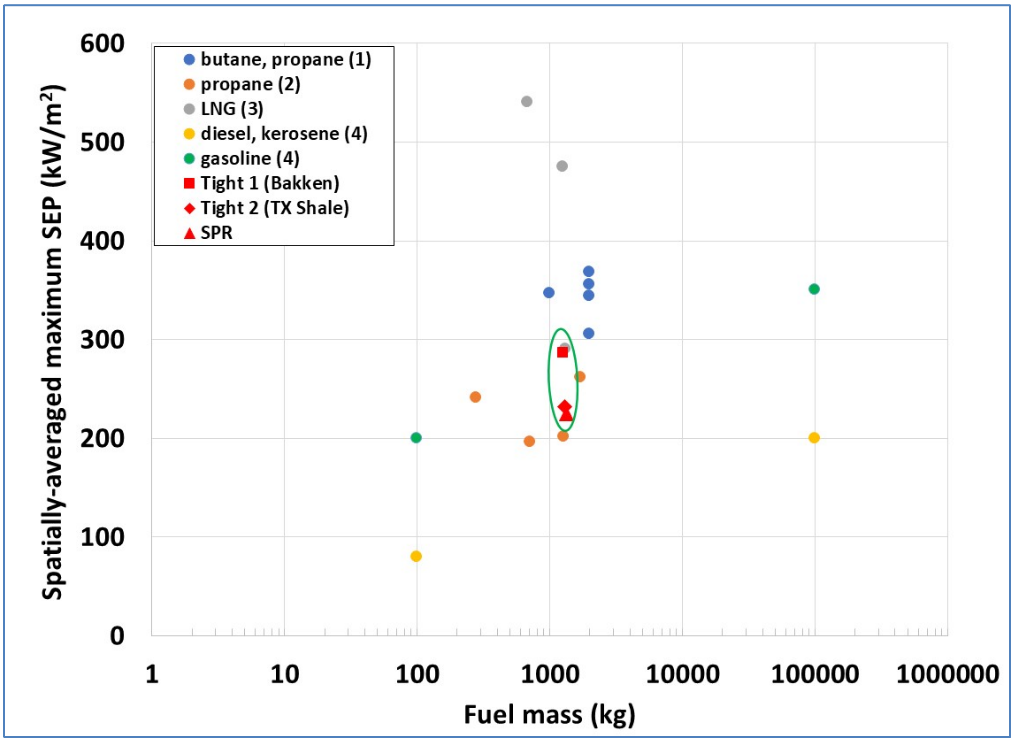
A comparison of maximum effective diameter versus fuel mass is provided in Figure 20 (Task 3 tested crude oils circled). The diameter is termed 'effective' since it is calculated by using area measurements to determine an equivalent diameter assuming a perfect circle. The comparison indicates that maximum effective diameters for the crude oils are similar with the other fuels and do not display outlier behavior.

Figure 20. Comparison of maximum effective diameter versus fuel mass data (1 – (Johnson and Pritchard 1990), 2 – (Roberts, Gosse et al. 2000), 3 – (Betteridge and Phillips 2015) , 4 – (Dorofeev 1995)).



A comparison of spatially averaged maximum SEP versus fuel mass is provided in Figure 21 (Task 3 tested crude oils circled). The comparison indicates that the fireballs observed from the present crude oils are within the range of values previously found for fireballs of propane and butane for similar fuel masses. There appears to be agreement with one LNG test, but it was noted in reference (Betteridge and Phillips 2015) that the much lower reading compared to the other LNG tests is still unresolved. Thus, the other two LNG tests performed are most likely more representative of the potential magnitudes, which are much higher than the other fuels.

Figure 21. Comparison of spatially-averaged SEP versus fuel mass (1 – (Johnson and Pritchard 1990), 2 – (Roberts, Gosse et al. 2000), 3 – (Betteridge and Phillips 2015), 4 – (Dorofeev 1995)).



VII. Conclusions

The major findings from evaluation of oil sampling and analysis methods include:

- Both open and closed industry standard sampling methods yielded comparable results for vapor pressure of crude oil [$VPCR_x(T)$] and hydrocarbon content against the tight-line TVP-95 system for oils that were tested. An important condition, however, is that the oils tested in Task 2 had likely equilibrated to local ambient pressure and temperature conditions prior to sampling by Sandia. As such, there is no basis in the current work for extending the findings on comparable performance for open and closed sampling to highly volatile oils that visibly boil when handled in open containers.
- The selection of vapor/liquid ratio (V/L) used in the $VPCR_x(T)$ measurement has important implications for reproducibility and sensitivity to small amounts of dissolved gas. The Task 2 study was unable to generate reproducible measurements of VPCR for V/L = 0.02 and 0.05, though it showed high reproducibility for V/L= 1.5 and 4. Also, for the oils tested, $VPCR_{0.2}(100°F)$ correlated closely with the bubble-point pressures for the same crudes as measured by the TVP-95.
- Three commercially available methods of pressurized compositional analysis were determined to give results of equal value to the baseline TVP-95 system for yielding “whole oil” compositions. One of these was implemented to determine oil compositions in Task 3 combustion studies.

The major findings from the combustion experiments include:

- The similarity of pool fire and fireball burn characteristics pertinent to thermal hazard distances of the three oils studied indicate that vapor pressure is not a statistically significant factor in affecting these outcomes. Thus, the results from this work do not support creating a distinction for crude oils based on vapor pressure with regard to these combustion events.
- Based on comparison to combustion data from public literature on common liquid fuels, primarily commercial grade propane and butane, the results of this study are considered to be pertinent to crude oils and most hydrocarbon liquids that exceed the vapor pressures of the crude oils tested here.

Based on the results of the Study, which assessed vapor pressure as it affects the thermal hazards from the combustion events studied; the Department of Energy and the Department of Transportation find that no further regulations by the Secretary of Transportation or the Secretary of Energy or further legislation is necessary to improve the safe transport of crude oil with specific regard to vapor pressure.

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