Preliminary Technical Guidance and Literature Review to Assist in Evaluation of Wellhead Burning as a Blowout Response:

Final Report

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Contents

Nomenclature

BBL	barrel of oil (volume unit equal to 42 gallons)
BOPD	barrels of oil (BBL) per day
D	diameter, m
DPP	development and production plan
E	entrainment fraction
g	gravitational acceleration, 9.8 m/s^2
GOR	gas/oil ratio, SCF/BBL
j	superficial velocity, m/s
MFR	mass flow ratio
MMSCF	one million (prefix: MM) cubic feet at standard conditions (suffix: SCF)
$\tilde{R}_{OG}$	dimensionless oil-gas mass flow ratio
Re	Reynolds number, dimensionless ($Re = \rho j D_{pipe} / \mu$)
SCF	cubic feet at standard conditions
WCD	worst-case discharge
We	Weber number, dimensionless ($We = \rho j^2 D_{pipe} / \sigma$)
μ	viscosity, Pa s
ρ	mass density, kg/m^3
σ	surface tension, N/m

Subscripts

g	gas
l	liquid
max	maximum
pipe	well pipe
vm	volume median

Volume conversion factors

	gallons	cubic feet	barrels of oil	cubic meters	MMSCF
1 gallon	1	0.1337	0.02381	3.785×10^{-3}	1.337×10^{-7}
1 cubic foot	7.481	1	0.1781	0.02832	10^{-6}
1 barrel of oil	42	5.615	1	0.1590	5.615×10^{-6}
1 cubic meter	264.2	35.31	6.290	1	3.532×10^{-5}
1 MMSCF	7.481×10^6	10^6	1.781×10^5	2.832×10^4	1

1.0 Introduction

Artificial drilling islands, such as the Endicott and Northstar Islands in the Beaufort Sea off the northern coast of Alaska[1], make it possible to conduct onshore oil drilling operations in shallow waters located a few to several miles away from natural coastline. A timely and relevant example is the Liberty Project currently in the planning stages by Hilcorp Alaska, LLC. Although the wellhead for the Liberty Island (and other man-made islands) will be located on land, blowout response is a special environmental concern due to the close proximity of surrounding seas. The Liberty Development Project Development and Production Plan (DPP) [1] states that the worst-case oil discharge (WCD) rate is an estimated 91,219 barrels of oil per day (BOPD), which (due to the large spill that could result from a blowout) underscores the importance of adequate preparation to deal with a blowout. Voluntary ignition of the gas and oil emerging from the wellhead is one of the options for blowout response to eliminate some or all of the oil before it reaches the sea surface. In fact, the Alaska Department of Environmental Conservation has approved voluntary ignition as a blowout response for wells that qualify based on conditions that are expected to efficiently burn oil[2]. The Liberty Project, however, is being planned in federal waters outside the jurisdiction of the State of Alaska. It is crucial to understand the burn efficiency of a Liberty Project blowout before such a method can be used effectively as a blowout response. This report reviews both literature related to predicting the burn efficiency and a (proprietary) investigation that predicts burning efficiency for a Liberty Project blowout.

This report is separated into two sections. The first section is aimed for public distribution and covers blowout conditions including those expected based on the Liberty Project DPP [1]. The Appendix is intended solely for official use by BSEE because it contains Hilcorp's proprietary information related to the Liberty Project.

The first section of the report begins with estimates of the oil spill sizes that could result from imperfect burning efficiency and ignition delays in a range of blowout scenarios wherein the maximum oil-discharge rate corresponds to the WCD in the Liberty DPP [1]. Next, we briefly discuss the physical and chemical phenomena affecting the burning efficiency of oil. The scientific literature related to these phenomena is then discussed and covers the conditions of gas-liquid flames, atomization and entrainment of oil in strong gas-liquid flows within a pipe, and flame-suppression threats such as water in the formation fluids. We conclude with a summary of our findings and our recommendations on future research. We also include supporting information at the end of the first section of the report.

2.0 Potential Oil Spill Volumes Resulting from Imperfect Burning Efficiency

First, it is important to estimate the effect of burning efficiency on potential oil spill volume resulting from a blowout. It should be noted that if the oil is unburned (zero efficiency), the potential oil spill volume from a blowout with a large oil discharge rate could result in grave

[1] See http://libertyprojectak.com/.
[2] See the corresponding regulation excerpt and discussion on p. 33 of this report.

environmental impact[3]. Burning the oil in the event of a blowout would very likely reduce potential spill volume and environmental impact; however, these could be very sensitive to the oil burning efficiency because most of the unburned oil eventually must settle on the ground and the water. Additionally, planned or unplanned delays between the blowout and ignition of the well could allow oil to spill onto surrounding waters. Awareness of the oil-spill volumes that could occur due to burning inefficiencies and/or ignition delays could facilitate the development of a comprehensive blowout-response plan that may or may not include wellhead burning.

In this section of the report, we estimate the amount of oil that could result from inefficient burning in the event of a WCD from a Liberty blowout (91,219 BOPD). The WCD corresponds to the maximum flow rate estimated for any single well in the Liberty Project. We note that the drilling plan [1] includes up to 16 wells that, in the event of a blowout, may have lower discharge rates[4]. Therefore, we also include estimates of unburned oil volume for smaller blowouts in our discussion. We consider oil flow rates as low as 30,000 BOPD, which is two to three times greater than the expected production rate of a single well [1].

The large oil discharge rate expected from a Liberty WCD blowout indicates that small burning inefficiencies[5] could lead to large oil-spill volumes. The Liberty WCD is 91,219 barrels of oil per day [1] (roughly 3.8 million gallons per day). At 99% burning efficiency (only slightly less than 100% oil removal by burning), the resulting unburned oil volume would be approx. 910 barrels per day (approx. 38,000 gallons per day). This is a large spill assuming all of the unburned oil settles back down to the surface[6]. For comparison, consider the recent oil spill in Santa Barbara, California on 19 May 2015: the total spill from the underground pipeline was approx. 105,000 gallons, and it is estimated that 21,000 gallons reached the Pacific Ocean [2]. Let us consider additional reference points for the spills that could occur due to inefficient oil burning: the National Oceanic and Atmospheric Administration (NOAA) reports at least 44 spills with total volumes exceeding 10,000 barrels (approx. 420,000 gallons) have occurred since 1969 [3]. In a Liberty WCD scenario, an unburned oil volume of 10,000 barrels would be reached *in a single day* if the burning efficiency was 89%. Assuming that the well could be capped in a typical period of 20 days following the initial blowout [1], the total volume of unburned oil would exceed 200,000 barrels (approx. 8.4 million gallons) in these scenarios if their corresponding efficiencies persisted until capping. Figure 1 shows the volume of unburned oil that would result from imperfect burning efficiencies[7] of 95%, 90%, and 85% for a Liberty WCD. For comparison with

[3] See the Liberty DPP for a discussion of specific environmental resources of concern for the Liberty Project and Hilcorp's strategies to mitigate impacts to these resources under normal operating conditions.
[4] Oil production and gas/water injection may, over time, decrease the WCD for wells drilled later in the drilling plan. Note that WCDs are not required for all wells in a multi-well drilling plan even though the associated flows could affect burning efficiency.
[5] By "burning efficiency", we mean the ratio of the oil evaporated and burned to that of the total oil spilled. We do not mean "combustion efficiency", which is a measure of the conversion of fuel and oxygen to carbon dioxide and water.
[6] Some of the oil could evaporate without the presence of a flame or disperse significantly before reaching the surface. It is not clear how much of the unburned oil would accumulate into a slick. We assume conservatively that all unburned oil contributes to the spill.
[7] It may not be obvious that crude oil, which is composed of flammable hydrocarbons, can burn at less than 100% efficiency when sprayed into a flame in ambient air. Evidence of incomplete burning efficiency has been witnessed, both by NRL and BSEE staff members, during an outdoor demonstration of a novel crude-oil burner (see Tuttle et al., 2014). The burner includes a flow-blurring nozzle that atomizes the crude oil into small droplets prior to burning. The test was performed using a relatively heavy oil (Oriente with API

previous major oil spills in U.S. waters, see Figure 2. Note that even if the WCD was decreased by 67% to 30,000 BOPD, the unburned oil volume would exceed one million gallons in 6, 8, or 16 days for burning efficiencies of 95%, 90%, or 85%, respectively. The potential spill volumes from blowouts with large oil discharge rates are large enough to make the following point: *the large magnitude of unburned oil that could potentially spill onto federal waters from a Liberty blowout shows the importance of reaching and maintaining nearly 100% burning efficiency.*

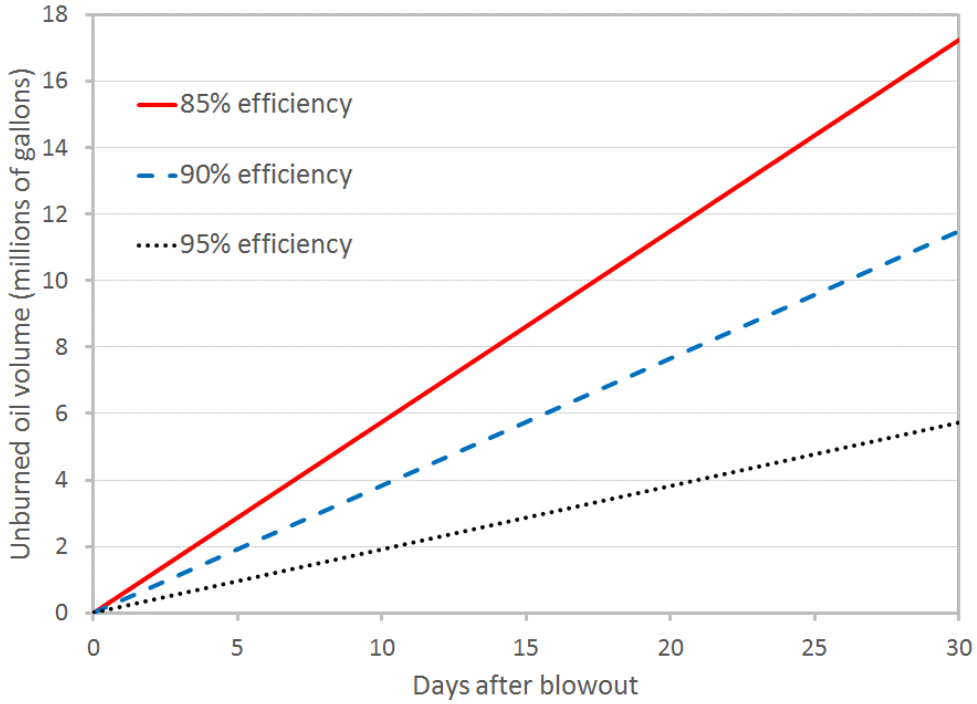

Figure 1. Unburned oil volume at burning efficiencies of 95%, 90%, and 85%. for the worst-case discharge [1] from the Liberty Project (91,219 BBL/day) assuming that all unburned oil contributes to spill. (See Figure 2 for a comparison with previous oil spills in U. S. waters).

gravity: 23.4). While the flame was burning during the demonstration, a portion of oil droplets escaped the flame and sprayed onto the clothes of the surrounding witnesses. Thus, oil burning efficiency can be less than 100%, but the conditions causing oil to escape a flame without burning remain to be understood.

