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Quantitative Evaluation of Risks from Crude-by-Rail Spills: A Case Study using the Proposed Shell Puget Sound Refinery Anacortes Rail Unloading Facility

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ABSTRACT

Abstract ID: 2017-143 – Industry considerations, regulatory recommendations, and public concerns have necessitated a quantitative approach to addressing the risks associated with crude-by-rail shipments. Risk is defined as the product of the probability of an event occurring and the potential consequences that may result. To adequately address both the probability and consequence sides of risk, a three-phased approach was developed for use. First, a probability assessment used historical freight rail accident data to calculate the probability of an accident occurring with adjustments specific to crude-by-rail transport, the likelihood that an accident involving a crude-by-rail unit train would result in the release of oil, and the potential size of that release. These results were then used as inputs to a consequence assessment. This necessitated an assumption that a spill had taken place and there either was or was not an ignition source nearby. In the second phase, two computational oil spill models (OILMAP Land and SIMAP) were used to determine the trajectory, fate, and effects of released oil onto land and into water. This analysis included determining where oil may be transported within the environment, how long it would take to get there, how it would weather and behave, what resources of interest may potentially be affected, and what the potential acute effects may be to specific biological receptors. The third phase included a fire and explosion analysis, which was used to determine the thermal radiation from pool fires and the overpressure from a vapor cloud explosion and boiling liquid expanding vapor explosion (BLEVE). This assessment was used to quantitatively

discuss both the probability and consequence sides of the risk associated with the proposed Shell Puget Sound Refinery Anacortes Rail Unloading Facility and was included in the Environmental Impact Statement (EIS) addressing Environmental Health and Risk.

INTRODUCTION

The proposed expansion project for the Shell Puget Sound Refinery (PSR) Anacortes Rail Unloading Facility (ARUF) at March Point in Washington State would allow the facility to receive rail deliveries of conditioned Bakken crude oil from the mid-continent area. However, during the public scoping process, many concerns were raised about the risk associated with the potential for spills, fires, and explosions that could occur during crude-by-rail transport. Risk is defined as the product of the probability of an incident occurring and the likely consequences that may result if that incident did occur. To reduce risk, one may reduce either the probability of an incident occurring, the consequences that may result, or both. Under the direction of the co-lead agencies (Skagit County and Washington State Department of Ecology) and in preparation of an environmental impact statement (EIS) for the Shell PSR rail unloading facility, quantitative methods were applied to formally characterize the probability of an accident and the potential consequences for the shipment of crude oil by rail (HDR et al., 2016).

Each year, between 1.5-2.0 million loads of hazardous material (e.g., crude oil, ethanol, and other flammable, corrosive, radiologic, or poisonous chemicals) are shipped by rail in the United States, of which approximately 99.99% arrive without incident (AAR, 2016). While oil shipments only make up approximately 2% of the total freight shipped by rail, crude-by-rail shipments in the U.S. have increased by over 108-fold between 2005 and 2014 (AAR, 2016; NCSL, 2016). There was a roughly 17% reduction in the shipment of crude-by-rail between

2014-2015, with the trend continuing into 2016 (EIA, 2016). While accident and injury rates per train-mile have dropped over this same period of time, the rapid increase in the frequency of rail shipments of crude oil has outpaced improvements and resulted in higher numbers of actual incidents (FRA OSA, 2016).

Many tracks currently being used to ship crude oil by rail pass through densely populated areas and are located adjacent to long sections of coastlines and rivers. Growing public concerns over accidents involving the shipment of crude-by-rail, which may include derailment, the release of oil, and potentially fire and explosion, have led to an increase in the number of federal and state agencies investigating the topic. The intent of these investigations is to more comprehensively understand the risks associated with the shipment of crude-by-rail.

Characterizing risk can be challenging, however several quantitative methods have been used to identify the probability and consequence. The probability of a spill can be derived through a fault tree analysis that incorporates the various sequential events that have to occur for a spill to come about. By integrating uncertainties and distributions of probabilities, a fault tree analysis can also be used to predict potential spill volumes (Etkin, 2015; Etkin, 2016; HDR et al., 2016: Appendix G). A comprehensive understanding of the range of potential consequences is typically assessed using computer models that have been developed to evaluate the potential effects of hydrocarbon releases from numerous sources, including offshore, pipeline, and rail (French McCay and Rowe, 2004; French McCay et al., 2012; Horn and French McCay, 2015; Horn and French McCay, 2016; HDR et al., 2016: Appendix H). An assessment of the consequences following a fire or explosion was also included, which investigated the thermal radiation and blast overpressure that may result following either immediate or delayed ignition (HDR et al., 2016: Appendix I).

