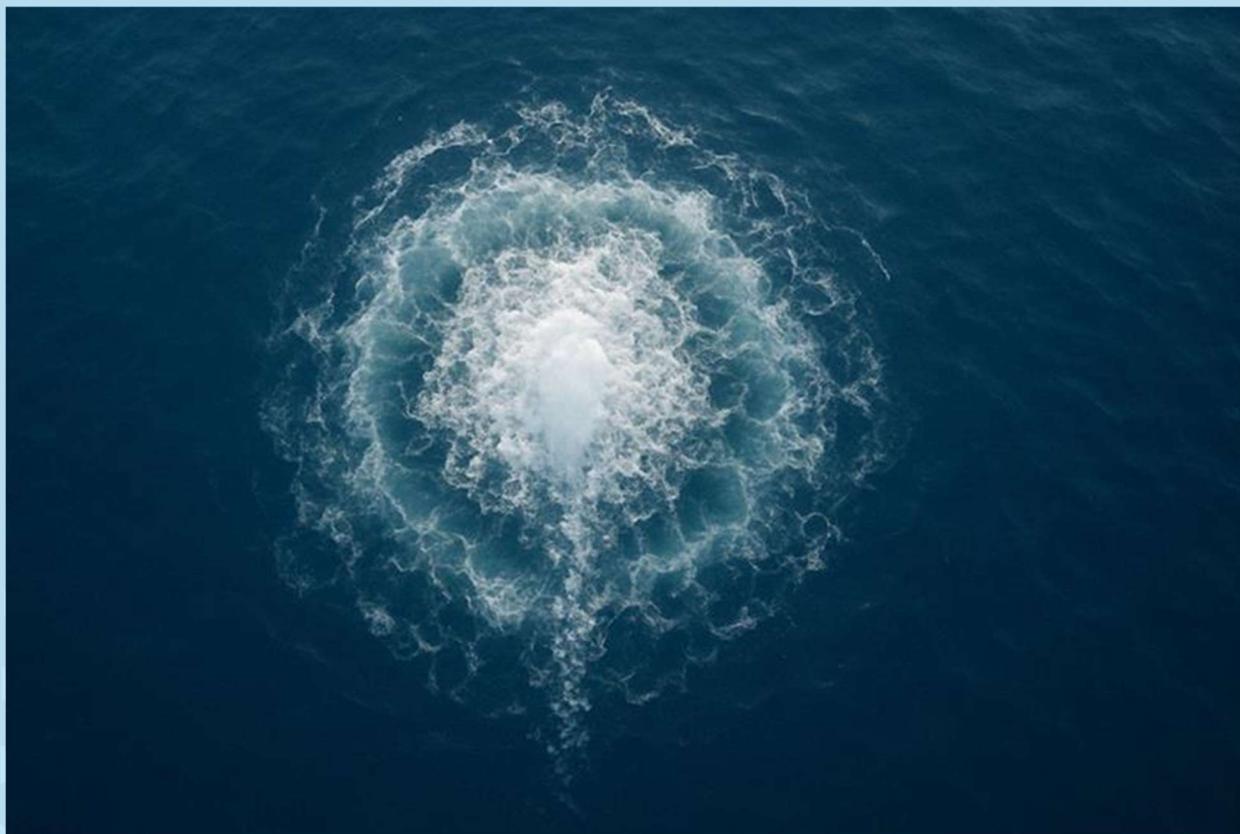


BOEM 2025-003

Pipeline Gas Release Impacts, Frequency, and Scenario Estimates for the Alaska Outer Continental Shelf

June 2025



Publication Information

| | |
|-------------------------------------|---|
| Title | Pipeline Gas Release Impacts, Frequency, and Scenario Estimates for the Alaska Outer Continental Shelf |
| Publication Date | June 2025 |
| Authors | Benjamin Roberts, Chris Culvern, Garrett Devol, Matthew Hubbard |
| Agreement or Contract Number | 140M0123P0010 |
| Prepared by | ABSG Consulting Inc. 1701 City Plaza Dr Spring, TX 77389 |
| Published by | U.S. Department of the Interior Bureau of Ocean Energy Management Anchorage, AK  |
| Citation | Roberts B, Culvern C, Devol G, Hubbard M (ABSG Consulting, Spring, TX). 2025. Pipeline gas release impacts, frequency, and scenario estimates for the Alaska Outer Continental Shelf. Anchorage (AK): U.S. Department of the Interior, Bureau of Ocean Energy Management. 185 p. Report No.: OCS Study BOEM 2025-003. Contract No.: 140M0123P0010. |
| Report Availability | Download a PDF file of this report at https://epis.boem.gov/Final%20Reports/BOEM_2025-003.pdf . Visit BOEM's website to search other studies funded by BOEM's Environmental Studies Program. |
| Disclaimer | Study concept, oversight, and funding were provided by the U.S. Department of the Interior, Bureau of Ocean Energy Management (BOEM), Environmental Studies Program, Washington, DC, under Contract Number 140M0123P0010. This report has been technically reviewed by BOEM, and it has been approved for publication. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the opinions or policies of BOEM, nor does mention of trade names or commercial products constitute endorsement or recommendation for use. |
| Funding by Fiscal Year | FY 2023: \$200,566.84 |
| Cumulative Project Funding | \$200,566.84 |
| Keywords | Alaska, environmental impacts, hazards, natural gas, outer continental shelf, pipeline, release scenarios, resources, risk assessment, socioeconomic impacts |
| About the Cover | Image of a subsea natural gas release. Source: ABSG Consulting Inc. |

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Acknowledgments

We extend our sincere gratitude to our colleagues at ABSG Consulting Inc. who made invaluable contributions to this research. Their collective expertise and dedication were instrumental to the successful completion of this project.

Technical Summary

Abstract

This report evaluates the threats, vulnerabilities, and risks associated with potential natural gas pipeline releases in the Alaska Outer Continental Shelf (OCS). Through literature review and analysis of historical natural gas pipeline release data from the Gulf of America and Pacific OCS regions, the study examines how traditional pipeline risks intersect with unique Alaska environmental conditions. The research synthesizes technical information on release frequency, spatial and temporal patterns, and consequences of natural gas pipeline releases, with particular focus on fire, explosion, and toxic gas exposure hazards. Analysis of Pipeline and Hazardous Materials Safety Administration (PHMSA) data reveals that while equipment failure and corrosion remain primary causes of releases, Alaska-specific factors like low temperatures, ice forces, and permafrost thaw create additional failure mechanisms. These include weather patterns, low temperature effects on materials and human performance, ice-related hazards, and unique seabed deformation processes. The research evaluates potential impacts across resource categories, ranging from physical resources like air and water quality to biological resources and sociocultural and socioeconomic considerations. The findings indicate that while some Gulf-based risk factors decrease in relevance for Alaska operations, different challenges emerge that require specialized design approaches and operational protocols. To quantify these risks, the study employs two complementary modeling approaches. These models are integrated with a qualitative assessment framework evaluating impacts across 12 resource categories ranging from physical and biological resources to sociocultural and socioeconomic considerations.

Background

The Bureau of Ocean Energy Management (BOEM) uses comprehensive technical information about natural gas pipeline releases to assess environmental impacts of offshore energy activities, as mandated by the Outer Continental Shelf Lands Act. Events like the Cook Inlet natural gas pipeline release in Alaska have increased public interest in understanding potential impacts to marine and coastal environments. BOEM faces challenges in analyzing natural gas releases because of dispersed information. Consolidated data on release hazards, release frequencies, and quantitative modeling results are needed to develop refined environmental assessments. Public comments have revealed concerns about natural gas impacts on endangered species, critical habitats, subsistence activities, commercial fishing, and climate change. These comments highlight the need for comprehensive risk assessment considering both environmental and socioeconomic factors.

This study created an authoritative reference synthesizing technical information about natural gas pipeline releases relevant to OCS development. By consolidating historical data, modeling results, and impact assessments, this information will enable BOEM to better evaluate and communicate potential environmental impacts while addressing public concerns about OCS development activities.

Objectives

Synthesize technical information on the frequency, volume, spatial and temporal footprint of the hazard, modeling, and consequences of historical U.S. natural gas pipeline releases. Estimate the frequency of

occurrence of U.S. onshore, offshore, and offshore OCS natural gas pipeline releases using relevant historical information from PHMSA and BSEE. Estimate the frequency of occurrence of onshore and offshore pipeline gas releases resulting in ignition, fire, and explosion, including specific estimates for the Alaska North Slope and Cook Inlet region, with discussion of causal or differentiating factors. Utilize typical pipeline release scenarios and modeling systems to quantify the spatial and temporal footprint of natural gas hazards through behavior, dispersion, ignition, fire, and explosion modeling.

Methods

The study employs two independent methodological approaches to evaluate natural gas pipeline releases in the Alaska OCS, combining quantitative modeling with qualitative impact assessment. The quantitative component centers on computational modeling using the MMS Pipeline Gas Release Computer Model (WCDgas) for simulating subsea releases, and a Gaussian plume model. These models track gas behavior from the initial pipeline breach through water column rise and atmospheric dispersion, generating specific predictions about release volumes, rates, and plume characteristics.

The qualitative framework focuses on environmental and social impact assessment across 12 resource categories, using a seven-point scale from negligible to major effects. This systematic evaluation considers geographical location, seasonal patterns, and resource vulnerability to provide a broader understanding of potential consequences. The study selected 100 representative Gulf pipeline segments to provide realistic operational parameters, including pipeline diameters, flow rates, operating pressures, emergency shutdown times, and gas compositions. These segments were then adapted for Alaska conditions while maintaining their core operational characteristics. The adaptation process involved modifying water depths to match Beaufort Sea and Cook Inlet bathymetry and adjusting ambient water temperatures to reflect Alaska conditions. Pipeline diameters were selectively adjusted to align with historical Alaska OCS infrastructure specifications, though these adjustments were minimized to maintain operational validity.

WCDgas simulations were then run on each adapted segment to generate Arctic-specific predictions for release volumes, durations, plume characteristics, and surface expression parameters. Then the Gaussian plume model, utilizing the Briggs rural dispersion coefficients, was employed to estimate how methane gas spreads through the atmosphere after underwater release. This approach maintains operational reality while accounting for the unique physical conditions of the Arctic environment, resulting in a more accurate prediction of potential Arctic release volumes compared to simple scaling of historical Gulf data.

Results

Scenario One: Simulations of a single pipeline showed larger holes (2–6 inches) caused significantly higher release volumes, especially with longer close-in times. Release volumes decreased with distance from the endpoint, with air quality showing the highest impact (minor risk). Most resources fell within negligible risk levels.

Scenario Two: A complex pipeline network revealed that topology influenced release dynamics, with larger breaches near junctions causing higher volumes. Risk scores were generally lower than Scenario One,

with air quality and subsistence activities showing notable reductions. Most resources remained in the negligible risk category.

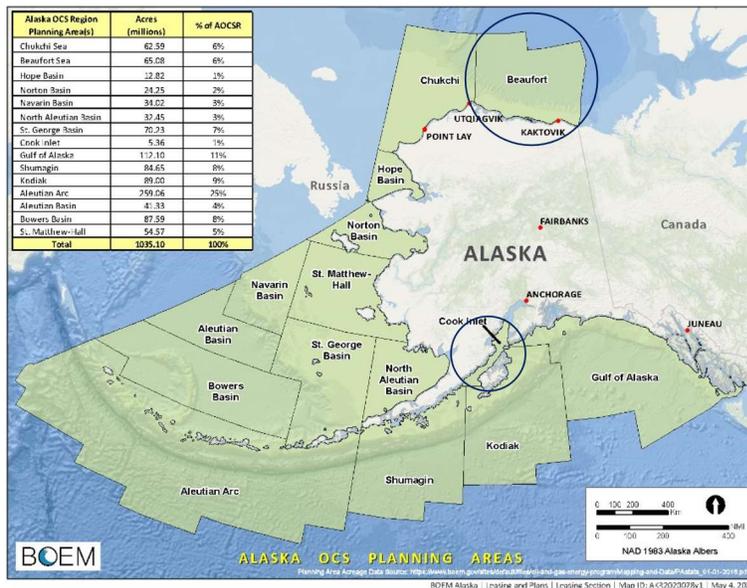
Conclusions

Pipeline hole size and close-in time significantly affect release volumes, particularly in complex networks. Alaska-specific conditions, such as ice forces and permafrost thaw, introduce unique challenges. Limitations include sparse Alaska-specific data and reliance on Gulf-based models. Future research should focus on improving detection, modeling, and understanding of natural gas impacts in Alaska, while considering climate change effects on pipeline integrity. Despite these gaps, the study provides critical insights for managing risks in the Alaska OCS.

Study Products

BOEM study report: Roberts B, Culvern C, Devol G, Hubbard M (ABSG Consulting, Spring, TX). 2025. Pipeline gas release impacts, frequency, and scenario estimates for the Alaska Outer Continental Shelf. Anchorage (AK): U.S. Department of the Interior, Bureau of Ocean Energy Management. 185 p. Report No.: OCS Study BOEM 2025-003. Contract No.: 140M0123P0010.

Map of Study Area



Map of Cook Inlet and Beaufort Sea

Image courtesy of BOEM Alaska (2020)

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List of Abbreviations and Acronyms

| | |
|------------------|---|
| ACGIH | American Conference of Governmental Industrial Hygienists |
| AIS | Automatic Identification System |
| API | American Petroleum Institute |
| ASTM | American Society for Testing and Materials |
| BOEM | Bureau of Ocean Energy Management |
| BS | Baker-Strehlow |
| BSEE | Bureau of Safety and Environmental Enforcement |
| BTEX | Benzene, Toluene, Ethylbenzene, Xylenes |
| CARB | California Air Resources Board |
| CC | Continuity Correction |
| CFD | Computational Fluid Dynamics |
| C.F.R. | Code of Federal Regulations |
| CINGSA | Cook Inlet Natural Gas Storage Alaska |
| DOI | Department of the Interior |
| DOT | Department of Transportation |
| EGIG | European Gas Pipeline Incident Data Group |
| EIS | Environmental Impact Statements |
| EPA | Environmental Protection Agency |
| ERW | Electric Resistance Welding |
| FR | Federal Register |
| H ₂ S | Hydrogen Sulfide |
| HAPs | Hazardous Air Pollutants |
| HDB | Hydrostatic Design Basis |
| HSE | Health and Safety Executive |
| IARC | International Agency for Research on Cancer |
| IDLH | Immediately Dangerous to Life and Health |
| LEL | Lower Explosive Limit |
| LES | Large Eddy Simulation |
| LFL | Lower Flammability Limit |
| LNG | Liquefied Natural Gas |
| MAOP | Maximum Allowable Operating Pressure |
| MCF | Thousand Cubic Feet |
| MDA | Malondialdehyde |
| ME | Multiple-Energy |
| MEM | Multi-Energy Method |
| MMS | Minerals Management Service |
| MOAP | Maximum Allowable Operating Pressure |
| MPa | megapascal |
| NACE | National Association of Corrosion Engineers |
| NASA | National Aeronautics and Space Administration |
| NFPA | National Fire Protection Association |

| | |
|-----------------|--|
| NGLs | Natural Gas Liquids |
| NHPA | National Historic Preservation Act of 1966 |
| NIOSH | National Institute for Occupational Safety and Health |
| mM | nanomolar |
| NO ₂ | Nitrogen Dioxide |
| NOAA | National Oceanic and Atmospheric Administration |
| NTP | National Toxicology Program |
| NTSB | National Transportation Safety Board |
| OCD | Offshore and Coastal Dispersion |
| OCS | Outer Continental Shelf |
| OCSLA | Outer Continental Shelf Lands Act |
| OSHA | Occupational Safety and Health Administration |
| PAEs | Phthalates |
| PE | Polyethylene |
| PEL | Permissible Exposure Limits |
| PHMSA | Pipeline and Hazardous Materials Safety Administration |
| PIR | Potential Impact Radius |
| PM | Particle Matter |
| PODS | Pipeline Open Database Standard |
| SCH | Schedule |
| SD | Sprague-Dawley (rats) |
| TAPS | Trans-Alaska Pipeline System |
| TEG | Triethylene Glycol |
| TLV | Threshold Limit Value |
| TNO | Dutch Organisation for Applied Scientific Research |
| TNT | Trinitrotoluene |
| TWA | Time-Weighted Average |
| UFL | Upper Flammability Limit |
| USACE | U.S. Army Corps of Engineers |
| USC | U.S Code |
| USCG | U.S. Coast Guard |
| USCGNRC | U.S. Coast Guard National Response Center |
| VCE | Vapor Cloud Explosion |
| VOCs | Volatile Organic Compounds |
| WCD | Worst Case Discharge |
| WCDgas | MMS WCD Pipeline Gas Release Computer Model |

1 Introduction

The Bureau of Ocean Energy Management (BOEM), under its mandate from the Outer Continental Shelf Lands Act (OCSLA), codified at 43 U.S.C. § 1331–1356b, requires comprehensive technical information about natural gas pipeline releases (hereafter releases) to effectively assess environmental impacts of offshore energy activities. The implementing regulations for pipeline operations on the Outer Continental Shelf (OCS) are primarily found in 30 C.F.R. § 250, administered by the Bureau of Safety and Environmental Enforcement (BSEE), and various parts of 30 C.F.R. Chapter II. Regulatory oversight of pipelines falls primarily to Pipeline and Hazardous Materials Safety Administration (PHMSA). According to 49 C.F.R. § 192.1(a), PHMSA maintains regulatory authority over the minimum safety standards for all pipeline facilities and gas transportation, including gathering pipelines within the outer continental shelf as defined by the Outer Continental Shelf Lands Act, though certain exceptions to this authority exist.

Natural gas pipeline transport operations and their associated risks (defined here as the probability of hazardous events multiplied by their potential environmental and safety consequences) require ongoing assessment, as demonstrated by incidents such as the Cook Inlet release in Alaska. Such events have prompted increased public interest in understanding potential impacts to marine and coastal environments in the Alaskan OCS (**Figure 1**). The Alaska OCS is the federally managed submerged land extending from 3 to approximately 200 nautical miles off Alaska's coast, divided into planning areas for leasing including the Beaufort Sea, Chukchi Sea, Cook Inlet, and Gulf of Alaska regions designated for potential exploration, development, and production of energy resources, primarily oil and natural gas.

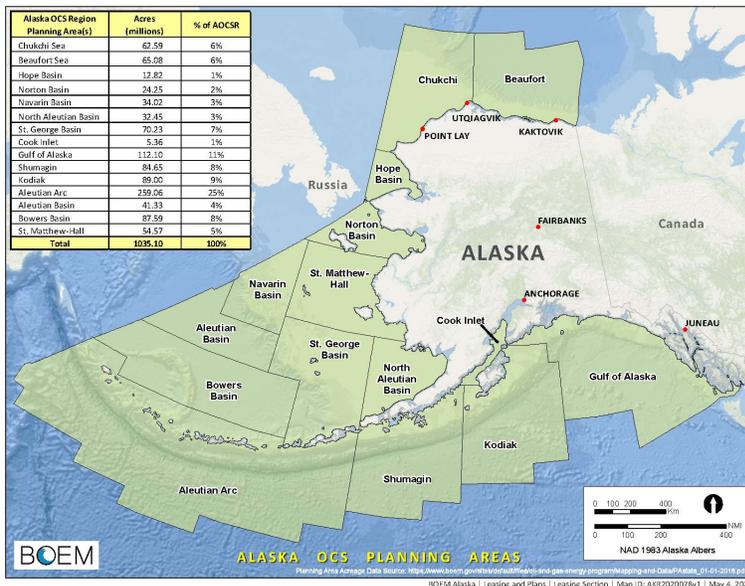


Figure 1 Alaska OCS planning areas

Courtesy of BOEM Alaska (2020)

BOEM currently faces challenges analyzing potential impacts of natural gas releases because of dispersed and incomplete information. Consolidated data on release hazards, release frequencies, and quantitative modeling results are needed to develop refined environmental assessments. This information is used for

two types of Environmental Impact Statements (EIS) across all OCS regions (Gulf of America, Atlantic, Pacific, and Alaska): those concerning OCS oil and gas leasing, and those addressing development and production activities. During any proposed action concerning offshore energy activities, the public is given the opportunity to review and comment on potential impacts. Public review and comment periods during the EIS process have revealed concerns about potential impacts on endangered species, effects on critical habitats and protected areas, threats to subsistence fishing and hunting affecting food security, impacts on commercial and sport fishing operations, environmental consequences of potential releases, and the contribution of natural gas activities to global climate change (BOEM 2022). These public comments highlight the need for comprehensive risk assessment that considers both environmental and socioeconomic factors.

When developing environmental assessments, BOEM draws from multiple data sources, including Pipeline and Hazardous Materials Safety Administration (PHMSA) records and BSEE reports. The agency also utilizes Exploration and Development scenarios and Development and Production Plans. Development and Production Plans provide specific details about pipeline parameters such as diameter, length, location, and annual gas volume. However, the current fragmented nature of this information makes it difficult to generate thorough release scenarios that account for hazard areas, dispersion patterns, and potential fire or explosion impacts.

This study aims to create an authoritative reference that synthesizes technical information about releases specifically relevant to Alaska OCS development. This report will serve as a foundation for BOEM's environmental analyses, supporting more informed decision-making processes for lease sales and development or production proposals. By consolidating historical data, modeling results, and impact assessments, this work will enable BOEM to better evaluate and communicate potential environmental risks to stakeholders and the public.

By creating a centralized repository of technical information about releases, BOEM will be better equipped to evaluate and communicate potential environmental risks while addressing public concerns about Alaska OCS development activities. This integrated approach ensures that both technical requirements and stakeholder interests are properly considered in the environmental assessment process, supporting more effective environmental protection measures and informed decision-making for offshore energy development.

1.1 Objectives

This report synthesizes literature from diverse sources to establish a foundation for understanding natural gas production processes, physical properties of potential hazards, hazards impacts on resources, historical release frequency, and risk assessment methodologies. This information supports the development of a tailored model for creating a raw risk index for typical pipeline release scenarios. The findings from this synthesis and the developed model inform assessments for both leasing and development & production plans, identifying resource impacts that may require additional mitigation measures.

The objectives of this study are to:

-
1. Synthesize technical information on the frequency, volume, spatial and temporal footprint of the hazard, modeling, and consequences of historical U.S. natural gas pipeline releases.
 2. Estimate the frequency of occurrence of U.S. onshore, offshore, and offshore OCS natural gas pipeline releases using relevant historical information from PHMSA and BSEE.
 3. Estimate the frequency of occurrence of onshore and offshore pipeline gas releases resulting in ignition, fire, and explosion, including specific estimates for the Alaska North Slope and Cook Inlet region, with discussion of causal or differentiating factors.
 4. Utilize typical pipeline release scenarios and modeling systems to quantify the spatial and temporal footprint of natural gas hazards through behavior, dispersion, ignition, fire, and explosion modeling.

1.2 Scope

This report focuses on impacts of accidental releases from transmission lines on biological and socioeconomic resources within the Alaska OCS during the leasing and development & production phases. Given that this report focuses on pipeline releases, activities that occur during the exploration phase are not considered because pipelines are not utilized during exploration. In addition, releases that occur in distribution lines or within underground storage are not considered. Distribution lines are typically found onshore or closer to end-users rather than in the offshore OCS areas. Furthermore, releases from offshore transmission lines would affect marine ecosystems directly, while distribution line or underground storage releases would have different environmental pathways and impacts.

Natural gas emissions' impact on greenhouse gases is well documented, but it is difficult to sufficiently connect documented wide-ranging impacts to specific localized resources. Therefore, greenhouse gas emissions are not addressed in this report because it focuses on natural gas' impact to specific localized resources.

Unconventional gas development, such as hydraulic fracturing (whether offshore or onshore), is excluded from this report because it involves fundamentally different contamination mechanisms compared to pipeline transmission releases in the OCS. While the releases addressed in this study primarily involve natural gas, hydraulic fracturing involves complex chemical mixtures from fracking fluids and flowback water concentrated around well sites. These operations typically occur during the exploration and initial development phases, before transmission pipelines are established. The different exposure pathways, chemical compositions, and environmental impacts of fracking operations make them distinct from the releases from established transmission lines that are the focus of this report's assessment of impacts on specific localized biological and socioeconomic resources within the Alaska OCS.

2 Technical Information Synthesis

This technical information synthesis consolidates the body of knowledge pertaining to historical natural gas pipeline releases in the United States, with emphasis on associated hazards, mathematical models, and impacts on resources. The review encompasses diverse scholarly and technical sources, including government agency technical reports, peer-reviewed scientific journal articles, conference proceedings, academic books, industry data sheets, and regulations. Particular attention was devoted to identifying

information relevant to Alaska's unique context, addressing regional-specific considerations within the broader analytical framework.