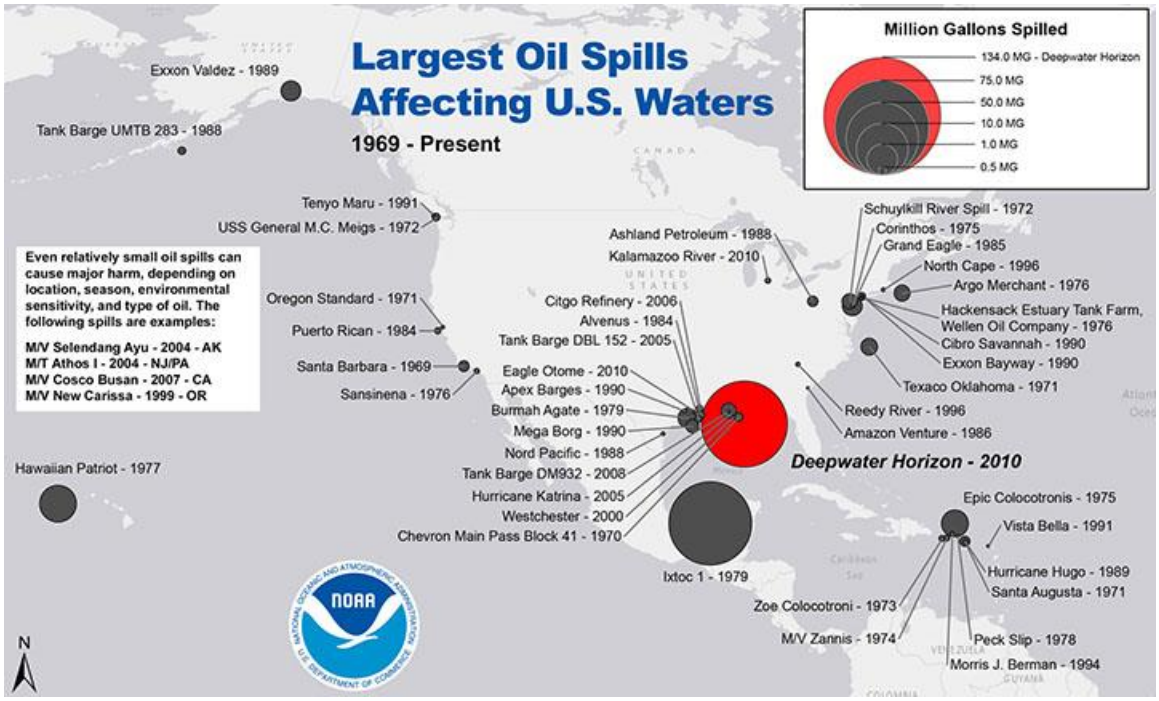

Figure 2. Largest oil spills affecting U.S. waters, as reported by the National Oceanic and Atmospheric Administration (image copied from NOAA website [3]).

Clearly, an accurate knowledge of the burning efficiency that would result from igniting a blowout is important for planning the blowout response. The cost and hazards associated with experimental testing to determine the burning efficiency using conditions of typical blowouts are prohibitive. An experimentally validated computational model offers the possibility of a less-expensive and non-hazardous method to predict burning efficiency. As we review the literature, such a model does not appear to exist to our knowledge and may need to be developed. Developing a computational model for burning efficiency with an uncertainty of one percent can be extremely challenging and may require experimental validation at different scales. Clearly, a high degree of accuracy in the predictions of burning efficiency would be necessary for WCD rates similar to that of the Liberty WCD due to the large spill volume that could result from inefficiencies as small as a single percent.

Delays between the blowout event and blowout ignition are another potential source for an oil spill. In a situation wherein the blowout is not ignited instantly by accidental spark, a delay may be desirable as a safety measure. Indeed, the Liberty DPP [1] states that ignition will be delayed to evacuate personnel, to move the drilling unit and associated movement system, to take environmental-impact-mitigation actions, etc. In Figure 3, we show the total oil volume that would be released during a delayed ignition for a Liberty WCD of 91,219 BOPD [1]. From Figure 3, it is shown that a million gallons would be released in roughly 6 hours following the blowout. Cases with lesser oil flow rates of 60,000 and 30,000 BOPD are also shown in Figure 3, which shows that spill sizes would reach one million gallons in approx. 9.5 and 19 hours, respectively. We did not find an estimated delay time in the Liberty DPP [1].

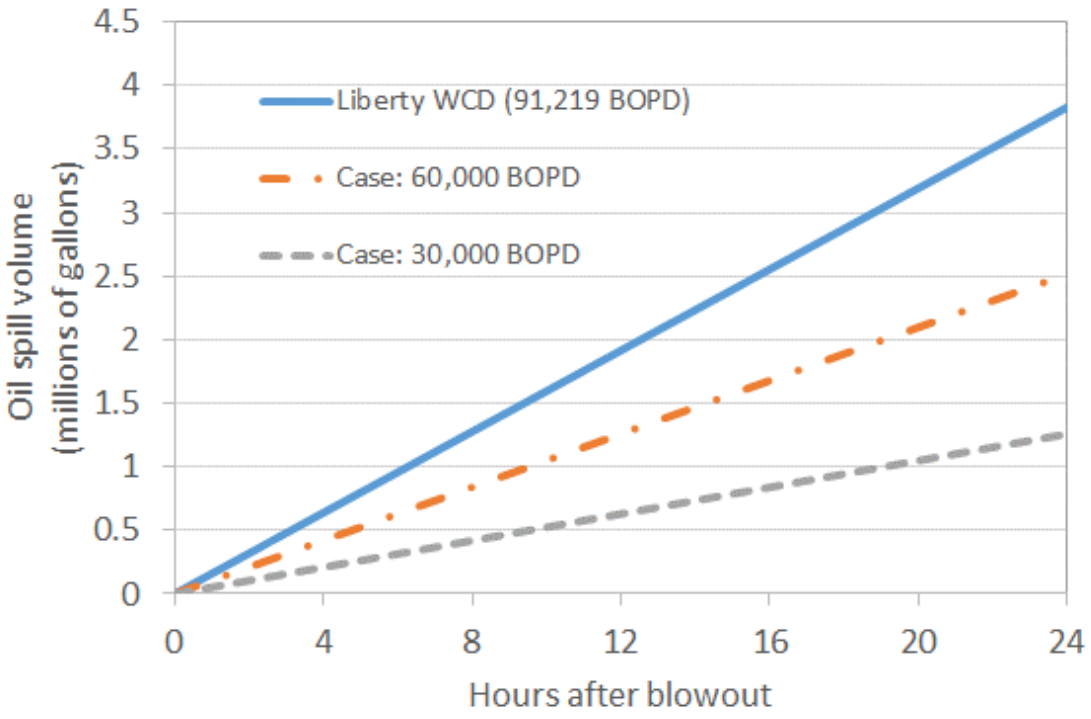

Figure 3. Total oil volume that would be released due to delayed ignition during the first 24 hours for a Liberty WCD of 91,219 barrels of oil per day (BOPD) [1] and for cases with lower flow rates of 60,000 and 30,000 BOPD. See Figure 2 for a comparison with previous oil spills in U. S. waters.

3.0 Phenomena Involved in Burning a Gas-Oil Blowout Jet

To assess the risk of a large spill in federal waters, it is desirable to obtain accurate predictions of oil burning efficiency. However, to our knowledge, no models are available that have been sufficiently validated with experiments and properly scaled to reliably predict burning efficiency for a Liberty Project blowout. The prediction of burning efficiency would require a model that describes coupled phenomena in combustion of a turbulent multiphase jet. Here, we attempt to provide a simplified overview of the key phenomena expected to have a significant effect on burning efficiency to motivate the sections found in this report and to point out their relevance.

From a simple perspective, oil droplets emerging from a wellhead need to absorb heat/energy from the hot gases of the flame to evaporate and burn[8]. In quantitative terms, there is an amount of energy *required* for evaporation and burning of the oil, and there is an amount of energy *delivered* by the flame; these quantities are plotted in Figure 4. Perfect burning efficiency occurs

[8] Mass transfer also plays a role in droplet evaporation that may be of secondary importance in the high-temperature conditions of a flame.

when these energies are equal, whereas liquid oil will not completely evaporate and burn when there is insufficient energy delivery from the flame.

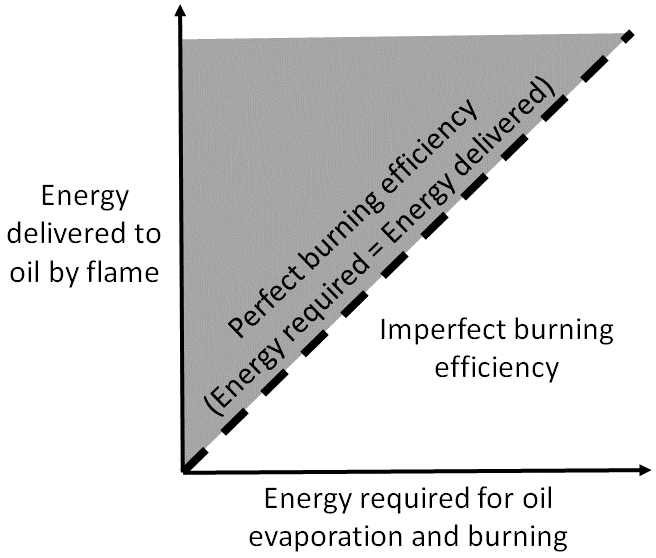

Figure 4. Simplified view of energy relationships involved in oil-burning efficiency.

The energy requirement (horizontal axis of Figure 4) for burning the oil is determined primarily by the total mass of the oil, its chemical composition, and its initial temperature. If chemical composition and associated enthalpies for heating, evaporation, and burning are unknown, the oil density can be a qualitative indicator of the chemical-composition-dependent energy requirement: heavier oils typically require more energy to heat, evaporate, and burn. The Liberty DPP states that the reservoir oil has an API gravity in the range of 24-27, which corresponds to a density range of 893-910 kg/m^3, and an initial average temperature of 102 °C (215 °F). For comparison with well-known fuels, diesel no. 2 has a density of 810-890 kg/m^3 and its components have boiling points ranging from 188-343 °C (370-650 °F)[9] [4]. For comparison with a pure alkane, eicosane ($C_{20}H_{42}$) is a solid at room temperature with density of 789 kg/m^3; it melts around 36 °C (97 °F) and boils around 344 °C (651 °F) [5]. It follows that the Liberty oil will likely need to absorb a significant amount of sensible heat before its components reach their boiling points even though the reservoir temperature is well above room and ambient Arctic temperatures.

In contrast, the delivery of energy from a flame to oil droplets (vertical axis of Figure 4) is relatively difficult to accurately quantify. The energy delivery is affected by many coupled phenomena. Below, we provide a partial list of coupled factors affecting the energy delivery

- Flame conditions
    - Flame temperatures
    - Flame dimensions (height, width, etc.)
    - Flame stability and flame speed
    - Combustion efficiency

[9] Note that diesel no. 2 is significantly less volatile and more difficult to ignite than gasoline (density 720-780 kg/m^3, boiling point 80-437 °F).

        - Soot production
    - Potential effects of natural suppressants (e.g., water, precipitation, etc.)
- Flow conditions
    - Droplet velocities
    - Jet velocity
    - Turbulent convection
    - Viscous drag on droplet
- Droplet properties
    - Droplet size distribution (atomization)
- Fuel properties
    - Gas/oil ratio (GOR)
    - Sooting character of gas and oil
    - Heat release by combustion of gas and oil

We have identified at least some phenomena that are potentially both important and challenging to accurately quantify/predict in blowout conditions; these phenomena are discussed further in the next section. Overall, the phenomena that we will discuss affect flame conditions and oil droplet sizes; we describe next how burning efficiency is impacted by flame conditions and oil droplet sizes.