Several federal regulatory requirements have been implemented to more comprehensively quantify risk. Following the Oil Pollution Act (OPA 90) the Environmental Protection Agency's (EPA) ability to prevent and respond to catastrophic oil spills was streamlined and strengthened (33 U.S.C. §2701 et seq.). Additional federal regulations for crude oil shipment in pipelines (CFR, Title 49, Parts 190-199 Hazardous Liquid Integrity Management), overseen by the Pipeline and Hazardous Material Safety Administration (PHMSA), and exploration and drilling in the offshore environment (30 CFR 254), overseen by the Bureau of Safety and Environmental Enforcement (BSEE), have required that trajectory and fate modeling be used to quantify the movement and behavior of released oil in the environment to better prepare for an incident. The EPA and Army Corps of Engineers (ACE) also oversee regulatory requirements for pollution control for all inland waters that also require modeling.

Recent regulations have been created by the U.S. Department of Transportation Federal Rail Administration (US DOT FRA) and several states to address concerns with the shipment of crude-by-rail (NCSL, 2016; Federal Register, 2016). One of the main goals is to reduce the risk of environmental impact associated with crude-by-rail transportation. This paper discusses quantitative methods that have been used to address the various aspects of risk associated with hydrocarbon products. The intent is to apply three approaches that have been used by the hydrocarbon industry to rail and answer the following three questions:

- What is the probability of an accident and release of oil from a train, including the predicted volume?
- What are the potential environmental consequences following a release of oil, including the trajectory, fate, and effects?
- What is the probability and what are the potential consequences of a release that results in a fire or explosion?

METHODS & RESULTS

Three separate approaches were required to address each of the three identified questions posed above. Environmental Research Consulting addressed the question of probability, while RPS ASA determined the environmental consequences from released oil assuming that there was no ignition source present, while Risknology Inc. considered the presence of an ignition source and determined the possible consequence following a fire or explosion. A description of each approach is provided, followed by the highest-level summary of results. For a more detailed description of the methods used and all results, refer to the full draft EIS and supporting appendices (HDR et al., 2016 and Technical Report Appendices G, H, and I).

Probability Assessment

The probability analysis specifically addressed: 1) probability of a crude oil spill associated with rail transport of crude oil to the facility; 2) probability of a diesel spill from locomotives transiting to or leaving the facility; 3) probability of a crude-by-rail spill at the facility; and 4) potential distribution of volumes associated with a crude-by-rail spillage.

The probability of a spill while in transit was determined through a fault tree analysis that first determined the probability that a crude-by-rail train would be involved in an accident (derailment, collision, fire/explosion incident, highway-rail crossing accident, or miscellaneous accident). Note that the fire/explosion category referred to a primary fire and/or explosion that could potentially cause the release of oil due to damage to one or more tank cars, and not to a fire or explosion that occurred as a result of a release of oil due to some other reason (e.g., a derailment with ignition source which is then followed by a fire). The second step involved determining the number of tank cars (or locomotives) that would potentially be derailed or otherwise damaged in each accident. The third step involved determining the likelihood of a tank car or locomotive releasing oil if involved in an accident. In other words, for a spill to occur, there needed to be an accident, the accident had to involve damage to tank cars or locomotives, and the tank cars or locomotives needed to release oil.

Because crude-by-rail transport is a relatively new phenomenon of the last several years, there are not enough accident (or spill) data specifically on crude-by-rail unit transport to conduct a robust and statistically sound analysis. For this reason, generic freight rail main line accident data from the Federal Railroad Administration (FRA) for the years 1975 through 2015 were analyzed to determine accident rates per transit-mile. The accident rates were then adjusted to take into account factors that would affect accident rates specifically for crude-by-rail trains, as well as more recent safety enhancements designed to decrease accident frequency.

To determine spill volume, the accident data were also analyzed to determine the number of tank cars and locomotives derailed or otherwise damaged in the various types of accidents and the proportions of hazmat tank cars that released content. The probabilities of tank car release were adjusted to take into account newer tank car designs that reduce the likelihood of release.

