FINAL REPORT SUMMARY FOR CRUDE OIL CHARACTERIZATION RESEARCH STUDY
Phase II Final Report for the North Dakota Industrial Commission Contract No. G-Sandia-01

Purpose of the Project

Rail accidents involving crude oil that occurred between 2013 and 2015 raised questions about the safety of rail transport of crude oil. In an effort to address these questions, the U.S. Department of Energy (DOE) commissioned a study to investigate the properties of tight crude oil as they relate to its safe handling and transport. DOE contracted Sandia National Laboratories (SNL) to conduct the study, and the Energy & Environmental Research Center (EERC) was contracted to provide technical support in execution of the project. In parallel, the North Dakota Industrial Commission (NDIC) established a contract with the EERC to fund progress reporting to NDIC.

Work Accomplished

The key objectives of the DOE study included characterizing crude oils based on their chemical and physical properties and identifying properties that may contribute to an increased potential for accidental combustion. A two-phase approach was developed to achieve these objectives. Phase I activities included a literature survey of publicly available information on crude oil properties and development of a conceptual crude oil characterization plan to address information gaps and enable a comprehensive characterization of crude oil properties. Phase II activities included crude oil sampling, chemical and physical property characterization, and combustion testing.

Project Results

Project activities resulted in the creation of three technical documents that characterize and define crude oils based on chemical and physical properties relevant to safe storage and transport:

1. "Literature Survey of Crude Oil Properties Relevant to Handling and Fire Safety in Transport" was completed and released on March 24, 2015, and documents publicly available information and data related to crude oil, especially oils produced from tight formations. The report can be accessed from SNL's website at http://energy.sandia.gov/tight-oil-study/.
2. "DOE/DOT Crude Oil Characterization Research Study, Task 2 Test Report on Evaluating Crude Oil Sampling and Analysis Methods, Revision 1 – Winter Sampling" was completed in June 2018 and documents results of an evaluation of crude oil sampling and analysis methods. The report is available at www.osti.gov/biblio/1458999-doe-dot-crude-oil-characterization-research-study-task-test-report-evaluating-crude-oil-sampling-analysis-methods-revision-winter-sampling.
3. "Pool Fire and Fireball Experiments in Support of the U.S. DOE/DOT/TC Crude Oil Characterization Research Study' was completed in August 2019 and provides results of combustion tests conducted on several North American crude oils. The report can be accessed through DOE's website at www.osti.gov/biblio/1557808. Additionally, the full report is included in Appendix A of this report.

Potential Applications of the Project

The information gathered as a result of this project will provide a technically valid basis for stakeholders as they work to ensure the safe and economic transport of crude oil to market.

Conclusion

The results from this work do not support creating a distinction for crude oils based on vapor pressure with regard to these two combustion events.

Energy & Environmental Research Center
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August 30, 2019

Ms. Karlene Fine
Executive Director
North Dakota Industrial Commission
State Capitol, 14th Floor
600 East Boulevard Avenue, Department 405
Bismarck, ND 58505-0840

Dear Ms. Fine:

Subject: Final Report for North Dakota Industrial Commission (NDIC) Entitled "Crude Oil Characterization Research Study – Phase II Final Report"; Contract No. G-Sandia-01 EERC Fund 20173

Enclosed please find the subject University of North Dakota Energy & Environmental Research Center (EERC) Phase II final report summarizing activities related to crude oil characterization. Sandia National Laboratories (SNL) released a final report that describes an experimental study of physical, chemical, and combustion characteristics of selected North American crude oils and how these associate with thermal hazard distances resulting from pool fires and fireballs. The report entitled "Pool Fire and Fireball Experiments in Support of the U.S. DOE/DOT/TC Crude Oil Characterization Research Study" is provided as Appendix A to this final report. The EERC's final project report provides a summary of key findings of SNL's report.

If you have any questions or require clarification of any point, please contact me by phone at (701) 777-5273 or by e-mail at cwocken@undeerc.org.

