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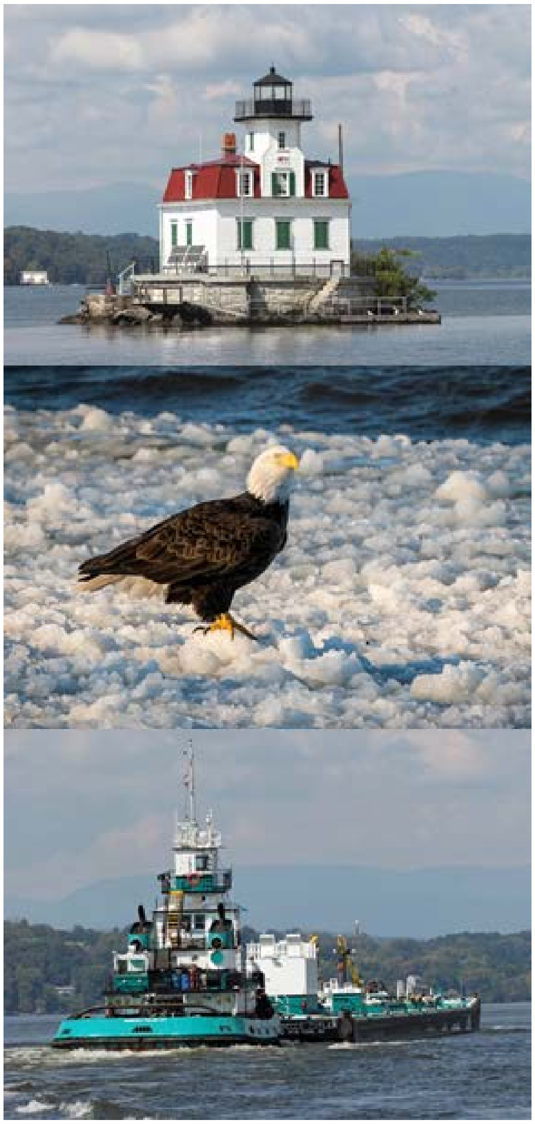

Hudson River Oil Spill Risk Assessment

Volume 5: Fire and Explosion Consequences

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Acknowledgments

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The HROSRA research team acknowledges the invaluable inputs and discussions with Scenic Hudson over the course of the study period (September 2017 through May 2018), including the selection and development of the hypothetical spill scenarios. The contents of the report, data, analyses, findings, and conclusions are solely the responsibility of the research team and do not constitute any official position by Scenic Hudson. The Hudson River Oil Spill Risk Assessment was conducted as an independent, objective, technical analysis without any particular agenda or viewpoint except to provide quantitative and qualitative information that could be used to work to a common goal of spill prevention and preparedness. The study is intended to inform officials, decision-makers, stakeholders, and the general public about oil spill risk in the Hudson River.

The diligent efforts of the RPS SIMAP modeling team of Deborah Crowley, Jenna Ducharme, Matt Frediani, Emily Skeehan, and Matt Bernardo provided the necessary data, results, maps, and graphics that formed the foundation of much of the analysis in the HROSRA.

The research team also acknowledges the Launch 5 Foundation of Ossining who provided the team with transportation on a two-day river cruise between the Tappan Zee Bridge in Tarrytown and the Port of Albany, New York, on the *Patrolman Henry A. Walburger No. 5* ("Launch 5") on 15-16 September 2017. The Launch 5 was piloted by Greg Porteus and Steve Kardian. The 26-hour two-way trip allowed the research team to personally see, photograph, evaluate, and measure the features of both banks of the Hudson River, as well as observe vessel traffic and river conditions.

Cover Photograph Credits

The photographs on the report cover were taken by Dagmar Schmidt Etkin (Esopus Meadows Lighthouse and articulated tank barge) and Steve Kardian (bald eagle) on the Hudson River.

Contents

List of Tables

List of Figures

Hudson River Oil Spill Risk Assessment Report Volumes

The Hudson River Oil Spill Risk Assessment (HROSRA) is composed of seven separate volumes that cover separate aspects of the study.

Executive Summary (HROSRA Volume 1)
The first volume provides a summation of results in relatively *non-technical* terms, including:

- Purpose of study;
- Brief explanation of risk as "probability times consequences" and the way in which the study addresses these different factors;
- Brief discussion of oil spill basics;
- Results – the "story" of each spill scenario, including the oil trajectory/fate/exposure, fire/explosion brief story (if applicable), and a verbal description of the consequence mitigation (response – spill and fire emergency); and
- Brief summation of spill mitigation measures with respect to response preparedness and prevention.

HROSRA Volume 2
The second volume provides an overview of the study process and general introduction to unique features of the Hudson River.

HROSRA Volume 3
The third volume reviews the potential sources of oil spillage. It also presents the analyses of the probability of occurrences of spills of varying sizes from the potential sources under different conditions of traffic and oil transport.

HROSRA Volume 4
The fourth volume presents the analyses of the potential consequences or impacts of hypothetical spills, including the trajectory and fate of spills to the water, and the potential exposure of resources above thresholds of concern, based on oil modeling (including Appendices with detailed figures, etc.).

HROSRA Volume 5
The fifth volume presents the analyses of potential consequences or impacts of hypothetical fire and explosion events that may occur secondary to oil spills.

HROSRA Volume 6
The sixth volume presents the analyses of spill mitigation measures to reduce the risk of spills through prevention, preparedness, and response. The volume includes response and preparedness considerations for the specific modeled scenarios, as well as overall response issues for Hudson. It also includes more generic descriptions of prevention measures (vessels, trains, facilities, etc.).

HROSRA Volume 7
The seventh volume presents the summary tables with data – including probabilities, spill modeling, fire/explosion analysis, and response considerations for each of the 72 modeled spills scenario. This volume pulls together everything from HROSRA Volumes 3, 4, 5, and 6.

Research Team

Dagmar Schmidt Etkin, PhD (Environmental Research Consulting)

Dr. Etkin has 42 years of experience in environmental analysis–14 years investigating issues in population biology and ecological systems, and 28 years specializing in the analysis of oil spills. Since 1999, she has been president of Environmental Research Consulting (ERC) specializing in environmental risk assessment, and spill response and cost analyses. She has been an oil spill consultant to the US Coast Guard, EPA, NOAA, Army Corps of Engineers, the Bureau of Ocean Energy Management, the Bureau of Safety and Environmental Enforcement, various state governments, the Canadian government, the oil and shipping industries, and non-governmental organizations. She is internationally recognized as a spill expert and has been a member of the UN/IMO/UNEP/UNESCO Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) since 1997. She has a BA in Biology from University of Rochester, and received MA and PhD degrees from Harvard University in Organismic/Evolutionary Biology, specializing in ecological modeling and statistics.

Deborah French McCay, PhD (RPS Ocean Science)

Dr. French McCay (formerly Dr. French) specializes in quantitative assessments and modeling of aquatic ecosystems and populations, oil and chemical transport and fates, and biological response to pollutants. She has developed water quality, food web and ecosystem models for freshwater, marine and wetland ecosystems. She is an expert in modeling of oil and chemical fates and effects, toxicity, exposure and the bioaccumulation of pollutants by biota, along with the effects of this contamination. Her population modeling work includes models for plankton, benthic invertebrates, fisheries, birds and mammals. These models have been used for impact, risk, and natural resource damage assessments, as well as for studies of the biological systems. She has provided expert testimony in hearings regarding environmental risk and impact assessments. She has over 30 years of experience in analyzing oil spills and is considered one of the leading international experts on the fate and effects of oil spills. She has a BA in Zoology from Rutgers College, and a PhD in Biological Oceanography from the Graduate School of Oceanography, University of Rhode Island.