The fault tree analyses (probability of an accident with spillage and distribution of spill volumes) were conducted in a Monte Carlo fashion, meaning that there were distributions or ranges of values for inputs to incorporate both uncertainties and potential variable values. In particular, different assumptions were incorporated to develop a Lower Estimate of Spills (LES) and a Higher Estimate of Spills (HES), respectively representing a more “optimistic” approach (i.e., accident and spill prevention measures would be successfully incorporated into the regional rail system), and a more “pessimistic” approach (i.e., prevention measures will not necessarily be incorporated in a timely manner or are not as effective as assumed). The two sets of adjustments to rail accident probability and release rate are summarized in Figure 1. Adjustments for release rate were only applied to the LES. The HES assumed that improvements in tank car design would not affect release rates.

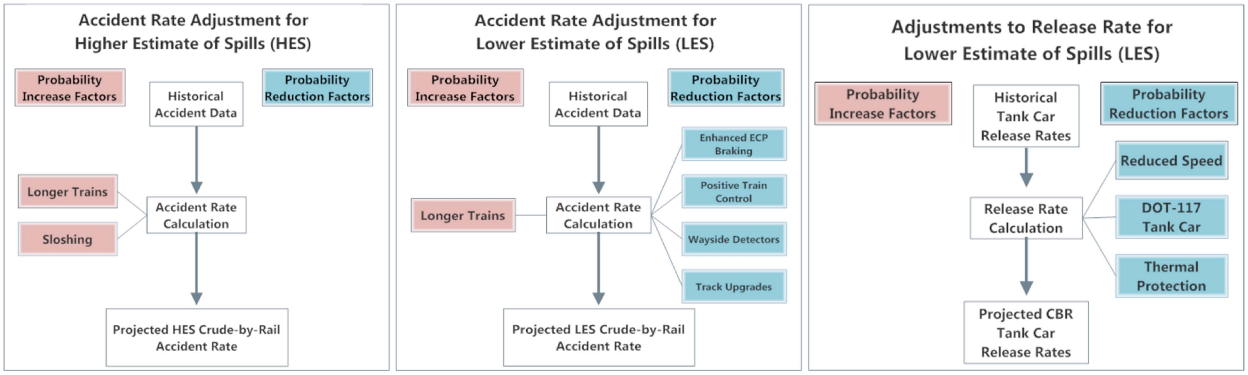

Figure 1: Adjustments to Accident and Tank Car Release Probability

The estimated spill volumes, frequencies, and corresponding return periods are summarized in Table 1 and Table 2. Overall, the likelihood of an in-transit crude-by-rail spill of any volume is about 0.026 to 0.046 per year. A very large spill (20,000 barrels [bbl]) is much less likely, with an estimated probability of 0.0055 to 0.0069 per year.

Table 1: Projected crude-by-rail spill frequencies for the Shell PSR – Higher Estimate of Spills

Spill Source	Oil Type	Small Spills	Moderate Spills	Very Large Spills
Loaded Crude-by-Rail Train in Transit (Tank Cars)	**Crude**	**250 bbl**	**5,700 bbl**	**20,000 bbl**
		0.046/year	0.032/year	0.0069/year
		1 in 22 years	1 in 31 years	1 in 140 years
Loaded Crude-by-Rail Train in Transit (Locomotives)	**Diesel**	**5 bbl**	**100 bbl**	**250 bbl**
		0.0047/year	0.00047/year	0.00024/year
		1 in 210 years	1 in 2,100 years	1 in 4,200 years
Empty Crude-by-Rail Train in Transit (Locomotives)	**Diesel**	**5 bbl**	**100 bbl**	**250 bbl**
		0.0038/year	0.00038/year	0.00019/year
		1 in 260 years	1 in 2,600 years	1 in 5,300 years
Crude-by-Rail Trains at Facility Transfers (Tank Cars)	**Crude**	**1 bbl**	*Projections of larger spills for transfers and other activities at the facility were not possible due to the lack of historical accidents on large tank car transfer accidents of any kind.*	
		0.026/year		
		1 in 40 years		
Crude-by-Rail Trains at Facility Rail Accidents (Locomotives or Tank Cars)	**Diesel or Crude**	**0.5 bbl–10 bbl**		
		0.000027/year		
		1 in 37,556 years		

Table 2: Projected crude-by-rail spill frequencies for the Shell PSR – Lower Estimate of Spills