Sincerely,

Chad A. Wocken
Principal Engineer and Transformational
Energy Group Lead

CAW/bjr

Enclosure

c: Brent Brannan, NDIC

CRUDE OIL CHARACTERIZATION RESEARCH STUDY

Phase II Final Report

Summary of Sandia National Laboratories Report: Pool Fire and Fireball Experiments in Support of U.S. DOE/DOT/TC Crude Oil Characterization Research Study

(for the period of February 1, 2015, through August 31, 2019)

Prepared for:

Karlene Fine

North Dakota Industrial Commission
State Capitol, 14th Floor
600 East Boulevard Avenue, Department 405
Bismarck, ND 58505-0840

Contract No. G-Sandia-01

Prepared by:

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2019-EERC-08-14

August 2019

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February 1, 2015–August 31, 2019

BACKGROUND

The U.S. Department of Energy (DOE), the U.S. Department of Transportation (DOT), Transport Canada (TC), and the University of North Dakota Energy & Environmental Research Center (EERC), working with Sandia National Laboratories (SNL), seek to identify the characteristics of crude oils that affect the risk of combustion during transportation, including rail transportation. The results are expected to lead to a more comprehensive understanding of the risks associated with crude oil as those risks relate to specific chemical and physical properties. The results also include the necessary sampling and testing methods required for measuring those properties. From this greater understanding, it can be expected that conclusions concerning the increased safety of transporting crude oil may be determined.

SNL was selected to conduct the study, and the EERC was contracted to provide technical support in the execution of the project. Under contract to the North Dakota Industrial Commission (NDIC), the EERC has provided progress updates and communicated project findings and reports to NDIC.

In Phase I of the project, a review of existing data and analysis completed in 2015 identified shortcomings in existing knowledge. To address these shortcomings, the interagency group agreed on a multitask sampling analysis and experiment (SAE) plan to be carried out by SNL. DOE and DOT, each funding half of the cost, committed to the completion of this work. Phase I activities have been completed, and project deliverables, including a literature review and SAE plan, were submitted to NDIC as part of a Phase I final report entitled "Final Report Summary for NDIC Resource Characterization."

Work on Phase II activities consisted of two primary activities. The first activity consisted of a comprehensive assessment of crude sampling and analysis methods. A report summarizing this assessment, entitled "DOE/DOT Crude Oil Characterization Research Study, Task 2 Test Report on Evaluating Crude Oil Sampling and Analysis Methods, Revision 1 – Winter Sampling" was submitted to NDIC in July 2018. The second activity is the subject of this report and consists of an experimental study of physical, chemical, and combustion characteristics of selected North American crude oils and how these associate with thermal hazard distances resulting from pool fires and fireballs. The report entitled "Pool Fire and Fireball Experiments in Support of the U.S. DOE/DOT/TC Crude Oil Characterization Research Study" is provided in Appendix A to this final report. The following summary of the above-referenced SNL report was prepared by the EERC for submittal to NDIC.

BASIS AND CONTEXT

Large-volume rail transport of crude oil coupled with several high-profile oil train accidents raised questions about whether, how, and to what extent oil physical and chemical properties affect the severity of hazard outcomes in accident-generated crude oil fires. The above-referenced report describes an experimental study of physical, chemical, and combustion characteristics of three

North American crude oils. The study was conducted by SNL as Task 3 of the Crude Oil Characterization Research Study (COCRS) sponsored by DOE, DOT, and TC. Prior reports in this series include a scoping document, literature survey (COCRS Task 1), and technical report on crude oil sampling and analysis methods (COCRS Task 2). Crude oils studied include two light (≥ 33°API gravity) "tight" oils from modern unconventional production and one stabilized/degassed medium (28°–33°API gravity) sour oil from historical conventional production. Each oil was sampled, characterized, and evaluated via a series of pool fire and fireball combustion (burn) tests designed to elucidate any significant oil-specific differences in recommended "thermal hazard distance." The metric for thermal hazard distance comparison is the distance—from the center of a given fire—at which a heat flux of at least 5 kilowatts per square meter (kW/m^2) is reached. This heat flux level is commonly used as a criterion to specify exclusion zones for emergency personnel. For reference, this heat flux level causes second-degree burns to bare skin after about 30 seconds of exposure.