The flame is the primary heat source that delivers energy to evaporate and burn the droplets; thus, the flame conditions are an important factor. Clearly, higher flame temperatures result in greater energy delivery/heat transfer to the droplets. When combustion efficiency and/or flame stability are reduced, the energy delivery to the droplets is decreased. Further, the flame size, along with the droplet velocities, also affect the energy delivery to the droplets. The oil droplets absorb heat primarily as they travel through the hot gases within the flame, and both the flame size and the motion of the droplets affect the time that the droplets reside within the flame. As indicated above, the flame conditions are coupled with the flow conditions, droplet properties, and fuel properties (among others).

Droplet sizes are known to be an important factor in spray combustion [6]. By decreasing droplet sizes in a given amount of oil, evaporation is achieved faster because the total surface area (where heat is absorbed) is increased. In quiescent conditions, the burning rate of a droplet is approximately inversely proportional to the square of its diameter [6]; while this dependence may change somewhat in the turbulent conditions of a blowout, it clearly indicates that droplet size is a parameter of significant sensitivity for droplet evaporation. The formation of droplets (i.e., atomization) and their resulting sizes depend on the mechanisms involved and the fluid dynamic interactions between the gas and oil.

4.0 Review of Scientific Literature Relevant to Wellhead Burning

To accurately predict burning efficiency, a sufficient understanding is needed regarding the important phenomena in an ignited blowout, their interactions, and how to incorporate them into a

model. We have identified a few potentially important phenomena affecting burning efficiency that may be very challenging to predict; these areas are the subjects of our literature review.

A somewhat uncommon aspect of ignited blowouts relative to typical flames is that there are two multi-component phases of fuel: both highly flammable gas and less-flammable oil emerge from a blowout. These fuels burn quite differently; for example, the liquid must absorb latent heat to evaporate before it becomes a gas that can be burned. Two-phase flames with significant loading of liquid fuel have received less attention in research relative to simpler pure gas or pure liquid-spray flames. In our literature review, we aimed to obtain relevant, existing research about two-phase flames similar to the natural gas and crude oil that would emerge from a blowout with particular focus on expected Liberty conditions.

Atomization of liquid droplets in a blowout scenario may also prove difficult to accurately capture. Correlations between droplet sizes and flow conditions are typically used to predict droplet diameters of sprays, but the value of the correlation is limited by how well the conditions used in its development match the target scenario. For the extreme conditions of a blowout, we questioned whether atomization mechanisms were understood and/or whether existing correlations would be valid. Further, atomization inside the well bore will depend on the extent to which the turbulent gas flow can entrain the oil; thus, correlations on entrainment in high-speed gas-liquid flows are also considered in the review in the following section(s).

Additionally, we considered the risk that water could suppress or extinguish an ignited blowout and threaten oil-burning efficiency. Besides precipitation, water can enter the flame if water has been injected into the reservoir to enhance production prior to a blowout. Further, water can be present naturally in the reservoir. Water flooding is planned to occur in the Liberty Project before the multi-well drilling plan is complete; however, the Liberty reservoir is expected to have negligible water content prior to water flooding[10]. Our corresponding aim in this project is to review research on fire suppression with water to determine approximately the water content that could threaten stability of a blowout flame and associated burning efficiency.

In the following sections, we review scientific literature related to the phenomena occurring in wellhead burning, including gas-liquid flames, oil atomization, liquid entrainment in the well pipe, and the threat of fire suppression by water in the formation fluids. We note that it is beyond the scope of this review to quantify the effect of these conditions on oil-burning efficiency, but we do comment on the expected qualitative effect that such conditions could have on burning efficiency.

4.1 Highly liquid-loaded flame research

The research group of J. P. Gore at Purdue University experimentally investigated turbulent jet flames formed by liquid fuels and methane gas [7, 8]. Dutta *et al*. [7] conducted experiments on flames from two-phase fuels using methane and Alberta sweet crude oil. While there are noteworthy differences between these experiments and an ignited blowout (to be discussed later in this section), their investigations included a range of gas-oil ratios (GORs) relevant for oil-well

[10] BSEE confirmed that the reservoir contained negligible water with both Hilcorp Alaska, LLC and BOEM.

blowouts. We note that relative gas and oil content in the oil industry is commonly specified as a GOR, which is a volume-based quantity in units of SCF/BBL[11]; on the other hand, Gore's group reports the (mass-based) gas-oil mass-flow ratio (MFR) for their experiments. In our discussion of the experiments, we provide both the MFR and corresponding GOR for the experiments. The methane-oil mass-flow ratios (MFRs) investigated range from 5% to 20 %; this range of MFRs corresponds approximately[12] to GOR values ranging from 330 to 1330 SCF/BBL. For comparison, the GOR expected from the Liberty project is 872 SCF/BBL [1], which corresponds to a gas-oil MFR of roughly 12%. Note that the GOR in the Liberty reservoir will likely increase during and after the drilling period as there are plans to re-inject up to 70% of the produced gas into the reservoir for enhanced oil recovery [1].

The experiments of Dutta *et al*. [7] showed significant effects of liquid loading in flames with both gas- and liquid-phase fuels. Soot production from the combustion of the heavy hydrocarbons originating in the oil increases radiation absorption because soot absorbs and emits radiation in a much broader region of the electromagnetic (light) spectrum compared to other combustion products. In contrast, methane flames do not generally produce any soot. Sooty flames lose more heat via radiation to their surroundings relative to that of a methane flame; as a result, lower temperatures may be expected for oil and gas fires of interest. Dutta *et al*. measured the heat loss to the surroundings in terms of the radiant fraction, which is the ratio of the energy lost via radiation to the maximum energy that can be released by fuel combustion. Their measurements show that the radiant fraction increased from approx. 10% to over 20% as the relative methane content was decreased from a methane-oil mass ratio of 20% to 5% (approximately 1330 to 330 SCF/BBL, respectively), which was attributed to greater soot production by the oil. Soot production was also claimed as the reason for decreased flame temperatures (by roughly 300 K) when the relative methane content was decreased; however, the temperatures were still rather high and indicate that oil burning was very efficient. Further, the flame height increased by over 30% as the methane-oil mass ratio was reduced from 20% to 5% (approximately 1330 to 330 SCF/BBL, respectively). The radiant fractions ranged from approx. 10% to 22%, which was unexpectedly low compared to measurements of methane flames (approx. 18%) and pool fires for Alberta sweet crude oil (approx. 30%). Dutta *et al*. report that the low values of the radiant fraction were not understood. Flame temperatures were also higher than expected: for methane-oil MFR of 10% (approximately 665 SCF/BBL), the peak flame temperature was just over 2000 K. The high flame temperatures indicated high combustion efficiency, which may suggest that incomplete combustion could not have caused the low radiant fractions. It is possible that the somewhat unexpected effects of soot on flame temperatures could be due to the addition of hydrogen (hydrogen-oil MFR ranges from 5 to 12%) from the pilot flame that was necessary to achieve flame stability. Experiments similar to those of Dutta *et al*. [7] and modeling may be needed for obtaining a more realistic understanding in the absence of hydrogen. Note that the fluids in a petroleum reservoir may not contain significant hydrogen content that can stabilize an ignited blowout.

For the effervescent atomizer used in the studies of Dutta *et al*. [7], decreasing the methane-oil MFR from 14% to 5% (approximately 930 to 330 SCF/BBL, respectively) at a fixed heat release rate increased the Sauter mean droplet diameter from approx. 24 to 39 μm. A rough estimate of

[11] Commonly used units for the GOR are cubic feet of gas at standard conditions (SCF) per barrel of oil (BBL). A barrel of oil is 42 gallons, which is roughly 5.6 cubic feet.
[12] Calculating the GOR from the MFR requires the density of oil and gas. Here, we assume a density of 830 kg/m^3 for Alberta sweet crude and a gas density of 0.7 kg/m^3 for methane.

the effect of this diameter change using the diameter-squared law describing droplet evaporation rates [6] indicates an increase in the droplet lifetime by approximately a factor of three. Also, the droplet diameter increased as the flow rate was increased (for fixed MFR). As discussed in further detail below, it is not clear how the relationships between droplet diameter and the flow rates of oil and gas measured for the effervescent atomizer apply to the atomization of a blowout jet exiting a well pipe.

The conditions of the high-liquid-loading flame experiments by the Gore group [7, 8] clearly differ from that expected for a Liberty blowout [1]. Key differences between the conditions are discussed here in further detail (additional comparison is made in **Error! Reference source not found.** of the Appendix). The experiments were conducted at a small scale, where flame heights were approx. 60 cm or less. They atomized the oil using methane gas with an effervescent atomizer; this nozzle achieved Sauter mean droplet diameters ranging from 23 – 46 μm for the conditions of their experiments. As discussed above, droplet diameter is clearly an important parameter in determining the evaporation rate of the oil. They did not carry out a study to measure the droplets emerging from an open pipe; thus, it is not clear how well the effervescent atomizer approximates the exit conditions of a blowout. Figure 5 shows simple illustrations for comparison of an effervescent atomizer and an open well pipe. The unique features of effervescent atomizers include (1) forcing liquid and pressurized gas through a very small, constricted section of the nozzle (typical diameter of 0.1 – 2.5 mm) and out of an exit orifice where thin films/ligaments form that facilitate atomization and (2) breakup of the thin films/ligaments by expansion of the gas into ambient pressure [9]. In contrast, the diameter of the well pipe for Liberty is uniform (from the outlet down to a few km in depth) and two to three orders of magnitude larger than the exit orifice of an effervescent atomizer. Further, the locus of liquid-film breakup into droplets is known to be at the exit of an effervescent atomizer [9]; but, as covered later in this review, most of the oil in a blowout is expected to be atomized into droplets (i.e., not in films or ligaments) within the well pipe before reaching the outlet. For these reasons, we do not expect quantitative agreement in droplet-size distributions between the effervescent atomizers in Refs. [7, 8] and a Liberty blowout; further, it is not clear that these two cases rely on the same atomization mechanisms.

An additional difference between the experiments of Dutta et al. [7] and ignited blowouts is that their flames are stabilized externally at the nozzle base with continuously burning hydrogen pilot flames. Hydrogen generates more stable flames because it burns faster and releases twice as much energy[13] as conventional hydrocarbons by mass, but with much more volume. The hydrogen-oil MFRs used in the experiments are similar to that of methane-oil MFRs: 5 to 12% (for comparison, the GOR expected from the Liberty project is 872 SCF/BBL [1], which corresponds to a MFR of approx. 12%). Hydrogen has a much smaller density than methane, so these MFRs correspond to large gas (hydrogen)-oil ratios of roughly 2800 to 6700 SCF/BBL. The stabilizing hydrogen pilot flame was introduced because previous work (e.g., [10]) showed that methane flames blow out (i.e., become unstable and extinguish) at a critical flow rate for small (approximately 4 cm for methane according to Ref. [10]) nozzle diameters. Dutta *et al*. also reported encountering difficulty with stabilizing a methane-oil flame at elevated methane-oil flows, even with the hydrogen pilot flame, when the hydrogen mass flow rate was fixed. Stable flames were only achieved when the hydrogen-oil MFR was approx. 5% or greater (GOR for

[13] The laminar flame speed of hydrogen is an order of magnitude larger than methane and its heat combustion is about 2.4 times larger.

hydrogen-oil greater than 2800 SCF/BBL). The stability problem was likely exacerbated due to the very small size of the atomizer used in the work (oil and methane outlet diameter: 0.38 mm; hydrogen outlet diameter: 4.76 mm). It is not clear whether flame stability could be an issue for oil-gas jets emerging from well pipes of typical diameter (>20 cm), which are much larger than critical exit diameters quantified in previous research for pure-gas, methane flames [10].