Spill Source	Oil Type	Small Spills	Moderate Spills	Very Large Spills
Loaded Crude-by-Rail Train in Transit (Tank Cars)	**Crude**	**250 bbl**	**5,700 bbl**	**20,000 bbl**
		0.0055/year	0.0036/year	0.0055/year
		1 in 180 years	1 in 280 years	1 in 1,800 years
Loaded Crude-by-Rail Train in Transit (Locomotives)	**Diesel**	**5 bbl**	**100 bbl**	**250 bbl**
		0.0012/year	0.00012/year	0.00061/year
		1 in 820 years	1 in 8,200 years	1 in 16,000 years
Empty Crude-by-Rail Train in Transit (Locomotives)	**Diesel**	**5 bbl**	**100 bbl**	**250 bbl**
		0.00098/year	0.00098/year	0.000049/year
		1 in 1,000 years	1 in 10,000 years	1 in 20,000 years
Crude-by-Rail Trains at Facility Transfers (Tank Cars)	**Crude**	**1 bbl**	*Projections of larger spills for transfers and other activities at the facility were not possible due to the lack of historical accidents on large tank car transfer accidents of any kind.*	
		0.026/year		
		1 in 40 years		
Crude-by-Rail Trains at Facility Rail Accidents (Locomotives or Tank Cars)	**Diesel or Crude**	**0.5 bbl–10 bbl**		
		0.000027/year		
		1 in 38,000 years		

Consequence Assessment: Trajectory, Fate, and Effects Modeling

Oil spill trajectory, fate, and effects modeling and analyses were performed to evaluate the consequence from potential unmitigated releases (no response actions) of crude oil into aquatic environments from proposed project trains. This assessment assumed that whatever the cause and however unlikely, oil had been released into the environment and that no ignition source was present. The analysis predicted where oil released into those environments could move, how it would behave and degrade, and the types of impacted resources that could be affected.

Analyses of oil spill trajectory, fate, and effects were modeled using the SIMAP and OILMAP Land modeling packages developed by RPS ASA (previously Applied Science Associates). SIMAP is a three-dimensional in-water trajectory, fate, and effects model, while OILMAP Land is a two-dimensional over-land trajectory and fate model. Multiple oil fates processes are modeled within each of the computational models (Figure 2). Both models are used extensively by industry and governments (French-McCay 2004, Horn and French-McCay, 2015).

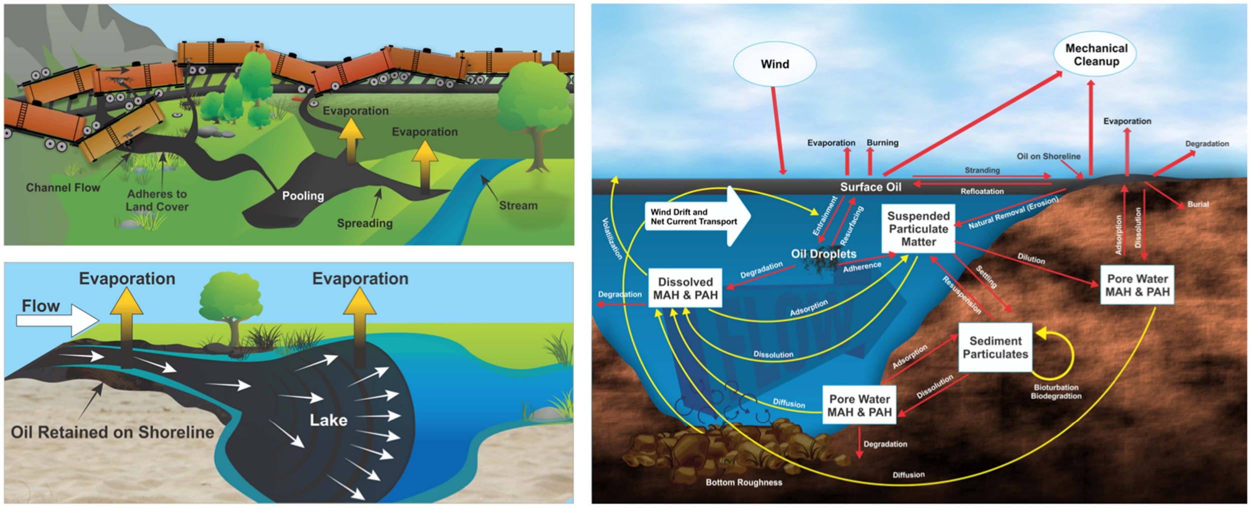

Figure 2: Modeled fates processes in the on land (top left) and in water (bottom left) portion OILMAP Land model and the SIMAP model (right).