Jill Rowe (RPS Ocean Science)

Jill Rowe specializes in biological and environmental data gathering, analysis and management; natural resource damage assessment (NRDA) modeling and analysis of pollutant fates and effects; ecological risk assessment; impact assessment of dredging and development projects, preparing sections of Environmental Impacts Statements; providing NEPA support, and GIS mapping and analysis. Ms. Rowe has applied her marine biological and GIS expertise to biological data set development, as well as mapping habitats and biological resource distributions that could ultimately be affected by oil/chemical spills and development projects. She performs quantitative assessments and modeling of aquatic ecosystems and populations, pollutant transport and fates, and biological response to pollutants. The populations to which she applies these models include plankton, benthic invertebrates, fisheries, birds and mammals. She has analyzed data and has applied water quality, food web and ecosystem models to case studies in freshwater, marine and wetland ecosystems. She has a BA in Biology from DePauw University, and an MS in Marine Biology from the College of Charleston.

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Deborah Crowley is a senior consulting environmental scientist and project manager at RPS. She has experience working on issues and projects related to various aspects of environmental science such as environmental data analysis, hydrodynamic and water quality modeling and analysis, coastal processes, oil and gas fate and transport assessment in the environment, operational discharge modeling and assessment, renewable energy project development assessment support, environmental impact assessment in coastal and marine environments and permitting and regulatory compliance analysis and support. Ms. Crowley's experience with renewable energy projects includes cable burial studies, wind resource assessment, climatology assessment including extremal analysis, wind turbine siting, turbine power production and site capacity analysis, turbine impacts assessment, turbine visualizations, regulatory, permitting and zoning review, planning and management of terrestrial met tower deployment and associated data management and analysis. Areas of experience include numerical modeling, model development and application, field program design and support, data analysis and visualization in Matlab™ and geospatial analysis in ArcGIS™. She has a BS in Mechanical Engineering from Worcester Polytechnic Institute and an MS in Civil & Environmental Engineering from University of Rhode Island.

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Mr. Joeckel is an executive management professional with a broad-based background in multi-modal transportation, oil, chemical and gas industry sectors, and manufacturing and production. He has extensive experience in legislative advocacy and regulatory compliance, crisis and consequence management, emergency preparedness and response, including hands-on response as an Incident Commander on multiple major emergency incidents and development of all hazard response/crisis management programs and plans including training and exercises. He has experience in ports, waterways and facility maritime security vulnerability analysis and security plan development including personnel training and exercise. Mr. Joeckel has a BS in Maritime Transportation from SUNY Maritime College, as well as many years of training in oil spill response. He has been involved in response research and development and supervising many spill response operations, including the BP Gulf of Mexico Deepwater Horizon incident, the Enbridge Pipeline Michigan oil tar sands crude oil spill in the Kalamazoo River, and the Exxon Valdez spill in Alaska.

Andrew J. Wolford, PhD (Risknology, Inc.)
Dr. Wolford is founder and President of Risknology, Inc., a company specializing in risk analysis of hazardous facilities. He is an expert risk engineer with 31 years of experience. He has directed risk assessments on a diverse range of engineered systems including; offshore and onshore oil and gas installations, mobile offshore drilling units, marine and land-based transportation systems, chemical and nuclear fuel processing plants, nuclear power and test reactors, and the Space Shuttle program. He has a BA in Physics from Wittenberg University, a BA in Nuclear Engineering from Georgia Institute of Technology, and a ScD from Massachusetts Institute of Technology.

Acronyms and Abbreviations

bbl: barrels (equivalent of 42 gallons)

CBR: crude-by-rail

FERC: Federal Energy Regulatory Commission

HCLP: high-consequence low-probability

HROSRA: Hudson River Oil Spill Risk Assessment

kW/m^2: kilowatts per square meter

LFL: lower flammability limit

mm: millimeters

m/s: meters per second

PHAST: Process Hazard Analysis Software Tool

psi: per square inch

RVP: Reed Vapor Pressure

UFL: upper flammability limit

VCE: vapor cloud explosion

HROSRA Volume 5 Summary

A comprehensive spill risk assessment of oil and hydrocarbon fuel transported on the Hudson River (HROSRA) is being conducted to provide an objective resource for planning, development, regulation and management of the risks by various stakeholders. One specific concern of the HROSRA is public safety, in particular, the potential for fire and/or explosion resulting from possible crude-oil and fuel releases. The public safety concern has been growing with the rise of unconventional extraction techniques leading to changing crude oil compositions, essentially increasing the content of light ends (ethanes and butanes) which flash off when exposed to the environment. The Department of Energy is currently conducting research to understand how the chemical composition of unconventional crude oils changes the risk they pose to the nation's transportation systems.[1]

The scope of work for this project addressed consequence modeling for potential crude oil and fuel releases for flammable vapor dispersion, thermal hazard zones derived from pool fires, and explosion overpressures resulting from vapor cloud explosions for five locations; the Port of Albany, Rondout, Newburgh Waterfront, Iona Island and the Yonkers Anchorage.

The worst-case hazard distances representative for each location are shown in Table 1. These compile the distances to hazard limits and the land use areas impacted. The table shows that the predicted land areas impacted by thermal radiation hazards from pool fires range from less than an acre to three acres, the major contributor being the Port of Albany, and explosion overpressure hazard distances range from 34 to 476 acres, the major contributor also being the Port of Albany, due to land development density. The entries marked with an asterisk (*), indicate no impacts from this scenario impact land use areas of the indicated type (the hazard does not reach the target).

Table 1: Worst-Case Hazard Impacts

Location and Hazard Type		Downwind Distance	Impact (Acres)				
			Total	Residential	Commercial	Industrial	Public Use
Port of Albany	**Fire**	581 ft	0.3	0.1	0.1	0	0.1
	Explosion	1.66 miles	476	305	47	124	0
Rondout	**Fire**	581 ft	0.8	0	0	0.4	0.4
	Explosion	2.19 miles	418	155	134	50	79
Newburgh Waterfront	**Fire**	581 ft	0.2	0	0.1	0	0.1
	Explosion	0.33 mile	34	22	8	0	13
Iona Island	**Fire**	581 ft	0.2	0	0	0	0.2
	Explosion	0.84 mile	68	0	0	0	68
Yonkers Anchorage	**Fire**	1,473 ft	3.1	0	1.6	1.6	0
	Explosion	0.033 mile	166	103	27	8	27

[1] [1] https://www.theatlantic.com/technology/archive/2018/02/the-great-crude-oil-fireball-test/552029/

Introduction

A comprehensive spill risk assessment of oil and hydrocarbon fuel transported on the Hudson River (HROSRA) is being conducted to provide an objective resource for planning, development, regulation and management of the risks by various stakeholders. One specific concern of the HROSRA is public safety, in particular, the potential for fire and/or explosion resulting from possible crude-oil and fuel releases. This report identifies and evaluates the consequences of fire and/or explosion from selected hypothetical crude oil and fuel releases along the Hudson River.

Releases of crude oil are high-consequence, low-probability (HCLP) events. The potential for incidents of this magnitude of frequency and consequence are present at many high-hazard industrial activities. However, facilities with HCLP risks manage those risks using engineered safeguards and administrative controls to achieve acceptable levels of safety.

The following types of incidents, though very unlikely, could occur and were considered in the analysis:

- **Pool Fire:** This is a fire that burns from a pool of vaporizing fuel. The primary concern associated with pool fires is hazards associated with increased temperatures from thermal radiation (heat). For crude oil and fuel transported along the Hudson River in ships, barges and crude-by-rail trains, a pool fire could occur if there is an incident leading to a release of crude oil that forms a pool on the river surface and then catches fire.

- **Vapor Cloud Explosion:** A vapor cloud explosion is the result of a flammable material that is released into the atmosphere, at which point the resulting vapor cloud is ignited. The primary concern from a vapor cloud explosion is overpressure (pressure caused by a shockwave). For crude oil and fuel transported along the Hudson River in ships, barges and crude-by-rail trains, such an explosion could occur if oil was released during an incident and evaporated into the air, forming a vapor cloud. This requires that there be no immediate ignition source.