BURN TEST DESCRIPTIONS

Pool fire tests were conducted to assess each crude oil based on burn rate, surface emissive power, flame height, and heat flux to an engulfed object. For each oil, four 5-m pool diameter tests were conducted, with each test utilizing a 600-gallon oil charge. Since most accident scenarios result in pool diameters of 10–100 m, a 5-m pool diameter represents the lower boundary of accident scenario scales, and combustion parameters acquired from 5-m pool tests provide for conservative estimates of thermal hazard distances. Fireball tests were conducted to measure hazard evaluation parameters, including fireball maximum diameter, height at maximum diameter, duration, and surface emissive power. Each test involved creating a fireball by releasing and igniting a 400-gallon oil charge as it emerged—in the form of a vapor/atomized mixture—from a 1000-gallon vessel heated and pressurized to 275°–300°C and 170–250 psi, respectively. The tests were designed to maximize the probability that the entire mass of each oil charge contributes to the fireball.

CRUDE OILS TESTED

The two tight oils tested were obtained from 1) a terminal upstream of a rail loading facility for Bakken production in North Dakota (Tight 1 – Bakken) and 2) a production facility sales point in the Texas Permian that handles tight shale production (Tight 2 – TX Shale). To ensure against light ends and volatility loss from the two tight crudes during sampling, transport, and storage prior to conducting burn tests, a specially designed/built tanker system was used to collect each sample from the field; transport it to the SNL test facility in Albuquerque, New Mexico; store it; and feed it into the experimental systems under closed, pressurized conditions. The stabilized medium sour conventional was obtained from the U.S. Strategic Petroleum Reserve (SPR). The degassed SPR oil was selected for testing because of its lower volatility than the two tight oils and most other oils in the U.S. supply chain. The SPR degasification program is part of a risk mitigation strategy designed to—in the event of a large-scale crude oil drawdown—maximize worker safety and minimize environmental impact by minimizing crude oil vapor emissions. Table F-1 summarizes sampling logistics for the three test oils, and Figure F-15 shows each oil undergoing unpressurized open-bottle sampling under ambient conditions at SNL. Note: All table and figure numbers and titles/captions are identical to those used in the SNL report.

Table F- 1: Summary of loading conditions for tanker samples

Oil Type	Loading Date	Quantity (gal)	Line Pressure (psig)	Line Temperature (°F)	Ambient Temperature (°F)[1]
SPR	1/24/2017	3,000	145	110	62
Bakken	8/17/2017	2,100	156	76	72
TX Shale	11/28/2017	3,000	40	77	60

[1] Mean ambient temperature from local airport data on sampling date.

Figure F- 15: 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).

The three crude oils were extensively characterized based on physical and chemical properties. Table 1-1 illustrates properties of key relevance measured just prior to test initiation. In the table, "$VPCR_4$(100°F)" refers to vapor pressure measured at a vapor/liquid ratio of 4.0 and temperature of 100°C, and "<C6 Content" refers to the summed amount (in mass% of total sample) of all detected and quantified C1–C5 species.

Table 1-1. Average vapor pressures and < C6 content for crude oil samples tested.

Oil Type	$VPCR_4$(100°F), psia	< C6 Content, mass%
Fireballs		
Tight 1 (Bakken)	9.6 ± 0.6	6.21 ± 0.04
Tight 2 (TX Shale)	7.8 ± 0.6	4.20 ± 0.05
SPR	1.9 ± 0.6	1.40 ± 0.02
5-m Diameter Pool Fires		
Tight 1 (Bakken)	10.2 ± 0.6	5.99 [1]
Tight 2 (TX Shale)	8.5 ± 0.6	4.03 ± 0.07
SPR	3.6 ± 0.6	2.07 [1]

POOL FIRE TEST RESULTS

Figure G-1 graphically summarizes the pool fire test results. In each graph, test-measured values are shown along with calculated standard deviation "error bars" that illustrate extent of experimental uncertainty. Figure G-1 shows results from several SPR oil tests conducted in addition to those discussed above. These additional tests were performed primarily to establish and validate pool fire test protocols. Acquired pool fire test data were used in conjunction with an integral model to calculate predicted pool fire thermal hazard distances for each of the three crude oils under a variety of environmental conditions. As one example, Figure 3-6 compares the oils based on predicted thermal hazard distance for a 5-m pool fire in three different wind speeds.