Multiple oil spill release scenarios were developed to characterize the range of potential impacts from a number of geographic, environmental, and oil spill release conditions (Table 3). The combination of three potential representative release locations, two release volumes of conditioned Bakken crude oil (5,700 and 20,000 bbl release, corresponding with a 30th and 90th percentile discharge, or a 7-8 car and 28-30 tank car release, respectively), and two variations in the dominant site-specific seasonal environmental parameter were modeled as unmitigated releases for 48 hours, resulting in a total of 12 modeled fates scenarios.

Table 3: Hypothetical release locations and envionmental conditions varied in each scenario

Release Location	Site Description	Seasonal & Environmental Condition
Edmonds Ferry Terminal	Open water environment (Puget Sound) in an urban setting with storm water drainage system	Summer – Low Wind
		Winter – High Wind
Swinomish Channel Swing Bridge	Confined embayment (Padilla Bay) with mudflats and a channel	Summer – Spring Tide
		Winter – Neap Tide
Skagit River Crossing	Freshwater river with a drinking water intake bifurcated channel entering Skagit Bay	Summer – High River Flow
		Winter - Low River Flow

Modeled outputs included trajectory and fate information such as mass balance, shoreline stranding, surface oiling, evaporation, entrainment, emulsification, dissolution, volatilization from the water column, adsorption and sedimentation, and degradation. Trajectory and fate information was then used to determine the potential effects following a release through the use of secondary analyses including an overlay analysis and a biological impacts assessment.

An overlay analysis was used to identify any resources located within the predicted spill footprint for each scenario that could potentially be affected. In essence, the overlay analysis is a binary enumeration of presence/absence of oil, with an assumption that any amount of oil has the potential to affect any resource in its path. Nearly 50 databases containing the spatial distribution of resources of interest were compiled from the National Oceanic and Atmospheric Administration, Washington State Department of Ecology, Washington Department of Health, and the Washington Department of Fish and Wildlife and categorized into groups of environmentally sensitive areas that included: 1) socioeconomic resources: parks, management areas, public access points, fishing areas, and tribal resources, 2) marine and freshwater resources: Shellfish locations, fish spawning areas, and seal haulout points, and 3) avian and terrestrial resources: Bird colonies, nesting areas, wetlands, biodiversity corridors, and wildlife observations. Separate summary tables were prepared for each of the 12 modeled trajectories to identify the type and count of each resource potentially affected by the simulated release. This overlay analysis was strictly a count of total number of resources that could be intersected by the oil trajectories and did not consider the concentration or duration of contaminants (i.e., exposure).

A biological impacts assessment was used to estimate the potential short-term (acute) exposure of organisms to floating oil and subsurface oil contamination (in-water and on sediments), and predict the resulting percent mortality. Biota potentially impacted by surface and shoreline oiling include waterfowl, aerial and diving birds, wetland and terrestrial wildlife, fur-bearing marine mammals, pinnipeds (seals and sea lions), and cetaceans (whales and dolphins). The acute exposure level to oil floating on the water surface or on shorelines with a thickness greater than 10 microns. The acute exposure level for organisms in the water column (i.e., exposure to dissolved aromatics) and sediment varies depending on the specific environment, season, and life stage of each species. Biota potentially impacted by water column toxicity include mobile and stationary demersal (bottom- dwelling) fish and invertebrates, small pelagic (swimming) fish and invertebrates, large pelagic fish, benthic organisms residing within the bottom sediments, and plankton that drift with the currents. For each of the 12 modeled fates scenarios, acute toxicity for in-water impacts was calculated for the two sensitivity thresholds (5 micrograms per liter [µg/L], representing highly sensitive species and protective of 97.5% of species, and 50 µg/L, representing average sensitivity species and protective of 50% of species), resulting in a total of 24 biological modeling scenarios. These results provided the predicted range of potential acute impacts that could occur following a release of oil to the environment. The acute toxicity to aquatic biota within the water column (pelagic species) and bottom-dwelling species that live within the sediment bottom and up to 1 meter above (demersal species) were evaluated separately. Equivalent areas of 100% predicted morality were estimated for both the surface/shoreline and the water column.