Because the range of locations, conditions, and release quantities for hypothetical scenarios can be an intractable number, specific scenarios were selected through a consultative process with Scenic Hudson and other stakeholders to provide a range of representative consequences of flammable releases.

Scope of Work and Study Objectives

The scope of work for this project included:

- Perform consequence modeling for potential crude oil and fuel releases for five representative locations, using two weather conditions for each;
- Determine the extent of flammable vapor dispersion;
- Determine the extent of thermal hazard zones derived from proposed pool fires, for both early and late ignition, and for flash fires;
- Determine the extent of explosion overpressure for vapor cloud explosions resulting from oil releases; and
- Determine the conditional probability of each of the consequence impacts given that a and release occurs.

Analysis

This section contains aa discussion of the analysis and parameters selected to evaluate the dispersion, fire, and explosion behavior required for this analysis. Some of the parameters are obtained from physical and engineering data, others from location-specific environmental data. The remaining data are associated with the specific models or calculations used.

System Description

The overall system is described generally in HROSRA Volume 2 and it includes the Hudson River corridor from Albany to New York City.

Selected Sites

Because the range of locations, conditions, and release quantities for proposed scenarios can be an intractable number, certain specific accident scenarios were selected through a consultative process with the client and stakeholders to provide a range of representative consequences of flammable releases. Five of the ten sites were analyzed for fire and explosion:

- Port of Albany
- Rondout
- Newburgh Waterfront
- Iona Island
- Yonkers Anchorage

Environmental Parameters

The environmental factors required to perform the dispersion analysis are; wind speed, direction, stability class, air temperature, and humidity. These factors can influence various hazard conditions; therefore, the probable conditions at the selected sites were investigated. The data from the Hudson River Environmental Conditions Observing System[2] for the years 2011 – 2016, from the following weather stations was collected and analyzed to characterize the environmental factors of interest:

- Albany
- Norrie Point
- Piermont
- Shodackis

The wind speeds considered for predicting vapor dispersion hazards for this analysis comprised the 5th and 95th percentile values for each of the weather stations. The 5th percentile represented the value below which the wind speeds fell 5% of the time that were observed at that site. Similarly, the 95th percentile represented the value below which 95% of the wind speeds fell, so this value was exceeded only 5% of the time.

In addition to wind speeds, a measure of the effect of turbulence on dispersion was also required for analysis. Turbulence increases the entrainment and mixing of air into the vapor cloud plume and thereby

[2] Hudson River Environmental Condition Monitoring System, www.hrecos.org.

acts to reduce the concentration of vapor the plume (i.e., enhances the plume dispersion). It was therefore important to categorize the amount of atmospheric turbulence present at any given time. According to the Pasquill Stability scale, there are six stability classes: A, B, C, D, E and F, with class A being the most unstable or most turbulent, and class F being the most stable or least turbulent. Stability class F was chosen for analysis at each site to ensure conservative results. Stability class F is specified for calculation of the dispersion of natural gas accidental releases in the permit approval process governed by the Federal Energy Regulatory Commission (FERC) for liquefied natural gas facilities[3].

Humid air absorbs / attenuates more thermal radiation than dry air, thereby decreasing the transmissivity of the air and reducing the thermal hazard distance. Air temperature and humidity were also selected to give realistic but conservative estimates. Air temperature and humidity were taken from the 5th and 95th percentile values observed at the four weather station data sets (Table 2).

Table 2: Weather Conditions

Location	Weather Dataset	Speed 5th m/sec	Speed 95th m/sec	Stability Category	Relative Humidity (%)	Temperature (C)
Albany	Albany	2	5.2	D, F	34, 95	-7.4, 26.5
Rondout	Norrie Point	2	5.5	D, F	39, 97	-6.5, 26.1
Newburgh Waterfront	Shodakis	2	5.8	D, F	35, 97	-7.8, 25,9
Iona Island	Piermont Point	2	7.8	D, F	47, 96	0.4, 26
Yonkers	Piermont Point	2	7.8	D, F	47, 96	0.4, 26

Properties of Crude Oil

The crude oil composition used for this analysis is known as *Conditioned Bakken Crude*. The composition for the Conditioned Bakken Crude was modeled as typical, based on the Crude Oil compositions familiar to Risknology. The modeling approach of a multi-component mixture is performed by assuming that the composition of the mixture does not change during the different stages in the dispersion process. During analysis, the composition of the crude oil was assumed to be the same as for the vapor cloud in all stages of dispersion. The properties of the mixture were calculated as a weighted average of each component property, and those averaged properties were used in the modeling in the same way as the properties for a pure component.

The information included on the composition analysis only provided the composition for the light hydrocarbons, which account for only 15% of the crude by volume. Therefore, some assumptions had to be made in order to estimate the contribution of the heavy ends to the thermodynamic properties of the mixture, which included the assumption that the remaining hydrocarbon mixture could be represented by n-nonane.

The volatility of the pseudo-component was verified by comparing the calculated Reid Vapor Pressure (RVP) in PHAST against the reported RVP of the Bakken crude. The RVP reported in a representative Bakken Assay was 5 pounds per square inch (psi), which is lower that the RVP of the pseudo-component mixture calculated in PHAST as 7 psi. This higher value of RVP provided a slight level of conservatism to the consequence modeling results.

[3] https://www.phmsa.dot.gov/pipeline/liquified-natural-gas/lng-plant-requirements-frequently-asked-questions

Model Input Data

There are numerous models of physicochemical behavior used in representing the overall consequences of the specified release scenarios:

- Multiphase discharge from a breach and associated flashing of vapor
- Liquid pool spread, heat transfer and evaporation
- Vaporization from liquid pool
- Vapor dispersion
- Combustion
- Attenuation of thermal radiation

All of these models had their own respective input data and parameters that were required. These are listed in the “Summary Report” output file included as Appendix A.

Technical Approach

Liquid hydrocarbon releases, when ignited, can result in pool fires and vapor cloud explosion hazards. For this study, the hazards were assessed independently and combined to represent the complete consequences of the hazard. Impacts to safety were limited to the area potentially affected by thermal radiation from fire scenarios, and the area potentially affected by overpressure resulting from vapor cloud explosion.

This dispersion, fire, and explosion analysis investigated specific—representative— - accidental crude oil release scenarios that were selected based on a range of locations of interest, resources potentially at risk from the consequential impacts of the release, and a statistical analysis of the likelihood of specific release quantities. Scenario specifications are presented in Table 3. The parameters required included:

- Location – Port of Albany, Rondout, Newburgh Waterfront, Iona Island, Yonkers Anchorage
- Volume Released – 11,000 bbl, 75,421 bbl, and 155,000 bbl
- Pool Surface - Water Surface (River)
- Dispersion Surface - Land
- Terrain Surface Roughness - mud flats, suburbs, city

Table 3: Scenario Matrix

Location	Oil Type	Volume Inventory (m^3)	Pressure (bar)	Hydrocarbon Temperature (°C)	Terrain for Dispersion (mm)	Type of Pool Substrate	Wind Speed (m/s)	Atmospheric Stability Class	Air Temperature (°C)	Relative Humidity (%)	Weather Date File
Albany	**Bakken**	24,642	0.138	21.5	Suburbs 1,000	Water	2	F	26.5	95	Albany
				21.5			2	D	26.5	95	
				12.8			2	F	-7.4	34	
				12.8			2	D	-7.4	34	
				21.5			5.2	F	26.5	95	
				21.5			5.2	D	26.5	95	
				12.8			5.2	F	-7.4	34	
				12.8			5.2	D	-7.4	34	
Rondout	**Bakken**	11,990	0.138	21.1	Open Flats to Low Crops 70	Water	2	F	26.1	97	Norrie Point
				21.1			2	D	26.1	97	
				21.1			5.5	F	26.1	97	
				21.1			5.5	D	26.1	97	
				3.5			2	F	-6.5	39	
				3.5			2	D	-6.5	39	
				3.5			5.5	F	-6.5	39	
				3.5			5.5	D	-6.5	39	
Newburgh	**Bakken**	1,749	0.138	20.9	Suburbs 1,000	Water	2	F	25.9	97	Schodakis
				20.9			2	D	25.9	97	
				2.2			2	F	-7.8	35	
				2.2			2	D	-7.8	35	
				20.9			5.8	F	25.9	97	
				20.9			5.8	D	25.9	97	
				2.2			5.8	F	-7.8	35	
				2.2			5.8	D	-7.8	35	
Iona Island	**Bakken**	1,749	0.138	21.0	Open Flats 30	Water	2	F	26	96	Piermont Point
				21.0			2	D	26	96	
				10.4			2	F	0.39	47	
				10.4			2	D	0.39	47	
				21.0			7.8	F	26	96	
				21.0			7.8	D	26	96	
				10.4			7.8	F	0.39	47	
				10.4			7.8	D	0.39	47	