The comprehensive review establishes a structured framework to examine the research problem through systematic organization and analysis of relevant knowledge. As a foundational component, it consolidates historical and contemporary understanding of natural gas release modeling and associated resource risks while identifying information needs requiring further investigation. The methodology employed a multi-tiered search strategy, prioritizing peer-reviewed literature, regulatory frameworks, and government technical reports directly related to releases within the Alaska OCS. Where pipeline-specific information was insufficient, the review expanded to include analogous environments such as landfill emissions and mining operations where natural gas hazards present comparable concerns.

All relevant sources were compiled into an annotated bibliography and managed using EndNote 21 to facilitate citation organization and cross-referencing throughout the analysis. The database included searchable abstracts, keywords, and tags to enhance information retrieval, with PDF documents attached when available for verification and consultation.

2.1 Natural Gas Properties

Natural gas is a complex hydrocarbon mixture primarily composed of methane. Methane comprises 70–90%, of the total composition with the remainder consisting of varying proportions of ethane, propane, butane, carbon dioxide, nitrogen, hydrogen sulfide, and trace amounts of other compounds. The composition varies widely depending on the source of natural gas, with notable differences occurring even between two wells producing from the same reservoir. Natural gas primarily consists of smaller, lighter hydrocarbons, particularly methane, which exist naturally in the gaseous state at atmospheric pressure due to their low molecular weight. In contrast, crude oil contains larger, heavier hydrocarbon molecules with more carbon atoms in their chains. This molecular mass difference is a key factor that determines whether organic matter becomes natural gas or oil during the formation process (Gold 1985).

Natural gas varies in composition and toxicity depending on its source, processing stage, and intended use, with several distinct classifications that present different hazards. Raw gas, which refers to natural gas directly extracted from wells before any significant processing or treatment, contains numerous impurities. These include both non-hydrocarbon contaminants such as hydrogen sulfide (H₂S), carbon dioxide, nitrogen, helium, and mercury, as well as heavier hydrocarbon components. These heavier hydrocarbon are primarily ethane, propane, butane, pentane, and hexane, with the latter two typically separated out as liquids during processing (Younger 2004). Many of these compounds present in unprocessed natural gas fall under the realm of volatile organic compounds (VOCs). VOCs are a large group of carbon-containing chemicals that are present in the raw natural gas mixture and can be released during extraction, processing, transportation, and storage activities. These compounds may also include various hydrocarbons such as benzene, toluene, ethylbenzene, xylenes (collectively known as BTEX), as well as other substances like formaldehyde and methanol. VOCs in higher concentrations are harmful to humans (McMullin et al. 2018). 40 C.F.R. § 51.100(s) states that VOCs are “any compound of carbon, excluding carbon monoxide, carbon dioxide, carbonic acid, metallic carbides or carbonates, and

ammonium carbonate, which participates in atmospheric photochemical reactions”. Some compounds with negligible photochemical reactivity such as methane or ethane are also excluded.

Natural gas comes in two main categories: wet and dry. According to the Gas Processors Suppliers Association (2004), wet gas contains more than 0.1 gallons of condensate per 1,000 cubic feet of gas, while anything below this threshold is considered dry gas. Dry gas, which consists of methane that has been processed to remove almost all heavier hydrocarbons and impurities, is almost entirely methane (typically 95–98%) with minimal heavier hydrocarbons. Dry gas needs minimal processing before distribution. Wet gas typically consists of less than 85% methane and contains increased amounts of ethane and other hydrocarbons. Wet gas contains higher proportions of heavier hydrocarbons like ethane, propane, butanes, and natural gas liquids (NGLs). These heavier components can have greater toxic effects than methane alone, particularly if inhaled in high concentrations. Wet gas requires extensive processing to remove heavier components such as ethane, propane, and butane, which can then be sold as individual products (Younger 2004). These variations in composition, dry gas and wet gas, each present considerations regarding processing requirements, flammability characteristics, toxicity profiles, and water solubility. Understanding these properties is important for understanding the consequences of natural gas pipeline releases.

Processed gas, which refers to natural gas that has undergone treatment to remove impurities and meet pipeline quality standards, is less toxic than raw gas as processing removes most harmful components. Natural gas pipeline transmission standards require minimum 75% methane content while limiting other hydrocarbons (ethane 10%, propane 5%, butanes 2%, pentanes+ 0.5%) (Kidnay and Parrish 2006). However, mercaptans (sulfur-containing compounds) are added during processing as odorants to help detect natural gas pipeline releases. Mercaptans are commonly added because it has a distinctive rotten egg smell that makes otherwise odorless gas readily detectable by humans at very low concentrations (Fang et al. 2019).

49 C.F.R. § 192.625 requires that combustible gases in distribution lines and certain transmission lines be odorized, commonly Mercaptan, or contain a natural odorant. Transmission lines must be odorized if they contain combustible gas and are located in Class 3 or Class 4 locations (typically more populated areas), with this requirement applying to lines after December 31, 1976. However, exemptions exist when at least 50% of the downstream pipeline length is in less populated areas (Class 1 or 2), when gas is transported to certain facilities that historically received unodorized gas before May 5, 1975, or when the gas is hydrogen intended for manufacturing. For lateral lines to distribution centers, odorization is not required if at least 50% of that line is in a Class 1 or 2 location. When odorization is required, transmission lines must follow the same standards for odorant properties and monitoring as other lines.

2.1.1 Flammability

Dry raw gas, wet raw gas, and processed natural gas have varying levels of flammability due to their composition. Dry raw gas consists primarily of methane and has the highest flammability due to its low moisture content and high concentration of light hydrocarbons. Wet raw gas contains heavier hydrocarbons (like ethane, propane, and butane) and some water vapor, which slightly reduces its flammability compared to dry raw gas. Processed natural gas, having undergone treatment to remove impurities and heavier hydrocarbons, has a more consistent composition and controlled flammability.

Similar to other fossil fuels, natural gas is very flammable. It can produce 38 megajoules of heat per every cubic meter or about 1050 British thermal units (Btus) per every cubic foot of gas (Riva et al. 2023). The flammable range is the concentration range of a gas or vapor in air within which a flame can be propagated if an ignition source is present. Outside this range, the mixture is either too lean or too rich to burn.

The flammability characteristics of natural gas greatly vary based on its composition, with important distinctions between dry raw gas, wet raw gas, and processed natural gas. Dry raw gas consists primarily of methane and has the highest flammability due to its low moisture content and high concentration of light hydrocarbons. Wet raw gas contains heavier hydrocarbons (like ethane, propane, and butane) and some water vapor, which slightly reduces its flammability compared to dry raw gas. Processed natural gas, having undergone treatment to remove impurities and heavier hydrocarbons, has a more consistent composition and controlled flammability. The flammability range, the concentration range within which a gas-air mixture can ignite when exposed to an ignition source, represents a physical property that determines combustion behavior. Understanding the specific lower and upper boundaries of this range is essential for designing safe handling procedures and prevention measures. This range is defined by specific lower and upper concentration boundaries that determine when natural gas-air mixtures will support combustion.

The Lower Flammability Limit (LFL) is the lowest concentration (percentage) of a gas or vapor in air capable of producing a flash of fire in the presence of an ignition source. At concentrations below the LFL, the mixture is too lean to burn. For methane (the primary component of natural gas), the LFL is typically around 5% by volume in air. This means that if the air contains less than 5% methane, the mixture won't ignite even with a spark or flame present (Liao et al. 2005).

The Upper Flammability Limit (UFL) is the highest concentration (percentage) of a gas or vapor in air capable of producing a flash of fire in the presence of an ignition source. Above this concentration, the mixture is too rich to burn. For methane, the UFL is typically around 15% by volume in air. If the air contains more than 15% methane, there's not enough oxygen for combustion to occur (Liao et al. 2005). For example, if we have a room filled with air and slowly add methane: at 0–4.9% methane the gas is not flammable as it is below the LFL. At 5–15% methane the gas is within the flammable range between the LFL and the UFL. Above 15% methane the gas is not flammable as it is above the UFL.

The range provided is a generalization. The flammable range is influenced by many factors. Silla et al. (2014) notes “the flammable limits depend on oxygen concentration, concentration of gases other than oxygen, the inert gas type and concentration, the size of the equipment, the direction of flame propagation, and the pressure, temperature, turbulence and composition of the mixture” (p.51). Li et al. (2019) found that both pressure and temperature had a substantial effect on the UFL, but the LFL was only marginally affected. This indicates that within special circumstances ignition may still occur. For a fire to occur, an ignition source, a spark or flame, must be present and the concentration of gas must be within the flammable range.

2.1.2 Toxicity

Natural gas pipeline releases can expose individuals to toxic substances including H₂S, NGLs, VOCs including BTEX, and odorizers such as Mercaptans. Methane, a simple asphyxiant, is the primary component of natural gas. VOCs are emitted from a diverse range of sources including industrial processes, vehicle emissions and consumer products in addition to natural gas development. The composition of VOCs from differing natural gas sources can be varied. Due to the vast number and variety of potential VOCs present in natural gas operations, a comprehensive analysis would be impractical; therefore, we have focused on common VOCs associated with NGLs such as BTEX compounds.

2.1.2.1 Methane

Methane's primary hazard is as a simple asphyxiant that can displace oxygen in confined spaces. Methane has no specific exposure limit as its main hazard is oxygen displacement. An exposure limit is a regulatory guideline or standard that establishes the maximum concentration of a substance in workplace air that is considered safe for workers to be exposed to over a specified time period. When oxygen levels fall below 19.5% of air volume asphyxiation becomes a risk as noted in 29 C.F.R. § 1926.55. It is classified as a "Simple Asphyxiant" in the Permissible Exposure Limits for Airborne Contaminants table of 29 C.F.R. § 1926.55. The severity of danger increases proportionally with higher gas concentrations: when gas comprises 25–30% of the air volume, individuals may experience symptoms such as ringing ears, euphoria, and behavioral changes. At 50% gas concentration, exposure of just a few breaths can lead to incapacitation, while a 75% gas concentration causes immediate incapacitation and death within minutes (Pinedale Natural Gas 2024). The presence of gas can typically be detected by odor at approximately 1% concentration in air, which is about one-fifth of the Lower Explosive Limit (LEL). In confined spaces, gases form distinct layers based on their density, with lighter gases like methane accumulating near the ceiling and heavier gases settling near the floor. This layering effect necessitates comprehensive sampling at multiple levels within the space to accurately assess risk levels, as concentrations can vary at different heights (Edwin G. Foulke 2024). Given that conditions can change rapidly, especially during work activities, continuous monitoring is essential for maintaining safety in confined spaces where natural gas may be present.

When another gas is introduced into an enclosed space, the oxygen concentration decreases proportionally. This follows the principle of volumetric displacement.

The equation can be expressed as:

$$O_2\% = 20.9\% \times (1 - C_g)$$

Equation 1. Volumetric Displacement

Where:

- $O_2\%$ is the resulting oxygen concentration percentage
- 20.9% is the normal oxygen concentration in air
- C_g is the concentration of the displacing gas expressed as a decimal

The equation for Volumetric Displacement (**Equation 1**) is important for safety assessments as it allows one to determine if the oxygen level will fall below the critical 19.5% threshold. The equation can be rearranged to determine the maximum allowable gas concentration that would maintain safe oxygen levels:

$$C_g = 1 - \frac{19.5\%}{20.9\%} = 0.067$$

Equation 2. Maximum Allowable Gas Concentration to Maintain Safe Oxygen Levels

The equation for maximum allowable gas concentration to maintain safe oxygen levels (**Equation 2**) indicates that a gas concentration of approximately 6.7% would result in the minimum safe oxygen level of 19.5%. Any gas concentration above this would create an oxygen-deficient atmosphere (Bugbee and Blonquist 2006).

2.1.2.2 Hydrogen Sulfide (H₂S)

H₂S is a highly toxic, colorless, and flammable gas that can have toxic effects even at relatively low concentrations. H₂S presents risk with an Immediately Dangerous to Life and Health (IDLH) level of 100 parts per million (ppm), becoming fatal at 500–1000 ppm and causing immediate collapse above 1000 ppm (Malone Rubright et al. 2017). Occupational Safety and Health Administration (OSHA) sets ceiling limit of 20 ppm for H₂S within Table Z-2 of 29 C.F.R. § 1910.1000. While, National Institute for Occupational Safety and Health (NIOSH) recommends a lower 10 ppm ceiling for 10-minute exposures (NIOSH 2007). Jianwen et al. (2011) found that hydrogen sulfide concentrations as low as 291 ppm could cause fatalities, with death rates increasing dramatically at higher concentrations.

H₂S is largely only a concern in gathering pipelines before the gas is processed and impurities like H₂S are removed. The dangers of H₂S exposure as the result of a natural gas pipeline release are largely limited to the immediate areas surrounding the pipelines from the platform to the short shoreline sections. Jianwen et al. (2011) found the severity of H₂S risks depends on the size of the pipeline breach. The study analyzed three scenarios with different hole diameters (60 millimeters (mm), 600 mm, and 1200 mm) and found that larger breaches create more extensive hazard zones. Even with a relatively small 60 mm hole, the gas release can create dangerous concentrations of H₂S near the ground level. With larger breaches, the hazard zones expand dramatically, the 1200 mm rupture scenario created hazardous areas extending several kilometers from the release point. The paper's analysis of the Gaussian plume dispersion model shows that weather conditions and release height affect H₂S dispersion. Since H₂S is heavier than air, it tends to accumulate in low-lying areas, creating potentially lethal concentrations. Population density near pipelines is an important factor as Jianwen et al. (2011) examined a case with 403 persons/square kilometer (km²) and found that even moderate-sized releases could potentially affect hundreds of people. Individual risk levels exceeded acceptable thresholds according to Health and Safety Executive (HSE) criteria. External interference (like third-party damage) emerged as the leading cause of pipeline failures, accounting for 51% of incidents. The failure rates caused by external interference are influenced by pipeline depth, wall thickness, and prevention methods. Jianwen et al. note that incidents such as the 2003 Kai Xian accident where 243 people died and 65,000 were evacuated, demonstrate the potential magnitude of H₂S release events depending on population density. Some consideration are needed in

interpreting these findings. Jianwen et al. (2011) focused on China, noting that in the 1980's natural gas containing H₂S accounted for a quarter of total gas reserves. Conditions, operations, and regulations are likely to be quite different.

In some rare historical cases within the United States, H₂S-contaminated gas entered both transportation and distribution pipelines (54 FR 24361 1989). Proposed rules within Federal Register (FR), 54 FR 24361 concerning 49 C.F.R. § 192, Transportation of Hydrogen Sulfide by Pipeline, discusses incidents involving the release of H₂S into the gas pipeline system. In the December 1983 California incident, Southern California Gas Company's distribution system was contaminated with 200 ppm of H₂S, leading to evacuation notices for over 20,000 people. Similarly, in August 1987, the Lone Star Gas Company in Texas discovered H₂S concentrations of 1,600 ppm or greater in their system after automatic safety equipment failed, necessitating a complete system purge. The National Transportation Safety Board (NTSB) investigation revealed that Lone Star had experienced 11 incidents involving excessive H₂S releases into its pipeline system since 1977, indicating a recurring safety issue. While the document does not specifically mention injuries or fatalities from these incidents, the emergency responses, including mass evacuations, demonstrate that these were considered serious public safety threats given that H₂S at concentrations of 100 ppm can cause unconsciousness within minutes of exposure.

H₂S can compromise pipeline materials through multiple deterioration mechanisms. Sulfide stress cracking is particularly concerning, as its severity varies based on factors including pressure, steel composition, and exposure duration. While even low concentrations of H₂S can trigger cracking if present long enough, high concentrations above 3,000 ppm combined with high applied stress levels can cause rapid pipeline failure, potentially within hours to days depending on material properties and environmental conditions. Additionally, hydrogen-induced cracking can develop without any stress present, potentially emerging within days of initial exposure. The presence of carbon dioxide and acidic condensates can further accelerate these degradation processes (NACE 2001).

2.1.2.3 Natural Gas Liquids (NGLs)

The American Petroleum Institute (2021) guide indicates that NGLs primarily pose inhalation risks rather than contact hazards, with their main danger being oxygen displacement in confined spaces. This guide defines NGLs as a petroleum products removed from natural gas that include ethane, propane, butane, and pentanes.

The IDLH levels vary by component:

Ethane: No IDLH data is available, but exposure may aggravate pre-existing eye, skin, or respiratory conditions

Propane: IDLH of 2,100 ppm, with vertigo reported at high concentrations (100,000 ppm for two minutes)

Butanes: IDLH of 1,600 ppm, with drowsiness at 10,000 ppm and more serious effects (including ventricular fibrillation, encephalopathy, pulmonary distress, and death) at concentrations above 100,000 ppm

Pentanes: IDLH of 1,500 ppm, with no mucous membrane irritation at 5,000 ppm

Safety protocols emphasize that responders must use proper protective equipment including Self-Contained Breathing Apparatus when entering areas where vapors may have collected. The guide focuses on emergency response to acute exposures rather than addressing prolonged exposure effects, though it notes that toxic clouds can extend further than flammable clouds since IDLH levels are set at 10% of the Lower Explosive Limit. All NGL products receive a low health hazard rating (1 on the National Fire Protection Association (NFPA) 704 scale) compared to their high flammability rating (4).

According to the Chevron Phillips (2018) Safety Data Sheet, exposure to NGLs can cause skin irritation and may be fatal if swallowed and enters airways. Symptoms of overexposure may include “headache, dizziness, tiredness, nausea and vomiting”. Concentrations substantially above the Threshold Limit Value (TLV) value (not specified) may cause narcotic effects.

Raw NGL contains several hazardous components:

Benzene: The substance is classified as a human carcinogen by the International Agency for Research on Cancer (IARC), the National Toxicology Program (NTP), and the American Conference of Governmental Industrial Hygienists (ACGIH). Laboratory tests revealed that the substance causes mutagenic effects, altering genetic material. However, when tested on animals, the substance did not demonstrate any negative effects on fetal development. Furthermore, studies on animals showed no evidence that the substance impacts fertility or reproductive capabilities. The IDLH is 1,100 ppm and the ACGIH has set a Time-Weighted Average (TWA), the average exposure to a contaminant, of 0.5 ppm.

Natural gas (petroleum) raw liquid mix: The substance is classified as possible human carcinogen. Laboratory tests revealed that the substance causes mutagenic effects. The IDLH is not listed, and the OSHA has set a TWA of 500 ppm within the Z-1A table in 29 C.F.R. § 1910.1000 as Petroleum distillates (Naphtha) (Rubber Solvent).

Hexane: The substance is not classifiable as a human carcinogen. Animal experiments have not demonstrated any mutagenic effects from this substance, nor has testing revealed impacts on fetal development. However, there is some evidence from animal studies suggesting potential adverse effects on sexual function and fertility, specifically testicular damage with loss of germ-cell line observed at exposure levels of 5,000 ppm. Repeated exposure to n-hexane can cause peripheral nervous system damage, affecting the nerves outside the brain and spinal cord. The IDLH is 1,100 ppm and the ACGIH has set a TWA of 50 ppm.

This list is not exhaustive as differing institutions or organizations may include other compounds due to the composition of a specific source.

2.1.2.4 VOCs (BTEX)

BTEX is an acronym that refers to a group of volatile organic compounds consisting of Benzene, Toluene, Ethylbenzene, and Xylenes. These chemically similar aromatic hydrocarbons are common environmental contaminants that may occur naturally in natural gas deposits and can be found in raw natural gas before processing. The toxicity of Benzene is discussed within NGLs.

Toluene: The substance is not classified as a carcinogen by IARC, NTP or OSHA. Laboratory tests revealed that the substance does not cause mutagenic effects, with negative results in various test systems including in vitro mammalian cell gene mutation tests, Ames tests, and chromosome aberration tests in rats. However, the substance is suspected of damaging fetal development and cause damage to the central nervous system through prolonged or repeated exposure. OSHA has set a TWA of 20 ppm (Sigma-Aldrich 2024b).

Ethylbenzene: The substance is classified as a possible carcinogen by the IARC, while not being classified by NTP or OSHA. Laboratory tests for mutagenicity, including chromosome aberration tests, mammalian cell gene mutation tests, micronucleus tests, and unscheduled DNA synthesis assays, all showed negative results. The substance has no data available regarding effects on fetal development or reproductive capabilities. Specific target organ toxicity identified for repeated exposure to hearing organs. NIOSH, while OSHA have set a TWA of 100 ppm (Sigma-Aldrich 2024a).

Xylenes: Commercial grade xylene is mixed, containing 20–30% Ethylbenzene. The substance is not classified as a human carcinogen by IARC, although ethylbenzene is. According to test results, xylene did not show mutagenic effects in various tests including Ames test, chromosome aberration test, sister chromatid exchange assay, and dominant lethal test. No information is provided concerning effects on fetal development, fertility, or reproductive capabilities. The ACGIH has set a TWA of 20 ppm, while OSHA has established a TWA of 100 ppm (Sigma-Aldrich 2025).

(ATSDR 2024) found that assessing the individual components excludes certain mechanism that occur as a joint compound. At low exposure concentrations typical of environmental scenarios (below 20 ppm of each component), metabolic interactions between these compounds are negligible, making an additive approach appropriate for assessing shared neurotoxic effects. In these cases, the Hazard Index method is recommended, which sums the ratios of exposure to health-based reference values for each component. However, for unique toxic effects such as benzene's hematotoxicity and carcinogenicity, individual assessment of benzene is necessary even at low concentrations, since these effects are specific to benzene and not produced by other BTEX components. At higher exposure concentrations (above 20 ppm), significant competitive metabolic inhibition occurs, potentially increasing neurotoxicity due to higher blood levels of parent compounds while paradoxically decreasing benzene's hematotoxicity by reducing formation of toxic metabolites.

2.1.2.5 Odorizers

Mercaptans, added as odorants to processed gas, are detectable by smell at very low concentrations (0.01–0.05 ppm) with irritation beginning around 50 ppm. OSHA has set the Permissible Exposure Limits (PEL) at 10 ppm for methyl mercaptan within Table Z-1—Limits for Air Contaminants” of 29 C.F.R. § 1910.1000.

Fang et al. (2019) found that exposure to methyl mercaptan at 0.5 ppm for 6 hours daily over 7 days caused several adverse effects in rats, including decreased food consumption and body weight gain in both sexes. Malondialdehyde (MDA) levels, a biomarker of oxidative stress, in lung tissue significantly increased in both males and females. Histopathological examination revealed terminal bronchiole constriction, alveolar congestion, and erythrocyte exudation in the lungs suggesting oxidative damage as a

key mechanism of toxicity. Elevated MDA levels and lipid peroxidation levels were identified as potential mechanisms leading to the observed terminal bronchiole constriction. Animal models of chemical inhalation exhibited pathophysiological changes over time similar to those observed in patients with inhalation injury, suggesting relevance to human exposures (Herndon et al. 1986).

Fang et al. (2019) concluded that "workers exposed to this concentration may cause some pulmonary stimulation and injury" and suggested that the current ACGIH, threshold limit value (TLV) of 0.5 ppm "may be too loose." ACGIH is a professional association that develops guidelines for workplace exposure limits to various hazardous substances. They establish TLVs which are recommended occupational exposure limits. These are not legally binding standards but are widely used as reference points for workplace safety. TLV is the safety standard that sets maximum acceptable concentration of a hazardous substance, while TWA is the measurement method used to calculate actual exposure levels over a workday or workweek to determine if that standard is being met. Workers exposed to high concentrations of sulfur compounds have shown "increased air flow obstruction, irritant-induced occupational asthma, and a suspected increase in mortality due to ischemic heart disease" (Torén et al. 1996). High concentrations may lead to severe shortness of breath, pulmonary effusion, headache, vomiting, nausea, and unconsciousness. While this study was only conducted for 7 days, the researchers connect their findings to potential long-term effects, noting that in early stages of damage, inflammatory cells infiltrate the tissue, followed by epithelial damage, and continuous exposure may lead to pulmonary fibrosis or edema. Torén et al. (1996), refers specifically to workers in pulp and paper mills who are regularly exposed to sulfur compounds including methyl mercaptan. Fang et al. (2019) focused on waste treatment facility workers, oil refinery workers, and those in manufacturing industries who may be exposed to methyl mercaptan as part of their job. Exposure duration and concentration may vary significantly in a pipeline release scenario compared to occupational settings, due to differences in workforce protocols, regulatory frameworks, and geographic factors that affect gas dispersion.

2.1.3 Water Solubility

The solubility of natural gas in water primarily depends on three key factors: temperature, pressure, and the specific composition of the gas mixture. At standard temperature and pressure, natural gas has relatively low solubility in water, with methane (the primary component) dissolving at approximately 0.0024 grams per 100 grams of water at 20°C. This solubility increases with rising pressure, following Henry's Law, which states that the amount of dissolved gas is directly proportional to its partial pressure in the gas phase. In underwater environments, pressure increases linearly with depth at approximately 1 atmosphere (atm) for every 10 meters (m) (32.80 feet (ft)) of water depth. This means that at a depth of 100 m, where the pressure is about 10 atm, the solubility of natural gas components could be roughly ten times higher than at the surface (Campbell 2021).