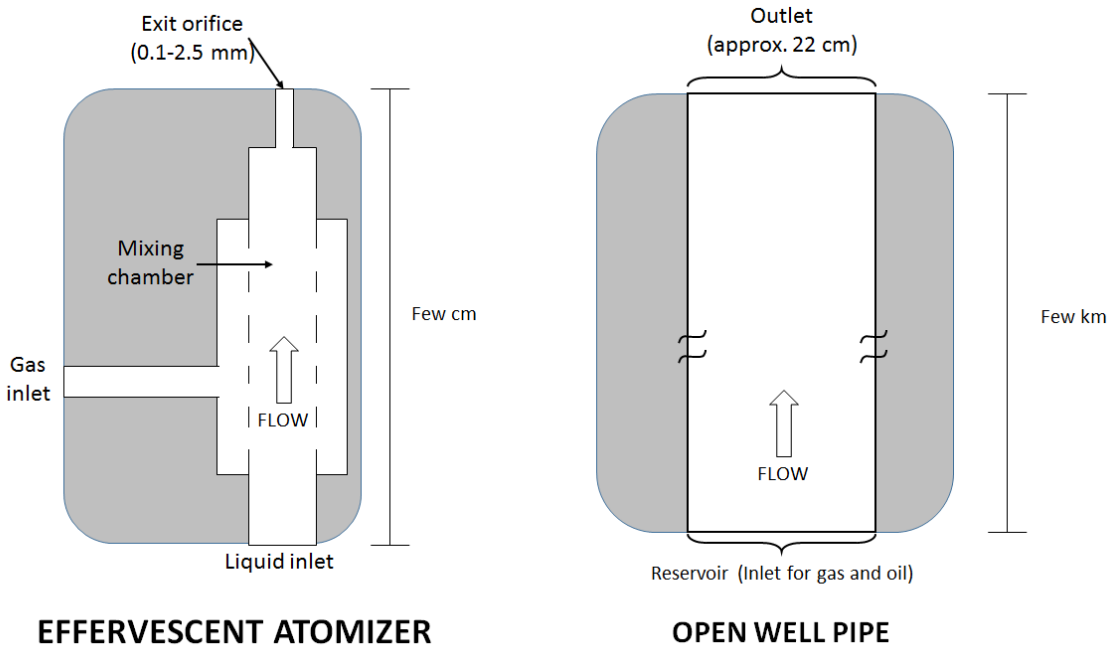

Figure 5. Illustrations (cross sections) of an effervescent atomizer and an open well pipe.

Advances in understanding the two-phase fuel fires in Dutta *et al*. [7] by the Gore research group are reported by Wade *et al*. [8]. The distance traveled by droplets prior to evaporation in the flame (i.e., evaporation length) was measured using a Mie-scattering apparatus that measures scattered light from the flame along its axis. They report that liquid droplets scatter light very close to the fuel exit (prior to evaporation), which can be distinguished from light scattered by soot particles in a region further along the flame axis. This claim is supported by measurements of two discernable regions of significant scattering along the flame axis. The measurements show that the evaporation lengths for the flames in Ref. [7] are an order of magnitude smaller than the flame length; hence, the increase in flame length encountered when the methane-oil mass ratio is reduced cannot be attributed primarily to droplet evaporation. Meanwhile, they emphasize the importance of atomization quality on the evaporation lengths: on occasion, their atomizers became clogged and created significantly larger droplets that were observed to have much longer evaporation lengths. They point out that poor atomization could lead to evaporation lengths becoming comparable to flame heights.

Additional experiments were performed using toluene, a liquid fuel that is known to produce sooty flames[14]. A motivation for using a liquid fuel that is known to produce heavy soot was the unexpectedly low radiant fractions measured with flames generated using Alberta sweet crude oil and methane. The experiments were performed with the same apparatus as Dutta *et al*. [7] and included an effervescent atomizer. The heat release rates ranged from 10 – 25 kW and produced flames with heights of 34 – 64 cm. The methane-toluene MFR was varied from 5% to 25 % (approximately 350 to 1390 SCF/BBL, respectively) and the effect of hydrogen on the flames was investigated at hydrogen-toluene MFRs of 13% and 5%.

In the toluene experiments, the evaporation lengths are reported to be less than 2% of the flame height, which indicates very effective liquid fuel burning. Since toluene has a boiling point that is much lower[15] than heavier hydrocarbons in crude oil (i.e., toluene is relatively volatile), smaller evaporation lengths are expected for toluene.

Their measurements show that the behavior of the radiant fraction for two-phase fuel flames differs from pure gas flames. In gas flames, the radiant fraction is independent of fuel input rate except at high flow rates, beyond which the radiant fraction decreases [8]. In contrast, the radiant fraction measured for two-phase fuel flames showed a range of trends, which varied with the methane-toluene MFR. For methane-toluene MFRs of 5% and 10% (approximately 350 and 695 SCF/BBL, respectively), the radiant fraction increased with increasing fuel flow rate; the maximum radiant fractions measured were roughly 30% and 40%, respectively. Greater methane-toluene MFRs (15%, 20% and 25%) produced flames with radiant fractions that either remained constant or decreased with increasing fuel flow rate.

In addition to radiant fractions, they measured profiles of temperature and visible-light transmittance (which decreases with increasing soot content) along the axis of the flames. The temperatures are measured by two-wavelength emission pyrometry, and the transmittance measurements are based on extinction of a He-Ne laser (visible red light with 632 nm wavelength). Note that the temperature-measurement apparatus can only measure temperatures from flames with sufficient luminosity; thus, this approach is consistent with measurements of flame height by visual observation. These results were reported for flames with methane-toluene MFRs of 5% and 25% at hydrogen-toluene MFRs of 13% and 5%. Very little soot was formed in the methane-toluene MFR 25% case (1390 SCF/BBL) at 10-kW fire size; this claim is supported by measurements of high transmittance (>90%), high peak temperatures (approx. 2200 K), low radiant fraction (approx. 10%), and relatively small visible flame height (temperature drops below 1000 K at flame height of approx. 33 cm). In contrast, the 10-kW flames with MLR 5% (350 SCF/BBL) were very sooty, showing strongly reduced transmittances (below 40%), lower peak flame temperatures (approx. 1900 K), high radiant fractions (approx. 32%), and longer flame lengths (temperature approaches 1000 K at or above 38 cm). These results show that high liquid loading in two-phase fuel flames can lead to heavy soot production and associated radiative heat loss, which can significantly reduce flame temperatures.

[14] Aliphatic aromatic compounds such as toluene typically begin to form soot at relatively small flame sizes (i.e. their smoke points are relatively small). For comparison, alkanes (e.g. methane, propane, etc.) typically produce relatively small amounts of soot and have smoke points one or more orders of magnitude larger. The chemical structure of aliphatic aromatics may facilitate the formation of polycyclic aromatic hydrocarbons, which are thought to be precursors for soot.

[15] Boiling point of toluene is about 111 °C, which is comparable to lighter hydrocarbons like heptane and octane with boiling points of 98.4 °C and 125 °C, respectively.

The effect of increased soot was also demonstrated by reducing the hydrogen-toluene MFR from 13% to 5% (approximately 7,000 to 2,700 SCF/BBL, respectively). Increased soot was reflected by a decrease in transmittance closer to the fuel exit (by approx. 5 cm), slightly lower temperatures throughout most of the flame length (by approx. 50 K), and decreased luminous flame length (the change is difficult to assess, but may be roughly 5 cm). They attribute the lower flame length observed in the flame with greater soot to the radiative cooling effect of the soot. Likewise, the radiant fractions of flames with less hydrogen were similar to or less than those with greater hydrogen content despite the greater soot content of the former; this finding was attributed to a complex interplay between the effect of soot on flame temperature and radiative heat transfer.

In the preceding discussion, we focused on the findings of the Gore research group related to the effect that liquid loading has on the flame conditions, especially the flame temperature. Each study showed that increased liquid loading results in lower flame temperatures, which (with all things being equal) would lead to reduced energy delivery to the droplets. As discussed above (see Figure 4), reducing energy delivered to droplets could lead to reduced burning efficiency. Further relevance of the studies discussed above to a blowout is as follows:

- The radiant energy loss from soot production in two-phase fuel flames at gas-oil MFRs relevant for oil-well blowouts has been measured at small scales to be roughly 15-40% of the potential heat release by combustion of the fuels. Measurements show that decreased flame temperatures and increased flame heights result from increased oil loading; these effects are attributed to soot generated by burning oil. The significant magnitude of radiant energy loss from two-phase fuel flames indicates that soot production and its effect on burning efficiency should be understood for an ignited blowout.
    - The observed trend of increasing radiant fraction with increasing fuel flow rate [8] at gas-oil MFRs similar to that expected for the Liberty Project provides additional support for the need to understand the effect of soot and its associated radiative cooling of the flame in the case of ignited blowouts that have much greater fuel flow rates than these bench-scale works [7, 8].
- The effervescent atomizer used in the research of the Gore group produced very small droplets with Sauter mean diameters of roughly 20-40 μm that burned very efficiently. It is not clear whether these droplet diameters are similar to those that would occur in a blowout.
- The sooting tendency of the formation fluids depends on the chemical composition, which varies from well to well. We do not know the detailed composition of chemical compounds in the Liberty oil, nor do we know their sooting tendencies. Extreme cases of soot-forming liquid fuels, such as aromatic compounds, may need to be considered to assess the possible effect of soot on burning efficiency.
- These studies [7, 8] avoid flame stability issues by adding hydrogen pilot flames, which is clearly different from an ignited blowout. Flame stability is a concern for two-phase fuel flames of natural gas and crude oil without a pilot flame. In contrast to methane flames, the blow-off stability limits (in terms of critical flow rate for small nozzle diameters) have not been measured for two-phase fuel flames. Because liquid oil requires considerably more energy to ignite than methane gas, we expect that two-phase fuel flames can blow off at larger exit diameters than for methane. It is not clear whether flame stability could be an issue for large diameters of typical well pipes, but it is more likely to be an issue in non-ideal cases wherein a blowout jet exits a smaller outlet.

- Hydrogen addition clearly has effects on the flame other than simply increasing stability, such as soot reduction, increased flame temperatures, and reduced droplet-evaporation lengths. The mass flow rates of methane and hydrogen in all experiments of Refs. [7, 8] are comparable; thus, it is not clear how the two-phase-fuel flames would behave without hydrogen addition. Unlike these experiments, wells may not contain significant amounts of hydrogen gas.

Note that while the studies discussed above reveal the effects of GOR values that are relevant for blowouts including a potential Liberty blowout, the length scales between the experiments and a typical blowout are vastly different; further, the works do not show how these effects depend on the scale of the flames. Additional research is necessary to understand how length scales and flow conditions affect the two-phase flame behavior.