Table 3: Scenario Matrix

Location	Oil Type	Volume Inventory (m^3)	Pressure (bar)	Hydrocarbon Temperature (°C)	Terrain for Dispersion (mm)	Type of Pool Substrate	Wind Speed (m/s)	Atmospheric Stability Class	Air Temperature (°C)	Relative Humidity (%)	Weather Date File
Yonkers	**Gasoline**	24,642	0.138	21.0	Suburbs 1,000	Water	2	F	26	96	Piermont Point
				21.0			2	D	26	96	
				12.8			2	F	0.39	47	
				12.8			2	D	0.39	47	
				21.0			7.8	F	26	96	
				21.0			7.8	D	26	96	
				12.8			7.8	F	0.39	47	
				12.8			7.8	D	0.39	47	

Consequence Analysis

Pool Size

Realistic representation of pool size depends upon the exact location, topography of the substrate area, rate of release of the crude oil or fuel from the breach and rate of vaporization. Pool spread models and Gaussian dispersion models rely on treating the shape of each of these effects as circular. This means that irregular shape release areas must be represented as a circular area for both the spreading phenomena and the vaporization source.

Releases onto river surfaces are represented as a circle of diameter up to the river width at the release location, as the river will confine the spread of liquid within the shoreline. If a release elongates along the river length, the dispersion distance perpendicular to the river will not change as a result.

Each of the pools at the three locations are constrained by the geometry of the release, but leading up to this dimension, the spread of the pool was calculated using the pool spread model in PHAST v8.0, which assumed that the driving force for the spread was formed by the hydrostatic difference between the thickness of the liquid layer and a minimum pool thickness characteristic for the substrate. This results in the rate of spreading decreased as the pool approached the minimum thickness. In this study, the crude oil / fuel release occurs on water. The minimum thickness characteristic of deep water is 1 mm. Where the pool has spread and vaporized to produce a pool of depth equal to the minimum thickness, the spreading is constrained to be consistent with this thickness. Thereafter the radius would no longer be a simple function of time.

Discharge Dynamics

As pool formation depends on the rate of release of crude oil from the breach, a breach size must be established to determine the release rate. The discharge behavior in an actual incident would be characterized by a number of tanks, each leaking from a unique breach size. In this analysis, a simplification was made to treat the release as a single volume flowing through a single breach, and then its equivalent size was calculated. The release duration of the contents from a crude carrier or tank barge was defined to be 4 hours, and the release from a crude-by-rail (CBR) train was defined to be 60 minutes, based on the default value for maximum release duration suggested by the US Environmental Protection Agency[4] for estimation of distance to flammable endpoints. A breach size was calculated knowing the total release volume and duration. The discharge model in PHAST was used assuming no frictional losses for the fluid as it flowed out of the hole.

Conditional Ignition Probability

Conditional ignition probability can be understood as the probability of ignition, if a release occurs. In other words, some vapor clouds generated from the release drift downwind and disperse without ever encountering an ignition source. The conditional probability of ignition characterizes the fraction of events that do ignite.

[4] 40CFR68.112(r)(7), Clean Air Act, Risk Management Program (RMP) Rule. 1990 (US EPA).

Ignition probability depends upon the vapor cloud encountering an ignition source. Since this study considers releases that could occur near populated areas as well as on railways located adjacent to roads with no controls on ignition sources (such as in an industrial site, for example), the ignition probability model used in this study assumed a uniform density of ignition sources within the dispersion plume.

The probability of a fire or explosion in the event of a release is dependent on an incident and a release first occurring. The release frequency rates were calculated and reported in the probability analysis of HROSRA Volume 3. The probabilities of oil release for the different scenarios depend on the source type (tank vessel, cargo vessel bunkers, rail) and oil volume (larger-volume spills are less likely within each source type category). Past research based on examining a number of fire incidents, provides generic probabilities of ignition and explosion. [5] This work demonstrated that there is an 8% probability of an ignition leading to a fire in the event of a release. Of these ignited events, there is a 30% probability that that fire would result in a vapor cloud explosion, hence a 2.4% probability (i.e. 8% x 30% = 2.4%). Table 5 outlines the expected frequencies and return periods of a fire or explosion based on the release frequencies calculated in the probability analysis.

The frequency and return period of these potential events were calculated. The calculated frequency of a pool fire ranged between 0.00096 and 0.00000003 pool fires per year, which is equivalent to between one in every 1,000 years to one in every 33 million years. The calculated frequency of a vapor cloud explosion ranged between 0.00029 and 0.0000000084 vapor cloud explosions per year or, between one in every 3,500 years to 120 million years.

Table 4: Frequency and Annual Probability of Fire or Explosion in Event of Release

Incident Type	Albany and Yonkers Tank Vessel Spills (150,000-155,000 bbl)		Rondout Tank Vessel Spills (75,421 bbl)		Newburgh and Iona CBR Spills (11,000 bbl)	
	Frequency (Event/Year)	Annual Probability	Frequency (Event/Year)	Annual Probability	Frequency (Event/Year)	Annual Probability
Oil Release	0.0000015	1 in 670,000	0.012	1 in 83	0.00000035	1 in 2,900,000
Pool Fire	0.00000012	1 in 8,300,000	0.00096	1 in 1,000	0.00000003	1 in 33,000,000
Vapor Cloud Explosion	0.00000004	1 in 25,000,000	0.00029	1 in 3,500	0.0000000084	1 in 120,000,000

Vapor Dispersion Hazards

Vapor dispersion was conducted for all crude oil releases along with any vaporization of hydrocarbon gas. Dispersions were performed using the validated Uniform Dispersion Model as coded in PHAST 8.0.

To maximize dispersion distances, all simulations were conducted on a flat surface. Objects (i.e., buildings, tanks, and other structures) were incorporated in the analysis as a surface roughness parameter. Objects have the potential to increase mixing, thereby reducing the distance to which the vapor clouds would travel.

[5] Cox et al. 1990.

The size of the hydrocarbon vapor clouds was defined based on the volume of hydrocarbon mixed with air within its flammable limits. The boundaries of flammable mass were defined using the lower flammability limit (LFL) contour, and the density of the cloud were determined assuming the cloud were homogenous with a concentration of the midpoint between the upper flammability limit (UFL) and the LFL.

Pool Fire Hazards

In the event that an ignition of a spreading crude oil pool occurred, the thermal radiation resulting from the ignited pool was analyzed. The pool fires were modeled in PHAST 8.0 using a solid flame model with no obstructions. Treating radiation without obstructions from pool fire radiation calculations increases consequence distances. The solid flame model solves for radiative intensities at distances away from the center of a fire and allows for a change in hazard distance due to tilting of the flame by wind. To determine the hazard distance, an average emissive power, a burn rate, and an atmospheric transmissivity was calculated during the analysis.

Explosion Hazards

The acute damage potential of vapor cloud explosions has been proven by many real-world accidents including the significant potential for loss of life, property and business interruption. A major example is the 2005 Buncefield explosion in the UK (Figure 1).[6] In this case, a series of explosions occurred in 20 large storage tanks at a large oil terminal that caused at least 43 injuries.