Conversely, the solubility decreases as water temperature increases, making natural gas more likely to come out of solution in warmer conditions. This inverse relationship between temperature and gas solubility, combined with the pressure-depth correlation, creates distinctive solubility profiles at different ocean depths where both factors vary simultaneously. Deep ocean waters exhibit higher gas solubility due to the combined effects of increased pressure and lower temperatures. Near the surface, warm water holds less gas despite lower pressure, while in the deep ocean, cold water under high pressure can retain

more dissolved gas. These varying solubility conditions across depth gradients directly affect natural gas distribution, transport, and stability in marine environments (Campbell 2021).

The presence of other compounds in natural gas affects its overall solubility characteristics. While methane has low water solubility, other components like carbon dioxide and hydrogen sulfide are considerably more soluble. This differential solubility can lead to changes in gas composition when natural gas contacts water, particularly in damaged pipelines.

Environmental considerations arise from these solubility characteristics. When natural gas is released underwater, approximately 95–99% of it rises as bubbles rather than dissolving, though some dissolution does occur (Leifer and Patro 2002; McGinnis et al. 2006). This behavior influences how natural gas behaves during underwater releases and affects strategies for environmental monitoring and remediation efforts.

While most natural gas rises as bubbles (>95%), the portion that dissolves undergoes a more nuanced interaction with the aquatic environment than previously understood. Traditional thinking suggested that methane-oxidizing bacteria exclusively require oxygen to break down dissolved gas, potentially creating oxygen-depleted zones hazardous to marine life. However, research reveals that certain methane-oxidizing bacteria demonstrate remarkable adaptability, continuing to oxidize methane even in oxygen-depleted conditions through alternative metabolic pathways (Ettwig et al. 2010; Knittel and Boetius 2009). This adaptation suggests that some aquatic ecosystems possess more resilient mechanisms for handling dissolved methane than previously recognized.

Nevertheless, the presence of oxygen remains important for methane processing in marine environments. This creates a two-tier system where different bacterial communities process methane at different depths and oxygen levels, forming a layered filtration mechanism in the sediment (Ruff et al. 2016). While this natural filtration system helps mitigate some environmental impacts, substantial methane releases may still overwhelm these biological processes, potentially leading to zones where marine life faces challenges in survival and may need to relocate (Su et al. 2022).

2.1.4 Cold Weather Impact

Zona et al. (2016) found that methane emissions from Arctic terrestrial systems remained even when temperatures were well below freezing, particularly during what they call the "zero curtain" period - when soil temperatures hover near 0°C. During this time, the frozen surface layer actually reduced methane oxidation (breakdown), allowing more methane to escape to the atmosphere. This is particularly relevant because it suggests that natural gas releases might persist longer and migrate greater distances through soil layers when ground temperatures are below freezing (0°C or lower) than previously thought. The soil conditions played an important role in methane transport. Unfrozen water films in soil particles persist until at least -10°C, creating pathways for methane movement even in largely frozen ground. The presence of snow cover also affected emissions by insulating the soil and maintaining warmer subsurface temperatures. These findings suggest that gas releases might find similar pathways through partially frozen soil, potentially traveling significant distances through these unfrozen channels. Sites with different soil moisture levels showed varying emission patterns. The driest sites actually had the highest cold-season methane emissions, contrary to expectations. This could be relevant for predicting how natural gas

releases might behave differently in various soil types and moisture conditions during cold weather. The study helps understand how freeze-thaw cycles affect methane movement through soil and may help explain why some gas releases might be more persistent or harder to detect during certain seasons.

2.2 Natural Gas Production

Alaska's natural gas plays an important role in powering homes, businesses, and industries across the state, and understanding how this energy source moves from the ground to homes is important for evaluating its environmental impact. This section explores where Alaska's natural gas comes from, how it is transported, stored, and used throughout the state. Two main regions, Cook Inlet (near Anchorage) and the North Slope (in the Arctic), present unique challenges and opportunities as the state works to balance energy needs with environmental protection. By examining how natural gas moves through Alaska's landscape, we can better assess its effects on the environment and local communities.

2.2.1 Natural Gas Formation and Extraction

Natural gas is found in reservoirs located up to 16,000 feet below the Earth's surface. Like other fossil fuels, natural gas originates from the remains of plant and animal life that were gradually buried underground and subjected to extreme conditions. These conditions transform the complex organic compounds into various hydrocarbons, including petroleum, natural gas, and coal. Natural gas formation occurs in different stages according to depth. At shallower depths, the biogenic stage occurs where anaerobic microbes convert decaying organic matter into methane. This process accounts for approximately 20% of the world's gas reserves (Riva et al. 2023). At greater depths, natural gas forms through thermogenic processes, high temperature and pressure, often alongside oil. At the deepest levels, conditions become so extreme that methane production becomes predominant. Gas reservoirs form when gas migrates through geological layers and becomes trapped in porous sediment and rocks beneath an impermeable cap rock. These are called conventional reservoirs. The gas composition and extractable volume vary greatly depending on reservoir characteristics. Extraction typically involves vertical drilling techniques both onshore and offshore. Companies construct drilling platforms at discovered well sites. The extraction process requires periodic maintenance and sometimes removal of liquids from the wellbore to maintain proper natural gas flow (Skone et al. 2014).

2.2.2 Natural Gas Sources

Alaska's natural gas resources are primarily concentrated in two major regions: Cook Inlet and the North Slope. Each region has distinct characteristics that influence its development and utilization (McKinley Research Group 2023; U.S. Geological Survey 2017).

The Cook Inlet basin, situated in Southcentral Alaska, represents one of the state's most economically important natural gas producing regions. This basin extends approximately 180 miles from Anchorage to the Gulf of Alaska, surrounding the Kenai Peninsula. Its strategic location near major population centers has made it essential in meeting Southcentral Alaska's energy demands since production began in the 1960s. The geological composition of Cook Inlet is particularly favorable for natural gas production. The basin features both thermogenic gas (formed through the thermal decomposition of organic matter at high temperatures and pressures) and biogenic gas (produced by microorganisms breaking down organic

material) systems within its Mesozoic and Tertiary sedimentary strata. The Sterling and Beluga formations are especially notable for their dry gas reservoirs, characterized by high-quality reservoir rocks and effective trapping mechanisms (Burdick and Meza 2023). Redlinger et al. (2018) notes that in 2018, Cook Inlet supplied 70% of electricity generation for Southcentral Alaska's Railbelt region, and 83% of electricity generation to Mat-Su Valley, Anchorage, and Kenai Peninsula. The Railbelt region of Southcentral Alaska refers to the area of Alaska that follows the Alaska Railroad corridor, stretching from Seward and the Kenai Peninsula in the south, through Anchorage, and north to Fairbanks in the Interior region. This area is the most populated and developed part of Alaska, containing about 70% of Alaska's population and the state's largest cities, Anchorage and Fairbanks. Mackenzie (2024) found that that in the last 15 years of the 34 new wells drilled during that time, only roughly 9% were successful. They also found that eight times more gas is needed to fill identified demand gaps than discovered within the last 15 years. Mackenzie (2024) speculate that due to this production from Cook Inlet may not be a viable option to meet long-term demand. **Figure A-22** and **Figure A-23** in **Appendix A** shows leasing (2025) and pipeline (2022) maps for Cook Inlet.

The North Slope region encompasses a vast area of approximately 89,000 square miles, extending from the Brooks Range to the Arctic Ocean. This region contains some of North America's largest hydrocarbon deposits, particularly within the Prudhoe Bay and Point Thomson fields. The U.S. Geological Survey estimates the North Slope's technically recoverable natural gas reserves at over 85 trillion cubic feet (Tcf) (US Department of Energy 2019). The region's geological framework centers on the Colville Basin, which contains extensive layers of organic-rich rock that have undergone thermal maturation over millions of years. This process has resulted in substantial natural gas accumulations, often associated with oil deposits (Houseknecht 2022). The assessment by Attanasi and Freeman (2009) found 24.3 billion barrels of oil across 179 accumulations and 103 Tcf of non-associated gas in 145 accumulations, with the National Petroleum Reserve-Alaska and Arctic National Wildlife Refuge 1002 Area containing 86% of the undiscovered oil. Most non-associated gas (61%) was assigned to the National Petroleum Reserve-Alaska, with total North Slope estimates ranging from 17.4–32.4 billion barrels of oil and 74.3–135 Tcf for non-associated gas. While Cook Inlet's proximity to population centers has facilitated natural gas development, the North Slope's vast resources remain largely untapped due to infrastructure limitations. The Alaska LNG Project aims to address this challenge by developing transportation infrastructure. This project proposes an 800-mile pipeline system to transport approximately 3.5 billion cubic feet (Bcf) of gas daily from the North Slope to southern markets. The gas supply would be sourced 75% from Prudhoe Bay and 25% from Point Thomson (AGDC 2024). **Figure A-24**, **Figure A-25**, and **Figure A-26** in **Appendix A** shows leasing (2025) and pipeline (2022) maps for the North Slope.

2.2.3 Natural Gas Transportation

Natural gas transportation follows several key stages: transportation from offshore and onshore wells through gathering pipelines; processing and treatment; transportation through transmission pipelines to local distribution; transportation through distribution pipelines to the end user; and shipping or storage.

2.2.3.1 Gathering Pipelines

Gathering pipelines are the initial transportation systems that collect natural gas from production facilities and deliver it to processing plants or transmission pipelines. These pipelines serve as the first step in

moving natural gas from extraction points to consumers. This network includes both subsea and onshore components. In offshore areas, subsea gathering pipelines connect platforms to onshore gathering systems, which may involve using preexisting gas pipelines, converting oil pipelines, or installing new infrastructure.

Mitigation measures during installation and operation of these gathering pipelines are implemented to prevent accidental natural gas releases. In one example, during the proposed installation of a new pipeline section, several steps are noted to reduce the likelihood of an accidental release:

Each pipeline section is inspected and hydrotested, and coatings verified. The offshore and transition zone portions of the pipeline will be coated with a fusion bonded epoxy and an additional abrasion resistant overlay coating. Additional segments are welded together, welds inspected, and coatings applied to welds in the onshore fabrication area (NOAA 2018).

Exposed gathering pipelines in the tidal transition zone are buried to protect them from ice damage, which is a concern for some portions of Alaska's gathering infrastructure. In addition, under certain pressure and temperature conditions within these gathering systems, water vapor can combine with natural gas to form hydrates—ice-like structures that can block flow and harm pipeline infrastructure. This requires careful monitoring and management throughout the gathering transportation system (Collett 2021).

2.2.3.2 Processing and Treatment

Natural gas processing and treatment is an operation that prepares raw gas for safe transportation and use. At facilities near production sites, the gas undergoes purification to remove impurities, water, and natural gas liquids to meet pipeline specifications. The first stage of processing begins at the production site, where the raw natural gas undergoes separation from oil, water, and other liquids. This initial separation utilizes multiple-stage separation vessels operating at progressively lower pressures. The process removes free liquids and particulates that could damage downstream equipment or create flow problems in pipeline systems. Water removal is a key processing step in cold climates. Gas dehydration typically employs glycol absorption systems, where triethylene glycol (TEG) contacts the gas stream to remove water vapor. This process is important where any remaining water vapor could form hydrates or ice in pipelines. Many facilities employ backup dehydration systems to ensure continuous operation during maintenance periods (EIA 2024b).

Processing facilities remove H₂S and carbon dioxide using amine treatment systems where these contaminants exceed pipeline specifications. The amine systems selectively absorb acid gases, with the treated gas proceeding to further processing while the absorbed contaminants undergo proper disposal or recovery. Mercury removal systems may also be employed where necessary, using activated carbon beds to prevent contamination of processing equipment (Addington and Ness 2010). Processing facilities may employ a combination of refrigeration and cryogenic processing to extract valuable components like ethane, propane, and butanes. The degree of natural gas liquids recovery varies based on market conditions and pipeline specifications, with some facilities designed for deep ethane recovery while others focus primarily on propane and heavier components (Linde 2025).

2.2.3.3 Transmission Pipelines

High-pressure transmission pipelines, typically 12–48 inches connect to compression stations spaced along the route to maintain gas flow over long distances. 49 C.F.R. § 192 Subpart B Materials, provides the minimum regulatory requirements for pipe and components used in pipelines. Steel pipe for pipelines must adhere to specific qualifications depending on whether it is new or used. New steel pipe must be manufactured according to listed specifications or meet requirements in Section II of Appendix B, Qualification of Pipe and Components, while used steel pipe must satisfy similar criteria plus demonstrate good condition from previous use. For both types, operating at lower pressures (less than 6,000 psi) is permitted after visual inspection confirms good condition without split seams or leakage defects. Welded pipe not manufactured to listed specifications must pass additional weldability tests. Cold expanded steel pipe must comply with mandatory provisions of API Spec 5L. Transportation requirements become more stringent for pipe with a diameter-to-wall thickness ratio of 70:1 or greater, with specific standards applying based on the transportation method (railroad, ship/barge, or truck). For steel transmission pipelines, operators must maintain records documenting physical characteristics including diameter, yield strength, tensile strength, wall thickness, seam type, and chemical composition for the entire lifespan of the pipeline.

Appendix B outlines the specifications for qualification of pipes and components under 49 C.F.R. § 192. It lists references to specific industry standards for pipe and components from American Petroleum Institute (API) and American Society for Testing and Materials (ASTM). For steel pipes with unknown specifications, Appendix B details required testing procedures for bending properties, weldability, visual inspection, and tensile strength to ensure safety. Additionally, it provides guidelines for using older steel pipes manufactured before November 1970, stipulating that these must meet specific inspection criteria, have similar specification requirements to newer standards, and undergo appropriate testing of welded seams.

49 C.F.R. § 192 Subpart B, Materials, references mandatory provisions within API Specification 5L which covers specifications for carbon steel pipes used in oil and gas transmission systems. The specification defines two quality levels, PSL1 and PSL2, with PSL2 having stricter requirements for chemical composition, strength testing, and inspection methods. These pipes come in diameters from ½ inch to 40 inches and can be made as seamless pipes or with different welding methods. The welding methods include Electric Resistance Welding (ERW) for smaller pipes and various arc welding techniques for larger diameters. API 5L pipes are categorized by strength grades, starting with Grade B and moving up through X42, X52, X60, and so on up to X80. Higher numbers indicate stronger steel that can withstand greater pressure. Wall thicknesses range from relatively thin (SCH 10) to very thick (SCH 160). Pipes can have different end types, surface treatments, and come in standard or custom lengths to meet various needs in the petroleum and natural gas industries (American Piping Products 2025; API 2018).

2.2.3.4 Distribution Pipelines

From the main transmission pipelines, natural gas flows into local distribution networks operated by utility companies that supply homes, businesses, and industrial customers. These networks take the high-pressure gas from transmission lines and reduce its pressure to safer levels for local use. The accessibility and usage of natural gas varies notably across Alaska's regions, with urban areas benefiting

from comprehensive distribution networks while remote communities often lack direct access. Approximately 70% of the Railbelt's electricity is generated from natural gas sourced from Cook Inlet heating over 140,000 homes and businesses (Redlinger et al. 2018). In contrast, many rural and remote communities do not have direct access to natural gas and often depend on more expensive alternatives like propane or fuel oil for heating (Ross et al. 2018).

The distribution systems employ different types of pipes suited to local conditions. Newer installations use plastic pipes, following regulations under 49 C.F.R. § 192 Subpart B Materials, and specifications under 49 C.F.R. § 192.121. Plastic piping is generally limited to distribution lines as the pressure requirements may exceed pipe designs as specified in concerning the design of plastic pipes. Older pipelines likely consist of steel pipes with protective coatings. The design regulations for plastic pipes used in pipelines provide safety parameters that reduce potential releases. Plastic pipes are subject to specific pressure limitations, with standard distribution pipelines generally restricted to 100 psig, though pressures may be higher, given the application and type of material chosen as specified. Plastic pipes are restricted from use when operating below -20 °F (-29 °C), as these pipes may not function properly in extremely cold environments. In some special case, if all pipes and components have a manufacturer cold temperature rating, plastic pipes may be used to -40 °F (-40 °C). There are also restrictions on higher temperatures determined by the Hydrostatic Design Basis (HDB). HDB is a measurement indicating the long-term strength of the pipe material at specific temperatures. It represents the estimated maximum stress a plastic pipe can withstand over a duration without failure. As temperature increases, the HDB and consequently the maximum allowable pressure decreases. All plastic pipe installations must maintain a minimum wall thickness of 0.062 inches unless otherwise specified. Several types of plastic pipelines may be used, including Polyethylene (PE) pipes that can withstand pressures up to 125 pounds per square inch gauge (psig) and come in diameters up to 24 inches, Polyamide (PA-11 and PA-12) pipes capable of handling higher pressures up to 250 psig but limited to 6 inches in diameter, and Reinforced Thermosetting Plastic pipes that have temperature restrictions preventing use above 150°F. Each pipe type has precisely defined wall thickness requirements corresponding to specific pipe diameters.

Operators may maintain monitoring and maintenance programs. This includes regular inspections to check for natural gas pipeline releases, ongoing assessment of pipe conditions, and systematic replacement of aging components.

2.2.4 Natural Gas Storage

Alaska's natural gas storage system primarily centers on the Cook Inlet region, employing multiple storage methods across several key facilities. The most important of these is Cook Inlet Natural Gas Storage Alaska (CINGSA), Alaska's first commercial natural gas storage facility, which began operations in 2012. CINGSA has a storage capacity of 11 Bcf and can inject or withdraw up to 150 million cubic feet (Mcf) of gas per day (TriSummit Utilities 2024). Other important facilities include Kenai Gas Pool 6, with a working volume of 17.5 Bcf and a total storage capacity of 50 Bcf (House Resource Committee 2024).

These facilities primarily utilize depleted gas reservoirs for underground storage. The storage system plays an important role in managing seasonal demand variations. On average, Cook Inlet natural gas users require about 190 Mcf of gas daily, but this demand can spike to about Mcf on the coldest days. Recent events, such as the cold snap in January 2024, have highlighted potential challenges in gas deliverability

during peak demand periods. In response, CINGSA is planning an expansion project that will increase deliverability by 65 Mcf per day and add 2 Bcf of storage capacity, at an estimated cost of \$72 million (Mitchell 2024).

In addition to underground storage, liquefied natural gas (LNG) storage facilities are also utilized. These employ cryogenic tanks designed with multiple containment layers and extensive monitoring systems. LNG storage tanks use durable materials capable of withstanding extremely low temperatures, typically around -160°C. They feature inner tanks made of materials like 9% nickel steel or aluminum alloy, outer tanks often made of prestressed reinforced concrete, and high-performance insulation between the layers. These LNG storage facilities are valuable not only for communities disconnected from pipeline networks but also for regions with constrained natural gas pipeline capacity. They offer important supply security through local storage and regasification capabilities, acting as a "bank account" for natural gas that can be used during peak demand periods. The combination of underground storage and LNG facilities provides Alaska with a diverse and flexible natural gas storage system (CIMC Enric 2022; TriSummit Utilities 2024).

2.2.5 Natural Gas Usage

Natural gas serves as an essential energy source across Alaska, fulfilling various roles for different types of consumers. In residential settings, homes rely on natural gas primarily for heating spaces, warming water, and cooking purposes in areas with established distribution networks. The industrial sector, another user of natural gas, utilizes it in a few important ways. Power plants commonly burn natural gas to generate electricity. In oil refining and natural gas processing facilities, natural gas is burned to power the equipment necessary for these operations. Commercial establishments, including businesses, schools, and government buildings, depend on natural gas for similar applications, heating their spaces, providing hot water, and supporting cooking operations where infrastructure exists.

U.S. Energy Information Administration (EIA 2024a), found that in 2023, Alaska ranked third among U.S. states for proved natural gas reserves with approximately 100 Tcf, and ranked fourth nationally in natural gas withdrawals with nearly 3.5 Tcf. Most of Alaska's natural gas withdrawals are not brought to market but are instead reinjected into oil reservoirs to help maintain crude oil production rates, as natural gas volumes from the North Slope exceed local demand and there is no pipeline to transport it to consumers in southern Alaska. In terms of consumption, the industrial sector used the largest share (48%) of Alaska's natural gas delivered to consumers in 2022, followed by the electric power sector (22%), the residential sector (17%), and the commercial sector (13%). Natural gas-fired generators provide about half of Alaska's utility-scale electricity, and nearly half of Alaskan households, primarily in the state's three biggest cities (Anchorage, Juneau, and Fairbanks), use natural gas for heating.

2.3 Natural Gas Pipeline Hazards

When a natural gas pipeline release occurs, it creates a potential sequence of hazards that evolve based on environmental conditions and ignition timing. Upon release, gas initially disperses, with concentration patterns influenced by wind conditions, atmospheric stability, and terrain features. In enclosed spaces this creates the potential asphyxiation hazards as the gas displaces oxygen. If an ignition source contacts the

dispersed gas within its flammable range, one of several combustion scenarios may develop resulting in fire or explosion. The specific pathway from dispersion to either fire or explosion depends on multiple variables including release rate, pressure, hole geometry, and ambient conditions, with each pathway presenting distinct hazard zones and durations.

2.3.1 Natural Gas Release Pathways

Natural gas pipeline releases may occur for many reasons: environmental factors, operational factors, or human factors. Pipeline releases typically develop through several pathways: material degradation through corrosion and aging of pipeline components; environmental stressors such as frost heaves and permafrost thawing that physically compromise pipeline integrity; operational issues including pressure fluctuations and mechanical damage; and human interventions, both accidental and intentional. Each pathway represents a distinct mechanism through which releases occur, allowing natural gas to escape from the pipeline system. These pathways may occur independently or interact with one another, creating complex failure scenarios.

2.3.1.1 Pipeline Corrosion

Both internal and external corrosion pose potential threats. Internal corrosion occurs due to moisture and contaminants in the natural gas stream, particularly in sections where flow rates are low. External corrosion may be exacerbated by soil conditions, especially in areas with high moisture content or where pipeline coatings have degraded. The freeze-thaw cycle can accelerate coating deterioration, exposing the pipe to corrosive elements. Operating specifications attempt to constrain corrosive agents below a meaningful threshold.

49 C.F.R. § 192 Subpart I outlines corrosion control requirements for protecting steel pipelines. These requirements establish minimum standards that pipeline operators must follow to prevent external, internal, and atmospheric corrosion. For external protection, operators must apply protective coatings to buried or submerged pipelines and install cathodic protection systems to prevent corrosion through electrical means. These systems must be regularly tested at least once per calendar year with intervals not exceeding 15 months and any deficiencies must be promptly corrected. When pipelines are exposed during maintenance, they must be examined for evidence of corrosion and appropriate remedial actions taken if damage is found. For internal protection, operators must investigate and take steps to minimize corrosion from gases being transported, including using monitoring devices like coupons that must be checked twice yearly. A coupon is a small metal sample inserted into a pipeline system to monitor internal corrosion rates by being periodically removed and inspected. Atmospheric corrosion protection requires cleaning and coating exposed pipelines and regular inspections every three years for most onshore pipelines, every five years for service lines, and annually for offshore pipelines. Records of all corrosion control activities must be maintained, with critical documents kept for the lifetime of the pipeline. These regulations apply to both new construction and existing pipelines, with specific requirements for different types of pipeline systems and installation periods, ensuring pipelines remain safe while transporting natural gas.

2.3.1.2 Pipeline Aging

Cast and wrought iron pipelines, many over 60 years old, present increased risks due to the degrading nature of iron alloys, age, and pipe joint design. In addition, bare steel pipelines, which lack protective coating, are typically higher risk compared to other pipelines and are candidates for accelerated replacement programs. In 2011, the Department of Transportation (DOT) and Pipeline and PHMSA issued a Call to Action to accelerate the repair, rehabilitation, and replacement of high-risk pipeline infrastructure, with pipeline age and material being significant risk indicators. The Pipeline Safety, Regulatory Certainty, and Job Creation Act of 2011 mandated that DOT conduct state-by-state surveys on cast iron pipeline replacement progress. The legislation strengthened regulatory oversight by increasing civil penalties for violations, requiring operator assistance during accident investigations, and eliminating exemptions from one-call notification systems. Safety improvements included provisions for automatic shut-off valves on new transmission lines, verification of maximum allowable operating pressure records, and consideration of seismicity in risk assessments. The Act mandated studies on leak detection and excavation damage while improving public awareness through enhanced mapping systems. It also created frameworks for tribal consultation, established strict accident notification timeframes, and required evaluation of safety technologies like excess flow valves (Pipeline safety, regulatory certainty, and job creation act of 2011, 2012). PHMSA maintains an annually updated online inventory tracking replacement progress of these high-risk pipelines by state. PHMSA (2025) found progress has been made in reducing cast and wrought iron pipelines through state and federal safety initiatives and pipeline operators' replacement efforts. Twenty-four states, including Alaska, and one territory have completely eliminated cast or wrought iron natural gas distribution lines. As of the end of 2024, approximately 99% of U.S. natural gas distribution pipelines were made of plastic or steel, with only about 1% remaining as iron pipe.