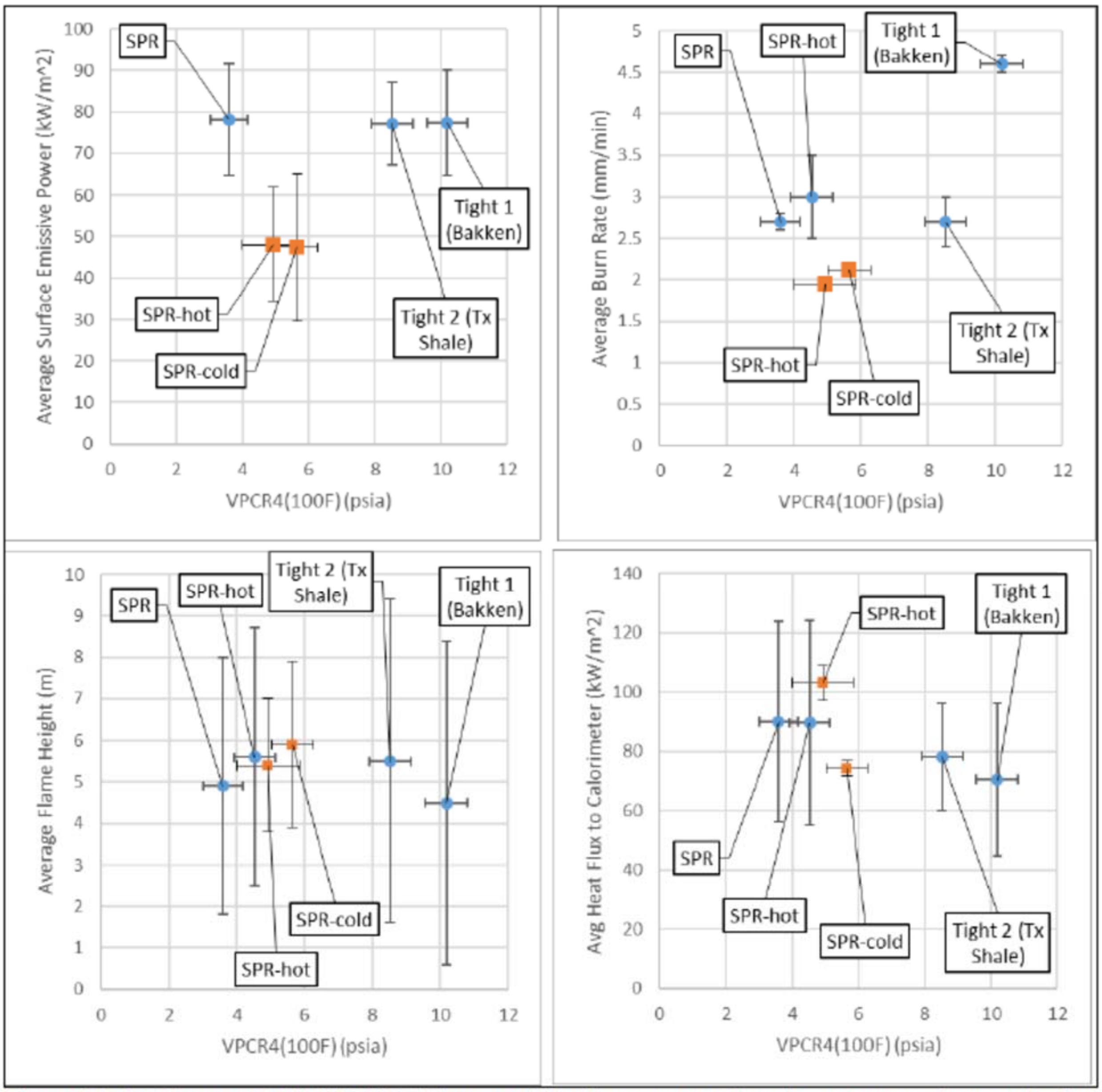

Figure G- 1: Oil property VPCR$_4$(100°F) vs pool fire burn properties a) average surface emissive power, b) average burn rate, c) average flame height, and d) average heat flux to calorimeter for 2-m (orange squares) and 5-m (blue circles) pool fires