Figure 1: Buncefield Explosion in Hemel Hempstead, Herts, UK in December 2005[7]

The importance of the unique explosion hazards posed by "tight crudes" – crudes produced by fracking of nonconventional reserves, are beginning to be recognized in the US[8]. Much of the motivation behind the

[6] See Atkinson et al. (2017) for a very recent review of vapor cloud explosions in 2005 Buncefield accident.
[7] https://www.telegraph.co.uk/finance/newsbysector/energy/oilandgas/3540214/Buncefield-explosion-Five-companies-face-prosecution.html
[8] https://www.theatlantic.com/technology/archive/2018/02/the-great-crude-oil-fireball-test/552029/

development of predictive models is a result of such catastrophic accidents. Physical and chemical properties of hydrocarbon vapor clouds and the layout of the surrounding area influences the dynamics of blast propagation during the explosion.

As a vapor cloud burns and expands, the gasses start to move and become consumed by the flame front. If the process takes place with the unburned gas flowing smoothly into the consuming flame front, the flame front propagates at the laminar burning velocity, which produces a flash fire. If there is turbulence in the gas, the flame velocity can greatly increase above this laminar burning velocity, which can produce high overpressures. Significant turbulence can be generated by obstacles encountered by a flame as it propagates through the vapor cloud in obstructed regions. This process can be reinforced by positive feedback, so that as more obstacles are encountered, more turbulence is generated and this further accelerates the flame. The obstacle density is also referred to as *congestion* in the literature.

A further key factor in determining the magnitude of overpressure generation is the degree to which the cloud is constrained from expanding. As the cloud burns, it heats and expands; if the cloud is constrained to expand in only one or two dimensions then the positive feedback mechanism leads to higher overpressures than if the cloud were to expand freely. This expansion constraint is referred to as *degree of confinement* in the literature.

For areas along the river corridor, confinement and congestion would vary; hence representative release locations of interest were selected that present realistic confinement and congestion scenarios. No damaging blast waves can occur for releases in the open.

To properly estimate the potential explosion associated with each release, the scenario in which the cloud or some portion thereof sits in a congested volume needed to be assessed. For the study, the explosion overpressure results were calculated with the TNO Multi-Energy model described in the Yellow Book[9] and contained in PHAST version 8.0, using 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. The area surrounding the release point was assigned a representative congestion and confinement level.

Damage Thresholds

Compilations of data on the impacts of thermal radiation are available in literature, Lees[10] provides damage levels to typical public receptors related to thermal flux. Exposure to thermal radiation requires line-of-sight to the source; therefore, exposure can be shielded by an object between source and receptor. Table 5 presents the impacts to receptors that could be expected at different thermal radiation exposure levels. For reference, approximately 1.2 kW/m^2 is the incident radiation heat flux from the sun at zenith[11]. A simple flux threshold value of 12.5 kW/m^2 was used as the "endpoint" of the consequence analysis in this study.

[9] TNO 1997.
[10] Lees 2012.
[11] Haddad 1981.

Table 5: Impacts of Exposure to Thermal Radiation on Receptors	
Thermal Radiation (kW/m2)	**Impacts to Receptors**
10-12	Vegetation ignites
12.5	Piloted ignition of wood
25	Non-piloted ignition of wood
37.5	Damage to process equipment

Data compiled by the Department of Defense[12],[13] summarizes the effects of increasing blast pressure on various structures. This data originates from weapons tests and blast studies to assess the impact of blast overpressure. Table 6 presents the impacts on structures that could be expected at different resulting overpressure levels. For this analysis, the distance to the overpressure endpoint of 2 psi was calculated.

Table 6: Impacts of Overpressure on Receptors	
Overpressure (psi)	**Impact on Receptors**
1 psi	Window glass shatters
2 psi	Moderate damage to houses
3 psi	Residential structures collapse
5 psi	Most buildings collapse
10 psi	Reinforced concrete buildings are severely damaged or demolished
20 psi	Heavily built concrete buildings are severely damaged or demolished

[12] Glasstone and Dolan. 1977.
[13] Sartori 1983.

Modeling Results

Modeling results reported for each site include:

- Dispersion distances to lower flammability limits (LFL);
- Thermal radiation impact distances to structural damage levels from pool fires; and
- Explosion overpressures impact distances to structural damage from vapor cloud explosions (VCE).

The flammability range is delineated by the upper and lower flammability limits. Outside this range of air/vapor mixtures, the mixture cannot be ignited (unless the temperature and pressure are increased). The LFL, usually expressed in volume percentage, is the lower end of the concentration range over which a flammable mixture of gas or vapor in the air can be ignited at a given temperature and pressure. The LFL decreases with rising temperatures; therefore, a mixture that is below its LFL at a given temperature may be ignitable if heated sufficiently. The UFL is the maximum percentage of flammable gas or vapor in the air above which ignition cannot take place because the ratio of the gas to oxygen is too high. The upper and lower flammability limits are also known as the upper and lower explosive limits.

A pool fire that occurs early in the release process, as may happen when ignition sources such as sparking or engine heat are available at the beginning of the release, result in a fire of relatively small dimension compared with a fire that occurs late in the release process and has allowed the pool to spread and cover a large area.

In this study, late pool fires were reported due to their greater hazard distances. In the case of the late pool fire, liquid pool spreading was assumed to take place prior to ignition. The pool diameter was then equal to the maximum dimension attained in the spreading process.

Overpressure (or blast overpressure) is the pressure caused by a shock wave over and above normal atmospheric pressure. The shock wave may be caused by an explosion and the resulting overpressure receives particular attention when measuring impacts on buildings and structures.

Interpretation of Results

The footprint of a vapor cloud dispersion represents the curve that sweeps out beyond the maximum perimeter of all locations exposed to a concentration of interest during the entire dispersion process. It is not a footprint of an actual cloud at a given time. Figure 2 was taken from a Computational Fluid Dynamics simulation of natural gas dispersion showing the time-dependent nature of the cloud. It is clear in the figure that when the cloud reaches its maximum extent to the flammability limit, it becomes greatly reduced in mass, and therefore the quantity of fuel available for combustion is also reduced.

The hazard zones associated with dispersion, thermal radiation, and explosion overpressure are a rotation of the footprint and of the impact of dispersion or combustion. Therefore, the circular plots overlaid on the area maps are not a portrayal of the impact at a given time.

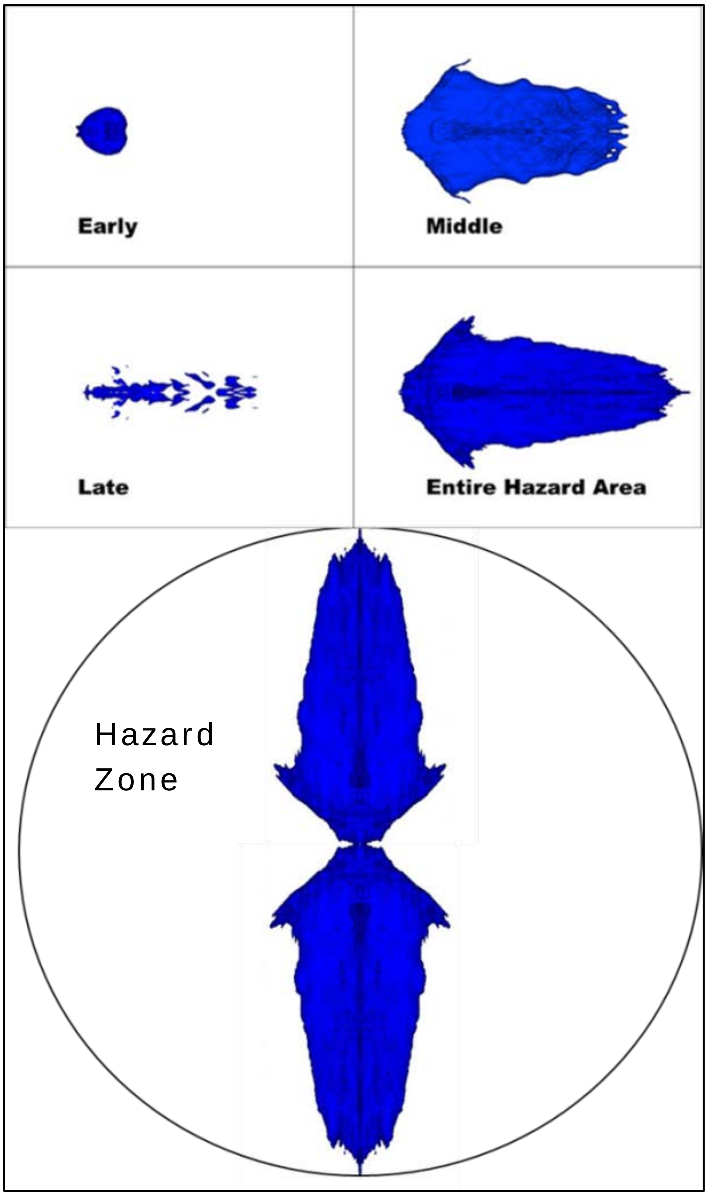

Figure 2: Time-Dependent Vapor Dispersion[14]