In general, trajectory and fates results are driven by the degree of transport that is expected in each scenario, which is dependent on the season and the modeled environmental parameters. The spatial extent for each modeled component ranged greatly, with dissolved aromatics having more variability than surface oil thickness. For example, greater tidal action (i.e., the Swinomish Swing Bridge summer scenarios) and high-wind conditions (i.e., the Edmonds Ferry winter scenarios) acted to increase the area impacted by surface oil. Neap tides (lower tidal currents) and low-wind conditions resulted in less area affected by the oil. Similarly, lower river flow conditions resulted in less area oiled relative to high flow conditions. During each of the 12 modeled fates scenarios, approximately 50% of the released oil was predicted to evaporate with the first 48 hours, as conditioned Bakken crude oil is a light hydrocarbon product with a high volatile content. Due to the short duration of the model, very little oil was predicted to decay in the 2-day timeframe. The largest percentage of oil remaining would be deposited on shorelines or form surface slicks during the first 48 hours.

Among all release scenarios, the greatest impacts from floating oil were on fur-bearing marine mammals, dabbling waterfowl, and surface diving birds. The least impacted groups were terrestrial wildlife and marine mammals. Maximum in-water impacts were primarily predicted for the sensitive plankton, pelagic fish and invertebrates, and demersal organisms. Potential impacts were much lower for sediment dwelling organisms. By definition, lower impacts were predicted for moderately sensitive species, when compared with high sensitivity species.

Consequence Assessment: Fire and Explosion Analysis

A complete analysis of the fate and effects following an accidental crude oil release needs to include the determination of the consequence associated with fire and explosion. A crude oil spill would lead to the pooling and flow of liquid hydrocarbons onto land and/or water surfaces. Flammable gas mixtures would vaporize from the surface of the pool, governed by numerous physical processes (Figure 3). Following the release of oil, there are two potential outcomes (i.e., fire or explosion) determined by the timing of any potential ignition source. The vapor cloud could ignite immediately or drift and disperse downwind before igniting at a distant location.

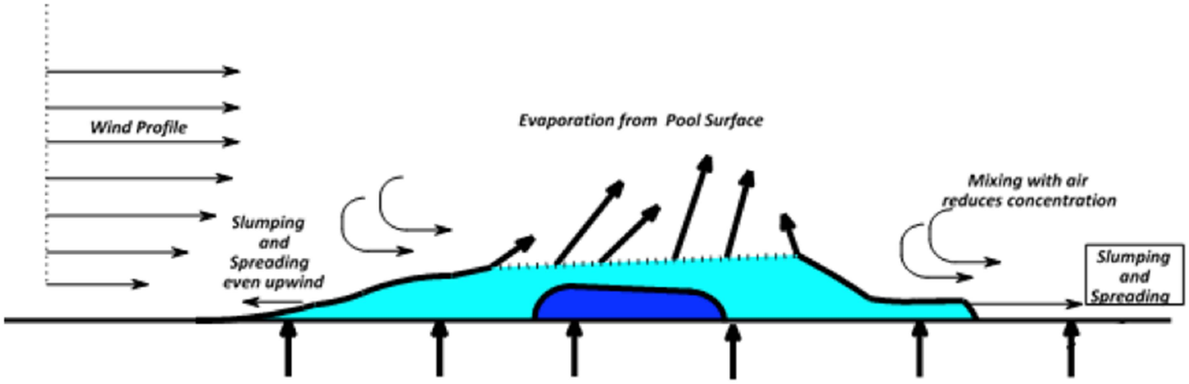

Figure 3: Modeled fates processes used in the assessment of consequence from fire and explosion.

If ignition occurred early, the vapors at the pool surface would burn. The radiant heat from this type of fire could be felt far from the fire itself. The fire would typically burn until all fuel was consumed, or fire response extinguished the fire. The effects of a fire could include be injuries and fatalities of people, as well as property damage in the surrounding area.

If the vapors did not ignite immediately, the vapor cloud would drift and disperse downwind, decreasing in concentration as the vapors mix with air. When the vapor to oxygen ratio decreased from its initial rich concentration to a value within the flammability range, it could ignite. Ignition of a flammable vapor cloud in an open space would lead to a flash fire, with impacts to people and structures inside and slightly beyond its volume. However, if the flammable vapor cloud ignited within an area that was both confined (walls, floor, ceilings, decks) and congested (objects densely occupying volume; such as cars, trees, industrial equipment) then a vapor cloud explosion could occur. Depending on the combination of fuel, confinement, and congestion, the combustion could either be subsonic (deflagration) or supersonic (detonation). A vapor cloud explosion, like a fire, could lead to effects on people and property. If the explosion occurred proximate to additional stored flammable materials, this could lead to escalation, the situation wherein additional fuel would be additive to the initial release inventory.