2.3.1.3 Weather

Ahmed et al. (2024) examines weather-related impacts on natural gas pipeline infrastructure, drawing from PHMSA records (2001–2020) documenting nearly 5,750 pipeline incidents, and European Gas Pipeline Incident Data Group (EGIG) data (1970–2016) covering 1,366 events. The study categorizes natural hazard factors affecting infrastructure as meteorological (36%), geological (26%), hydrological (24%), and climate-related (14%). Weather conditions threaten pipeline stability through multiple mechanisms: corrosion acceleration from moisture and corrosive elements; structural stress from temperature extremes causing expansion, contraction, and frost heave; and physical damage from storms, floods, and landslides.

In Ahmed et al. (2024) frost heaves were noted as an impact to pipeline infrastructure. Li et al. (2021b) found that natural gas pipelines in permafrost regions face distinct challenges compared to oil pipelines due to their temperature profiles. While oil pipelines typically operate at warm temperatures (38–63°C for the Trans-Alaska Pipeline System (TAPS)), gas pipelines may chill below 0°C. This temperature difference leads to differential frost heave, where chilled gas pipelines cause freezing of unfrozen soil around the pipe, potentially lifting sections of the pipeline. This freezing process may impact overall pipeline stability. The Fairbanks Frost Heave Experiment was a full-scale test in Alaska that analyzed chilled pipeline deformation in discontinuous permafrost (Li et al. 2021b). The Fairbanks Frost Heave Experiment examined how chilled gas pipelines behave in Arctic environments where permafrost and non-permafrost

soils meet. Conducted from 1999 to 2005 in Alaska, researchers monitored a 105-meter steel pipeline (0.9 m diameter) circulating -10°C air, with one-third buried in permafrost and two-thirds in non-permafrost soil. The study revealed that as frost bulbs developed around the pipeline in non-permafrost areas, upward movement occurred, creating bending stress at the boundary between soil types. During summer months, researchers observed an unexpected phenomenon where the pipeline in the permafrost section would suddenly move upward as the overlying frozen ground thinned from seasonal thawing, sometimes breaking through this layer. This cycle repeated in subsequent summers, with clear evidence that frost heaving of the foundation caused the pipeline's vertical displacement in non-permafrost sections (Akagawa et al. 2012). To address these challenges, engineers have developed several approaches including above-ground installation (which minimizes thermal disturbance but increases costs), thermal insulation to reduce heat transfer between pipeline and soil, and controlled cooling techniques like thermosyphons to maintain stable frozen conditions around the pipeline (Li et al. 2021b).

Alaska Department of Natural Resources (2020) found that at Lost Creek Hill (Pipeline Milepost 392), part of the TAPS, permafrost thawing had caused slope movement that tilted and bent vertical support members, threatening pipeline integrity of the above-ground pipeline. When permafrost thaws due to warming temperatures or seasonal fluctuations, it creates ground instability that can damage pipeline structures through subsidence or lateral movement. The engineering solution proposed included installing approximately 100 thermosyphons (heat pipes), adding insulating wood chips, and incorporating horizontal ventilation pipes. Permafrost thawing be an ongoing concern as Hjort et al. (2018) found that permafrost thaw threatens Arctic infrastructure, showing that buildings, roads, and other structures are located in areas with high potential for ground instability. The researchers used ground temperature observations and environmental data to model future conditions at 1 kilometer (km) resolution. By creating three geohazard indices, they identified areas where infrastructure is most vulnerable, focusing on near-surface permafrost (less than 15 m deep) that is critical for structural stability. The study analyzed three climate scenarios to understand potential impacts under different levels of warming. The study identified the central and western regions of Alaska as areas at risk of damage due to permafrost degradation, including 550 km of TAPS.

2.3.1.4 Operating Conditions

Pressure fluctuations is a potential operational risk factor in pipeline systems. The careful monitoring and control of pipeline pressure is essential for maintaining structural integrity and preventing failures. Based on the PHMSA guidance document, pressure management is important for natural gas pipeline systems due to the compressible nature of the medium. For natural gas pipelines, pressure fluctuations must be carefully monitored from discharge compressor stations to suction compressor stations to ensure compliance with Maximum Allowable Operating Pressure (MAOP). Operators must verify pressure regulation at key points including city gates, regulator stations, and delivery points, with annual verification of pressure limiting station capacity as required by 49 C.F.R. § 192.743. Particular attention is needed for grandfathered pipelines under 49 C.F.R. § 192.195, which may require modified overpressure protection systems. The guidance emphasizes that effective pressure management for natural gas pipelines requires integrated consideration of gas composition changes, interconnection points, and system design to prevent exceedance of MAOP. This includes ensuring appropriate pressure testing and protection mechanisms are in place, especially when pipelines are converted from other services (PHMSA 2014).

Michael Baker Jr. Inc. (2009) found that mechanical damage to pipelines occurs in three primary forms: dents, gouges, and combined defects. Each represents different types of physical damage that can compromise pipeline integrity in distinct ways. Dents are deformations in the pipe wall caused by direct contact with an object that creates a depression or disturbance in the pipe's natural curvature. These commonly occur when construction equipment impacts the pipe or when pipes settle against rocks. Dents can be categorized as either "constrained" or "unconstrained" based on whether the indenting object remains in contact with the pipe. Constrained dents, typically caused by rocks, remain fixed in place because the object continues pressing against the pipe. Unconstrained dents, usually from temporary contact with equipment, can partially spring back when the object is removed and may change shape as internal pressure varies. Gouges represent a different form of damage where material is either removed or displaced from the pipe wall surface. These typically occur when an object, such as an excavator tooth, scrapes across the pipe surface. Beyond the visible surface damage, gouges can create deeper structural issues including changes to the pipe's microstructure, cracking, and other material defects that may compromise the pipe's integrity. The most serious form of mechanical damage occurs when denting and gouging combine at a single location, creating what are known as combined defects. These are particularly concerning because they pair the stress concentrations caused by the dent's shape change with the material damage from the gouge. Combined defects commonly result from construction equipment that both impacts and scrapes the pipe, or from rocks that press into and slide along the pipe surface. The severity of mechanical damage depends not only on the visible damage but also on various factors including the pipe material properties, operating pressures, and the specific circumstances of the damaging event - such as the size and shape of the impacting object, the force of impact, and the angle of contact. Understanding these variables is important because many instances of mechanical damage go unreported since the damaging event often occurs without witnesses. This makes prevention, detection, and assessment of mechanical damage an ongoing challenge for pipeline operators.

2.3.1.5 Human Factors

Pipeline infrastructure faces both accidental and intentional human-caused risks that can lead to safety and environmental concerns. Accidental damage may occur during routine maintenance operations, where heavy equipment operators may inadvertently strike or stress pipeline components. Unintentional risks include improper valve operation, substandard welding during repairs, and insufficient structural support during maintenance activities. These risks are often amplified by environmental factors that can compromise structural integrity.

Intentional threats pose equally serious challenges to pipeline safety. These include deliberate tampering with monitoring systems and valves, intentional damage using heavy machinery, and ballistic impacts. Cyber-attacks targeting control systems represent an emerging threat, potentially disrupting operations and compromising safety protocols. While pipeline operators maintain comprehensive safety measures, they must constantly adapt to address both aging infrastructure concerns and evolving security challenges.

Jabbari et al. (2021) found that the highest risks to pipelines came from operational activities rather than external threats. Hot work, involving open flames, emerged as the most substantial risk factor, followed by fires involving pipelines and nearby facilities, and pressure-related issues from valve operations.

Interestingly, factors that might intuitively seem dangerous, such as natural disasters, human negligence, or even deliberate sabotage, were found to pose relatively lower risks. Similarly, Williams and Glasmeier (2023) found that 77% of pipeline errors across 24 pipeline incidents were “latent conditions” (organizational or policy failures that remain dormant until contributing to an incident), while only 16% were “active errors” (immediate mistakes with direct feedback). The remaining 7% fell into an “ambiguous” category.

Rusin et al. (2021) examines the safety risks associated with excavator damage to high-pressure natural gas transmission pipelines and analyzes the potential consequences of resulting releases, fires, and explosions. The researchers conducted detailed computer modeling of different scenarios where an excavator bucket strikes a 0.5-meter diameter pipeline operating at pressures of 1–5 megapascal (MPa). Their analysis revealed that such impacts can create holes ranging from 20% to 50% of the pipeline's cross-sectional area, depending on factors like the bucket's position and the operator's response after initial contact. The consequences of such damage can be severe. When gas ignites immediately upon release, it creates a jet fire that can produce lethal thermal radiation within a 200-meter radius. If ignition is delayed, the leaking gas can form explosive clouds. The study found that dangerous concentrations of gas (4.4% to 17%) can develop within 7–16 seconds, depending on pressure. When these clouds ignite, they can create devastating explosions whose impact depends on factors including the distance to the ignition source, time between leak and ignition, gas pressure, and size of the damage. To illustrate real-world implications, the researchers modeled scenarios in populated areas, demonstrating that even with relatively modest damage (20% of pipeline cross-section), the hazard zones can extend into residential areas when operating at 5 MPa pressure. The danger increases with delayed ignition as larger gas clouds have time to form.

The interaction between human-caused risks and environmental factors creates complex safety considerations that require ongoing assessment and mitigation strategies. Operating companies typically implement monitoring systems and regular maintenance protocols, adapting to changing environmental conditions.

2.3.2 Dispersion

The complexity of modeling and assessment of natural gas dispersion stems from the interplay of multiple factors that influence how gas disperses in the atmosphere after an accidental release. When evaluating the risks associated with natural gas releases, both immediate physiological hazards (components released) and potential ignition scenarios (LFL and UFL limits) must be considered.

Nair et al. (2022) used a scenario-based methodology for gas dispersion modeling. The scenario-based methodology has three primary components, source characteristics, environmental conditions, and impact assessment. The source characteristics includes the gas composition and operational conditions. Operational conditions include pressure, temperature, hole size, hole orientation and phase behavior, as may emerge as vapor, liquid, or in a two-phase state depending on the conditions. The environmental conditions include wind speed and direction, atmospheric stability, and terrain. Wind speed and direction serve as primary drivers of dispersion, while atmospheric stability influences the vertical mixing of the gas cloud. The terrain's roughness affects turbulence levels, with urban areas typically showing shorter dispersion distances due to increased mixing. Humidity and ambient temperature may also influence the

dispersion process. Source characteristics and environmental conditions and determine dispersion behavior as follows different patterns based on the gas properties relative to air. The gas cloud may rise (buoyant behavior), sink (dense gas behavior), or remain neutral, depending primarily on its molecular weight compared to air, its temperature, and the concentration of components like H₂S. Using this information, the elements of impact assessment, impact zone, toxicity concentration, and potential ignition, can be determined.

The mathematical modeling of gas dispersion typically employs a combination of release rate calculations and concentration distribution equations. The release rate is determined by factors such as pressure difference, hole size, and fluid properties. The subsequent concentration distribution often follows a Gaussian dispersion model for neutral or buoyant gases, with modifications required for dense gas behavior. Impact zones from these releases can vary dramatically in horizontal distance, ranging from less than 50 ft to over 5,000 ft depending on conditions. The most extensive dispersion distances typically occur under stable atmospheric conditions with low wind speeds. These impact zones are evaluated against specific concentration thresholds, considering both toxic effects (H₂S exposure limits) and flammability boundaries (Aristatek 2008; Jia et al. 2023; Nair et al. 2022).

2.3.2.1 Release Rate of Dispersion

$$Q = C_d A \sqrt{2\Delta P_p}$$

Equation 3. Release rate of dispersion

This release rate equation (**Equation 3**) calculates the initial mass flow rate of gas escaping from a containment system, such as a pipeline or vessel, where:

- Q = Mass release rate (kilograms per second (kg/s))
- C_d = Discharge coefficient
- A = Release area (square meters (m²))
- ΔP = Pressure Difference
- P = Fluid density (kilograms per cubic meter (kg/m³))

It applies to both atmospheric and underwater releases, though additional considerations may be needed for underwater scenarios due to hydrostatic pressure and different dispersion behaviors. The equation is based on Bernoulli's principle and assumes steady-state flow conditions, no significant temperature changes during the release, and that the discharge coefficient (C_d) accounts for non-ideal flow effects. For underwater releases, the model should incorporate the additional hydrostatic pressure at depth when calculating the effective pressure differential (ΔP_p), as this will influence the driving force behind the gas release and subsequent dispersion patterns in the aquatic environment.

This is an oversimplification of real world conditions. Hou et al. (2020) addresses a challenge in natural gas pipeline safety: accurately calculating leakage rates. The study is a comprehensive analysis and improvement of existing leakage calculation models. The authors recognize that accurate leakage rate estimation is important for risk assessment, failure analysis, and emergency response planning in natural gas infrastructure. The researchers begin by examining the historical development of leakage models, noting that while various approaches have been proposed since the 1970s, each has limitations. They then

reclassify and analyze four distinct models for calculating natural gas leakage rates. The simplest approach, the Storage Tank Model, is designed for scenarios where natural gas pipeline releases occur near the pipeline's starting point and have small diameters. This model assumes the pressure inside remains constant after leakage and ignores friction effects. While it works well for large containers like storage tanks, it tends to overestimate leakage rates when applied to pipelines. The Small Hole Model represents an improvement as it takes into account pipeline friction effects. This model works specifically for small leak apertures and assumes the pressure at the leak point remains constant after leakage occurs. While more accurate than the storage tank model, its application is limited to very small holes, (typically with d/D ratios much less than 0.1, where d is the hole diameter and D is the pipeline diameter). For catastrophic failures, the Pipe Model is a better choice. This model is specifically designed for complete pipeline ruptures or when the leak diameter approaches the pipe diameter. It assumes the gas state at the leak point matches atmospheric conditions and equates the leakage rate to the pipeline flow rate. However, it cannot accurately assess scenarios involving holes smaller than the pipe diameter. The Modified Hole-Pipe Model, addresses the limitations of previous approaches. The Modified Hole-Pipe Model can calculate leakage rates for any hole diameter and considers both friction effects and pressure changes. Importantly, it accounts for how leakage affects upstream flow rates and uses a successive approximation method to calculate these effects. The model takes into account the complex feedback relationship between pressure and flow rate changes, resulting in lower, more realistic leakage rate estimates compared to traditional models. Through simulation studies, the authors demonstrate that their modified hole-pipe model provides more accurate results across a wider range of scenarios than previous models.

2.3.2.2 Radius of Dispersion

$$C(x, y, z) = \frac{Q}{2\pi\sigma_y\sigma_zU} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \exp\left(-\frac{z^2}{2\sigma_z^2}\right)$$

Equation 4. Gaussian plume model

Simplified equation (Huang 2015; Micallef and Micallef 2024)

The Gaussian plume equation (**Equation 4**) provides concentration values at any point in three-dimensional space (x, y, z) , where:

- C = Concentration (kg/m³)
- x, y, z = Spatial coordinates (m)
- U = Wind speed (m/s)
- σ_y, σ_z = Dispersion coefficients (m)

To determine a radius of dispersion, we typically solve the equation for a specific concentration of interest (for example: the IDLH level for H₂S at 100 ppm).

To find the radius, we rearrange the equation to solve for y at a given height z and downwind distance x . For a ground-level release and receptor ($z=0$), the equation simplifies to:

$$y = \sigma_y \sqrt{-2 \ln\left(\frac{2\pi\sigma_y\sigma_zUC}{Q}\right)}$$

Equation 5. Gaussian dispersion radius equation

The Gaussian dispersion radius equation (**Equation 5**) gives us the lateral distance to a particular concentration at specified downwind distance, where:

- C = Concentration (kg/m^3)
- x, y, z = Spatial coordinates (m)
- U = Wind speed (m/s)
- $\sigma_y \sigma_z$ = Dispersion coefficients (m)
- Q = Emission rate of the source (m^3/s)

The dispersion downwind forms an elliptical pattern, not a perfect circle, due to wind effects.

Several practical considerations affect the accuracy of these calculations:

- The equation assumes ideal conditions and may not accurately represent complex terrain or very stable/unstable atmospheric conditions.
- Wind direction variability means the actual impact zone might be better represented as a circle rather than the theoretical elliptical pattern.
- The model becomes less reliable very close to the source and at large distances where other factors begin to dominate.
- Results depend on selection of dispersion coefficients.

2.3.2.3 Duration of Dispersion

The duration or persistence of a gas release and its dispersion can be calculated. The calculation depends on whether we are looking at a continuous release or a finite release with a specific volume.

The equation for duration of dispersion can be expressed as:

$$t = \frac{V_p}{Q}$$

Equation 6. Duration rate

For a continuous release, the duration is typically determined by the time required to empty the source container or until emergency isolation occurs. This can be calculated using the release rate equation (**Equation 6**), where:

- t = duration of release (s)
- V = initial volume of contained gas (m^3)
- P = density of the gas (kg/m^3)
- Q = mass release rate (kg/s)

This equation essentially determines how long it will take for a specific volume of gas to be released based on the release rate and the gas properties. For example, if you have a container with 100 m^3 of gas that has a density of $1.5 \text{ kg}/\text{m}^3$, and it is releasing at a rate of $0.5 \text{ kg}/\text{s}$, you could calculate the duration as: $t = (100 \text{ m}^3 \times 1.5 \text{ kg}/\text{m}^3) / 0.5 \text{ kg}/\text{s} = 300 \text{ seconds}$ or 5 minutes.

The duration helps determine how long the hazard might persist. However, it is important to note that this is a simplified calculation that assumes a constant release rate. In real situations, the release rate often changes over time as the pressure in the container decreases.

2.3.2.4 Subsea Dispersion

Ellethy et al. (2021) used computer models to see how gas bubbles travel through water and reach the surface. They found that water depth impacts gas dispersion patterns and rise time, with gas in deeper water (13 m) taking approximately three times longer to reach the surface compared to shallower water (4 m). The study observed that gas plumes in deeper water tended to have larger diameters, affecting how the gas disperses as it travels upward. Additionally, hole size dramatically influenced dispersion characteristics and fountain height, with larger holes (90 mm) producing fountains roughly 2.1 times higher than smaller holes (25 mm) and creating different dispersion patterns at the water surface. Drag forces, as a result from water resistance caused gas bubbles to split into smaller bubbles and spread out horizontally as they rise, creating the plume pattern observed in real underwater gas leaks.

2.3.3 Fire

In gathering and transmission pipeline systems, natural gas fires can occur through several primary mechanisms. When a high-pressure release occurs, the gas typically forms a plume that, upon ignition, can create either a jet fire (from smaller releases under pressure) or a larger fireball in cases of sudden, substantial releases.

The ignition dynamics differ from residential scenarios due to the higher pressures and volumes involved. The gas-air mixture in pipeline ruptures can ignite through several mechanisms during a release event. High-velocity gas releases generate static electricity, which serves as a potential ignition source. During the initial rupture, rocks and debris propelled by the escaping gas can create sparks upon impact. Operating vehicles and equipment in the vicinity pose additional ignition risks through their engines and electrical systems. Environmental factors like lightning strikes or other electrical sources in the area can also trigger ignition. The rupture event itself presents ignition hazards through metal-to-metal contact as pipeline components interact during the failure. These various ignition sources, combined with the proper gas-air mixture concentration, can lead to fire events in gathering and transmission pipeline systems. The resulting fires in transmission pipelines are particularly challenging because of their intensity and the continuous fuel supply at high pressure, although this intensity can decrease over time as emergency valve closures activate and reduce gas supply. These fires exhibit higher heat release rates than residential gas fires due to the greater volumes and pressures involved, with the specific magnitude depending on pipeline diameter, operating pressure, and the timing of emergency response measures. The flame characteristics often include a vertical component due to the buoyancy of the hot gases and the momentum of the release. The approach to managing these fires must account for factors such as pipeline pressure, gas composition, terrain, and weather conditions, making each incident unique in terms of response requirements (Leishear 2019).

2.3.3.1 Intensity of Fire

When a natural gas pipeline releases, the resulting heat can be measured in two ways. Heat radiation flux is the total heat energy reaching a specific area, measured in watts per square meter (W/m^2). This measurement quantifies the total heat impact at a defined distance from the release point, regardless of direction. Using this measurement the potential thermal damage to resources can be determined. Heat radiation intensity measures how the heat is distributed in different directions, measured in watts per square meter per steradian ($W/m^2 \cdot sr$). This quantifies the directional distribution of thermal radiation, indicating whether energy is concentrated in specific directions or dispersed more uniformly across the surroundings. Both measurements help determine safe distances during a pipeline incident, but they provide different information: heat radiation flux tells you the overall heat impact at a location, while heat radiation intensity reveals how that heat is distributed across the area, which is important for planning evacuation routes and positioning emergency responders. Intensity is often used to refer to both heat radiation flux and heat radiation intensity concepts. Throughout this section, unless otherwise specified, 'intensity' primarily refers to heat radiation flux (Brenda Jacklitsch et al. 2016; Heus and Denhartog 2017).

The intensity of a fire resulting from a natural gas pipeline leak is influenced by the complex interaction of several key factors. The gas release rate is a primary determinant of fire intensity. This rate is largely governed by two factors: the pressure differential between the pipeline and the surrounding environment, and the size of the leak or rupture. If a gas pipeline release occurs underwater, the ambient pressure becomes higher due to water depth. This increased ambient pressure reduces the effective pressure differential between the pipeline and the surrounding water, resulting in a lower gas release rate compared to an identical rupture at atmospheric conditions. A higher pressure differential will cause gas to escape more rapidly, potentially fueling a more intense fire. Similarly, a larger hole or rupture will allow more gas to escape, increasing the potential fire intensity. The relationship between these factors is not linear; small changes in pressure or hole size can lead to substantial changes in gas release rates. The physical characteristics of the pipeline itself also play a role. The diameter of the pipeline and its operating pressure are particularly important. Larger diameter transmission pipelines, typically 20 to 48 inches, contain a greater volume of gas, which can sustain a more intense and longer-lasting fire if ignited. Higher operating pressures not only increase the gas release rate but also the potential energy available for combustion. As a result, fires from high-pressure, large-diameter transmission pipelines tend to be more severe than those from smaller, lower-pressure distribution lines, typically 6 to 12 inches.

The timing and nature of ignition is an important factor. Immediate ignition of a gas leak typically results in a jet fire, a high-velocity stream of burning gas. These fires can be extremely intense and difficult to extinguish, but they are often localized to the area immediately surrounding the leak. In contrast, delayed ignition allows gas to accumulate and mix with air, potentially leading to flash fires or explosions. Flash fires can cover a larger area but are typically of shorter duration, while explosions can cause damage over a wide area. These factors interact in complex ways. For example, a high-pressure leak from a large pipeline might result in a very intense jet fire if ignited immediately, but could lead to a devastating explosion if ignition is delayed and the gas is allowed to disperse. Environmental conditions such as wind speed and direction, ambient temperature, and humidity can also influence fire behavior and intensity (Brenda Jacklitsch et al. 2016; Heus and Denhartog 2017).

In addition to intensity, the effects of thermal radiation, i.e., heat transfer, may be important. Li et al. (2024) examines jet fires from both pure natural gas and hydrogen-natural gas mixtures. When examining pure natural gas jet fires from pipeline ruptures, the flame height demonstrates a direct relationship with pressure and mass flow rate. Under high-pressure conditions of 7.16 MPa, natural gas flames can reach heights of approximately 100 m before gradually diminishing as the pressure decreases. The flames exhibit distinctive visual characteristics, appearing as stable structures with yellow-orange coloring due to soot formation, a pattern more consistent than that observed in hydrogen-enriched mixtures. Natural gas produces more intense thermal radiation compared to hydrogen-enriched mixtures at equivalent pressures, primarily due to its higher radiative heat transfer properties and characteristic soot formation during combustion. At approximately 65 m from the flame centerline, the thermal radiation level of 25 kW/m² presents a lethal hazard zone. The risk of second-degree burns extends to about 100 m where radiation levels reach 9.5 kW/m², while first-degree burn risks persist up to 145 meters at 4 kW/m². The research indicates that hazard distances vary with pipe pressure and hydrogen blending ratio, so the specific safe distance would depend on these operational parameters (Brenda Jacklitsch et al. 2016; Heus and Denhartog 2017).

2.3.3.2 Impact Radius of Fire

$$r = 0.69\sqrt{pd^2}$$

Equation 7. Potential impact radius

The equation for Potential Impact Radius (PIR) (**Equation 7**) is defined within 49 C.F.R. § 192.903, where:

- 0.69 = Factor for natural gas
- r = PIR of the thermal radiation of the jet/trench fire (ft)
- p = Pipeline maximum allowable operating pressure (MOAP) (pounds per square inch (psi))
- d = Pipeline nominal diameter (inch (in))

This formula is based on the premise that thermal radiation from a jet/trench fire is the dominant hazard in a pipe rupture and ignition scenario (PHMSA 2025).