The following paragraphs present the results for the 5 scenarios, showing the hazard zones for dispersion, thermal radiation from fire and explosion overpressure from VCE. Each is a single scenario representation of a possible release and ignition scenario, but many more event/situations are possible. Therefore, these results are representative but not complete in the representation of risk.

In each figure (Figure 3 through Figure 7), the blue circle indicates the extent of the pool fire, the yellow ellipse indicates the dispersion of flammable vapor to half the flammability limit which is customary for reporting flammable hazard footprints, and the red circle indicates the explosion overpressure hazard zone.

[14] Blue area represents flammable region of vapor cloud.

Port of Albany

The worst-case hazard distances representative for the Port of Albany are shown in Figure 3. The dispersion of flammable vapor is shown in yellow, towards Albany center. The maximum extent of thermal radiation from a pool fire reaches 3.6 meters (12 feet) into the shoreline. The explosion overpressure hazard zone is shown in red. The red circle is located inland from the source of vapor approximately 2.6 km (1.6 miles). This explosion overpressure scenario results in exposure of many residential structures to damaging pressure levels – nearly 500 acres of developed land.

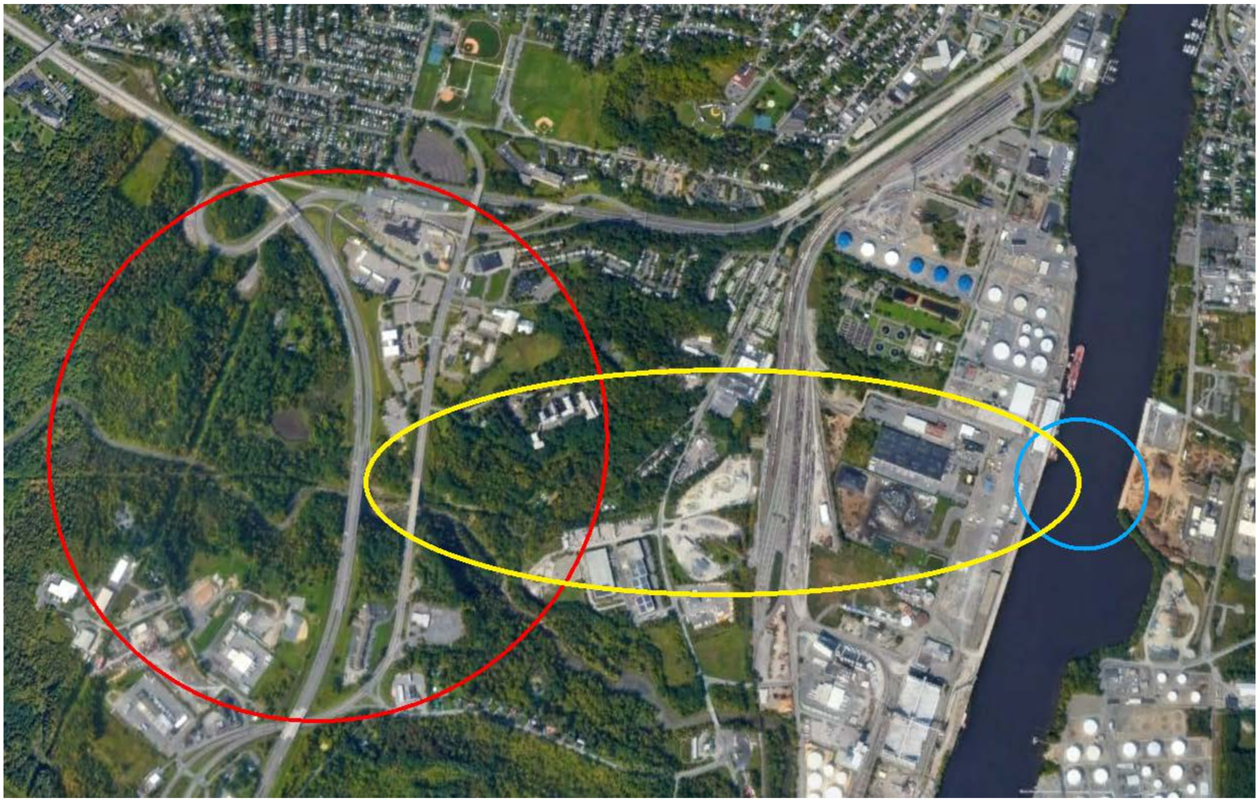

Figure 3: Port of Albany Worst-Case Hazard Distances

The blue circle indicates the extent of the pool fire, the yellow ellipse indicates the dispersion of flammable vapor, and the red circle indicates the explosion overpressure hazard zone.

Off Rondout (ACP Scenario)

The worst-case hazard distances representative for ACP off Rondout are shown in Figure 4. The dispersion of flammable vapor is shown in yellow, in the direction of Kingston Center.

The maximum extent of thermal radiation from a pool fire on the river is shown in blue. In this scenario, the pool spreads to 350 meters (1,148 feet). The thermal radiation extends only 14 meters (46 feet) into the shoreline, and impacts less than one acre of shoreside land. The explosion overpressure hazard zone is shown in red. The red circle reaches inland from the source of vapor approximately 3.5 km (2.2 mile). This explosion overpressure scenario results in exposure of many residential structures to damaging pressure levels – more than 400 acres of developed land, including 155 acres of residential areas.

Figure 4: Rondout (ACP Scenario) Worst-Case Hazard Distances

The blue circle indicates the extent of the pool fire, the yellow ellipse indicates the dispersion of flammable vapor, and the red circle indicates the explosion overpressure hazard zone.

Newburgh Waterfront

The worst-case hazard distances representative for the Newburgh Waterfront are shown in Figure 5. The dispersion of flammable vapor is shown in yellow, in the direction of Newburgh Center. The maximum extent of thermal radiation from a pool fire on the river is shown in blue. In this scenario, the pool does not spread to the entire width of the river as the vaporization and combustion of vapors remove fuel at a faster rate than it can spread. The thermal radiation contour extends 12 meters (39 feet) into the shoreline impacting 0.2 acres of developed land. The explosion overpressure hazard zone is shown in red. The red circle is located inland from the source of vapor approximately 540 meters (1,770 feet or 0.33 mile). This explosion overpressure scenario results in exposure of 34 acres of developed land, including 22 acres of residential property.

Figure 5: Newburgh Waterfront Worst-Case Hazard Distances

The blue circle indicates the extent of the pool fire, the yellow ellipse indicates the dispersion of flammable vapor, and the red circle indicates the explosion overpressure hazard zone.