Below, we discuss additional research to demonstrate differences between pure-gas and two-phase flames. In particular, we are concerned with the change in flame behavior when the mass flow of liquid oil becomes significantly larger than that of the gas. Flame temperature is one physical property of the flame behavior that would affect burning efficiency and could be different between gas-dominated flames and two-phase (or liquid spray) fires. We consider a few studies that demonstrate the differences in flame temperatures between pure-gas flames and those with high liquid loading.

Mao *et al.* [11] performed a combined experimental and modeling study on liquid spray fires, wherein a relatively well-understood gaseous jet flame was also studied as a baseline. The experiments in Ref. [11] were performed on pure-gas jet flames with propane and on liquid spray fires using *n*-pentane; an air atomizing nozzle was used for both fuel types. The scale of the tests was relatively small: the outlet diameter of the nozzle[16] was 1.194 mm, indicating that the flame length corresponding to Figure 6 is less than a single meter. Atomizing air was used along with the *n*-pentane liquid spray at a liquid-air mass flow ratio of 4.4, which may have partially premixed the liquid fuel and air. Both the gas and liquid spray flames were stabilized by hydrogen flames near the injector; due to its very fast laminar flame speed, the hydrogen flames likely enhanced ignition and decreased the flame liftoff distance. Based on the fuel mass flow rates of 0.176 and 0.35 g/s, the nominal heat release rates for the propane and *n*-pentane flames are approx. 8 and 16 kW, respectively.

Figure 6 includes the measurements by Mao *et al.* [11] and shows that the *n*-pentane spray fire has a peak centerline temperature that is less than the propane flame by over 180 K. Additionally, the flame length is smaller for the liquid spray, as shown by the relatively narrow region of high temperature. High temperatures appear farther away from the nozzle exit in the liquid spray relative to the gas flame, which could be caused by latent heat absorption by the liquid droplets.

Gore *et al.* [12] performed a combined modeling and experimental investigation of two-phase flames along with a methane gas flame as a baseline. The experiments were conducted at a much larger scale relative to Ref. [11]. Two types of two-phase flames were studied that differed only in the liquid phase (heptane or Alberta sweet crude oil), and both used simultaneous co-flow and atomizing flow of methane gas. In these flames, a twin fluid atomizer[17] using methane and liquid fuel was positioned just beneath the orifice; atomization with methane gas instead of air

[16] Spraying Systems Company (Model 1/4 J 2050 fluid nozzle and 67147 air nozzle)
[17] Spraying Systems Company (Model 1J, spray setup 172, fluid nozzle 6251000, air cap 11251625)

eliminated effects of premixing (air and fuel), which is consistent with the nonpremixed conditions of a blowout. The fuel flow exited an orifice plate with a diameter of 50.4 mm. The mass flow rates of methane and heptane were 0.16-0.17 and 0.22 kg/s, respectively[18]; the corresponding liquid-gas mass flow ratio was 1.3-1.4 and GOR was approximately 4,550 SCF/BBL. The nominal heat release rates were 8 and 18 MW for the gas and two-phase flames, respectively, which yielded flame heights of approximately 7-10 meters.

The temperature measurements by Gore *et al.* [12] are also shown in Figure 6. The measurements are only available for a portion of the total flame height, but lower temperatures are shown in the two-phase flames relative to the methane flame. The thermocouple farthest from the exit measured two-phase flame temperatures less than that of the methane flame by over 100 K. The peak flame temperatures were probably not measured because the farthest thermocouple was at approx. 3.5 m from the orifice plate, which was less than half of the observed flame heights.

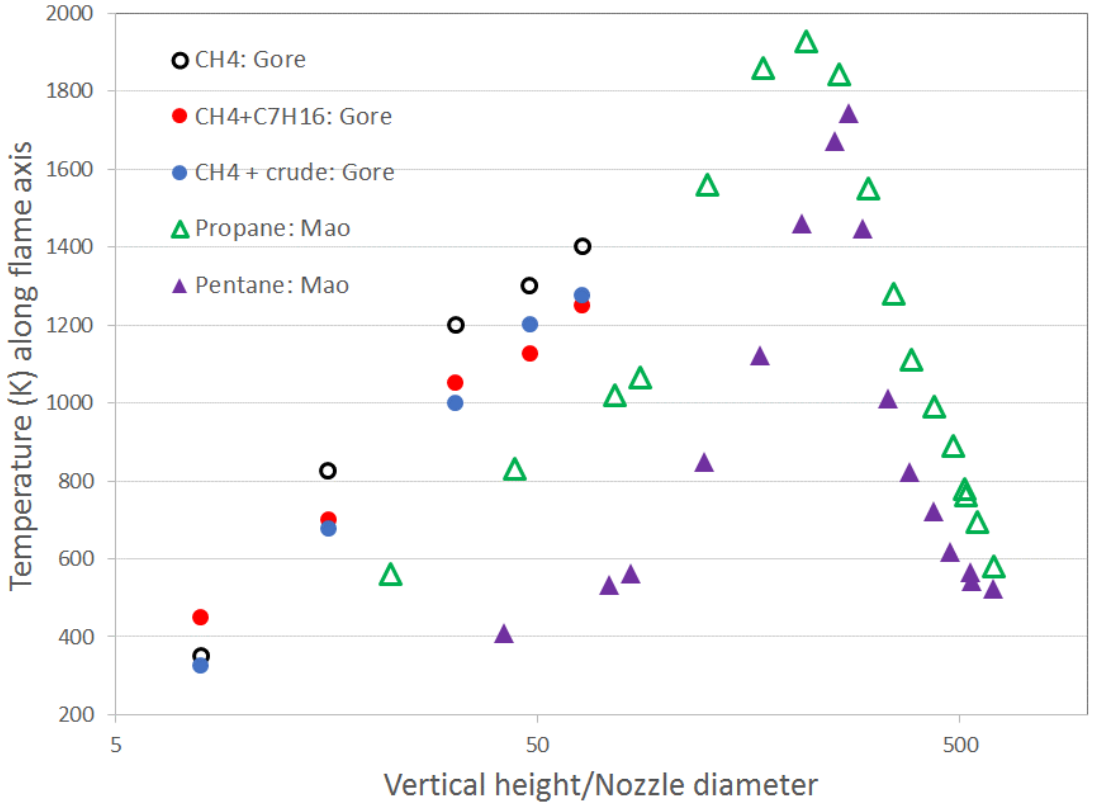

Figure 6. Measured temperatures along the flame axis for pure-gas, liquid spray, and two-phase flames as reported in Refs. [11, 12]. The data points are approximate and were determined by digitizing the original plots.

[18] The mass flow rates and total heat release rates for the two-phase flames with Alberta sweet crude oil are not reported.

Overall, these studies of gas, liquid, and two-phase flames provide further support that gas-flame temperatures are greater than those involving significant liquid content. Thus, in a qualitative sense, the lower temperatures in a two-phase flame would result in reduced oil burning efficiency relative to the conditions of a pure-gas flame. Quantifying the sensitivity of oil burning efficiency to flame temperatures would require a validated oil-burning model; predictions from such a model are a necessary next step to determine the validity of approximating a two-phase blowout flame as a pure-gas flame.

4.2 Atomization literature

Atomization is the process by which bulk liquid breaks apart into smaller fragments such as drops. Atomization can occur by different mechanisms, and the size of the resulting fragments will depend on the mechanism in addition to flow conditions and relevant length scales. Atomizers or nozzles used in combustion research (such as the combustion experiments discussed above by Wade *et al*. [8] and Dutta *et al*. [7]) or in industrial applications rely on mechanisms and conditions that can produce very small droplets. The mechanisms and conditions responsible for atomization of oil spraying from a blown-out well may be different from typical nozzles and may therefore produce different droplet sizes. As discussed above, droplet size has a significant effect on droplet evaporation and therefore it is an important parameter affecting oil burning efficiency.

Even if the atomization mechanisms are understood for a given spray application, predicting the resulting droplet diameters from basic conservation principles is a very difficult problem that is too costly for typical spray applications. Instead, empirical correlations between droplet diameter and flow characteristics are typically employed to predict droplet diameters. The accuracy of the prediction depends on the validity of the correlation for the spray application. Caution should be exercised when using correlations because they are typically valid only for making predictions within the range of conditions over which the correlation was developed.

Further, correlations can be developed based on a theoretical mechanism or based primarily on mathematical fitting without theoretical basis. A key principle underlying many theory-based droplet size correlations is a comparison of characteristic forces affecting atomization. A typical example is that of a critical Weber number required for breakup of a droplet surrounded by a flowing gas. The Weber number is a dimensionless ratio of fluid inertial forces to surface tension forces; the former acts to atomize the liquid, whereas the latter acts to prevent atomization. The critical Weber number value corresponds to the condition when inertial forces overcome surface tension forces, resulting in breakup of the liquid. An established, theory-based correlation may be necessary to extrapolate to the large scale of a Liberty blowout based on conservation principles because it could allow greater insight into how atomization may change with increasing scale (relative to a correlation based purely on mathematical fitting to data generated from experiments that do not match the target conditions).

The oil flowing rapidly into a well pipe during a blowout will form droplets at some point in its journey into the ambient air. The initial droplet-forming process is primary atomization. Based on research involving high-speed, multiphase (gas-liquid) flows in pipes, primary atomization is likely to occur inside the well pipe before the oil reaches the surface. Further, the gas flow in a blowout such as the Liberty WCD is extreme and may approach the conditions wherein atomized

droplets can undergo secondary atomization. Below, we review research related to atomization of droplets as relevant for atomization of oil in blowout conditions.

4.2.1 Primary Atomization

The annular flow regime, characterized by relatively high-velocity, multiphase flow through a pipe, likely corresponds to the flow conditions for the gas-oil jet flowing out of a well following a blowout. In annular flow, the liquid phase is partitioned between a film that covers the pipe surface and droplets that flow with the gas in the inner region of the pipe. There are multiple correlations in the literature that attempt to quantify droplet sizes in annular flow [13]. A relatively well-cited paper by Kataoka *et al*. [14] claims that the measured droplet sizes in annular flow are too small to be caused by gas-flow-induced droplet breakup and conclude that the small size must be caused when drops are formed from the outer liquid film before the droplets enter the gas flow. They propose a mechanism for droplet entrainment in annular flow wherein the turbulent gas flow shears and breaks up the crests of roll waves formed in the liquid film on the pipe surface. They derive a critical Weber number based on the condition when the drag force on the wave crest overcomes the surface tension force of the liquid wave. The expression derived for the critical Weber number contains a coefficient with unknown parameters pertaining to the roll wave; the value of this coefficient is found by correlation with experimental data. The experiments used to correlate the data are taken from four studies conducted with air and water using vertical conduits with hydraulic diameters from approx. 1 to 3.5 cm. Flows in the experiments are either up or down with gas Reynolds numbers ranging from approx. 2×10^4 to nearly 2×10^5, liquid Reynolds numbers ranging from 100 to 9700, and pressures at either 1 or 2 atm. Using the data, they determined a correlation coefficient such that the volume median diameter data agree mostly within ±40% of the correlation.