The definition of PIR within 49 C.F.R. § 192.903 was discussed in FR 69778 noting it is based on the C-FER model. When developing the C-FER model, Stephens (2000) found that natural gas pipeline failures posed hazards primarily through thermal radiation from sustained trench fires. Outcomes are based on three factors: immediate versus delayed ignition, release characteristics (obstructed vs. unobstructed), and local versus remote ignition points. Outcomes range from fireballs transitioning to jet/trench fires (in immediate ignition scenarios) to no significant hazard (in cases of delayed remote ignition with no ignition). However, the dominant hazard identified was thermal radiation from sustained jet or trench fires, as flashfires are unlikely due to natural gas's buoyant properties preventing persistent vapor cloud formation. This informed the three-part model consisting of: a fire model relating gas release to heat intensity as a function of distance; an effective release rate model approximating transient release with a decay factor based on Dutch Organisation for Applied Scientific Research (TNO) research showing rapid reduction in flow after rupture; and a heat intensity threshold of 5,000 Btu/hr-ft² defining potential harm levels. Model validation utilized pipeline incident reports from the NTSB and TSB dating back to 1970, comparing actual burn areas and injury distances against predicted hazard zones. The comparison

demonstrated that the model consistently provided conservative estimates, with calculated hazard radii typically exceeding actual burn extents.

Advanced models for calculating the intensity of fires from natural gas pipeline releases incorporate several complex factors to provide more precise estimations. These models go beyond basic formulas to account for the dynamic nature of gas releases and fire behavior. Mass flow rates through the pipeline, combustion characteristics of natural gas, and environmental conditions, all influence fire intensity calculations. The rate at which gas escapes depends on the pipeline's internal pressure, rupture size and shape, and gas composition. Advanced models use computational fluid dynamics to simulate gas flow through breaches, while incorporating detailed chemical kinetics to account for the specific composition of natural gas and its combustion properties including heat of combustion, flame temperature, and burning velocity. These sophisticated approaches provide more accurate estimations of fuel availability, flame structure, heat release rates, and combustion products than simpler methods. While basic calculations using steady-state assumptions and simplified gas behavior may lack precision, they serve important purposes in preliminary hazard assessments, emergency response planning, and situations where computational resources are limited. Simple models provide quick estimates that, despite their limitations, can help establish safety zones and inform initial decision-making during incidents. Advanced models, however, excel when detailed analysis is required for infrastructure design, regulatory compliance, or forensic investigation of incidents. Environmental conditions alter fire behavior and are carefully considered in advanced models. Wind speed and direction can dramatically alter the shape and direction of the fire, affecting its intensity and the area at risk. Temperature and humidity influence the rate of fuel vaporization and the mixing of gas with air, which in turn affects combustion efficiency. Atmospheric stability conditions can impact the dispersion of the gas cloud and the potential for delayed ignition scenarios. Advanced models often use computational tools like Large Eddy Simulation to account for these environmental factors and their complex interactions with the fire dynamics (Li et al. 2024).

These advanced modeling techniques allow for more tailored simulations of pipeline fire scenarios, enabling better risk assessment and emergency planning. Site-specific factors such as local terrain, typical weather patterns, and nearby infrastructure can be incorporated to generate predictions that more accurately reflect the unique characteristics of each location. However, it is important to note that even the most sophisticated models have limitations, and real-world fire behavior can still deviate from predictions due to unforeseen variables or extreme conditions.

2.3.3.3 Duration of Fire

The duration of a fire resulting from a natural gas pipeline leak is determined by several interconnected factors. The most important factor is the characteristics of the fuel supply itself, specifically the volume and pressure of natural gas contained within the pipeline segment. Higher pressure systems and larger diameter pipelines contain greater fuel volumes that can sustain combustion for longer periods. The ability to isolate the affected section through emergency shutdown systems and block valves plays an important role, as the fire may continue until either the fuel supply is exhausted or successfully isolated.

Environmental conditions substantially influence fire duration through their effects on gas dispersion and combustion. Wind patterns affect how the gas mixes with air and how the fire behaves, while ambient temperature and humidity levels impact both dispersion patterns and combustion characteristics. The

physical configuration of the pipeline breach is also determinative, a small crack produces different burning dynamics compared to a complete line rupture.

The duration is further shaped by emergency response capabilities, particularly how quickly operators can isolate the affected pipeline segment and how effectively emergency services can manage the incident. The positioning of the ignition source relative to the gas leak affects the fire's stability and persistence. When ignition occurs at the optimal fuel-air mixture point, the resulting fire tends to be more stable and longer-lasting than if ignition happens at the edges of the gas plume.

It is important to note that in many cases, the duration of these fires is actively managed rather than left to natural extinction. Emergency responders often employ a controlled burn strategy, allowing the fire to continue while managing the fuel supply, as this is typically safer than extinguishing the fire while gas continues to escape. This approach prevents the formation of explosive gas clouds but means that fire duration becomes a function of emergency response protocols rather than purely natural factors.

2.3.3.4 Types of Fire

Natural gas pipeline releases can result in several distinct types of fires, each with unique characteristics and hazard profiles. The most common type is a jet fire, which occurs when pressurized gas is released through a relatively small opening and immediately ignited. These fires produce a concentrated, high-velocity flame that can extend long distances from the release point. Jet fires pose particular risks to nearby structures and equipment due to their intense, focused heat output and potential for direct flame impingement. Liu and An (2024) demonstrate that the shape of leakage holes in buried natural gas pipelines affects leak rates and diffusion patterns. According to their findings, irregular leak holes (like cracks) produce higher leakage rates than regular shapes (like circular holes) of the same area. Specifically, their research shows that crack-shaped leaks have the highest leakage rates, followed by rectangular holes, irregular hole shapes, and circular holes have the lowest rates. The difference between crack and circular hole leakage rates was quantified at 5.89×10^{-4} kg/s under comparable conditions. The irregular hole shapes also showed asymmetric pressure and velocity distributions near the leak point, unlike the more symmetrical patterns of circular holes. The paper notes that diffusion speeds and distances for irregular leak holes are consistently larger than those of regular shaped holes, with crack-shaped leaks reaching diffusion distances of 1.331 m compared to only 1.122 m for circular holes under the same conditions. Release pressure influenced jet fire characteristics. At 7,000 kPa pressure, flames extended almost twice as far as comparable 2,000 kPa releases, demonstrating how higher pressures intensify the jet fire hazard zone. This pressure effect was particularly pronounced in horizontal releases, where flames remained stable around 10–13 m downstream from the release point. Hankinson et al. (2000) found that wind conditions also play a complex role in jet fire behavior. Downwind releases produced longer flames and extended hazard zones compared to upwind releases, with flame lengths approximately 25% longer. However, higher wind speeds actually reduced flame length through enhanced mixing, though the flames remained more directionally stable. This was evident in the experimental data where increased wind speeds led to shorter but more predictable flame patterns.

Other types of fire include pool fires, flash fires, vapor cloud explosions, and combination fires. Pool fires can develop when liquefied natural gas (LNG) components accumulate in low-lying areas before ignition. While less common in typical pipeline scenarios, these fires can occur in situations where the gas has

been cooled or pressurized to the point of liquefaction. Pool fires spread horizontally and typically produce lower flame heights but cover larger surface areas than jet fires. Flash fires occur when a vapor cloud of natural gas ignites without generating substantial overpressure. These fires burn rapidly through the premixed fuel-air cloud and typically last only seconds, but they can trigger more sustained fires if additional fuel sources are present. Flash fires pose particular risks because they can affect large areas almost instantaneously. Vapor cloud explosions begin as deflagrations (fires) before potentially transitioning to sustained fires. These events occur when leaked gas forms a vapor cloud that becomes confined or encounters turbulent conditions before ignition. The resulting explosion can lead to sustained fires at the release point or multiple locations where flammable materials are present. Combination fires can develop when initial releases evolve through multiple fire types. For example, a jet fire might lead to secondary pool fires, or a vapor cloud explosion might result in sustained jet fires at the pipeline breach point. These complex scenarios often present the greatest challenges for emergency response teams due to their dynamic nature and multiple hazard zones. The type of fire that develops depends largely on the release conditions, environmental factors, and the timing of ignition relative to the initial gas release (Sluder et al. 2022).

2.3.4 Explosion

Pressure transients have been identified as the primary trigger for natural gas pipeline explosions. Pressure transients are sudden changes in pressure within a pipeline system, similar to pressure waves or surges that travel through the pipeline like sound waves through air. The process involves a specific combination of three elements: air accumulation at pipeline low points, the presence of methane gas, and pressure changes that compress this mixture to the point of ignition. Ambient air, being heavier than methane, naturally settles at low points in the pipeline system. This air can enter the system in two ways: either as trace quantities within the natural gas itself or during maintenance procedures when the pipeline is opened to the atmosphere. When this air mixes with methane at these low points, it creates conditions for a potential explosion. These conditions specifically include: the right air-to-Methane ratio that forms a combustible mixture (methane is explosive between 5–15% concentration in air); sufficient compression from the pressure transient to raise the temperature of this mixture; and when that temperature exceeds the ignition point of the methane-air mixture spontaneous ignition occurs without the need for an external ignition source (Leishear 2019).

Leishear (2019) examined three accidental explosions within natural gas pipelines in Carlsbad, New Mexico; San Bruno, California; and Amherst, South Dakota. The Carlsbad, New Mexico explosion killed twelve people who were 675 ft away from the site. A crater (113 × 51 ft) may indicate air had accumulated at a low point in the pipeline. While corrosion had weakened the pipe, it was not the direct cause of rupture. Pressure transients weren't investigated but Leishear (2019) suspects were they likely present yet undetected due to inadequate measurement systems. The San Bruno, California explosion killed ten people and created a 1000-foot high fireball. Intentional pressure transients were measured at the time of the explosion. The explosion occurred at a localized low point in the pipeline where air had collected, creating ideal conditions for the methane-air mixture to ignite. The Amherst, South Dakota explosion was preceded by a documented pressure increase from 1,170 psig to 1,352 psig (a 15.6% increase). This pressure increase may have created the compression needed to trigger the explosion mechanism. These three cases demonstrate how pressure transients may result in explosions.

The NTSB (2023) found in the Kinder Morgan explosion investigation that the pipeline rupture and explosion occurred due to a chain of events. The primary cause was a phenomenon called “stress corrosion cracking” that developed along the pipeline's longitudinal seam weld. This occurred because of a defect in how the pipeline's protective coating was applied, The spiral wrap tape coating had separated from the pipe surface at the weld seam. This created a gap between the coating and the pipe surface, allowing moisture to collect. The moisture accumulation was particularly problematic because the tape coating shielded that area from the pipeline's cathodic protection system, which would normally help prevent corrosion. Over time, three separate regions of stress corrosion cracking developed at the weld seam. These cracks eventually spread and connected into one larger fracture, which ultimately caused the pipeline to rupture catastrophically. A contributing factor was that Kinder Morgan's records incorrectly listed the pipeline's coating type as fusion-bonded epoxy rather than spiral wrap tape in their Pipeline Open Database Standard (PODS). This error meant their risk assessment process failed to identify the elevated risk of stress corrosion cracking at this location, as spiral wrap tape coating is known to be more vulnerable to stress corrosion cracking than other coating types. The rupture resulted in the release of natural gas that ignited (no source indicated) and exploded, creating a blast wave and gas-fed fire. The explosion destroyed a farmhouse approximately 451 ft away, killing two occupants and seriously injuring a third. The blast also damaged about 33 acres of surrounding vegetation and ejected a 47-foot segment of pipe about 133 ft from the crater.

2.3.4.1 Strength of Explosion

The strength (or intensity) of a natural gas explosion is determined by several factors and can be calculated using specific models. Liu et al. (2023) discusses the use of the TNO Multi-Energy Method (MEM) commonly used to predict explosion strength. This method assumes a hemispherical steam cloud ignited at the center and uses explosion intensity curves based on experimental and simulation data. The explosion intensity is graded on a scale of 1 to 10, with 10 being the strongest. These terms are used interchangeably because in the TNO MEM model, the explosion "strength" is quantified as an "intensity" grade (1–10), which becomes the key parameter for calculating blast effects like overpressure and impulse. The grade is determined by considering factors such as ignition energy, presence of obstacles, and confinement. For example, strong ignition with obstacles and confinement results in a grade of 7–10, while weak ignition without obstacles or confinement yields a grade of 1–2.

The equation for proportional distance can be expressed as:

$$r' = r(p_a/E)^{\frac{1}{3}}$$

Equation 8. Proportional distance

Once the intensity grade is determined, the explosion load is calculated using the proportional distance formula (**Equation 8**) where:

- r' = proportional distance (m)
- r = distance from the explosion source (m)
- E = energy released during explosion (joules (j))
- p_a = atmospheric pressure

This proportional distance is a scaling parameter that connects explosion strength to its effects at different distances. "Explosion strength" refers to the energy released during the explosion (E), while "explosion load" refers to the actual forces exerted on structures, primarily through overpressure. By calculating proportional distance, engineers can predict how the explosion's destructive potential diminishes with distance, regardless of the initial explosion energy. The peak overpressure (P_s) at any given distance from the explosion center represents the maximum pressure exceeding atmospheric pressure that structures will experience during an explosion. This overpressure is the primary component of the explosion load on surrounding structures. As the proportional distance increases, the peak overpressure decreases, following established blast wave propagation principles. The concentration of natural gas affects explosion strength. The explosion limit for natural gas is 5%–15%, with the most violent explosion occurring at a concentration of about 9.5%. At this concentration, the explosion intensity reaches its maximum, with a peak overpressure of 3.473 kilopascals (kPa). The explosion wave overpressure attenuates as it moves away from the center. This attenuation follows a specific pattern that can be modeled and predicted, which is important for assessing potential damage at various distances from the explosion source.

2.3.4.2 Radius of Explosion

The equation for cloud radius can be expressed as:

$$r = \sqrt{\frac{3Q}{4\pi \times 0.095}}$$

Equation 9. Cloud radius

The radius of the cloud for a natural gas explosion, is estimated using **Equation 9**, where:

- Q = leaked natural gas (m^3)
- 0.095 = the natural gas concentration (9.5%) with the most violent explosion potential

The formula assumes that the leaked gas forms a hemispherical cloud on the ground, the gas is uniformly mixed with air at the most explosive concentration (9.5%), and all leaked gas contributes to forming the explosive mixture. This equation is derived from the volume formula of a hemisphere (**Equation 10**):

$$V = \frac{2}{3}\pi r^3$$

Equation 10. Hemisphere volume

V is the volume of the gas-air mixture at 9.5% concentration. Since Q represents the volume of pure natural gas, we divide it by 0.095 to get the total volume of the gas-air mixture in **Equation 11**:

$$\frac{2}{3}\pi r^3 = \frac{Q}{0.095}$$

Equation 11. Mixture volume

Solving for r gives us the formula used to calculate the explosion cloud radius. This calculation helps estimate the potential size of an explosion (Liu et al. 2023). Note that this calculation assumes non-

gaussian dispersion and likely overestimates the radius of the vapor cloud. If gaussian dispersion estimates are available, they are likely more accurate.

2.3.4.3 Duration of Explosion

The duration of an explosion, also known as the positive pressure duration, is an important parameter in assessing the potential damage caused by an explosion. It is typically calculated using the TNO Multi-Energy Method (MEM) along with other explosion characteristics.

$$t_p = t_p' \frac{\left(\frac{E}{P_a}\right)^{\frac{1}{3}}}{a_a}$$

Equation 12. Pressure duration

The actual positive pressure duration is determined using **Equation 12** where:

- t_p = positive pressure duration
- t_p' = dimensionless positive pressure duration
- E = explosion energy of the gas cloud
- P_a = atmospheric pressure
- a_a = speed of sound in the atmosphere (340 m/s)

The importance of the explosion duration lies in its role in determining the total impulse delivered to structures and objects, the likelihood of structural failure or collapse, and the potential for injury to personnel. A longer positive pressure duration can cause more severe damage, even at lower peak overpressures, as it allows more time for the pressure to act on structures and objects. The positive pressure duration is closely related to other explosion parameters such as peak overpressure and scaled distance (r'). These factors provide a comprehensive understanding of the explosion load and its potential effects on the surrounding environment (Liu et al. 2023).

2.3.4.4 Types of Explosions

Natural gas pipeline releases can lead to several types of explosions with distinct characteristics and potential consequences. The main types include:

Vapor Cloud Explosion (VCE): This occurs when a large amount of natural gas releases and mixes with air, forming a flammable vapor cloud. If ignited, it can result in a powerful explosion. The severity of a VCE depends on factors such as gas concentration, ignition energy, presence of obstacles, and degree of confinement.

Jet Fire: Although not strictly an explosion, a jet fire can occur when high-pressure gas escapes from a pipeline breach and is immediately ignited. This can cause increased damage due to the intense heat and flame.

Fireball: If a large amount of gas is released suddenly and ignited, it can form a rising fireball. This type of explosion is characterized by a brief but intense release of heat and light.

Confined Explosion: This occurs when leaked gas accumulates in an enclosed or partially enclosed space before ignition. Due to pressure buildup, confined explosions can be more severe than those in open areas.

The distinctness of these categories, in real-world incidents, explosions rarely fall neatly into a single category. These classifications serve more as a reference framework for understanding the predominant mechanism rather than mutually exclusive categories. Many pipeline incidents involve multiple explosion types occurring in sequence or simultaneously. For example, an initial jet fire might lead to a broader vapor cloud explosion as conditions evolve. The categorization helps with risk assessment and mitigation planning, but actual events often demonstrate overlapping characteristics depending on factors such as release rate, environmental conditions, confinement, and ignition timing. Explosions from subsea natural gas pipelines generally occur at the water/atmosphere interface and not underwater. This is because natural gas requires oxygen for combustion, which is limited in underwater environments where high pressure further inhibits explosive reactions. When gas escapes from a subsea pipeline breach, it rises through the water column and creates a flammable mixture upon reaching atmospheric oxygen at the water's surface. This interface zone becomes the most likely location for ignition and subsequent explosion to occur, rather than at the underwater pipeline breach point itself (Liu et al. 2023).

2.3.4.5 Explosion Model Comparisons

Park and Lee (2009) compare various models for predicting gas explosions, including correlation models and Computational Fluid Dynamics (CFD) models. The TNO model, Baker-Strehlow (BS) model, and Multiple-Energy (ME) are all correlation models. The TNO model, assumes that only the combustion energy in confined or obstructed parts of the flammable cloud contributes to pressure generation during an explosion. It accounts for the positive feedback mechanism of gas explosions, where flame acceleration occurs in turbulent regions due to obstacles. The model uses a flux-corrected transport code to simulate the explosion of a centrally ignited hemispherical, homogeneous, stoichiometric cloud with constant flame speed. It employs blast charts to determine peak overpressure and the duration of the positive phase, relating dimensionless overpressure to the combustion energy scaled distance. The TNO model introduces a source strength index, ranging from 1 (weak explosion in an unobstructed region) to 10 (detonation), which determines which curve to use in the blast charts. The source strength depends on the number, type, and orientation of obstacles present in the obstructed region, as well as the fuel reactivity. BS is an empirical approach for predicting gas explosion effects that uses dimensionless parameters to relate overpressure and positive impulse to energy-scaled distance. It focuses on spherical air explosions rather than hemispherical ones. The model determines explosion severity by evaluating maximum flame speed based on fuel reactivity, confinement degree, and obstacle density. Its uniqueness lies in using numerical modeling of constant and accelerating flame velocities to establish blast wave strength proportional to the Mach number achieved within the cloud. Though more advanced than trinitrotoluene (TNT)-equivalence methods for vapor cloud explosion prediction, the model still has limitations in handling non-symmetric clouds and accounting for specific obstacle locations. The ME model shares similarities with the BS model, particularly in how they define source energy and determine initial explosion strength or flame speed based on confinement and obstruction. Correlation models, such as the TNO, ME, and BS model, are relatively simple to use and provide quick estimates. CFD models provide the most detailed and potentially accurate results, but they require substantial computational

resources and expertise to use effectively. They are useful for initial assessments and screening studies. For specific situations, when available, specialized models tailored to particular industries or scenarios (e.g., models developed for offshore platforms or specific types of process equipment) can provide more accurate and relevant results. However, these should be used in conjunction with, rather than instead of, more general models to ensure a comprehensive risk assessment. Overall, TNO provides a balance between simplified empirical models and complex CFD models, making it a useful tool for predicting gas explosion in various industrial settings.

2.4 Physical, Biological, and Socioeconomic Resources Potentially Impacted by Natural Gas Pipeline Releases

During any proposed action, all interested parties are given the opportunity to review and comment on the concerns of potential impacts they may face. When a gas development project is proposed the comments within EIS highlight the public's concern of oil and gas activities on local endangered species, critical habitats/ protected areas, subsistence fishing and hunting that may impact food security, commercial and sport fishing, and potential impact on local resources from a gas release.

Researching the effects of natural gas pipeline releases on physical, biological, and socioeconomic resources in Alaska presents challenges due to a lack of specific, in-depth studies tailored to this unique environment. While there is abundant research on related topics, much of it fails to address the particular circumstances found in Alaska. Many studies concentrate on oil production, exploration, and development phases rather than specifically addressing natural gas pipeline releases, leading to gaps in understanding the distinct impacts of these releases. Furthermore, research on unconventional gas exposure often involves different chemical makeups compared to the natural gas transported through Alaskan pipelines, making it difficult to draw direct comparisons and apply findings to Alaska's situation. Studies conducted in other locations may not account for Alaska's unique climate and remote nature, as the state's harsh weather conditions, permafrost, and vast wilderness create a set of environmental factors that are not easily comparable to other regions. Alaska's weather and isolated landscapes pose unique challenges for pipeline infrastructure and release detection, potentially influencing how gas releases behave and impact the surrounding environment. The state's diverse and often vulnerable ecosystems may react differently to natural gas pipeline releases compared to more developed or temperate regions, requiring specialized research to understand potential impacts fully. Additionally, Alaska's economy and communities are closely tied to its natural resources, including oil and gas development, necessitating a nuanced approach to studying the socioeconomic impacts of natural gas pipeline releases.

2.4.1 Air Quality

Natural gas pipeline releases present challenges for air quality management due to the complex nature of emissions. The impact of these releases may be complicated by environmental conditions such as temperature variations, as well as geographic factors like topography, which can influence how emissions disperse and concentrate in the atmosphere. Research indicates that a small percentage of facilities, known as "super-emitters" (primarily production sites) can be responsible for a disproportionate amount of total emissions, often due to equipment malfunctions or maintenance (Garcia-Gonzales et al. 2019). Lattanzio (2016) found that the economic feasibility of the Environmental Protection Agency's (EPA)

federal air standards of 2012 implementing control measures for the “Crude Oil and Natural Gas Production” and “Natural Gas Transmission and Storage” source categories, requiring producers to reduce emissions escaped methane and VOCs by 95%, remains debated. Regulatory projections put the implementation cost at \$170 million annually and calculate a net gain of \$11–\$19 million per year from selling recovered gas. Industry estimates however dispute these figures, suggesting a much higher compliance cost exceeding \$2.5 billion annually (Lattanzio 2016). This highlights the debate about the economic feasibility of emissions controls relative to their benefits. EPA regulations mentioned in Lattanzio may have changed since 2012 and not reflect current conditions.

Natural gas emissions fall into three distinct categories as identified by the Congressional Research Service: fugitive, combusted, and associated emissions (Lattanzio 2016). Fugitive emissions encompass both intentional venting and unintentional natural gas pipeline releases during operations, releasing methane, VOCs, and hazardous air pollutants (HAPs). When natural gas is burned during operations, whether for safety through flaring or to power equipment, it produces combusted emissions including carbon dioxide, carbon monoxide, nitrogen oxides, and trace amounts of sulfur dioxide and particulate matter. The third category, associated emissions, comes from secondary sources such as fossil fuel combustion for equipment and transportation needs (Lattanzio 2016). The challenge of measuring and quantifying these emissions remains a hurdle in understanding their full impact on air quality. While some emission sources can be estimated with reasonable accuracy, others prove more elusive, particularly fugitive emissions from activities like hydraulically fractured well completions and flowback. The industry primarily relies on a 1996 EPA and Gas Research Institute methane study for emissions data, which, despite updates, may not fully reflect current industry practices (Lattanzio 2016). This has led to competing emissions estimates from various stakeholders, highlighting the need for a comprehensive national inventory based on direct measurements.