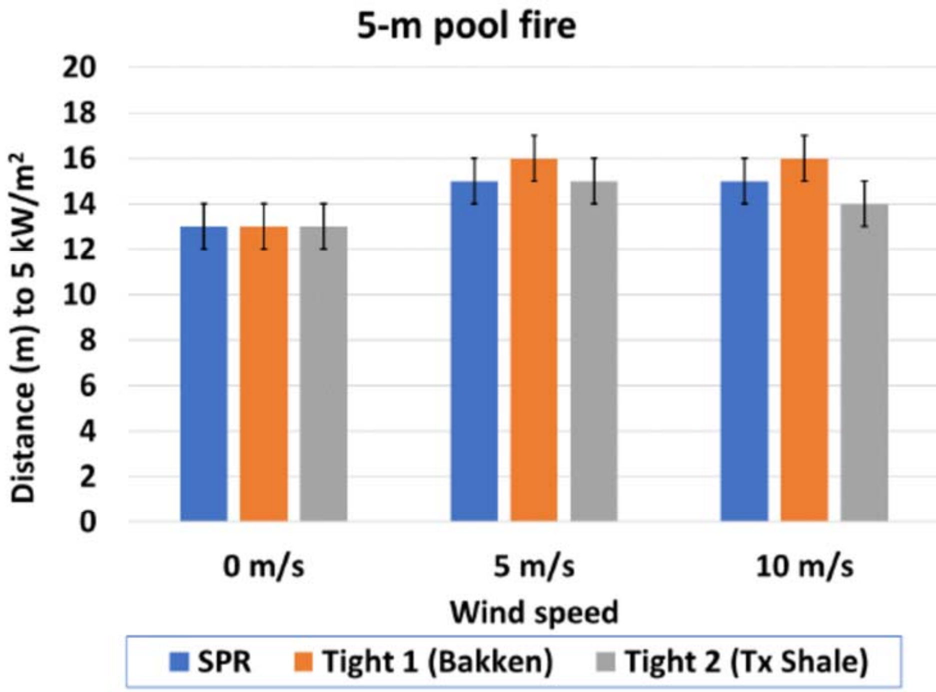

Figure 3-6: Comparison of predicted distances to 5 kW/m² for a 5-m diameter pool fire for various wind speeds.

POOL FIRE TEST OUTCOMES/TAKEAWAYS

- Predicted thermal hazard distances for contained pool fires fueled by the three tested oils are within 14% of each other, with overlapping standard deviation ranges. Predicted thermal hazard distances are for comparison purposes only and not intended to be applied to railcar accidents.
- Predicted thermal hazard distances using the measured parameters and a second-degree burn criterion for an uncontained or spreading pool resulting from an oil release of 30,000 gallons—the approximate capacity of a standard (DOT-111) rail tanker—indicate that the Bakken oil results in 16%–27% lower distances than the other two oils.
- However, historic accidents have demonstrated that hazards can exceed the distances calculated in this work because of damage of numerous railcars, leading to significant amounts of oil contributing to a fire which can then propagate to surrounding fuel sources, such as wooden structures, vegetation, and other hydrocarbons.

FIREBALL TEST RESULTS

Figure G-7 graphically summarizes the fireball test results. For comparison of fireball thermal hazard distances, a thermal dose unit (TDU) of 240 $(kW/m^2)^{4/3}s$ (s = seconds) is used as the criteria, since this TDU is capable of inflicting second-degree burns at a 30-s exposure.