Using the coefficient obtained from correlating the data, the correlation for the volume median diameter of the droplets is given by the expression

$$D_{vm} = 0.028 \frac{\sigma}{\rho_g j_g^2} \mathrm{Re}_l^{-1/6} \mathrm{Re}_g^{2/3} \left(\frac{\rho_g}{\rho_l} \right)^{-1/3} \left(\frac{\mu_g}{\mu_l} \right)^{2/3}, \quad (1)$$

where the indices l and g refer to the liquid and gas phases, respectively. In the equation above, σ is the surface tension, ρ is mass density, j is superficial velocity, Re is Reynolds number (based on superficial velocities of each phase and the pipe diameter as a length scale), and μ represents viscosity. The measured droplet-diameter distributions were also fit to an upper-limit log-normal distribution that yielded a relationship between the maximum droplet diameter and the volume median diameter, given by

$$D_{max} = 3.13 D_{vm}. \quad (2)$$

We searched the scientific literature for more recent works on droplet diameter correlations in annular flow to find relevant research advances. Berna *et al*. [13] recently reviewed research on droplet entrainment in annular flow. They review five empirical correlations taken from Refs. [15-23] for droplet diameter in annular flow, including the correlation by Kataoka *et al*. [14, 18].

The correlations are compared to a representative subset of data taken from the literature (Refs. [15, 17, 23-26]), including both horizontal and vertical upward flows. Most data were taken at ambient temperatures and pressures with exception to Ref. [17], which contained experiments performed at 38 °C and at pressures of approx. 3.5 and 17 bar. The pipe diameters for the data sets range from approx. 1 mm up to approx. 9.5 cm. The maximum gas and liquid superficial velocities of the data sets are approx. 50 m/s and 0.1 m/s, respectively. In contrast, pipe diameters at a wellhead are significantly larger, and a blowout can significantly exceed these conditions on temperature, pressure, and velocities. We estimate that, for the Liberty WCD, the pipe diameter is approx. 22 cm, the oil superficial velocity is approx. 4.6 m/s, the superficial gas velocity is on the order of 10^2 m/s, and the (exit) pressure is roughly 14 bar.

In the review [13], the representative data are plotted against the correlations in terms of the volume median droplet diameter scaled by the pipe diameter, D_{vm} / D_{pipe}. At least a portion of the data fall well outside of a 50% error margin for each of the five correlations including that of Kataoka *et al*. (Eqn. (1)). Further, at least a portion of the data fall outside a 50% error margin for all correlations reviewed at relatively high gas Weber numbers and relatively small droplet-pipe diameter ratios, which is the regime relevant for typical blowout conditions including a Liberty blowout. The comparisons suggest that existing correlations are unable to accurately describe the droplet-size data available for annular flow.

Fore et al. [17] provide additional insight into the shortcomings of the Kataoka correlation. A unique aspect of their work [17] is that they measured droplet-size distributions for annular flow at elevated pressures of 3.4 and 17 bar, whereas the Kataoka correlation was developed from data taken at 1 or 2 atm (note: 1 bar $\approx$ 0.987 atm). At the lower pressure of 3.4 bar, the measured volume median diameters agree with the Kataoka correlation. However, the higher-pressure data (17 bar) show a significant deviation from the Kataoka correlation, which significantly underpredicted the data. They also compared data from experiments conducted with a higher-viscosity liquid [24] that yielded a similar deviation. They conclude that the Kataoka correlation does not properly account for the effects of gas density and liquid viscosity [17]. These conclusions are relevant to the conditions of a blowout: the pressure within the well pipe is likely to be significantly higher than atmospheric.

Berna *et al*. [13] used their representative data set to develop two new correlations; one for vertical upward flows and the other for horizontal flows. The correlations appear to have been achieved based only on fitting the data and therefore do not directly provide insight into the atomization mechanism. The relevant flow for a blowout is vertically upward, and the corresponding correlation by Berna *et al*. [13] is given by

$$D_{vm} = D_{pipe}\left[0.11\,\mathrm{We}_g^{-0.68}\,\mathrm{Re}_g^{0.33}\,\mathrm{Re}_l^{0.11}\left(\frac{\rho_g}{\rho_l}\right)^{0.31}\right]. \tag{3}$$

The representative data for the vertical upward flows are compared with the representative data and shown to agree within nearly 25% to that predicted by Eq. (3); thus, this correlation achieved better accuracy in describing the representative droplet-size data than any of the other correlations considered.

In the Appendix, we compare the volume median droplet diameters predicted by the Kataoka and Berna correlations in estimated Liberty conditions. We show that the Berna correlation predicts

larger droplets (exceeding 400 μm in diameter) by about an order of magnitude for the full range of oil flow rates under consideration (30,000 – 91,219 BOPD). Thus, the droplet lifetimes inside a flame predicted by these two correlations would differ by one to two orders of magnitude, which could significantly affect burning efficiency.

The preceding discussion points out challenges associated with accurately predicting oil droplet diameters in blowout conditions. As discussed previously, the evaporation rate of a droplet depends significantly on its diameter, and larger droplets survive flame conditions longer. Hence, a modest increase in droplet sizes could lead to significant reduction in burning efficiency, which underscores the importance of accurate predictions of oil droplet distributions for predicting burning efficiency in a blowout. Additional salient points on our atomization review include:

- The correlations available for droplet diameter in annular flow are developed from experiments under conditions significantly different from typical blowout conditions including those relevant for the Liberty Project [1].
- Existing correlations differ significantly in their predictions of droplet diameters resulting from blowout conditions.
    - The well-cited Kataoka *et al*. [14] correlation has been shown to be significantly less accurate than a more recent correlation by Berna *et al*. [13]. Predictions of average droplet diameters resulting from Liberty blowout conditions by these correlations differ by an order of magnitude, with the Kataoka correlation predicting smaller droplets.
- If secondary atomization occurs in a blowout, the smaller, resulting droplets will enhance burning efficiency because they evaporate and burn more rapidly. However, the primary atomization step must be predicted with an accurate and valid model to achieve accurate predictions of the final droplet diameters.

4.3 Liquid entrainment in annular flow

The entrainment fraction is a crucial parameter because the liquid film that is not broken up into droplets would not entrain into the gas stream and burn; instead, the unbroken part of the film could emerge from the blowout pipe causing a spill. Therefore, it is important to consider droplet formation from the film by its interactions with gas for predicting entrainment fraction as well as for predicting the droplet diameters. Correlations for droplet diameter in annular flow (e.g., [14, 17]) do not consider the contribution of the film from which the droplets are entrained. In fact, experimental apparatus [17] are specifically designed to extract the film with gas downstream of the position at which droplet sizes are measured. If a significant amount of liquid remains in the film along the well pipe in a blowout, then one may also need to consider how the film atomizes at the outlet and how it could affect the correlation for the resulting droplet sizes and velocities. We reviewed literature on the entrainment of liquid in annular flow with the aim to determine whether the annular film should be considered to accurately predict atomization in blowout conditions. As discussed above, droplet sizes resulting from atomization are important parameters for oil burning efficiency.

The review by Berna *et al*. [13] discusses research to quantify the entrainment fraction, which is the fraction of the total liquid that is in the form of entrained droplets. The liquid that is not

entrained in the form of droplets remains in the flowing film that covers the pipe surface. Research shows that in a pipe with annular flow there is a transition from developing flow at the inlet, wherein the droplet entrainment and deposition rates are unequal, to a fully developed flow, beyond which the entrainment fraction does not change [13]. Two expressions are provided [18, 27] for the transition length to achieve equilibrium; for estimated Liberty blowout conditions, the predicted transition lengths are on the order of tens of meters. The predicted transition lengths are much smaller than typical well depths that exceed a mile (>1,609 m)[19], suggesting that the fully developed flow regime applies to the conditions at and far below the well exit.

The review [13] covers several correlations for predicting the amount of entrained liquid in fully developed annular flows. We focus on the correlations for entrainment fraction, as opposed to mass of entrained liquid, for better understanding of how the liquid in the pipe is partitioned between the film and droplets. Further, we consider the correlations for vertical upward flow to be most relevant because they correspond to the flow condition in a well pipe. Sawant [28] proposed an empirical correlation for the entrainment fraction wherein an asymptotic value is approached with increasing gas Weber number. The maximum entrainment fraction is primarily determined by the liquid Reynolds number (Re_l) and increases with increasing Re_l. The review points out that the correlation reaches a limiting value of the entrainment fraction of approx. 80% that is approached as the liquid Reynolds number is increased; this correlation is reported [13, 15] to have poor accuracy for Re_l greater than 4×10^3. Berna *et al*. [13] suggest a modification to the Sawant correlation such that the entrainment fraction approaches an asymptotic value of 100% at sufficiently large liquid Reynold numbers. A correlation attributed to Ishii and Mishima [29] for the entrainment fraction also has a maximum value of 100% that is reached with increasing gas Weber numbers (stronger effect) and liquid Reynolds number (weaker effect).

The Oliemans entrainment fraction correlation [13] is in the form of a power law of fluid properties and flow conditions from a database generated from experiments with gas-liquid systems including air-water, air-ethanol, air-trichloroethane, and steam-water. The correlation appears to be achieved purely by fitting. Similar to other correlations, the variables and their exponents clearly indicate a dependence on the gas Weber number and liquid Reynolds number.

Again, we mention that correlations are not necessarily valid outside of the range of conditions for which they are formed. Thus, before discussing the entrainment fractions predicted by these correlations in conditions expected for a Liberty blowout, we compare blowout conditions with those for which the correlations have been developed and/or tested in Table 1.

As seen in Table 1, the gas Weber and liquid Reynolds numbers corresponding to approximate blowout conditions are rather large compared to the estimated values for the studies used to make the entrainment correlations. Thus, one would expect high entrainment based on the dependence of the correlations on these numbers. At the extreme conditions of a blowout with a large oil-discharge rate, the correlations by Ishii and Mishima and Oliemans [13] unanimously predict 100% entrainment. The predictions of 100% entrainment with these correlations is insensitive to the oil flow rate in the range of 30,000 to 91,219 BOPD for the parameters relevant to the Liberty Project (estimated predictions given in Appendix). The maximum entrainment value of 100% is also supported by the empirical correlation of Berna *et al.* [13]. The Sawant correlation [28] is not applied because it has been reported to underpredict entrainment at high liquid Reynolds numbers

[19] The planned measured depths of production and injection wells for the Liberty Project exceed two miles according to Liberty DPP.

[13]. The predictions of 100% entrainment in approximate blowout conditions provide a degree of support in favor of neglecting droplet sizes resulting from atomization of the annular film.

Table 1. Comparison of the conditions for experiments used to develop entrainment fraction correlations with blowout conditions expected for the Liberty Project.

	Sawant	Oliemans	Ishii and Mishima	Estimated blowout conditions
Gas weber number	**less than 10^5	NR	**less than 10^5	10^5 - 10^7
Liquid Reynolds number	**less than 10^4	Laminar and turbulent (no number reported)	370 - 6400	up to 10^6
Pressure (atm)	1.2 – 6 #2.8 – 8.5	NR	1.0– 2.7 *1 – 4	10 - 100
Fluids	Air-water #Organic fluids	Air-water air-ethanol air-trichloroethane steam-water	*Air-water	Natural gas-crude oil
Pipe diameter (cm)	0.94 #1.02	0.06 – 3.2	*0.95 – 3.2	21.6
Gas density (kg/m^3)	NR	<56	1.2 – 4.8	>0.7
Liquid superficial velocities (m/s)	0.05 – 0.75 #0.08 – 0.4	NR	**less than 1	1 - 10
Gas superficial velocities (m/s)	15 – 100 #6 – 24	NR	< 100	100 - 500
Surface tensions (N/m)	**Air-water ~ 0.07	0.012 – 0.073	**Air-water ~ 0.07	0.03 - 0.07

*Correlation reported to satisfactorily compare with data in these conditions
Organic fluid experiments (unspecified fluids)
** Estimated based on available information and assumed typical properties
NR: not reported in Ref. [13]

Our concerns about extrapolating the correlations to blowout conditions include that, in the Berna *et al*. review [13], the reported measurements of entrainment for vertical upward flows do not exceed 70%; however, the review [13] itself lacks evidence to show near-complete entrainment behavior at large gas and liquid flows corresponding to blowout conditions. Another issue is that the various correlations for entrainment show significant error in the review [13] such that the predicted and measured entrainment fractions can differ absolutely by more than 50%. In fact, even the improved correlation proposed in the Berna *et al*. review [13] shows absolute error in the entrainment fraction by up to approx. 30% in some conditions. The large error is a concern because even a modest percentage of the oil flow rate in a blowout can correspond to a large volume of oil. Finally, if nearly all of the liquid is entrained in droplets that move chaotically in a turbulent gas flow through a well pipe that is up to a few miles long (corresponding to residence times of several seconds), the droplets may collide and coalesce to produce larger droplets that are more difficult to burn. Droplet coalescence does not appear to be considered in the works [13, 14, 17] discussed above.