2.4.1.1 Environmental Conditions and Monitoring

Temperature variations and permafrost conditions can potentially compromise pipeline integrity, increasing the risk of fugitive emissions, the unintentional release of methane gas that escape during production, processing, transmission, storage, and distribution of natural gas (Lattanzio 2016, 2020). Due to their scale, transmission, and storage sectors, including extensive pipeline networks, represent substantial emission sources. While these downstream activities generally involve processed gas with lower VOC and HAP content, methane remains a primary concern for natural gas pipeline releases (Lattanzio 2016; 2020). Kvenvolden et al. (1993) examined methane concentrations in the Beaufort Sea continental shelf by comparing their measurements of ice-covered water near Oliktok Point, Alaska with previously published data (Macdonald 1976) on ice-free water near the Mackenzie River Delta in Canada. Their research revealed that methane concentrations under winter ice were substantially higher (3 to 28 times greater) than in summer when ice was absent, ranging from 10.7 to 111.8 nanomolar (nM) compared to approximately 3.8 nM in ice-free conditions. The researchers found the highest methane concentration in water (111.8 nM) at a sampling station near the Colville River. More notably, an ice sample collected from the same location contained a methane concentration ten times higher (1,100 nM). When scientists analyzed the carbon isotope ratio of this ice sample, they found a value of -78.4‰ (per mil, or parts per thousand). This highly negative isotope value is characteristic of methane produced by microorganisms. This distinguishes it from methane originating from geological processes like those that

form natural gas deposits, which typically have less negative isotope values (around -39‰). This isotopic evidence confirms that the methane trapped in the ice came from biological activity rather than from deep underground gas sources. The researchers concluded that methane accumulates under sea ice during winter and rapidly ventilates when ice melts in summer. These findings have potential implications for natural gas pipeline releases in Arctic and possibly sub-Arctic regions such as Cook Inlet. During ice-free summer months, methane from pipeline leaks would likely disperse more readily into the atmosphere, creating more diffuse impacts. Conversely, winter conditions could allow methane to accumulate under ice cover, potentially creating higher localized concentrations that release suddenly during spring break up.

Garcia-Gonzales et al. (2019) found in their synthesis of peer-reviewed literature on hazardous air pollutants (HAPs) associated with upstream oil and natural gas development that there were limitations of short-term sampling in capturing episodic emission events, which would be magnified in some remote Alaskan locations where continuous monitoring may be logistically difficult. The review identified specific emission sources including wellheads, compressors, dehydrators, separators, and storage tanks, with the production phase showing potential to emit the highest concentrations and most varied mixture of HAPs over extended periods. The review found that 10% of facilities primarily production sites with equipment malfunctions, condensate tanks with ineffective controls, and compressor stations contribute disproportionately to total emissions, which could be particularly relevant where infrastructure faces seasonal temperature extremes ranging from -60°F to 80°F. Understanding atmospheric transport of emissions has added complexity in some Alaskan regions due to unique weather conditions that affect pollutant dispersion. Cold surface temperatures often create stable air layers that trap pollutants close to the ground, while air flowing downhill from mountains can quickly transport concentrated emissions into populated valleys.

2.4.1.2 Major Incident Case Study: Aliso Canyon in California

The Aliso Canyon natural gas leak occurred at well SS-25 in Los Angeles County, California, approximately 20 miles Northwest of Los Angeles. It began on October 23, 2015, and continued for 112 days until February 11, 2016. The immediate technical cause was a breach in the 7-inch production casing at approximately 440 feet below ground. This well was one of 115 wells at the underground storage facility owned by Southern California Gas Company. While the technical failure point was identified, the root cause was still under investigation when the paper was published (Jacobson 2019). The release resulted in public health impacts for nearby communities, particularly in Porter Ranch in Orange County, California which was at the epicenter of the release. Over 2,300 odor complaints were filed, and more than 6,800 households had to be relocated. Residents experienced multiple health symptoms including odor-related issues, dizziness, headaches, nausea, eye and throat irritation, and nosebleeds. The primary component was methane at 97,100 tonnes, followed by ethane at 7,300 tonnes and propane at 595 tonnes. The leak also released smaller amounts of potential health concern compounds such as benzene (2.43 tonnes), toluene (3.57 tonnes), and xylenes (2.90 tonnes). Various other hydrocarbons were emitted including butanes (approximately 112 tonnes combined), pentanes (about 35 tonnes combined), and several hexane variants (totaling around 19 tonnes).

The Aliso Canyon gas leak also impacted air quality throughout the Central Valley, San Francisco Bay area, and the Los Angeles Basin. The methane plume and other hydrocarbons spread widely throughout these

areas, triggering photochemical reactions that increased levels of harmful secondary pollutants including carbon monoxide, formaldehyde, acetaldehyde, peroxyacetyl nitrate, and ozone. The methane's effect on atmospheric stability reduced precipitation, which limited the natural removal of particulate matter from the air. This resulted in an increase in PM_{2.5} (particulate matter with a diameter of 2.5 micrometers or smaller) concentration. These extremely fine particles are dangerous to human health because they can penetrate deep into the lungs and even enter the bloodstream. The increase in PM_{2.5} resulted in an estimated 32–43 additional premature mortalities within the study area during the study period. While the Aliso Canyon leak occurred in Southern California, many of the estimated premature mortalities occurred north in the Central Valley and San Francisco Bay Area, demonstrating that localized pollution events have widespread health consequences through complex atmospheric mechanisms beyond direct exposure to primary pollutants (Jacobson 2019).

The environmental impact of the Aliso Canyon gas leak was substantial, with approximately 87,100 metric tonnes of methane released (Jacobson 2019). The California Air Resources Board's (CARB) measurements showed this single source increased California's greenhouse gas emissions by about 25% above normal levels during the incident period (California Air Resources Board 2016). Both Jacobson's paper and the CARB report emphasize how this represented an unprecedented release that far exceeded routine industrial emissions, making it the largest documented methane release in U.S. history at the time of the event.

2.4.1.3 Human Health Impact Studies

Research has shown that long-term exposure to natural gas and its components may lead to several chronic health effects: respiratory issues, neurological effects, cancer risk, and reproductive/developmental effects (Hasselblad et al. 1992). These adverse effects may be the result of nitrogen dioxide and carbon monoxide exposure, which are a byproduct of indoor combustion processes regardless of fuel type. Prolonged exposure to natural gas can cause respiratory problems, including asthma and other breathing difficulties. Children are particularly vulnerable, with studies showing a 20% increase in the odds of developing respiratory illness from gas stove exposure (Hasselblad et al. 1992). Gruenwald et al. (2023) found that 12.7% of childhood asthma cases in the U.S. are attributable to gas stove use. Long-term exposure, as a result of carbon monoxide, may result in neurological symptoms such as headaches, dizziness, fatigue, and cognitive impairments and that symptoms persist even after a leak is fixed (Rose et al. 2017). Exposure to nitrogen dioxide (NO₂), a by-product of gas combustion, has been linked to increased mortality and chronic lung disease (Saki et al. 2020). In some cases natural gas may contain benzene, a known carcinogen. Long-term exposure to benzene can increase the risk of developing leukemia and other blood disorders. Some components in natural gas have been associated with reproductive and developmental issues, potentially affecting fetal development (Michanowicz et al. 2022a).

Willis et al. (2020) examined the relationship between natural gas development and pediatric asthma hospitalizations in Texas from 2000–2010. The researchers found health impacts from both conventional (vertical) and unconventional (horizontal/directional) drilling methods. Their analysis showed that zip codes with unconventional drilling had up to 59% higher odds of pediatric asthma hospitalizations compared to areas without drilling, while conventional drilling was associated with up to 23% higher odds of hospitalizations. The study further revealed that increasing natural gas production volumes were

associated with increased pediatric asthma hospitalizations in an exposure-response relationship, suggesting that production-related activities may be driving these associations. The study also found that while unconventional drilling showed higher rates of pediatric asthma hospitalizations, its impact appeared to be tied to specific operational characteristics: deeper well penetration, greater resource intensity (water, chemicals, materials), and higher waste production volumes. Conventional drilling, though associated with lower hospitalization, presents distinct exposure pathways through its typically higher well density within smaller geographic areas, creating potentially widespread community exposure despite lower individual well emissions. Production volume appeared to be a key factor, demonstrating an exposure-response relationship with asthma hospitalizations. This suggests that ongoing emissions during the production phase, including pipeline releases and other operational emissions beyond the initial drilling period, contribute to respiratory health outcomes across affected communities (Willis et al. 2020). Multiple studies show an increase in respiratory issues in communities near natural gas development sites (Lattanzio 2016).

Additionally, pipeline workers deal with occupational safety considerations due to chemical exposure. According to a study by Montero-Montoya et al. (2018) workers in industrial settings may be exposed to BTEX compounds (benzene, toluene, ethylbenzene, and xylenes) with even low-doses having negative impacts. Benzene produces recognized toxic metabolites including benzene epoxide, benzene dihydrodiol, hydroquinone, catechol, benzoquinones, and muconaldehyde. While BTEX compounds are not harmful on their own, our body's attempt to process them creates a dangerous scenario where our liver first transforms them into more reactive forms and then tries to make them water-soluble for elimination. During this process, however, these transformed substances can damage our nervous system, bone marrow, and other organs, causing neurological impairment. Of particular concern is benzene exposure, which can cause severe hematological effects including aplastic anemia and acute myelogenous leukemia through reactive metabolite action.

Occupational safety concerns also include H₂S, which is commonly found in natural gas, and has varying health effects depending on exposure levels (Lim et al. 2016). Industrial workers exposed to H₂S may experience both acute and chronic health effects, particularly affecting respiratory function and the central nervous system. Studies of sewer workers and oil/gas industry workers found some evidence of cognitive impairment and respiratory issues with chronic low-level exposure. The study also noted H₂S exposure is hazardous at high concentrations, potentially leading to immediate collapse or death. Lim et al. (2016) study examined several community-based studies, including research conducted in geothermal areas that release natural gas or methane. These studies found mixed evidence regarding long-term health effects, with some studies showing associations between H₂S exposure and respiratory conditions, particularly in children with asthma, but the largest studies did not find consistent evidence of chronic health effects from ambient exposure (Lim et al. 2016). Kenessary et al. (2017) showed that even low-level chronic exposure to H₂S can cause serious health effects. Their research, conducted at the Karachaganak oil and gas condensate field in Kazakhstan, showed that chronic exposure can cause DNA damage and irreversible brain effects, and called for mandatory economic damage evaluations for industrial facilities with air pollution risks.

Methane exposure is also an occupational safety consideration for natural gas workers. A study by Jo et al. (2013) discussed the health impact of exposure to a methane gas tank in a medical supply company

after the tank was mistaken for a nitrogen tank and opened in an enclosed room, creating a confined space situation. The exposure duration was brief, only about one minute of direct gas release, but the harm manifested in both immediate and lingering effects. The 21-year-old worker initially lost consciousness and developed severe respiratory distress, requiring mechanical ventilation upon arrival at the emergency department 4.5 hours later. Medical imaging showed bilateral air-space consolidations in his lungs, and pulmonary function tests revealed a restrictive ventilatory defect. The patient also experienced symptoms including drowsiness, hypoxemia (low blood oxygen), and cyanosis. However, it is noteworthy that he recovered relatively quickly and was discharged after 5 days without long-term complications. OSHA (2016) warns that oil and gas extraction workers face significant health and safety risks when manually gauging or collecting samples from tanks. These hazards occur when workers open tank hatches, releasing pressurized hydrocarbon gases and vapors directly into their breathing zone. Workers are exposed to concentrated hydrocarbon gases (methane, ethane, propane, butane), hydrocarbon vapors (pentane, hexane, benzene, xylene), and oxygen-deficient atmospheres. Harrison et al. (2016) noted that for tank measurements, the combination of high hydrocarbon gas and vapor concentrations and oxygen deficiency can cause sudden cardiac death, even in workers without pre-existing conditions. Their monitoring revealed oxygen levels as low as 7–11% near open tank hatches, well below OSHA's 19.5% requirement. Hydrocarbon concentrations frequently exceeded the lower explosive limit, high enough to cause acute central nervous system effects. The research documents that even brief exposures can be lethal. Harrison et al. (2016) noted that workers near natural gas pipelines generally face different and typically lower risks, with the key difference being in exposure patterns: tank gauging creates particularly hazardous conditions as workers must manually open hatches, directly exposing themselves to concentrated plumes of hydrocarbon gases and vapors while positioned above tank openings. This creates a dangerous combination of very high hydrocarbon gas concentrations (>100,000 ppm) and oxygen-deficient atmospheres (<15% O₂), which can rapidly lead to loss of consciousness and cardiac events. Pipeline workers, in contrast, typically encounter more diffuse exposures from leaks rather than concentrated plumes. While pipeline leaks can create hazardous conditions, especially in confined spaces or poorly ventilated areas, the exposure pattern tends to be more gradual and at lower concentrations compared to the sudden, intense exposures documented in the tank-related fatalities (Harrison et al. 2016).

2.4.2 Water Quality

Methane's interaction with water has several implications for water quality. DeGraff (2011) modeled methane releases at depths of 300 m, 750 m, and 1500 m, demonstrating how methane's behavior differs substantially from carbon dioxide due to its distinct physicochemical properties. Methane has relatively low solubility in water and much lower density compared to seawater. When released underwater, methane bubbles rise toward the surface due to buoyancy, but their fate depends on release depth. The research showed that methane released at 300 m reached the surface rapidly (within 0.2 hours) with a flux of 29,883.17 m³/hour. However, releases at 750 m and 1500 m did not surface at all, as the methane completely dissolved during ascent, a process enhanced by hydrate formation below 570 m (the hydrate dissociation level). Mau et al. (2007) found at the Coal Oil Point deep seep field in the Santa Barbara Channel, California, only 1% of dissolved methane entered the atmosphere within their study area. The behavior of released methane is highly dependent on water depth. In deep seeps like those at Coal Oil Point, much of the methane dissolves in the water column before reaching the surface. Alternatively, Reed

et al. 2006 found that shallow to moderate depth releases include different dynamics where gas bubbles released in shallow water have short residence times, resulting in minimal dissolution. In these cases, the majority of methane is likely to reach the atmosphere rather than remain in the water column (Reed et al. (2006).

The presence of methane affects water density. DeGraff's (2011) study quantified that in areas with high methane concentrations, bulk seawater density decreased from the normal 1020–1025 kg/m³ to below 1000 kg/m³ near the surface. This 25–30 kg/m³ reduction can affect water column stability and mixing patterns. However, in deeper releases where methane forms hydrates (which have a density of approximately 900 kg/m³), the impact on water density was substantially less pronounced because the density differential between hydrates and seawater is much smaller than between methane gas and seawater. DeGraff (2011) research also indicates that the impact of methane on water quality extends beyond simple density changes. When methane reaches the surface in large quantities (as demonstrated in Case one with 29,883.17 m³/hour flux), it alters water column properties. Reed et al. (2006) documented methane concentrations reaching up to 1040 nmol/L in seawater (approximately 500 times higher than atmospheric equilibrium), creating a plume that spread over 70 km².

While DeGraff's thesis does not specifically quantify oxygen displacement, it does note that the presence of large methane concentrations (reaching 3.5 mol/m³ in some areas) substantially changes the physicochemical properties of the water column. Methane hydrate formation occurs under specific temperature and pressure conditions found in deeper ocean environments. According to DeGraff's research, these ice-like structures form at depths below approximately 570 m in the Gulf of America, where water temperatures and pressures create suitable conditions for hydrate stability. These hydrates do not form gradually, they develop rapidly during underwater gas releases, typically reaching steady-state conditions within just 1–3 hours after the initial release. The formation of methane hydrates creates different water quality impacts compared to free methane gas. While free methane gas reduces water density (potentially below 1000 kg/m³), hydrates have a less dramatic effect on water density because hydrates themselves (at approximately 900 kg/m³) are closer to seawater density than gaseous methane. However, these hydrates dissolve more slowly than free gas bubbles, meaning they can persist longer in the water column. This extended presence suggests that hydrate-forming methane releases might create more prolonged, though less intense, alterations to local water chemistry than shallow releases where the gas primarily escapes to the surface. The severity of these impacts depends greatly on the volume of methane released, water depth, temperature, and local currents. Smaller releases in well-mixed waters may have minimal impact, while large-scale releases, especially in confined or stratified water bodies, can have more substantial effects on water quality and marine life. Additionally, the distinct temperature profiles of different water masses affected methane behavior, including hydrate formation and dissolution rates. These temperature variations between water masses determine how methane releases interact with the marine environment. This means that identical methane releases in different water masses could produce substantially different environmental impacts depending on the specific hydrographic conditions present DeGraff (2011).

Reed et al. (2006) also identified distinct pathways for methane in the marine environment: transport by ocean currents along specific density surfaces, microbial oxidation within the water column, and gradual release to the atmosphere at locations distant from the original source. The researchers observed that

methane was transported along specific density surfaces in the ocean, with elevated concentrations detectable at distances up to 700 km offshore. The distribution patterns were heavily influenced by sub-mesoscale current fields, with cyclonic and anticyclonic eddies affecting concentration and plume dimensions. For any application to pipeline scenarios, especially in Alaskan waters, the specific environmental conditions would be important factors. Water temperature affects microbial oxidation rates, with colder temperatures potentially slowing the biological breakdown of dissolved methane. Additionally, local current patterns, water stratification, and depth of release would all substantially influence how methane disperses through the marine environment. DeGraff (2011), Mau et al. (2007), and Reed et al. (2006) show that methane impacts marine environments differently based on depth, water temperature, and ocean currents. Site specific factors will determine methane's fate and environmental impact.

Seasonal effects in cold climate regions can also influence methane impact on water quality. Kvenvolden et al. (1993) found that methane levels were 3–28 times higher than equilibrium concentrations under winter ice in the Beaufort Sea. The study also found elevated methane levels near river outlets, indicating that areas where pipelines cross or run parallel to waterways may be particularly vulnerable to accumulating released methane in winter conditions. When spring breakup occurs, the sudden release of accumulated methane could impact the environment as the gas is rapidly released from the water body. The concentrated methane could alter water chemistry, potentially depleting dissolved oxygen as methane-oxidizing bacteria consume the gas. This could stress aquatic organisms, particularly in smaller or poorly circulated water bodies (Grossart et al. 2011). Bacteria require oxygen to oxidize methane to formaldehyde and carbon dioxide in a metabolic process that substantially depletes dissolved oxygen levels. Grossart et al. (2011) found that in stratified lakes such as Lake Stechlin, researchers measured high methane oxidation rates that were directly linked to decreased oxygen concentrations where these bacteria were active. The more recent work by Schorn et al. (2024) confirms that these common methane-eating bacteria can work effectively even when oxygen is scarce. Their research shows these bacteria can consume methane at high rates. This biological methane consumption could quickly deplete already limited winter oxygen supplies beneath ice-covered surfaces.

2.4.3 Pelagic Communities

Pelagic communities consist of groups of organisms that live in the vast open water column of the ocean, excluding regions near the bottom and the shore. The majority of these communities are found within the epipelagic zone, the uppermost layer of the pelagic environment. The epipelagic zone receives sufficient sunlight to support photosynthesis, the production of primary energy in marine ecosystems. Phytoplankton, which rely on sunlight for photosynthesis, form the base of the food web in this zone. They serve as a food source for zooplankton and small fish, which in turn are preyed upon by larger fish, squid, marine mammals, and birds. These organisms may be harmed by natural gas pipeline releases, but the extent of the impact remains unclear due to limited research. In the event of environmental disruptions, certain at-risk species may be more vulnerable than others. The ability of these communities to recover is difficult to assess, as the nature and scale of the impact are poorly understood. Additionally, we were unable to locate specific research on how natural gas or methane affects the condition of this ecosystem.

The pelagic region is divided into five zones based on water depth:

- **Epipelagic Zone:** 0 to 200 m (0 to 660 ft)

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- **Mesopelagic Zone:** 200 to 1,000 m (660 to 3,300 ft)
 - **Bathypelagic Zone:** 1,000 to 4,000 m (3,300 to 13,100 ft)
 - **Abyssopelagic Zone:** 4,000 to 6,000 m (13,100 to 19,700 ft)
 - **Hadopelagic Zone:** 6,000 m (19,700 ft) and deeper

The primary pelagic environments surrounding Alaska include the Gulf of Alaska, Bering Sea, Chukchi Sea, and Beaufort Sea, with oil and gas leasing areas largely concentrated within the Cook Inlet Basin and North Slope Basin. Bathymetric surveys of Cook Inlet indicate that the central channel reaches depths of approximately 50 m (165 ft), with depths exceeding 100 m (328 ft) near or outside the inlet entrance (Zimmermann and Prescott 2014). The North Slope Basin encompasses both the Chukchi Sea and Beaufort Sea. The Beaufort Sea features a continental shelf extending up to 145 km (90 mi) from the shoreline, with depths generally less than 64 m (210 ft), while beyond the shelf, water depths increase dramatically to 4,680 m (15,360 ft). In contrast, the Chukchi Sea has an average depth of 80 m (260 ft), with nearly 50% of its total area being less than 50 m (165 ft) deep (Hunt et al. 2013).

2.4.3.1 Potential Hazards

Organisms within the pelagic region may be within proximity to offshore natural gas pipelines if a natural gas pipeline release were to occur. Due to the location, such a release would only involve offshore pipelines (both gathering and transmission), as pelagic communities would not be impacted by onshore releases. In the cases of an offshore release organisms might experience impacts from a rapid release or sustain prolonged exposure depending on the scale of the incident.

Underwater ignition is unlikely as the underwater environment lacks an ignition source and sufficient oxygen. If the gas were to reach the surface in a high enough concentration, ignition becomes a concern, as Engebretsen et al. (1997) indicates that high concentrations of hydrocarbon gases in the air can lead to explosion and fire hazards. Their research shows that gas from underwater releases disperses into the atmosphere from an area approximately six times larger than the central boil region (the area directly above the underwater gas release where bubbles first reach the surface and create visible turbulence or "boiling" in the water). If a high enough concentration were to reach the surface and encounter an ignition source, a hazardous situation could develop due to the "boiling activity" on the surface manifested by a high transient fountain (a temporary upward spray of water and gas above the water surface) and strong radial currents (outward flowing water movement from the center of the release). This scenario would still require an ignition source, likely in close proximity to the operational platform. Any exposure would be limited to the immediate area, though the research indicates gas dispersion may extend beyond what was previously expected.

2.4.3.2 Vulnerability

Research by Knutsen and Serigstad (2001) indicate that depending on the scale and duration of a release, a vertical column of gas bubbles may form from the release site to the water surface. Organisms within the immediate vicinity may sustain asphyxiation due to oxygen depletion in the surrounding water as the gas displaces dissolved oxygen, leading to a stunning effect or possible death. There is the possibility that a release disrupts normal distribution of local organisms as they either react to or are displaced by the release. However, this subject is poorly researched, and no conclusion can be drawn on the effects to sea

life. This research was conducted at 844 m in the Norwegian Sea (Bathypelagic Zone) making it potentially less applicable to the Epipelagic Zone (0–200m) due to several key differences. The Epipelagic Zone experiences lower hydrostatic pressure, which affects gas bubble behavior and dissolution rates. It also hosts greater biodiversity, including photosynthetic organisms, and maintains higher baseline oxygen levels due to photosynthesis and atmospheric exchange. Additionally, the presence of sunlight in the Epipelagic Zone could influence organism behavioral responses to visible gas bubbles, while its warmer, more variable temperatures would affect gas solubility and organism metabolism differently during exposure events. These substantial environmental differences suggest that both the physical dynamics of released gases and the resulting biological impacts could vary dramatically between these ocean zones (Allen and Cross 2006; Paulus 2021).

In cases of oxygen depletion asphyxiation may cause short-term or long-term sensory impairment. Sensory impairment may cause behavioral changes including altering swimming patterns, feeding behavior, or predatory avoidance (Svobodova et al. 1993). For some organisms, it is possible that components of natural gas are toxic as the release occurs within transportation and gathering lines before processing. Possible toxic compounds include H₂S, BTEX, mercaptans, CO₂, mercury, radon, or higher hydrocarbons such as ethane, propane, or butane. The composition of natural gas will vary substantially depending on the source.

The severity of impact of a release depends on factors like the size of the release, water depth, current patterns, water temperature, and specific ecosystems. In general, organisms in early-stage development, those small in size, and those already at risk tend to be more vulnerable. While organisms within the immediate vicinity may suffer harm up to and including death, it is unlikely to have a substantial effect on the overall populations. However, at-risk species may struggle to recover in the short term, which may affect their populations over the long term. Loss of or reduction in species that act as a food source may have an extended impact on the greater food chain. We were unable to locate research on the effects of natural gas on marine life, making it difficult to determine both the short-term and long-term implications of exposure with certainty.

2.4.4 Coastal and Estuarine Habitats

Natural gas pipeline releases can have substantial and varied impacts on vegetation and ecosystems, with effects ranging from immediate damage to long-term ecological changes. Research across multiple studies demonstrates that these impacts occur through several key mechanisms, affecting both above-ground vegetation and below-ground soil conditions. Understanding these effects is important for environmental management and ecosystem protection.