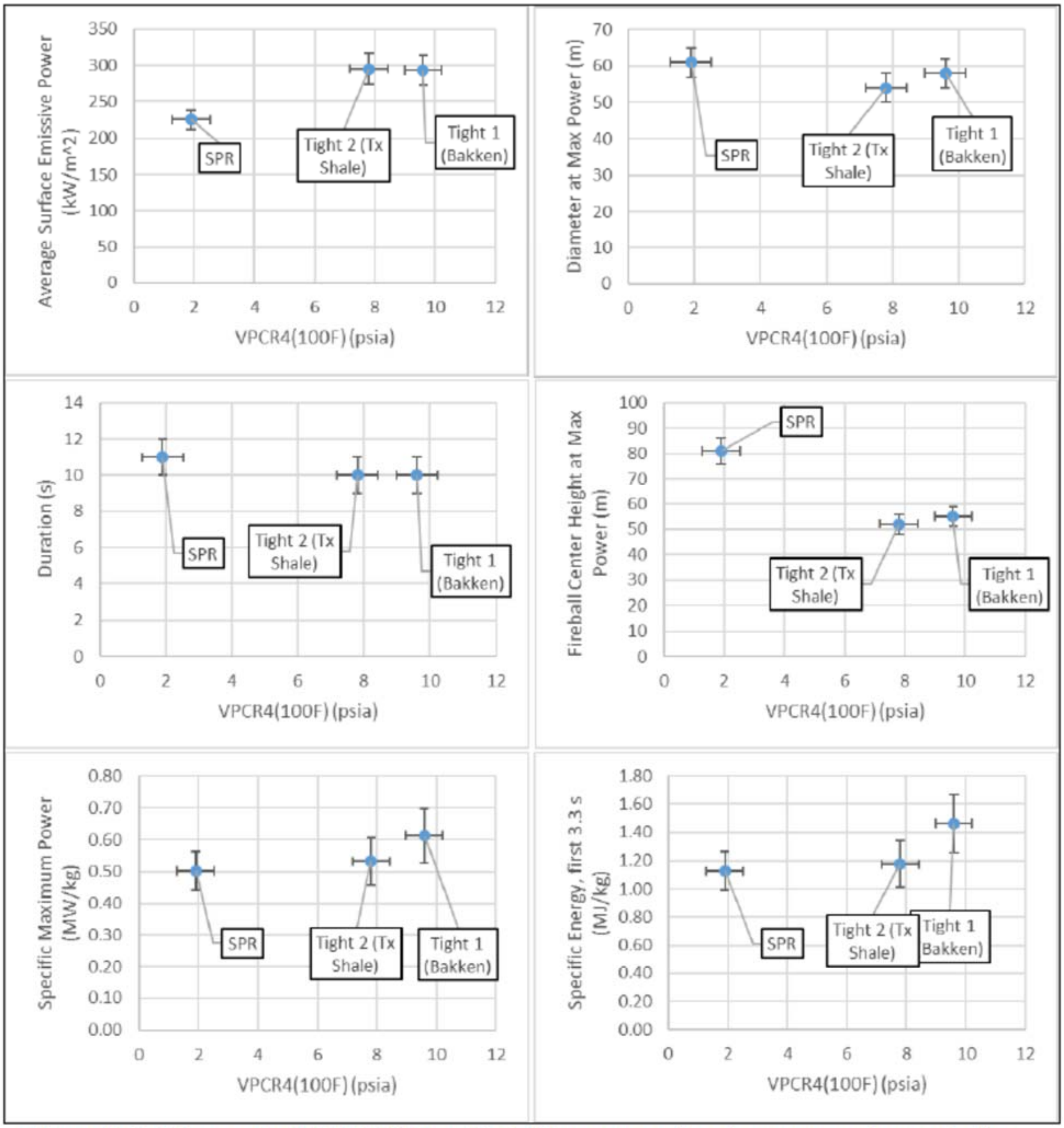

Figure G- 7: Oil property $VPCR_4(100°F)$ vs fireball burn properties a) average surface emissive power at max power, b) diameter at max power, c) duration, d) fireball center height at max power, e) specific maximum power, and f) specific energy from the first 3.3 s

Fireball test data from each oil and an integral model were utilized to predict distances at which a TDU of at least 240 $(kW/m^2)^{4/3}s$ is sustained. Figure 3-23 compares the three oils based on this predicted metric for fireballs generated from an oil release of 30,000 gallons—the approximate capacity of a standard (DOT-111) rail tanker. Although not shown in the figure, distances are in meters.