In summary, a model must accurately predict droplet sizes to achieve accurate predictions of burning efficiency, and most methods to predict droplet sizes via atomization do not consider how liquid is partitioned between entrained droplets and the film in annular flow. Our review of literature on the entrainment of droplets in annular flow can be summarized as follows:

- The conditions of the experiments used to develop the entrainment-fraction correlations are significantly different from those expected for a typical blowout, including the Liberty Project WCD.
    - Recent correlations predict complete entrainment of the liquid into droplets in blowout conditions.
- Additionally, the measured and predicted entrainment fractions using even the better correlations are shown to differ absolutely by up to 30% [13]. The magnitude of the error suggests that entrainment-fraction correlations may not be able to achieve the desired accuracy of a few percent in blowouts with large oil discharge rates.

4.4 Fire Suppression by Water

Water can be present in the formation fluids naturally or be added during production to enhance oil recovery from a reservoir. Water sprays have been demonstrated to be rather effective at suppressing and extinguishing blowout fires. As we will show below, a small volume% of water in the formation fluids could have a significant suppression effect on a flame. The suppression of a flame by water could significantly reduce oil burning efficiency by strongly reducing the flame temperature and size. Likewise, flame extinction by water would cease oil burning completely. At the end of this section, we discuss the threat of fire suppression via water in the case of a Liberty blowout.

Large-scale experiments (for example, Refs. [30, 31]) have been conducted to measure the amount of water required to extinguish gas-well blowout flames. Evans and Pfenning [31] performed large-, medium-, and bench-scale studies on turbulent-diffusion methane flames extinguished by water. At medium and bench scales, the flame heat release rates in their experiments ranged from 0.1 to 10 MW (1 to 5 m flame heights, respectively) with gas flow rates of approx. 0.2 to 0.8 MMSCF/day[20] exiting a 4-in diameter pipe. The effect of water spray orientation was examined in the smaller-scale studies. For the orientations tested, it was found that spraying water parallel to the flame axis was the most effective spray orientation. The lowest mass flow ratio (water/methane) required for flame extinction in the small-scale tests was obtained for the best orientation and was measured as 4.2. The maximum mass flow ratio (water/methane) reported for extinction was 9.5, which was obtained for sprays pointed perpendicular to the flame axis. Large-scale tests involved gas flow rates of 178 – 196 SCF/s (15.4 – 16.9 MMSCF/day) with heat release rates ranging from 185 - 205 MW. The gas was primarily methane (>96 volume%). Water was sprayed from four nozzles aiming up and parallel to the flame axis. The lowest mass flow ratio (water/methane) that successfully extinguished the flame was measured as 2.2; however, extinguishment was not achieved in a trial with mass flow ratio 1.6. A later report by this research group [32] discusses tests of water sprays within the gas stream ("internal") where a gas flame at 11.9 MMSCF/day was extinguished with a water/gas

[20] Note: One MMSCF is equal to one million cubic feet of gas at standard conditions.

mass flow ratio of approx. 0.6; however, a gas flame with 18.3 MMSCF/day was not extinguished with a mass flow ratio of approx. 0.9. The reason(s) for this trend are not discussed.

In the large-scale tests, the effect of the water spray at mass flow ratios less than that required for extinction on the fire was measured. For a test with mass flow ratio (water/methane) of 1.6 that did not extinguish, the flame height reduced significantly[21] and the peak flame temperature reduced by approximately 100 K.

Chauvin and Bourgoyne [30] also conducted large-scale studies to measure gas-well flame extinction with water. The research extends previous work by studying higher gas flow rates (up to 35 MMSCF/day) and quantifying the change in water/gas mass flow ratio required to extinguish flames when obstructions are above the wellhead and in the flame. The large-scale water-extinguishment tests were performed with natural gas composed primarily (92 volume %) of propane flowing through a 4-in. orifice plate mounted on a 6-in diameter pipe. The water was sprayed from four nozzles surrounding the orifice, similar to that of the experiments by Evans and Pfenning [31]. Temperatures within the flame were not measured. The experiments showed that the mass flow ratio (water/natural gas) required for extinction decreased monotonically from approx. 6 to 2 with increasing gas flow rate from 5 to 35 MMSCF/day. They report that this trend is not well understood, but offer the possibilities that (1) higher flow rates may enhance water droplet entrainment into the flame to increase the suppression effect and (2) flames may decrease in stability with increasing flow rate and therefore become easier to extinguish with water.

Two types of obstructions were included in the experiments to examine their effect on the amount of water required for flame extinction. For a 4-in I-beam placed two feet above the gas exit orifice, the water/gas mass ratio required for flame extinction increased significantly. The extinction water/gas mass ratio decreased monotonically from approx. 11 to 5 as the gas flow increased from approx. 6 to 13 MMSCF/day. Larger flames were not studied because the equipment could not deliver enough water to extinguish the flames at higher gas flow rates. An additional obstruction, a square platform (54-in side length) placed above the flame greatly lowered the suppression effect of water such that the flame could only be extinguished at a low gas flow rate of 2 MMSCF/day with a water/gas mass flow ratio of 30.

Additional studies have been conducted on fire suppression with water at small scale by current members of the Combustion Dynamics and Modeling section at the Naval Research Laboratory. Fisher *et al.* [33] measured the amount of water required to extinguish a laminar, nonpremixed propane flame in a cup burner where the fuel stream was surrounded by a co-flow of air. The propane flow rates were relatively miniscule compared to a blowout (approx. 0.0074 SCF/min). Water was delivered with an ultra-fine mist generator that formed droplets less than 10 μm in diameter. Extinction occurred at 12.5 mass% water; the equivalent concentration was 14.4 mass % after correcting for the water vapor and nitrogen in the air. For comparison with the large-scale works, we calculate the corresponding water-propane mass flow ratio as approx. 2.8[22]. Further, extinction of propane flames with ultra-fine water mist in a cup burner apparatus has been

[21] To estimate the magnitude of the effect of water addition on flame height, we compared the height of the greatest reported isotherm, 1200 °C (1473 K). Without water, the isotherm height was 20 m -12 m = 8 m; after water addition, the isotherm height reduced to 14 m - 9 m = 5 m. Thus, the addition of water reduced the height of the isotherm by 40%.

[22] The water mass corresponding to each mole of propane can be determined from the water mass% in air using a balanced equation for propane combustion, $C_3H_8+5O_2->3CO_2+4H_2O$, where 5 moles of air are needed to supply each mole of oxygen.

modeled by Ananth and Mowrey [34]. Their work demonstrates the importance of droplet diameter on the extinction dynamics. The minimum predicted water droplet concentration required for extinction was approx. 10.5 mass%, which corresponds to a water-propane mass flow ratio of approx. 1.9. Thus, the water-gas mass flow ratios required for flame extinction with pure-gas flames appear to be rather insensitive to the scale of the fire.

There are differences in the flames and water between the works discussed above and that of the Liberty Project. The works above used gaseous fuels, whereas the Liberty Project would have a significant amount of crude oil in addition to gas. For gaseous fuels, it appears that flame extinction could occur in a blowout when the water-gas mass flow ratio approaches roughly 2. This value corresponds to a very small volume percentage of water: we estimate that less than 0.4 volume% could cause extinction of a gas flame. Suppression effects could become important even at smaller water content. Further, these works use fresh water to suppress fires, but it is likely that salt water (from surrounding seas) would be present in the reservoir. The addition of salt to water increases its ability to suppress flames (as shown in, for example, Refs. [35, 36]). Little work has been done to measure the amount of salt water required to suppress and extinguish two-phase flames; based on the results for gas flames and fresh water, one might expect that suppression could occur when the water mass flow rate becomes comparable to the total mass flow rate of oil and gas. Thus, the water content of the well should be known within sufficient accuracy to assess its effect on flame behavior and burning efficiency.

The discussion above points out that energy delivery to droplets in a blowout could be significantly reduced or completely ceased if water is introduced in the flame in sufficient quantity to cause flame suppression or extinction. Thus, water poses a significant threat to oil burning efficiency. The relevance of these works [30, 31] to blowouts is as follows:

- The flames studied here are pure gas flames, whereas the typical blowouts would have a two-phase flame. The effect of a significant amount of oil on suppression was not considered in these works.
    - Latent heat absorption by oil may reduce the amount of water needed for suppression.
    - Gas has a much lower density than water and oil, but oil and water have densities that are relatively similar. Assuming that suppression would be an issue when the water mass flow is similar to or greater than the fuel mass flow, a significantly larger volume% of water would be needed to suppress a two-phase flame with high oil loading.
- The tests were performed at a large scale, but with much smaller flows and heat release rates than typical blowouts.
- If water was in the formation fluid of a well, it would emerge along the flame axis with the fuel, which was found to be a highly effective water spray orientation for suppression.
- If the water content is a significant fraction of that required for extinction, the flame temperature and height could be reduced, potentially lowering the burning efficiency of the oil.
- Extrapolating the observed trend of decreasing water/gas mass flow ratio necessary for extinction with increasing gas flow rate suggests that lower water/gas flow ratios could extinguish an ignited blowout.
- Obstructions could be above the flame in the event of an accidental ignition of a blowout; the obstructions may enhance flame stability. If debris and/or equipment is removed, less water would likely be required to suppress/extinguish an ignited blowout.

Currently, the Liberty reservoir is expected to contain very little water that will not cause flame suppression in the event of a blowout. However, the drilling plan [1] includes drilling of a water-injection well for water flooding after the first production well is drilled (with up to 12 wells to be drilled after water flooding begins). Thus, water would be in the fluids emerging from the well casing if a blowout were to occur during drilling of the subsequent wells. We have roughly estimated the water content in the reservoir at the end of the drilling period based on the following information:

- The Liberty DPP [1] states that the capacity for water injection wells is 80,000 barrels of water per day[23].
- The reservoir is estimated to contain 230 million barrels of oil.
- The maximum oil production rate during the drilling period is expected to be approx. 60,000 barrels of oil per day.
- The drilling period is planned to be approx. 2 years.