2.4.4.1 Hypoxia Impacts to Vegetation

Based on Hoeks (1972) research, natural gas releases impact vegetation through both direct and indirect pathways, with soil aeration problems being the primary damage mechanism. While natural gas contains ethylene in concentrations of 2–3 ppm that can directly affect plants, the more substantial impact results from dramatic soil gas composition changes. When natural gas leaks into soil, it creates distinct zones with very low oxygen and high carbon dioxide concentrations, conditions that severely impact plant root systems. Hoeks (1972) examined the extent of natural gas leaks from distribution pipelines in the urban

areas of the Netherlands. The leaks were a result of change over from town gas to natural gas. During this change, gas pressure increased from 0.0065 to 0.025 atm. This pressure change affected the oakum joint seals, causing more gas to release. The symptoms of damage develop gradually, typically becoming visible 1–3 months after a release begins, and include yellowing and premature leaf fall, death of branches, failure to bud in spring, and premature blossoming or fructification, eventually leading to plant death. These symptoms stem from root system damage, as anaerobic conditions immediately halt root growth, with roots typically dying within days to one week of exposure, while also reducing water and nutrient uptake and decreasing root respiration. Plant sensitivity varies among species, with bottomland tree species showing greater tolerance than upland species due to their natural adaptation to occasional flooding conditions. Some plants can adapt to poor aeration through specialized mechanisms such as developing air cavities for oxygen transport, forming adventitious roots, or developing anaerobic respiration capabilities, though plants remain particularly vulnerable during the growing season compared to winter months when metabolic activity and oxygen demands are lower. The effects of natural gas releases persist long after the release is repaired with soil continuing to exhibit low oxygen levels and high carbon dioxide concentrations, while toxic reduced substances like ferrous iron, manganous manganese, and sulfides along with organic acids, remain present. These lingering effects impact recovery and replanting efforts. The success of replanting varies based on multiple factors, including the time elapsed since release repair, soil conditions, the season of replanting, and the specific plant species being introduced (Hoeks 1972).

Hoeks (1972) found that natural gas releases alter soil chemistry in multiple ways. In acidic soils, the pH increases (as demonstrated in Hoeks' experimental field where pH rose from 3.8 to 4.3 during a two-year leakage), while in alkaline and calcareous soils, pH typically decreases. These pH shifts occur due to hydrogen ion involvement in oxidation-reduction processes and carbon dioxide's influence on pH at alkaline levels. The altered pH affects nutrient availability to plants, particularly phosphorus and micronutrients. Under anaerobic conditions near gas releases, the soil develops strongly reducing conditions with very low redox potentials (-0.15 to -0.20 V), leading to the formation of potentially toxic reduced compounds including ferrous iron, manganous manganese, and sulfides. The study found increases in organic matter content near gas leaks due to accumulated intermediates of methane oxidation, bacterial excretions, and dead microbial cells, while nitrogen content often increases through fixation by anaerobic bacteria.

Schollaert et al. (2020) built upon Hoeks (1972) work with a quantifiable case-control approach that demonstrated trees exposed to detectable soil methane levels had 30 times higher odds of death compared to unexposed trees. The researchers were able to document an important mechanism of harm, showing how methane creates anaerobic soil conditions through both direct oxygen displacement and increased methanotroph activity. The study also establishes a clear link between infrastructure releases and vegetation damage by finding the highest methane concentrations nearest to urban natural gas distribution pipelines that run beneath street surfaces. The research specifically points to leaks from aging urban natural gas infrastructure as the likely source of methane exposure. While Schollaert's research provided valuable mechanistic insights into methane's effects on vegetation in urban settings, Attalage et al. (2023) further expanded that understanding by examining methane impacts in landfill environments. This more recent study offers additional relevance since natural gas is primarily composed of methane (typically 70–90%). Attalage et al. (2023) demonstrated that methane exposure affects plant health

through hypoxia as a result of oxygen displacement in the root zone. When methane displaces oxygen in the soil, it creates hypoxic conditions that severely impact plant growth. Plants require at least 10% oxygen concentration in soil for healthy development. When oxygen levels fall below this threshold, plants experience substantial growth impairments. The study documented notable reductions in multiple growth parameters, with plant height decreasing by up to 51% and root length declining by up to 35%. Both above-ground and below-ground biomass showed marked decreases compared to control groups. Plants respond to methane-induced hypoxia through various stress responses. Low oxygen conditions trigger the formation of reactive oxygen species that damage plant DNA, membranes, and proteins. Visual symptoms include chlorosis (yellowing of leaves), which corresponds with measured reductions in chlorophyll content ranging from 24% to 40%. Some plant species attempt to adapt to these conditions by forming aerenchyma, gas-filled spaces in their roots that can help transport oxygen.

The research by Attalage et al. (2023) revealed variations in how different plant species respond to methane exposure. Plants with deep taproot systems, such as alfalfa, demonstrated greater resistance to methane exposure compared to those with shallow fibrous roots. Native grasses proved particularly sensitive to methane exposure, while some species showed the ability to develop adaptations to cope with low oxygen conditions. This variation in response suggests that the impact of natural gas pipeline releases may vary considerably depending on the affected vegetation type. Regarding exposure thresholds, the study found that relatively low methane flux rates of 75 g CH₄/m²/d at the soil surface were sufficient to impact plant growth by reducing oxygen concentrations in the root zone below the critical 10% threshold. The severity of impacts increased proportionally with higher gas concentrations, though extremely high rates exceeding 845 g CH₄/m²/d were required to cause complete vegetation death. This finding suggests that even small natural gas pipeline releases could potentially impact plant health, with the severity of damage increasing with the size of the release and duration of exposure. While the study is focused on emissions from landfills, high levels of methane are the primary driver for plant vulnerability and emulates likely exposure from a pipeline release in the immediate. The research suggests that pipeline leaks occurring underground may seep into the soil to create the hypoxic conditions that affected plant growth in the study. It is important to note that the study by Attalage et al. (2023) does not suggest that atmospheric methane directly damages plant foliage, since methane released above ground would typically dissipate into the atmosphere without substantially affecting soil oxygen levels, but instead suggests that underground leaks are the primary concern for vegetation impacts.

Gao et al. (2021) found that methane migration is governed by advection (dominant within 1–1.5 m of leak sources) and diffusion (dominant in far-field migration), with soil texture and moisture significantly affecting distribution patterns. Their research shows that clay layers can create localized methane accumulations or "hot spots," while higher soil moisture increases methane concentration near leak points but reduces far-field spread, potentially explaining the variations in vegetation impact observed by Hoeks (1972) and Schollaert et al. (2020). Importantly, Gao's findings about methane lingering after leak repair support Hoeks' observations on delayed recovery, while their documentation of migration distances helps explain the spatial patterns of vegetation damage documented by both Schollaert et al. (2020) and Attalage et al. (2023), offering the physical foundation for understanding how pipeline leaks create the hypoxic soil conditions that ultimately damage plant life.

All four studies, Hoeks (1972), Schollaert et al. (2020), Attalage et al. (2023), and Gao et al. (2021), confirm that oxygen depletion in soil is the primary mechanism through which natural gas damages vegetation. They consistently demonstrate that when natural gas (primarily methane) displaces oxygen in the soil, it creates anaerobic conditions that severely impair root function, ultimately leading to visible above-ground symptoms and potential plant death. The studies also agree on the gradual nature of symptom development, with plant damage typically becoming visible only after prolonged exposure to these hypoxic conditions. Each study documents similar plant responses to natural gas exposure, including yellowing leaves (chlorosis), reduced growth, premature leaf drop, and eventually plant death. They all note that these symptoms primarily result from root system damage caused by oxygen-depleted soil conditions rather than direct toxic effects from the gas itself.

2.4.4.2 Effects of a Natural Gas Rupture on Vegetation

The immediate impact of a pipeline rupture on vegetation is severe with complete vegetation loss in areas closest to the rupture point. Scasta et al. (2023) examined vegetation response after a natural gas pipeline rupture and fire in Canada's montane cordillera, approximately 13 km northeast of Prince George, British Columbia. The buried pipeline had an average depth cover of 1.34 m and released and ignited approximately 140 Mcf of natural gas, affecting 5.2 hectares of land. The intense heat from the sustained jet fire, which burns hotter than typical forest fires due to higher heat yield from natural gas compared to wood fuels (natural gas has a heat yield 2–3 times greater than wood), created zones of varying burn severity radiating from the epicenter. The most severe effects were concentrated around the rupture crater that measured 35 m long, 13 m wide, and 9 m deep with complete vegetation loss. Researchers tracked vegetation recovery over three years (2018–2021) and found that after the third year, woody plants and forbs had largely recovered to levels similar to unburned reference plots. The dominant species that emerged included thimbleberry and fireweed, both known to respond positively to disturbance. Ground cover, including litter and bare soil, showed trajectories suggesting return to pre-disturbance conditions within 3–5 years. However, the vegetation structure remained substantially altered. While shrubs and herbaceous plants recovered quickly, the tree canopy that previously reached heights of about 25 m remained absent. Overall, plant biodiversity metrics, including species richness, evenness, and diversity, recovered to levels statistically similar to undisturbed areas by the end of the study, however, plots closest to the rupture that experienced "extreme" burn severity showed greater botanical dissimilarity compared to other areas, suggesting more persistent alterations to plant communities in these zones. While vegetation showed substantial recovery, the damage created lasting heterogeneity in plant communities. The researchers noted that longer-term monitoring would be needed to assess full recovery of the conifer tree canopy and soil microbiota, which may take decades to return to pre-disturbance conditions (Scasta et al. 2023).

2.4.5 Fish and Motile Invertebrates

Understanding the impacts of natural gas pipeline releases on marine ecosystems requires examining both direct and indirect effects of methane exposure. The research spans various aquatic environments, from Arctic lakes to offshore installations, providing insights into how methane influences marine life through multiple pathways. One such impact is how methane affects fish populations. Campbell et al. (2014) found that when methane is present under ice, its oxidation reduces available oxygen, creating

hypoxic conditions that stress fish populations. Additionally, anaerobic oxidation of methane can produce H₂S, which is highly toxic to fish. Even species adapted to low-oxygen environments, like the Alaska Blackfish which can breathe air, show physiological stress responses such as edema and may experience mass die-offs when exposed to these conditions.

2.4.5.1 Ecological Effects in Lakes, Confined, and Ice-Covered Water Bodies

In Arctic and subarctic regions, methane emissions are commonly associated with thermokarst lakes, which form as permafrost melts (Walter et al. 2008). As these lakes expand both vertically and horizontally, increased microbial activity in the thawed ground produces substantial methane emissions, with studies documenting 73–78% methane content by volume and discharge rates averaging 27,450 milligrams of methane per square meter daily (Walter Anthony et al. 2010). This creates consistent year-round discharge points or "hotspots" with methane concentrations as high as 88.7%, maintaining open holes in winter ice through bubbling (Walter et al. 2008). These natural systems demonstrate how methane can affect aquatic ecosystems both directly through toxicity and indirectly by altering water chemistry and oxygen availability (Bridgham et al. 2013). As permafrost degradation accelerates as a result of global warming, increasing methane emissions may pose growing threats to fish populations (Campbell et al. 2014). This suggests that methane exposure from anthropogenic sources like natural gas pipeline releases could similarly impact fish populations through oxygen depletion and toxic effects, particularly in confined or ice-covered water bodies where gases cannot readily dissipate.

Wimalaratne et al. (2015) demonstrates that dissolved methane from releases can impact water quality through microbial interactions that deplete dissolved oxygen levels. Their modeling showed that while oxygen depletion tends to be localized, it could create potentially dangerous hypoxic conditions in stagnant waters, with impacts extending up to 15,000 m horizontally and between 400–800 m vertically in the water column. A key discovery was that dissolved methane spreads much more extensively than gaseous methane, after 6 hours, dissolved methane plumes extended 1,500 m compared to just 200 m for gaseous plumes. This difference occurs because methane has higher dissolution rates compared to oil, causing most of the gas to dissolve before reaching the surface. These transport patterns have implications for how we understand the spread and impact of natural gas releases in various environments and how those impacts affect marine environments.

Campbell et al. (2014) and Wimalaratne et al. (2015) document that methane's impacts on aquatic organisms primarily focus on indirect effects rather than direct biological mechanisms. The literature demonstrates that methane primarily affects fish through environmental oxygen depletion, as methane oxidation by bacteria consumes dissolved oxygen, creating hypoxic conditions that stress aquatic life. Additionally, anaerobic methane oxidation can produce toxic hydrogen sulfide when oxygen is depleted, particularly in ice-covered lakes. The specific biological pathways and cellular mechanisms through which methane might directly affect fish physiology remain unexplored in the currently reviewed literature, with the studies focusing on ecological rather than physiological impacts.

2.4.5.2 Methane Degradation and Oxygen Depletion in the Deep Sea

The Deepwater Horizon incident released an estimated 500,000 tons of gaseous hydrocarbons into deep ocean waters (Joye et al. 2011). Following the incident, which occurred at a depth of 1500 m, researchers

discovered that natural gases (methane, ethane, and propane) released from deep-water releases did not immediately rise to the surface as previously thought. Instead, they formed persistent plumes at depths between 800–1200 m, spreading several kilometers from the source (Valentine et al. 2010). This finding challenged the understanding of how natural gas pipeline releases impact marine environments, as these persistent plumes created long-lasting zones of altered chemistry in the deep ocean. This study revealed a complex chain of biological responses triggered by these gas plumes. When the gases first entered the water, they prompted a rapid response from marine bacteria, particularly from genera like *Cycloclasticus* and *Colwellia*. These bacteria selectively consumed propane and ethane before methane, creating what the researchers called a "bloom" of hydrocarbon-degrading bacteria. This bacterial activity led to notable oxygen depletion in the marine environment, with propane and ethane consumption accounting for the majority of oxygen loss in fresh gas plumes (Valentine et al. 2010). Joye et al. (2011) also found that microbial consumption of these gases led to increased oxygen depletion in the affected waters, which had the potential to stress or kill oxygen-dependent marine life. Researchers observed discrete layers of dissolved hydrocarbon gases between 1,000–1,300 m depth, where concentrations exceeded background levels by up to 75,000 times (Joye et al. 2011).

In the Valentine et al. (2010) study, the research team's calculations revealed that natural gas components created a substantially greater oxygen demand than oil components in the water column. Methane in particular required massive amounts of oxygen for complete degradation, demonstrating how even seemingly small natural gas releases can have outsized effects on deep-water oxygen levels. This oxygen depletion created zones of low oxygen that could impact deep-sea organisms, particularly in deep waters where oxygen replenishment occurs slowly. The formation of oxygen-depleted zones created challenging conditions for deep-sea organisms adapted to the stable conditions typically found in deep ocean environments. Deep-sea creatures like fish, squid, and various invertebrates may have been forced to relocate to avoid these low-oxygen areas, potentially disrupting established deep-water ecological patterns. The persistence of methane plumes, which the study found to degrade more slowly than other gases, suggested these impacts could last for extended periods in the deep sea. Furthermore, the dramatic shifts in deep-water microbial communities could alter fundamental biogeochemical processes unique to these depths (Valentine et al. 2010).

The research also revealed that these impacts followed a predictable pattern, with different components being degraded in sequence. This created what the authors called "boom and bust cycles" of bacterial succession in the deep ocean, starting with propane and ethane consumers, followed by organisms that broke down other hydrocarbons, and finally methane consumers. This sequential process meant that different components of the deep-water ecosystem were affected at different times and in different ways as the plume aged and moved through the water column. The study's findings suggested that natural gas releases in deep water didn't just create immediate chemical changes in the marine environment, but triggered long-lasting cascading effects through altered microbial activity, oxygen availability, and deep-sea food web dynamics (Valentine et al. 2010).

In 2011, Kessler et al. (2011) found that methane was the most abundant hydrocarbon released during the 2010 Deepwater Horizon oil spill in the Gulf of America. The researchers tracked hydrocarbon intrusions throughout the northern Gulf of America and found a complete absence of elevated methane in the affected waters months after the emissions ceased, despite the presence of persistent oxygen anomalies.

Analysis revealed that within approximately 120 days from the onset of the release, about 3.0×10^{10} to 3.9×10^{10} moles of oxygen were respired, primarily by methanotrophic bacteria. DNA analysis confirmed the presence of methylotrophic bacteria at each sampling site, with relative abundances ranging between 5 and 36% of sequences, even though methane was no longer present. The researchers concluded that a deepwater bacterial bloom was responsible for the respiration of the methane. This demonstrates the ocean's natural biofilter capabilities against methane releases, though with the environmental trade-off of substantial oxygen depletion in affected waters.

2.4.5.3 Methane in Marine Food Webs and Species Vulnerability

A study by Sanseverino et al. (2012) examined how methane-derived carbon moved through aquatic food webs and discovered that as methane-oxidizing bacteria played a role as an intermediary, they converted methane into biomass that could be consumed by higher organisms. In natural systems, these bacteria oxidize up to 50–56% of methane produced in freshwater lakes before it reaches the atmosphere, while simultaneously providing an important carbon source for aquatic organisms from zooplankton to fish. The Sanseverino et al. (2012) study found evidence of methane-derived carbon throughout the food web by tracking specific fatty acid biomarkers and carbon isotope ratios, with some organisms showing up to 13–22% of their carbon coming from methane sources. This study along with the studies of Joye et al. (2011), Valentine et al. (2010) and Kessler et al. (2011) regarding the Deepwater Horizon incident suggest that while acute methane releases might initially be harmful, if the releases are slow and chronic, and depending on the location of release in the water column, the methane could potentially be partially processed by methane-oxidizing bacteria and incorporated into the food web. Sanseverino et al. (2012) identified organisms that might be most affected by a reliance on methane-derived carbon, including bottom-feeding fish, aquatic insects, and zooplankton that feed near sediments where methane oxidation occurs.

Smith and Brown (2002) examined marine fish distributions in the northeast Pacific Ocean, focusing on an area that shares similar latitudes with parts of Alaska. The research analyzed 409 pelagic fish species, finding that most marine fish concentrate in the upper ocean layers, with peak diversity in waters less than 200 m deep. This distribution pattern is particularly relevant to Alaska's coastal waters, where many commercially and ecologically important species inhabit similar depth ranges. The study revealed that fish distributions strongly correlate with water temperature and food availability (plankton biomass), both of which decrease rapidly with depth. Many species, especially in shallower waters, have restricted depth ranges, suggesting they may be particularly sensitive to environmental changes. The research also found interesting differences between teleost fish (like salmon and cod) and elasmobranchs (sharks and rays) in how they utilize different ocean depths. This research suggests that shallow coastal areas would be of particular concern for ecological impacts of natural gas pipeline releases since they harbor the highest diversity of species, many of which have limited ability to move to different depths.

The North Sea studies by Delefosse et al. (2018) acknowledge their constrained applicability to regions like Alaskan waters, where different species assemblages and environmental conditions prevail. This regional specificity creates uncertainty about how Arctic and sub-Arctic species respond to methane exposure compared to their temperate counterparts. The seasonal nature of observations, particularly in Arctic regions where ice coverage affects both wildlife behavior and monitoring capabilities, further

complicates these geographical limitations. Marine mammal observations skew heavily toward spring and summer months, leaving winter behavior patterns poorly documented. Questions remain about how disruptions to methane-oxidizing bacteria populations might cascade through marine food systems or how species adaptations might impact outcomes. Additionally, while some studies document marine mammal presence around offshore installations, we have limited understanding of how small natural gas pipeline releases might alter these interaction patterns.

2.4.6 Marine/coastal Birds

Marine and coastal bird species show varying levels of vulnerability to gas flares. Day et al. (2015) examined gas flaring at an artificial oil production island in Arctic Alaska and found that gas flaring caused notable disruption to normal bird migration patterns and flight behavior, with birds exhibiting increased erratic movements and circling around bright gas flares. The bright illumination can attract birds from considerable distances, causing them to circle continuously rather than continuing their migration. This can cause substantial impact on birds, particularly regarding energy expenditure during migration. For example, long-tailed ducks in the study flew an estimated extra 155–280 miles during one night of circling the flare. This additional energy expenditure could reduce birds' fat stores needed for successful migration. Some birds also showed extreme collision-avoidance behavior near structures illuminated by flares, highlighting the physical risks posed by the combination of bright lights and structures. The study found that different bird species showed varying levels of vulnerability to gas flares, with long-tailed ducks and glaucous gulls particularly affected in this study. Waterfowl and seabirds migrating at low altitudes (below 100m) were most vulnerable to the effects. The attraction to flares was strongest during nighttime and overcast conditions, with the most pronounced effects occurring in the early evening hours after sunset. However, the effects tended to decrease over the course of the night, and birds showed some habituation to the lights over time (Day et al. 2015). While no direct bird mortalities were observed in the study, the illumination attracted birds from up to 1000 m away or more, creating potential risks for collisions with structures. These findings could be particularly relevant for understanding potential bird impacts from prolonged gas fires or explosions resulting from releases, especially in areas along migration routes or near important bird habitat.

In a study examining how natural gas infrastructure affected grassland bird species in Alberta, Canada, Hamilton et al. (2011) used point counts to compare bird occurrence between areas with high well density (16 wells/2.59 km²) and low well density (9 wells/2.59 km²). Their findings revealed species-specific responses: Savannah Sparrows showed higher occurrence in high-density areas, demonstrating tolerance for human disturbance; Chestnut-collared Longspurs appeared ubiquitous across the study area with no relationship to well density; and Sprague's Pipits exhibited lower occurrence in disturbed areas, with models showing a significant negative relationship between occurrence and anthropogenic disturbance. Landscape features like elevation, topography, and soil type had minimal predictive power for all species. The research demonstrates that even relatively small-scale disturbances (affecting only about 3.25% of the total land area) can influence grassland bird distribution patterns, particularly for specialized species of conservation concern like Sprague's Pipit.

2.4.7 Marine Mammals

Despite the growing concerns about marine mammal health and increasing offshore energy development, research investigating the impacts of natural gas pipeline releases on marine mammals remains notably limited. While extensive literature exists examining various anthropogenic pollutants including plasticizers, pesticides, and oil spill-related compounds, the specific effects of natural gas exposure on marine mammals are largely unexplored.

Aksenov et al. (2014) focused on natural gas pipeline releases and VOC impacts on mammals. The study demonstrated that dolphins, which are long-lived mammals that feed high in the food chain, can accumulate environmental contaminants including VOCs through multiple exposure routes, through their skin, through inhalation, and through ingestion. Researchers detected various VOCs in dolphin breath samples, including compounds from both biological sources and environmental contamination. The sources of VOCs identified in the study included industrial activities, commercial airports, boat traffic, and urban runoff in the San Diego and Sarasota Bays, and the VOCs included phthalates (PAEs), 2,4-diisocyanato-1-methyl-benzene, and other industrial compounds. The detection of VOCs in dolphin breath samples indicated that these mammals were exposed to and metabolizing these chemicals from their environment. This study's findings have implications for understanding how VOC exposure, including from sources like natural gas pipeline releases, could impact other mammalian species through similar exposure pathways and metabolic processes (Aksenov et al. 2014).

In a study on marine mammal presence around oil and gas installations in the North Sea, Delefosse et al. (2018) documented 131 marine mammal sightings (approximately 288 individuals) over a three-year period around platforms located 200 km off the Danish coast. They identified seven different species, including five cetaceans (harbour porpoise, minke whale, white-beaked dolphin, killer whale, and pilot whales) and two pinniped species (harbour and grey seals). The most frequently observed species were harbour porpoises (41% of sightings) and minke whales (31%), suggesting these species would have the highest potential exposure risk in the event of a gas release. The study found that marine mammals actively used these installations, with animals observed swimming under platform legs and, in some cases, seals using the structures as temporary resting places. This behavior indicates prolonged presence around these structures rather than just passing through the area. The Delefosse et al. (2018) study suggests that these offshore installations may act as artificial reefs that attract fish species, which in turn attract marine mammals seeking prey. This ecological relationship means that marine mammals might be consistently present around these structures, potentially increasing their vulnerability to any natural gas pipeline release (Delefosse et al. 2018). This study is important to understand potential wildlife exposure during natural gas releases.

2.4.8 Terrestrial Mammals

Current wildlife studies related to oil and gas development may have taxonomic biases and underexplored ecological effects, specifically for terrestrial mammals. Chalfoun (2021) finds that studies have predominantly focused on birds across various groups including passerines, gallinaceous birds, raptors, waterfowl, and shorebirds. When studies do examine mammals, they disproportionately target "economically important" species with commercial or recreational hunting value, particularly ungulates like

pronghorn and mule deer. This economically-driven research focus has created an unbalanced ecological understanding, with minimal attention given to small non-game mammals such as mice, chipmunks, and rabbits. Large carnivores appear in very few studies, with only one focusing on grizzly bears. The taxonomic imbalance extends further with amphibians appearing in just a handful of studies, while no studies have specifically addressed reptiles in this context.