Iona Island

The worst-case hazard distances representative for Iona Island are shown in Figure 6. The dispersion of flammable vapor is shown in yellow, towards Bear Mountain State Park. The maximum extent of thermal radiation from a pool fire on the river is shown in blue. In this scenario, the pool does not spread to the entire width of the river as the vaporization and combustion of vapors remove fuel at a faster rate than it can spread and there are no impacted properties from exposure from the fire. The explosion overpressure hazard zone is shown in red. The red circle is located inland from the source of vapor approximately 1.3 km. (0.8 mile). This explosion overpressure scenario does not expose any properties due to the rural/state park usage of the land, however, public use implies potential exposure of the general public using the park, should an accidental fire or explosion occur.

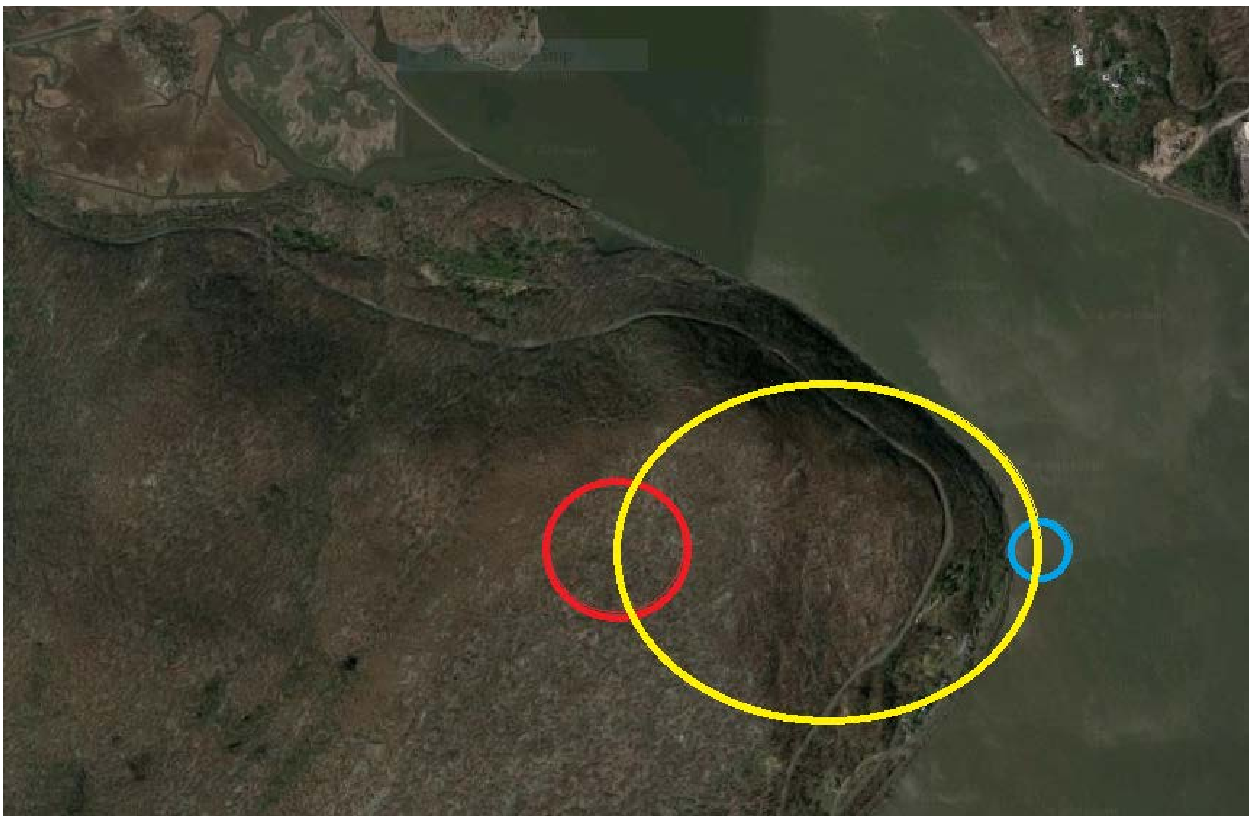

Figure 6: Iona Island Worst-Case Hazard Distances

The blue circle indicates the extent of the pool fire, the yellow ellipse indicates the dispersion of flammable vapor, and the red circle indicates the explosion overpressure hazard zone.

Yonkers Anchorage

The worst-case hazard distances representative for the Yonkers Anchorage scenario are shown in Figure 7. The dispersion of flammable vapor is shown in yellow, in the direction of development. The maximum extent of thermal radiation from a pool fire on the river is shown in blue. In this scenario, the pool does not spread to the entire width of the river as the vaporization and combustion of vapors remove fuel at a faster rate than it can spread. The thermal radiation contour extends 24 meters (79 feet) into the shoreline impacting 3.1 acres of developed land. The explosion overpressure hazard zone is shown in red. The red circle is located inland from the source of vapor approximately 1.3 km (0.8 mile). This explosion overpressure scenario results in exposure of many residential structures to damaging pressure levels – more than 100 acres of residential developed land.

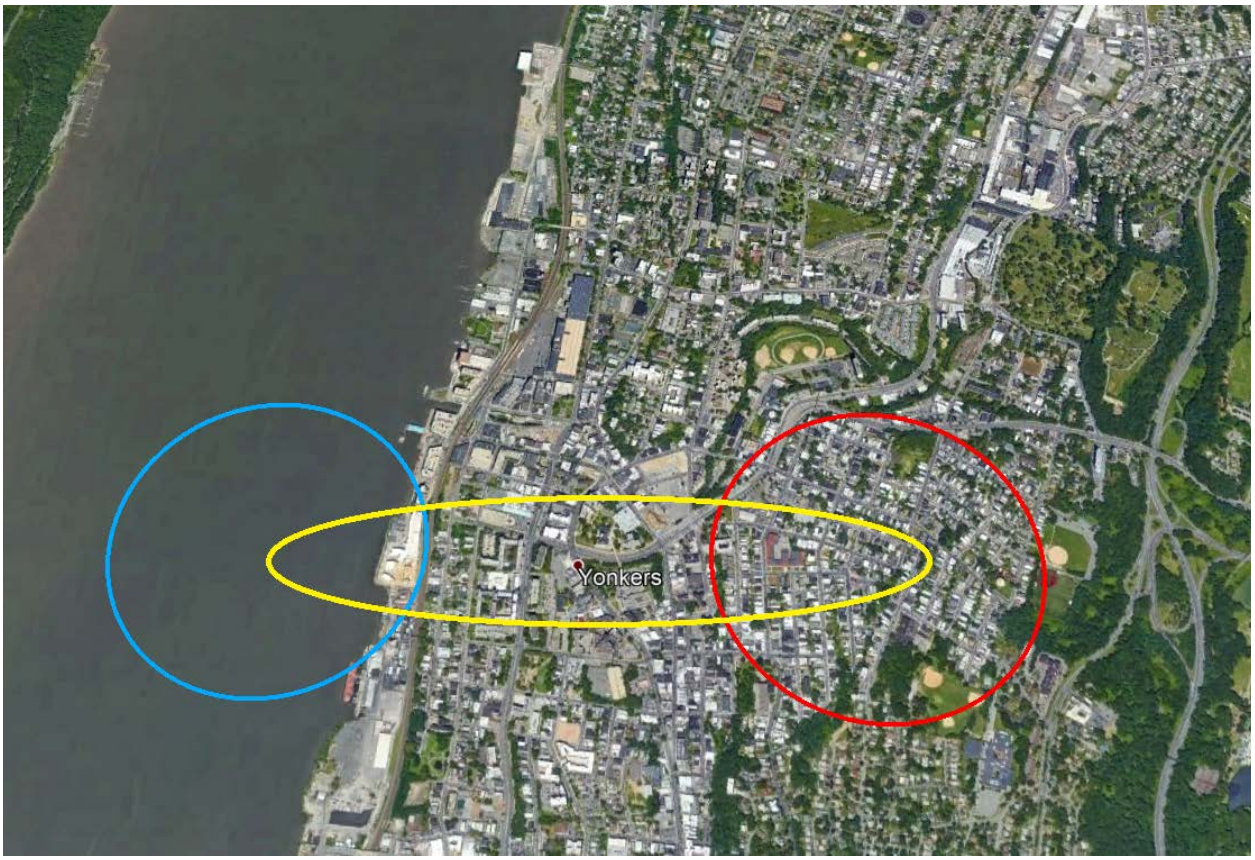

Figure 7: Yonkers Anchorage Worst-Case Hazard Distances

The blue circle indicates the extent of the pool fire, the yellow ellipse indicates the dispersion of flammable vapor, and the red circle indicates the explosion overpressure hazard zone.