Specific scenarios were chosen to provide a range of representative consequences of flammable releases, including combinations of three release locations, two release volumes, and two wind speed regimens and corresponding weather conditions. The objective of this analysis was to present the potential zones affected by dispersion, thermal radiation, and explosion overpressure for the identified scenarios. Additionally, parametric sensitivity evaluation was provided to illustrate the range of potential impacts.

Pool vaporization accounted for heat conduction from the surface, ambient convection from the air, radiation, and vapor diffusion. These are the main mechanisms of boiling and evaporation. Pool fires were modeled using the Right Circular Cylinder Method (Moorhouse, 1982). Analytical models of pool fire required the specification of a number of physical parameters, including average emissive power and an atmospheric transmissivity.

Integral, or correlation models of dispersion were based on underpinning the behavior of the dispersed vapor in air to experimental results, the most widely known of these is the Gaussian Dispersion model. Vapor dispersion was modeled using the PHAST v7.11 computer modeling suite, which incorporates a Gaussian model, capturing the fluid dynamic processes affecting the downwind distance to which the released gas migrates, including convection, buoyancy, and dissipation.

Vapor Cloud Explosion (VCE) is the most consequential hazard of interest, as this causes damage as a result of a pressure wave moving through and past objects of interest, including the public, buildings, and structures with public occupation. Damage by exposure to a pressure wave occurs due to impulsive pressure loading. Models of VCE behavior include physical and chemical properties of hydrocarbon vapor clouds, the congestion (obstacles encountered by a flame as it propagates), and confinement (constraint to expand in only 1 or 2 dimensions) provided by the layout of the surrounding area. The TNO Multi-Energy model described in the Yellow Book (TNO, 1997), and incorporated in PHAST, allows for specification of the reactivity of the fuel in the cloud, the mass of fuel within the source volume, and the congestion/confinement level representative of the explosion source. Results are used to predict the maximum explosion overpressure at specific locations relative to the source.

Boiling Liquid Expanding Vapor Explosion (BLEVE), also referred to as a thermal tear, may occur if the rail cars containing crude oil are exposed to the flames of a pool fire or other high radiation flux, leading to a sudden explosive rupture and consequent overpressure. The blast effect of a BLEVE results from the rapid flashing of liquid and the expansion of vapor in the vessel's headspace, when the pressure drops suddenly to atmospheric pressure. The conditions that govern the effects of a BLEVE are railcar tank failure temperature and pressure.

The potential consequences of a pool fire were measured by the level of exposure to thermal radiation (heat) that would be experienced. Because thermal radiation levels decrease as the distance from the center of the pool fire increases, three thermal flux levels were assessed including: 4 kilowatts per square meter (kW/m^2) producing pain within 15-20 seconds and injury after 30 seconds, 12.5 kW/m^2 producing extreme pain within 20 seconds of exposure, whereby movement to shelter is instinctive and fatality if escape is not possible, and 35 kW/m^2 resulting in immediate fatality. Maximum predicted distances from the center of a pool fire were calculated for each of the modeled thermal radiation levels (Table 4).

Table 4: Thermal radiation level from a pool fire

		Maximum Distance from Pool Fire (meters)					
		Level of Thermal Radiation					
		4 kW/m^2		12.5 kW/m^2		[£]35 kW/m^2	
Release Location	**Release Size (barrel)**	**Early Pool Fire**	**Late Pool Fire**	**Early Pool Fire**	**Late Pool Fire**	**Early Pool Fire**	**Late Pool Fire**
Swinomish Channel Swing Bridge	5,700	136	203	49	74	--	--
	20,000	136	203	49	74	--	--
Skagit River Crossing	5,700	136	199	48	72	--	--
	20,000	136	199	48	72	--	--
[§]Edmonds Ferry Terminal	5,700	67 / 67	67 / 67	21 / 21	21 / 21	--	--
	20,000	75 / 75	75 / 75	23 / 23	23 / 23	--	--

[£] The 35 kW/m^2 level of thermal radiation was not reached under any scenario.
[§] The modeling at the Edmonds Ferry Terminal includes analysis of land and water.