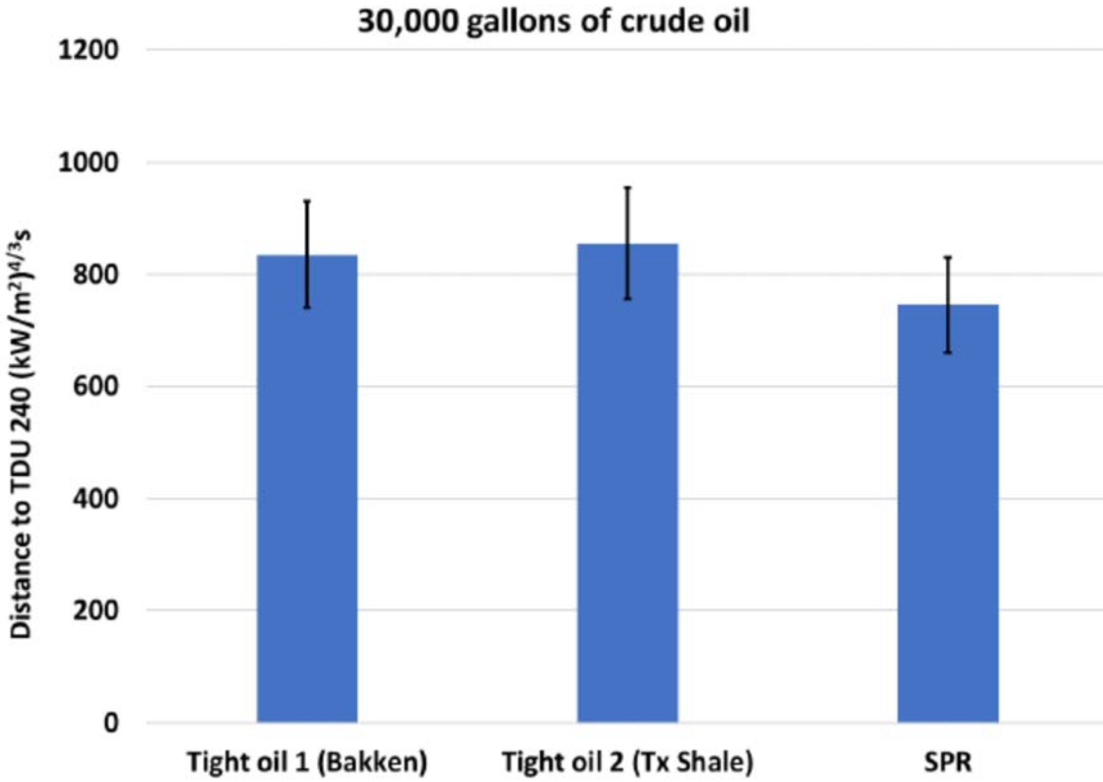

Figure 3-23: Comparison of predicted distances to TDU of 240 $(kW/m^2)^{4/3}s$ for a 30,000-gallon release fireball.

FIREBALL TEST OUTCOMES/TAKEAWAYS

- For each oil, thermal hazard distance was predicted for a 400-gallon-release-generated fireball using the injury criterion of second-degree burns after 30-s exposure to a TDU level of 240 $(kW/m^2)^{4/3}s$. Results indicate the distances for the tight oils are about 20%–30% higher than for the SPR oil.

- Predicted thermal hazard distances for a 30,000-gallon release differ by about 12%, with the range of uncertainties overlapping. Thus the predicted thermal hazard distances among the oils are comparable.

CONCLUSION

The similarity of pool fire and fireball burn characteristics pertinent to thermal hazard outcomes of the three oils studied indicates 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 two combustion events.

CONSIDERATION

This study did not include experiments involving ignition potential. Based on the COCRS Task 1 effort, the premise is that most train accidents provide enough kinetic energy to exceed the parameter thresholds indicating flammability; consequently, ignition is highly probable regardless of the crude oil type.

MEMBERSHIP AND FINANCIAL INFORMATION

This project is being sponsored by the NDIC Oil and Gas Research Council (OGRC). Table 3 shows the awarded budget of $150,000 for this project, expenses to date, and balance.

Table 3. Project Cost

Funding Source	Budget	Expenses to Date	Encumbered/Planned*	Remaining Balance
NDIC OGRP	$150,000	$142,289	$7,711	$0
Total	**$150,000**	**$142,289**	**$7,711**	**$0**

* Encumbered/planned expenses are estimates of the final payroll, which as of August 31, 2019, has not posted.