Summary of Hazard Zones

The extents of the hazard zones for each scenario are presented in Table 7. These compile the distances to hazard limits and the land use areas impacted. Table 7 shows that the dispersion hazard distances range from 619 to 2,240 meters (2,031 to 7,349 feet, or 0.40 to 1.4 miles), thermal radiation hazard distances range from 104 to 448 meters (341 to 1,470 feet, or 0.06 to 0.3 miles), and explosion overpressure hazard distances range from 539 to 3,524 meters (1,770 to 11,562 feet, or 0.33 to 2.2 miles).

The extents of the impacted areas for each scenario are presented in Table 8. This shows that the predicted land areas impacted by thermal radiation hazards range from 3 to 21 acres, the major contributor being the Port of Albany, and explosion overpressure hazard distances range from 34 to 476 acres, the major contributor also being the Port of Albany, due to land development density. The entries marked with an asterisk *, indicate no impacts from this scenario impact land use areas of the indicated type (the hazard does not reach the target).

Table 7: Worst Case Maximum Hazard Distances

Source	Distance (Miles)	Downwind to Lower Flammability Limit	To 12.5 kW/m^2	To 2 psi Overpressure
	Effect	Possible Vapor Cloud Ignition	Piloted Ignition of Wood	Moderate Damage to Houses
Port of Albany				
Tanker Dock Accident 155,000 bbl Bakken Crude		0.98	0.12	1.65
Rondout				
Tank Barge Spill 75,421 bbl Bakken Crude		1.39	0.19	2.19
Newburgh Waterfront				
Crude-by-Rail Spill 11,000 bbl Bakken Crude		0.19	0.07	0.33
Iona Island				
Crude-by-Rail Spill 11,000 bbl Bakken Crude		0.51	0.06	0.84
Yonkers Anchorage				
Tanker Spill 155,000 bbl Gasoline		0.38	0.28	0.84

Table 8: Worst-Case Hazard Impacts

Location and Hazard Type		Downwind Distance	Impact (Acres)				
			Total	Residential	Commercial	Industrial	Public Use
Port of Albany	**Fire**	581 ft	0.3	0.1	0.1	0	0.1
	Explosion	1.66 miles	476	305	47	124	0
Rondout	**Fire**	581 ft	0.8	0	0	0.4	0.4
	Explosion	2.19 miles	418	155	134	50	79
Newburgh Waterfront	**Fire**	581 ft	0.2	0	0.1	0	0.1
	Explosion	0.33 mile	34	22	8	0	13
Iona Island	**Fire**	581 ft	0.2	0	0	0	0.2
	Explosion	0.84 mile	68	0	0	0	68
Yonkers Anchorage	**Fire**	1,473 ft	3.1	0	1.6	1.6	0
	Explosion	0.033 mile	166	103	27	8	27

Fires and Explosions Related to the Transport of Oil

With the actual or potential transport of more volatile, flammable petroleum, such as gasoline and Bakken crude, on or along the Hudson River, there is the possibility of fires and explosions. While the probability of such an incident in the HROSRA study area is very low, as described above, incidents that have occurred elsewhere in the US or the world have received a great deal of attention and heightened concerns. While the fact that these catastrophic incidents occurred does not alter the probability of such an incident occurring in the Hudson River, they do raise public awareness of the risks of the transport of flammable products.

Crude-by-Rail Accidents[15]

The July 2013 crude-by- rail (CBR) train accident in Lac-Mégantic, Quebec, that caused a fire and explosion resulting in 47 fatalities revealed the risks of CBR transport to the North American public (Figure 8). This incident was followed by several other accidents in the US and Canada that involved fires and/or explosions (Table 9).

Figure 8: Lac-Mégantic, Quebec Train Accident[16]

[15] For a more comprehensive discussion of CBR accidents refer to HROSRA Volume 3.
[16] Photo: Paul Chiasson/The Canadian Press

Table 9: Notable CBR US and Canadian Accidents with Fires during 2013–2016[17]		
CBR Incident	**Accident Date**	**Outcome Synopsis**
Calgary, Alberta	3 April 2013	• 7 tank cars derailed • 2 tank cars released oil • Fire (put out by local firefighters) • 640 bbl spilled
Lac-Mégantic, Quebec	5 July 2013	• 63 tank cars derailed • 37,719 bbl spilled • 47 fatalities • 2,000 people evacuated • Extensive damage to town
Gainford, Alberta	19 October 2013	• 9 propane cars derailed • 4 crude cars derailed • 3 propane cars burned • No crude burned • One home damaged
Aliceville, Alabama	7 November 2013	• 30 tank cars derailed • 12 tank cars burned • 10,846 bbl spilled • No injuries • Fire • Wetland impact
Casselton, North Dakota	30 December 2013	• Collision • 20 crude cars derailed • Explosion/fire • > 9,524 bbl spilled • 1,400 residents evacuated • No injuries
Mount Carbon, West Virginia	16 February 2015	• 27 tank cars derailed • 14 tank cars burned • 9,800 bbl spilled • Oil entered Kanawha River • Drinking water source for two counties affected
Gogama, Ontario	14 February 2015	• 35 tank cars derailed • 7 tank cars caught fire • 4,900 bbl spilled
Gogama, Ontario	7 March 2015	• 69 tank cars derailed • 7 tank cars caught fire • 4,709 bbl spilled
Mosier, Oregon	3 June 2016	• 11 tank cars derailed • Several cars burned • 1,000 bbl spilled • Some oil entered Columbia River

While there is currently little if any CBR transport through the Hudson River corridor, the possibility of future resumption of this traffic is considered in the HROSRA for future risk planning. Included in that

[17] Etkin et al. 2015.

analysis was the modeling of the two CBR scenarios with respect to probability (see HROSRA Volume 3), spill effects (see HROSRA Volume 4), and fire and explosion risk (here in HROSRA Volume 5).

Tanker Accidents[18]

The transport of gasoline by tank vessel is currently occurring in the Hudson River and the transport of Bakken crude may resume in the future.[19] (There is also the possibility of a fire or explosion with the transport and handling of other types of oils, including home heating oil, but this is less likely than with more volatile products). This potential is the impetus behind the inclusion of three tank vessel fire/explosion scenarios in the HROSRA.

A prime example of a major tanker fire is the September 1990 incident involving the tanker Jupiter in the Saginaw River near Bay City, Michigan (Figure 9)[20]

Figure 9: Tanker Jupiter Spill and Fire in Saginaw River[21]

This incident occurred during offloading operations at a terminal. The tanker's transfer hose, grounding cable, and several of its mooring lines were parted due to the wake of a passing bulk carrier. In the fire and explosion, more than a dozen crew members were injured and one man drowned while trying to swim for safety.

Another more recent example is the explosion of the tanker Sanchi after it collided with a cargo ship in the East China Sea off the coast of Shanghai, China in January 2018. In this case, the tanker was carrying a cargo of 952,000 bbl of light crude condensate.

[18] For a discussion of fires in tanker spills, see HROSRA Volume 6.
[19] For information on tank vessel traffic in the Hudson River, see HROSRA Volume 3.
[20] For a more detailed discussion of the Jupiter incident, see HROSRA Volume 6.
[21] Source: Bay City Times.

Figure 10: Tanker Sanchi Explosion in January 2018[22]

[22] Source: IRNA

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Appendix A: Consequence Summary Reports

The complete output for the PHAST modeled scenarios is provided in HROSRA Volume 5-Appendix A [a separate volume of 107 pages.]