Based on these approximate inputs, the water content of the reservoir would reach a maximum of approx. 58 million barrels at the end of the two-year drilling period and the minimum oil volume in the reservoir would be approx. 190 million barrels. Thus, on average, there would be 3 to 4 times more oil than water in the reservoir by volume (this would not differ significantly in terms of mass since the oil is expected to have a specific gravity of roughly 0.9 [1]). Our literature review suggests that the water mass would need to be comparable to the fuel mass for flame extinction to be a significant risk. Based on the average water content, fire extinction may not be a risk, but we cannot rule out the possibility of a suppression effect of the water based on the literature reviewed. Further, it is not the average water content but the local water content of the reservoir adjacent to the entry point of the well that will determine the water content of the jet in a blowout. If there exist regions of high water content within the reservoir and a well is drilled into such a region, suppression and extinction could be a risk in the event of a blowout. Thus, important considerations include whether such high-water areas would exist and, if so, whether Hilcorp would be able to avoid them during drilling.

5.0 Conclusions

The large magnitude of oil discharge rates anticipated for a Liberty Project blowout clearly indicates that the response method of voluntary ignition requires nearly perfect burning efficiency to prevent a large oil spill. For the WCD of 91,219 BOPD, our simple estimates reveal that slightly imperfect burning inefficiencies from 95% to 85% can release volumes of unburned oil on the order of millions of gallons in less than a single week after a blowout event. In the conditions expected for a Liberty blowout, each percent reduction in burning efficiency corresponds to a significant amount of spilled oil. We believe that predicting burning efficiency with an accuracy of even a few percent is an extreme technical challenge. To our knowledge, no model has been shown to predict burning efficiency with such high accuracy by comparison with relevant experiments. We recommended that models used by BSEE to predict burning efficiency

[23] It is not clear from the DPP whether a barrel of water is considered to be 31.5 gallons or, as in the case of an oil barrel, 42 gallons.

and make decisions affecting blowout-response regulations should be well validated with experimental measurements to demonstrate their accuracy at different scales.

Additionally, a delay of just six hours between the blowout event and ignition can result in the release of approx. one million gallons of unburned oil. If accidental ignition can be avoided, Hilcorp plans to delay voluntary ignition in the Liberty Project for safety reasons and to prevent damage to drilling equipment [1]. An estimate of delay time from Hilcorp in the event of a blowout may be useful for BSEE in determining an appropriate spill response.

Our review of research literature was focused on phenomena involved in burning oil in blowout conditions that may cause challenges in accurately predicting the oil-burning efficiency. Part of our review focused on research involving the effect of high oil content (by mass) relative to natural gas in a fuel jet on the flame conditions. The conditions of the flame affect oil-burning efficiency because they determine the rate of heat transfer to the droplets that drives oil evaporation. Further, we review literature related to oil droplet atomization in the regime of high-speed, multiphase flows that would occur in a blowout. Droplet sizes are important for burning efficiency because they are known to strongly affect droplet evaporation rates. Both the flame conditions and droplet diameters for the Liberty Project are difficult to predict due to gaps in knowledge in the literature as described below.

We reviewed literature related to flames with two-phase fuels, which have received significantly less attention in the literature relative to single-phase flames. All experiments were conducted at much smaller scales than those involved in a potential Liberty blowout, which is probably because experimenting at larger scales carries an enormous cost and allows limited measurement capability. The studies achieved nearly complete oil-burning efficiency, but used very effective atomizers that may produce smaller droplet sizes than that of a blowout. Experiments showed that when the amount of oil becomes significant compared to that of the gas, soot formation begins to have an effect on flame conditions that could act to reduce burning efficiency. The radiant energy loss from soot production in two-phase fuel flames at GORs relevant for oil-well blowouts is a significant fraction of the potential heat release by combustion of the fuels. Measurements show that decreased flame temperatures and increased flame heights result from increased oil loading; these factors could have competing effects on oil burning efficiency. The significant magnitude of radiant energy loss from two-phase fuel flames indicates that soot production and its effect on burning efficiency should be understood for an ignited blowout. Also, the studies reviewed show that two-phase fuel flames alone encounter stability issues in the experimental conditions; these works strategically avoid the natural instability by adding hydrogen pilot flames. An unstable flame would not release as much heat as a stable flame and would not burn oil as efficiently. In contrast to methane (gas) flames, the blow-off stability limits (in terms of critical flow rate vs. nozzle diameters) have not been measured for two-phase fuel flames. It is not clear whether flame stability could be threatened for ignited two-phase fuel jets with significant oil loading when issued from large-diameter well pipes, but stability problems are more likely to be encountered in non-ideal blowout cases wherein the jet exits a smaller-diameter opening. We recommend that the effects of two-phase flames, including soot production and flame stability and associated heat losses, be considered in research leading to a predictive tool for BSEE to assess burning efficiency in potential blowouts with significant oil loading, which includes the Liberty Project.

We also reviewed literature related to primary atomization of oil in annular (high-speed, multiphase) flow. The correlations available for droplet diameter in annular flow are developed from experiments under conditions significantly different from that of a potential Liberty

blowout. Therefore, it is not clear that the available correlations can reliably be extrapolated to blowout conditions. We provide an example to support this point: a commonly used, mechanism-based correlation by Kataoka *et al*. [14] for predicting droplet diameters in annular flow has been shown [13, 17] to be inaccurate in predicting data outside of the conditions (e.g. at elevated pressures that are relevant for a blowout) within which the correlation was developed. A more recent fitting-based correlation by Berna *et al*. has shown significantly greater accuracy in predicting a representative data set than the several other correlations reviewed in Ref. [13]; this correlation predicts droplet sizes that are over an order of magnitude larger than that of the Kataoka correlation for our estimated Liberty conditions (comparison shown in Appendix). These correlations would lead to very different predictions of droplet lifetimes in an ignited blowout. Further, the differing dependence of these correlations on the flow variables and the discrepancy in their predictions suggests that the atomization mechanism(s) are not well understood. We recommend research on atomization to quantify droplet-size distributions at relevant blowout conditions and to identify/develop a corresponding correlation to predict atomized droplet diameters with sufficient accuracy.

Our review of droplets' atomization in annular flow considered literature aiming to quantify how the flowing liquid is partitioned between droplets and the annular film; this aspect of the flow in the conduit (pipe/casing for a blowout) was not considered in correlations [14, 17] for droplet diameter. Liquid originating in the film that is not entrained as droplets into the gas stream is not likely to burn efficiently and could lead to a spill. A recent review paper of entrainment-fraction correlations [13] indicates that the experiments used to develop the correlations are significantly different from those expected for a typical blowout. Despite the difference between experimental and Liberty blowout conditions, we used three recent correlations [13] to predict the amount of liquid entrained in the form of droplets at estimated blowout conditions,. These correlations unanimously predict 100% entrainment, which provides a degree of support for neglecting how the annular film affects the droplet size distribution exiting the pipe. Since the correlations were developed using experiments with conditions significantly different from a blowout, we recommend that future experimental research aiming to test/develop atomization correlation(s) at blowout conditions should test for (and measure, if present) an annular film.

Our review considered research on the amount of water that could suppress or extinguish a blowout flame and reduce or eliminate the evaporation-driving heat transfer to oil droplets emerging from a blowout. Water obviously can have a suppressive effect on flames and will be in the formation fluids of the Liberty reservoir during the planned two-year drilling period [1]. We reviewed literature on the suppression of flames by water sprays; the available studies involve only gas flames, which differ from the two-phase flames that would occur in a Liberty blowout. Experiments from bench scale to large scale show that water can extinguish gas fires when the water-gas mass flow ratio is approx. 2 or greater. Although these results may only apply in a strict sense to gas flames, they indicate that flame suppression and/or extinguishment may be a risk when the water mass flow rate becomes similar to or exceeds the fuel mass flow rate. Our rough estimates of water mass fraction in the Liberty reservoir (based on information provided in Ref. [1]) indicate that, on average, there will be at least three to four times more oil than water at any time during the two-year drilling period. However, the water content will not likely be uniform since water will be injected locally and may transport slowly through the porous rock in the reservoir. We suggest to ensure that drilling is avoided into regions of the reservoir with locally high water content wherein the water volume fraction may be comparable to that of the formation fluids. For more clearly defined limits on the water content that will diminish or nullify burning

efficiency of an ignited blowout, future research should be done on water suppression of two-phase flames.

6.0 Supporting Information

6.1 Correspondence on Alaska Guidelines

The state government of Alaska has approved wellhead burning under qualifying conditions as a blowout response in state waters. The qualifying conditions are found in the following guideline from Alaska Department of Environmental Conservation (ADEC):

18 AAC 75.434 (g): If an operator proposes the planned voluntary ignition of a well blowout, the operator shall submit data, analyses, and supporting documentation that indicates to the satisfaction of the department that any discharged oil would have an American Petroleum Institute (API) gravity of 35 or greater, a gas-oil ration in excess of 2,000, and an anticipated combustion efficiency of at least 90 percent, that well ignition would not exceed national ambient air quality standards set under 42 U.S.C 7409 (Clean Air Act), and that well ignition will be protective of human health, safety, and welfare, and of the environment. The department will adjust the response planning standard determined under (b) – (e) of this section based on the submitted data. The department may consult with the Alaska Oil and gas Conservation Commission and other agencies in evaluating the data provided by the operator under this subsection.

As pointed out previously, the Liberty Project is in federal waters that are outside of the jurisdiction of the State of Alaska. The estimated Liberty conditions [1] do not meet some of the guidelines required by the State of Alaska for approval of planned voluntary ignition of a well blowout: the Liberty GOR is estimated to be 872 SCF/BBL, and the API gravity is estimated to be 24 – 27. On the other hand, the DPP [1] claims that voluntary ignition would eliminate over 90% of the discharged oil. Further, the Liberty DPP includes plans to be protective of human health, safety, and welfare, and to some extent, the environment. We did not find a discussion in the DPP of whether voluntary ignition (or in situ burning) would exceed national ambient air quality standards under the US Clean Air Act.

We contacted ADEC to ask for the authors of the guidelines and/or technical reports used to make them. A response from ADEC staff in the Division of Spill Prevention and Response indicates that there are no specific technical reports from which these standards were developed. ADEC reportedly proposed the well ignition regulation as an option for operators to choose as an oil spill response, and the standards were based on the properties of some of the oil and gas fields on the North Slope. Further, ADEC reports that they are not aware of a voluntarily ignited blowout that could have provided empirical evidence to support the qualifying conditions. Presently, only the Exxon Mobil Point Thompson Project is approved for voluntary ignition under Alaska jurisdiction.

We can only conclude from the information obtained from ADEC that the standards were chosen without knowledge and/or evidence of the conditions that will lead to efficient oil burning. The fact that the expected Liberty Project blowout conditions would not meet the qualifying conditions required for voluntary ignition under Alaska jurisdiction is not a reliable indicator of expected burning efficiency.

6.2 Entrainment Fraction Correlations

The following correlations for the entrainment fraction were obtained from Ref. [13]. See the nomenclature (at the beginning of this report) for the physical meaning of the symbols.

Oliemans' correlation

$$\frac{E}{1-E} = 10^{-2.52} \rho_l^{1.08} \rho_g^{0.18} \mu_l^{0.27} \mu_g^{0.28} \sigma^{-1.80} D_{pipe}^{1.72} j_l^{0.70} j_g^{1.44} g^{0.46}$$

Ishii and Mishima correlation

$$E = \tanh\left(\left\{7.25 \cdot 10^{-7}\right\} \mathrm{We}_g^{1.25} \mathrm{Re}_l^{0.25}\right)$$

Berna *et al.* correlation (for maximum entrainment only)

$$E_{max} = 1 - \exp\left[\frac{\mathrm{Re}_l}{1400}\right]^{0.6}$$

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