The potential consequences of a vapor cloud explosion were measured by the overpressure generated by a shockwave and considered the impacts on people and structures from various distances relative to the center of the explosion. Three explosion overpressures were assessed, including: 1 pound per square inch (psi) whereby window glass shatters and light injuries from fragments occur, 3.5 psi whereby residential structures collapse and serious injuries are common, and 8 psi whereby destruction of buildings occur and most people are killed. Maximum predicted distances from the center of the explosion were calculated for each of the modeled overpressure levels (Table 5).

Table 5: Overpressure from a Vapor Cloud Explosion

		Maximum Distance from Vapor Cloud Explosion (meters)		
		Level of Overpressure		
Release Location	**Release Size (barrel)**	**1 psi**	**3.5 psi**	**8 psi**
Swinomish Channel Swing Bridge	5,700	1,164	837	758
	20,000	1,156	834	756
Skagit River Crossing	5,700	777	509	444
	20,000	773	508	444
[§]Edmonds Ferry Terminal	5,700-	1,204 / 317	938 / 172	729 / 119
	20,000	1,045 / 273	790 / 148	729 / 119

[§]The modeling at the Edmonds Ferry Terminal includes analysis of land and water.

In the event of a BLEVE, the resulting overpressure from the explosion was analyzed. In all cases BLEVE overpressures resulted in lower effect zones than for VCEs.

DISCUSSION

The assessment of environmental and human health risk for the proposed Shell Puget Sound Refinery Anacortes Rail Unloading Facility was comprehensive, comprised of three parts, including a probability assessment and two interrelated consequence assessments. Through the use of this highly quantitative assessment, a more complete understanding of the likelihood and magnitude of a suite of potential releases and a detailed accounting of the range of potential consequences following an unmitigated release of oil were provided. The probability assessment identified the likelihood of a release and the release volumes that may be involved, as well as informing the consequence modeling with justifiable and representative source terms for their respective phenomenological simulations. The trajectory and fate analysis investigated the potential effects of unmitigated release volumes within the environment based upon a range of geographic and environmental conditions. The first part of the consequence assessment predicted where oil would move, how it would behave and weather within the environment, and the types of resources and the predicted percent mortality that may be expected following a release. The fire and explosion analysis assessed potential consequence to humans by identifying the predicted hazard effect distances that could reach multiple thresholds of interest for thermal radiation and blast overpressure. The lower probability, larger volume release accidents were investigated to provide the upper range of anticipated effects should a release occur into the environment. In the event of a smaller volume release, the areas, volumes of water, distances, and potential effects are predicted to be lower.

This work advances the traditional generalized and qualitative assessments of risk that have been previously conducted. These earlier assessments frequently nondimensionalize effects or use generic sites to come up with single answers that do not contain consideration of site-specific geographic or environmental variability, which are known to affect potential consequences. They therefore fail to recognize the range of potential effects that can occur along linear features, which cover broad landscapes and transect diverse physiographic and environmental settings. In other assessments that do consider geography, many have focused on a simplified approach, which buffers the rail corridor by a fixed width, often identified as a “hazard corridor” or “blast zone.” However this approach ignores the effects of local topography and geographic features, hydrographic networks, and features that may affect explosive forces. As examples, 1) oil would flow downhill from a release location, which is typically to one side of the rail corridor, 2) oil has the potential to move greater distances in water, as rivers and tidal fluctuations would likely carry oil outside of buffered zones, and 3) thermal radiation and explosive forces are known to vary based upon confinement and obstacle density, which varies greatly depending on location. These oversimplifications have the potential to overestimate and underestimate potential effects at different release locations and under different conditions. Without an understanding of minimum and maximum extents and the magnitude of effects, it is difficult to have a comprehensive understanding of the range of potential effects.

The type of quantitative analysis presented here can assist in the assessment of risk and consequence as well as provide useful information in guiding planning, emergency response, and other aspects of design, construction, operation, or decommissioning for projects that involve hazardous substances such as oil.

This quantitative analysis is believed to be the first of its kind for rail – a fully integrated probabilistic assessment of the environmental and human safety consequences of oil spill fate and effects to support regulatory decision-making. As such, it also provides a methodology and template and baseline for comparison of similar projects in the future.

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