Hebblewhite (2008) identifies underexplored ecological effects in understanding the effects of H₂S emissions on wildlife populations. Despite this, the authors noting a growing evidence connecting H₂S emissions to health impacts in humans and domestic cattle, remarkably few studies have examined these effects on wildlife (Scott et al. 2003; Waldner et al. 1998). This oversight is particularly concerning given that H₂S is known to be a broad-spectrum toxicant with cumulative impacts on vital organs including the brain, lungs, and heart. While researchers have documented direct habitat loss and behavioral changes in wildlife due to energy development, the physiological and long-term population effects remain largely unexplored.

While studies could not be found on the effects of natural gas pipeline explosions on terrestrial mammals, research by Li et al. (2021a) did investigate the effects of coal mine gas explosions on animals. focusing on Sprague-Dawley rats as test subjects, with a notably small sample size of only 18 rats per test location. The study was conducted in response to China experiencing some of the world's most serious coal mine gas explosion accidents, which cause numerous casualties and substantial harm. Due to the difficulty in obtaining data on human injuries from explosions, researchers used animal experiments to better understand the damage mechanisms and potential harm to mine workers. The study found mortality at varying distances from the explosion source, with the highest death rate (13 of 18 rats) occurring at 80 m from the blast. Even at 240 m from the explosion, some rats (3 of 18) were killed, demonstrating the extensive reach of lethal effects. The injuries observed varied by distance from the explosion. Rats within 40 m experienced combined injuries including burns from high temperatures, blast trauma, and respiratory damage. Beyond 40 m, injuries were primarily from blast effects, with rats exhibiting breathing difficulties, body tremors, fractures, and internal injuries including organ rupture and bleeding. Notably, some rats that initially survived died within 8 hours due to internal injuries and respiratory system damage, while others succumbed to secondary effects such as drowning after being disoriented by the blast.

2.4.9 Archaeological and Historic Resources

There are roughly 400 historic places within the State of Alaska that are registered with the National Register of Historic Places. The National Register of Historic Places was created by the National Historic Preservation Act of 1966 (NHPA). This National Register is the United States federal government's official list of districts, sites, buildings, structures, and objects deemed worthy of preservation for their historical significance. Sites located within Alaska are indicated in **Figure 2**, below.

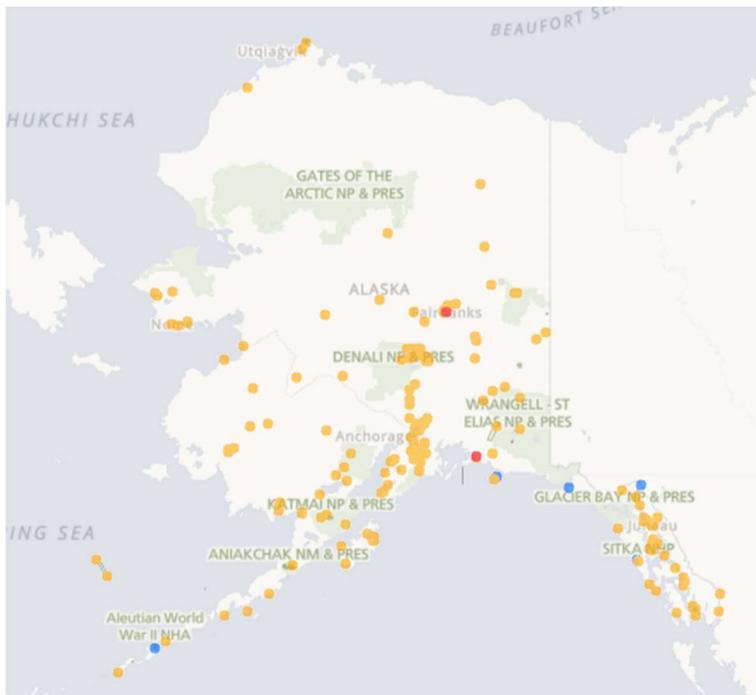


Figure 2. National Register of historic places in Alaska.

National Park Service U.S. Department of the Interior. Updated September 2020.

30 C.F.R. § 550.105 defines an archaeological resource as:

[T]he material remains of human life or activities that are at least 50 years of age and that are of archaeological interest, including any historic property described by the National Historic Preservation Act, as defined in 36 C.F.R. § 800.16(l).

Within 36 C.F.R. § 800.16(l) historic properties is defined in context of the NHPA:

Historic property means any prehistoric or historic district, site, building, structure, or object included in, or eligible for inclusion in, the National Register of Historic Places maintained by the Secretary of the Interior. This term includes artifacts, records, and remains that are related to and located within such properties. The term includes properties of traditional religious and cultural importance to an Indian tribe or Native Hawaiian organization and that meet the National Register criteria.

(2) The term eligible for inclusion in the National Register includes both properties formally determined as such in accordance with regulations of the Secretary of the Interior and all other properties that meet the National Register criteria.

The National Register maintains a database documenting historically significant sites across the United States. We extracted property records from this database and organized them according to their areas of historical significance. This categorization reveals the diverse types of heritage sites found throughout Alaska. The National Register database contains detailed information for each site, including property identification and location, historical significance classification, administrative status, and reference documentation. By grouping Alaska's registered sites into ten distinct categories (Cultural Heritage and Identity, Settlement and Community Development, Economic Activities, Transportation and Engineering, Social Institutions, Arts and Recreation, Maritime History and Activities, Conservation and Environmental

Management, Mixed Heritage and Complex Sites, and Architecture and Built Environment), we can better understand the distribution of Alaska's historically significant places.

Category Definitions:

- **Cultural Heritage and Identity:** Sites representing diverse cultural traditions, historical narratives, and identities of various peoples, with emphasis on Native American heritage, prehistoric sites, and indigenous cultural expressions.
- **Settlement and Community Development:** Historical processes of land occupation, community formation, urban planning, and architectural development that shaped human settlements across regions.
- **Economic Activities:** Commercial, industrial, and resource-based enterprises that drove economic development, including trade networks, manufacturing centers, and resource extraction sites.
- **Transportation and Engineering:** Infrastructure, technical innovations, and networks that facilitated movement of people and goods, showcasing human ingenuity in overcoming geographical challenges.
- **Social Institutions:** Organizational structures supporting community life, including educational facilities, religious establishments, governmental institutions, and military installations providing essential social functions.
- **Arts and Recreation:** Creative and leisure-focused sites where cultural expression, entertainment, and recreational activities flourished, including venues for artistic production, performance spaces, and leisure destinations.
- **Maritime History and Activities:** Coastal and waterway-related sites demonstrating the relationship between communities and bodies of water, including ports, shipbuilding facilities, and maritime commerce centers.
- **Conservation and Environmental Management:** Locations dedicated to natural resource preservation, environmental stewardship, and sustainable management of landscapes.
- **Mixed Heritage and Complex Sites:** Places with multiple overlapping historical narratives, diverse cultural influences, and complex site histories that defy simple categorization.
- **Architecture and Built Environment:** Structures, building complexes, and designed spaces demonstrating significant architectural styles, construction techniques, and spatial organization principles.

Figure 3, shows the distribution of National Registered Sites in Alaska by Area of Significance in 2024.

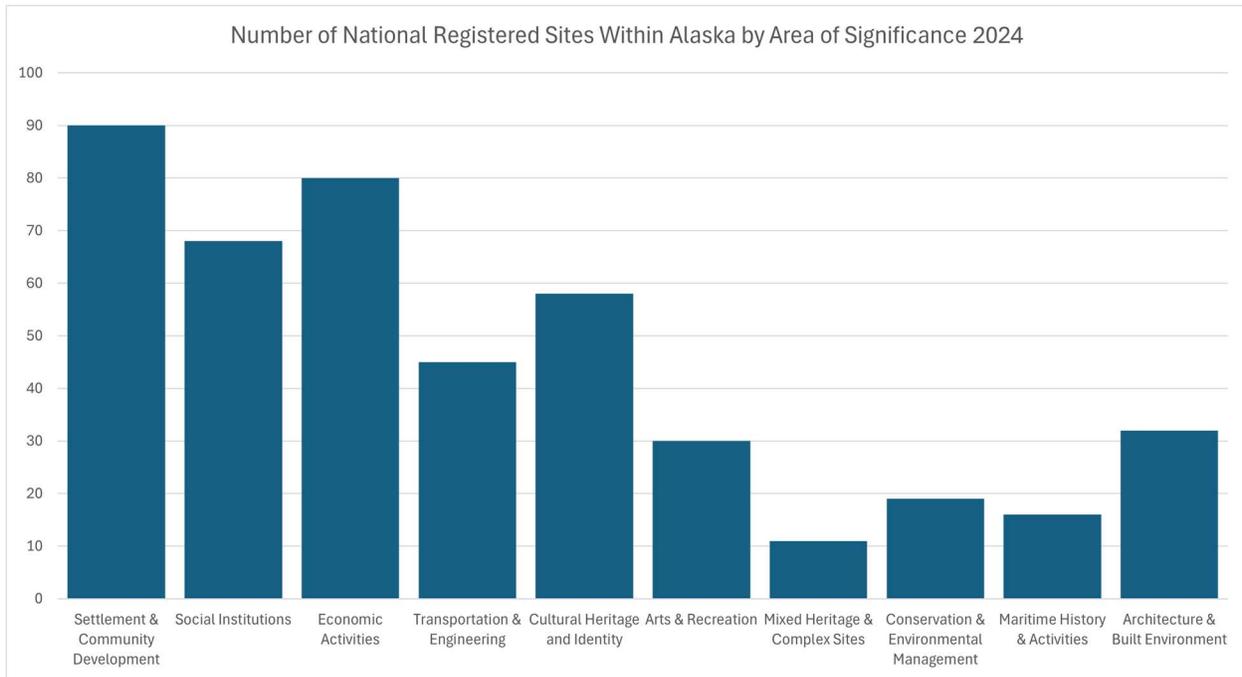


Figure 3. National registered sites in Alaska by area of significance 2024

(National Park Service 2024)

Section 106, concerning regulations within 36 C.F.R. § 800, is a critical component of the NHPA that requires federal agencies to consider the effects on historic properties of projects they carry out, assist, fund, permit, license, or approve throughout the country. It establishes a review process that must be followed before proceeding with these federal undertakings. The Section 106 process applies to both properties already listed on the National Register and those eligible for listing. If eligibility hasn't been determined yet, federal agencies can identify eligible properties through informal consultation with State Historic Preservation Offices or Tribal Historic Preservation Offices.

89 FR 71160 (2024) found that the predictive model for locating marine archaeological resources on the Outer Continental Shelf has proven unreliable after over 40 years of empirical evidence and multiple update attempts. Statistical analyses revealed no significant difference in the likelihood of finding shipwrecks in areas designated as high-probability versus those not so designated, with many shipwrecks discovered in unexpected locations. The model's fundamental flaw stems from insufficient historical documentation, as over 58% of identified Gulf of America shipwrecks cannot be conclusively linked to any archival evidence. This problem is especially severe for older resources, which are often the most historically significant but have the least reliable documentation. Since implementing direct survey requirements in 2011, over 100 previously unknown shipwrecks have been identified, including three historically significant discoveries that would have remained undetected under the predictive model approach. BOEM proposed to eliminate the "reason to believe" standard and require archaeological reports with all plans that propose seabed disturbance, using high-resolution geophysical surveys instead of the unreliable predictive model. This led to an amendment in 30 C.F.R. § 550.194 and 30 C.F.R. § 550.195.

30 C.F.R. § 550.194 provides requirements for submitting an archaeological assessment. When planning seafloor-disturbing activities, operators must submit an assessment prepared by a qualified marine archaeologist. This can be either a new high-resolution geophysical survey report, a reference to a previously approved survey report, or evidence of prior good-faith archaeological identification efforts. The archaeological assessment must identify possible resources within the area potentially affected by proposed activities. Qualified archaeologists must meet the Secretary of the Interior's professional standards and have experience with marine surveys (89 FR 71160 2024). 30 C.F.R. § 550.195 provides requirements when a potential archaeological is discovered during operations. When this occurs, operators must halt all seafloor disturbing operations within at least 305 m (1,000 ft) of the discovery area and report it to the Regional Director within 72 hours. If BOEM determines the resource may qualify for National Register of Historic Places listing, they will specify protective measures operators must implement. For activities under BSEE jurisdiction, BOEM will refer the discovery for assessment of potential adverse impacts. BSEE's Regional Director will then require you to either demonstrate no adverse impacts occurred or document their extent, potentially specifying additional remediation measures. BSEE will ultimately report its findings and any imposed remediation requirements back to BOEM.

2.4.10 Subsistence

Subsistence fishing plays several interconnected roles in rural Alaskan communities (Holen 2014). In a study on communities in Chenega Bay, Kokhanok, and Tyonek, Holen (2014) demonstrated that subsistence fishing is fundamentally important for food security, especially given the high costs of store-bought food in remote areas where most supplies must be flown in. The study showed remarkably high per capita harvests of salmon in these communities - ranging from 62 to 198 kg per person annually, compared to just 10 kg in urban areas of Alaska. Subsistence and commercial fishing often operate in tandem; households involved in commercial fishing tend to harvest 125.8% more subsistence foods than other households. This suggests that impacts to fish resources could create compounding effects by simultaneously threatening both subsistence food security and economic opportunities in these communities. Any disruption to fish populations or habitat could impact multiple aspects of community wellbeing and resilience in rural Alaska (Holen 2014).

Holen (2014) also found that subsistence fishing extends far beyond basic nutrition. The practice serves as a cornerstone of cultural continuity and community cohesion. The actual process of fishing brings extended families together to coordinate harvesting, processing, and distributing the catch. This shared work strengthens social bonds and provides opportunities for passing traditional knowledge between generations. The study found high rates of sharing, with up to 75% of households giving salmon to others in the community, creating networks of reciprocity and mutual support (Holen 2014). The study also highlights how subsistence fishing practices reflect and depend on intimate knowledge of local ecosystems developed over generations. Communities maintain traditional practices like returning salmon parts to the water during processing to support the natural cycle. This suggests that subsistence fishing communities may be especially attuned to and vulnerable to environmental changes that affect fish populations or habitat. Subsistence fishing is deeply intertwined with community identity and sense of place. Residents expressed that fishing is not just an activity but fundamentally shapes who they are as individuals and as a community. This strong cultural connection to fishing resources means that

environmental impacts threatening fish populations could have ripple effects beyond just food security, potentially undermining social fabric and cultural continuity (Holen 2014).

Research by Wheeler and Thornton (2005) also indicated that subsistence fishing constitutes both an important economic activity and a cornerstone of cultural identity and survival in Alaska Native communities. Fishing practices represent an integrated system of social, cultural, and spiritual relationships that define traditional ways of life. Quantitative evidence reveals substantial reliance on subsistence resources in rural Alaska, where fish harvests account for roughly 60% of total subsistence production. Rural residents harvest between 153–664 pounds per capita annually, approximately ten times the amount harvested by urban dwellers (Wheeler and Thornton 2005). This marked disparity underscores fishing's essential role in maintaining food security and economic stability across remote regions.

2.4.11 Commercial and Recreational Fisheries

Commercial fishing vessels frequently interact with subsea pipeline infrastructure during normal operations (Rouse et al. 2018). Approximately one-third of Scottish demersal fishing trips operated within 200 m of pipelines over a 5-year period in the North Sea. This regular interaction creates potential safety concerns, including risks of gear snagging and possible damage to pipeline integrity from repeated contact with fishing equipment (Rouse et al. 2018). Infrastructure such as underwater pipelines, wellheads, and associated debris creates navigational hazards and can damage fishing gear, particularly for demersal (bottom) fishing equipment. Since 1989, Oil and Gas United Kingdom have recorded approximately 1,500 incidents of damage to gear or vessels, with around 450 occurring since 2000, indicating this remains an enduring problem despite warning systems (Pascoe and Innes 2018).

The effects of pipelines on commercial fishing vary based on pipeline size, geographic location, fishing methods, and target species. Larger diameter pipelines tend to attract more fishing activity, though this varies by region and the type of commercial species being pursued. Bottom trawling interactions also differ substantially from other fishing techniques around pipeline infrastructure. For example, in the southern North Sea, where fishing largely targets flatfish that tend to associate with soft bottom habitats, there was less fishing activity around pipelines compared to the northern North Sea (Pascoe and Innes 2018). Additionally, fishing activities and fisheries face impacts both onshore and offshore through multiple mechanisms. One of the primary concerns involves physical displacement and loss of fishing grounds. Oil and gas rigs create safety exclusion zones that typically extend 500 m around structures, restricting access to approximately 0.8 km² per installation. While individual exclusion zones may be relatively small, multiple installations can lead to substantial cumulative loss of fishing area, forcing fishing vessels to concentrate in remaining accessible areas, potentially causing overcrowding and localized depletion (Pascoe and Innes 2018). Increased vessel traffic and port congestion, and the competition for facilities between fishing and energy sectors can lead to delays getting in and out of port, further impacting commercial fishing (Pascoe and Innes 2018).

While pipelines may affect fishing grounds access, their impact is generally less restrictive than other oil and gas infrastructure like platforms which have mandatory exclusion zones. Notably, pipelines can actually have beneficial effects on commercial fishing (Rouse et al. 2018). Research indicates that some vessels deliberately target pipeline areas as fishing grounds, likely benefiting from artificial reef effects where pipelines create habitat structures that attract fish. This is supported by data showing that fishing

effort near pipelines (2.52% of total effort) was nearly double what would be expected based on the area they occupy (1.32% of the region), suggesting meaningful aggregation of fishing activity around these structures (Rouse et al. 2018). Pascoe and Innes (2018) also found that the physical structures of pipeline operations can act as artificial reefs, potentially enhancing local fish abundance. Their study indicated that fish communities living on oil platforms off California had the highest secondary production per unit area of seafloor of any marine ecosystem for which similar estimates exist. In some regions, particularly the Gulf of America, fishers have found additional income opportunities by providing support services to offshore operations (Pascoe and Innes 2018).

The impacts of pipelines on commercial and recreational fisheries may vary considerably depending on specific context. Effective communication between fishing and energy sectors, along with careful planning and appropriate compensation mechanisms, appears important for minimizing negative interactions. This research suggests that while initial development phases often create notable disruption, many fisheries can adapt and continue operating successfully alongside oil and gas infrastructure, provided appropriate management frameworks are in place. This effective communication may also be an important factor in decommissioning decisions. The choice between pipeline removal versus leaving them in place presents different implications for the fishing industry. While removal might eliminate potential snagging hazards, it could also remove beneficial artificial reef effects that some fishing operations have come to rely on for their catches (Pascoe and Innes 2018).

Data from the Alaska Department of Fish and Game shows in 2024 866,722 licenses, tags, and stamps, generated over \$41.7 million in revenue, with non-residents making up the largest portion of both license volume (371,799) and revenue (\$14.9 million). Fishing licenses had a high sales volume, with non-resident fishing licenses alone generating over \$12.2 million (State of Alaska Department of Fish and Game 2024). To better understand the factors affecting recreational fishing participation of Alaska residents Romberg (2006) conducted a statewide survey in 2001. Romberg (2006) dividing respondents into active anglers (those who fished in the previous three years), inactive anglers, and non-anglers. The study revealed that inactive anglers primarily cited crowding at fishing sites, lack of interest, absence of fishing partners, and time constraints as their main reasons for not participating. Non-anglers generally lacked interest in fishing and faced barriers related to time, equipment, and fishing companions. For active anglers, having sufficient time was the most critical factor in maintaining participation, followed by access to fishing sites and knowledge of fishing opportunities. Regional differences were minimal, though Southcentral Alaska residents were more likely to mention crowding as a reason for becoming inactive. The study also found that approximately 20% of active anglers obtained licenses primarily for personal use fisheries rather than sport fishing. We were unable to find what percentage of recreational fishing is occurring in the offshore versus inshore lakes and streams.

2.4.12 Employment and Income

McDowell Group (2020) combines oil and natural gas economic impacts into a single report which makes it difficult to analyze these sectors independently. The report indicates that in 2018, the combined oil and gas industry supported approximately 77,600 jobs in Alaska (about 24% of all wage and salary jobs) and generated \$4.8 billion in wages. This includes both direct employment by primary companies as well as indirect and induced economic effects through support services and broader economic activity. McDowell

Group (2020) also found that industry jobs provide higher wages than average, both in direct industry employment and in support sectors. Additionally, the study found that natural gas production had declined in Alaska (falling 30% between 2005–2018) (McDowell Group 2020).

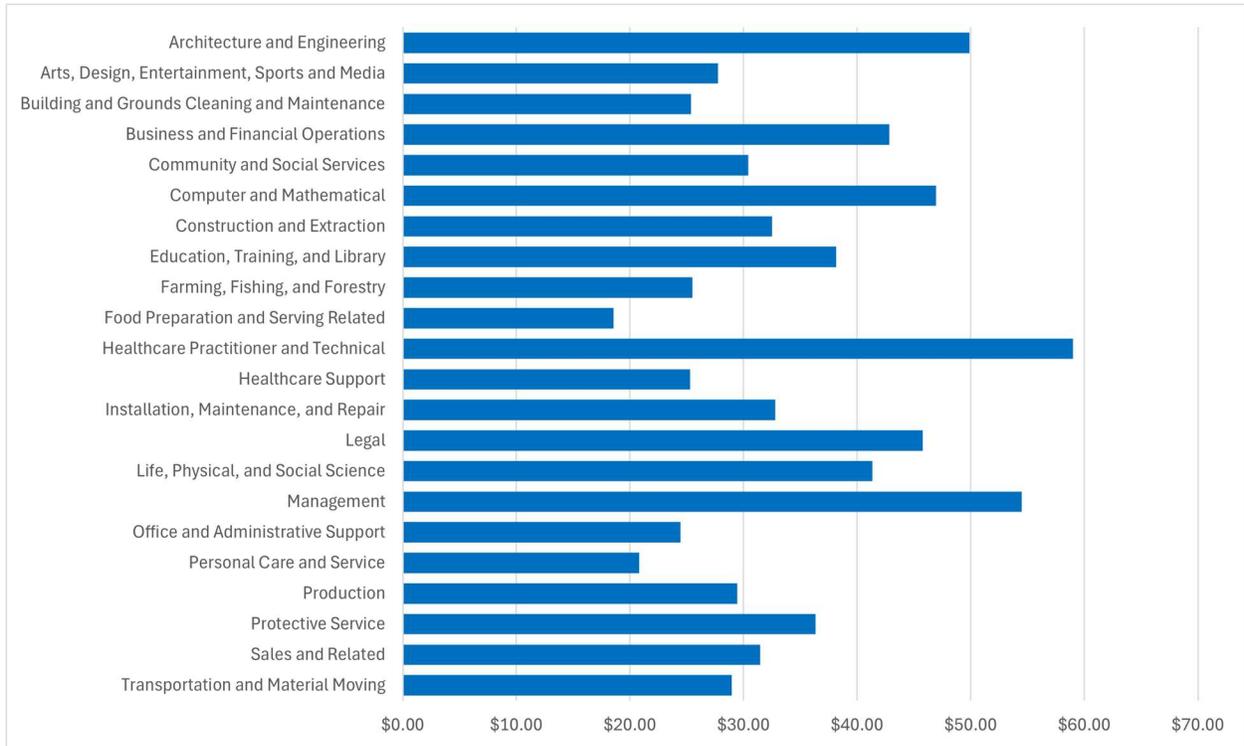


Figure 4. Median wage by labor category 2023

Dataset: (State of Alaska Department of Labor and Workforce Development 2023)

Figure 5, below, shows the monthly and yearly employment in Alaska for 2001–2024. Alaska’s employment rates decreased significantly in 2020 during the COVID-19 pandemic. Specific to oil and gas, Alaska lost 20% of its jobs in 2020 and another 18% in 2021, with only modest 5% growth beginning in 2022. While projections show a 38% growth by 2032, this represents recovery of jobs, not an expansion of employment (State of Alaska Department of Labor and Workforce Development 2024b).

Job losses have also occurred in Alaska’s fishing industry with an 8% decline in jobs during 2023, pushing total employment below 5,900, the lowest level since record-keeping began in 2001 (State of Alaska Department of Labor and Workforce Development 2024a). This downward trend is part of a decade-long pattern that has seen fishing employment decrease by more than 30% over ten years. Alaska’s fishing industry has faced multiple challenges including closed fisheries (i.e., the valuable Bering Sea snow crab fishery), declining fish prices despite adequate harvests, competition from Russian seafood flooding global markets, and processors refusing catches due to low profitability. These economic pressures discouraged participation, with 12% fewer crew licenses purchased and 8% fewer permit holders actively fishing compared to the previous year. While fish populations remain healthy for most species, suggesting good biological conditions, the economic headwinds have severely impacted the industry, and recovery isn’t

expected in the near term unless prices substantially improve (State of Alaska Department of Labor and Workforce Development 2024a).

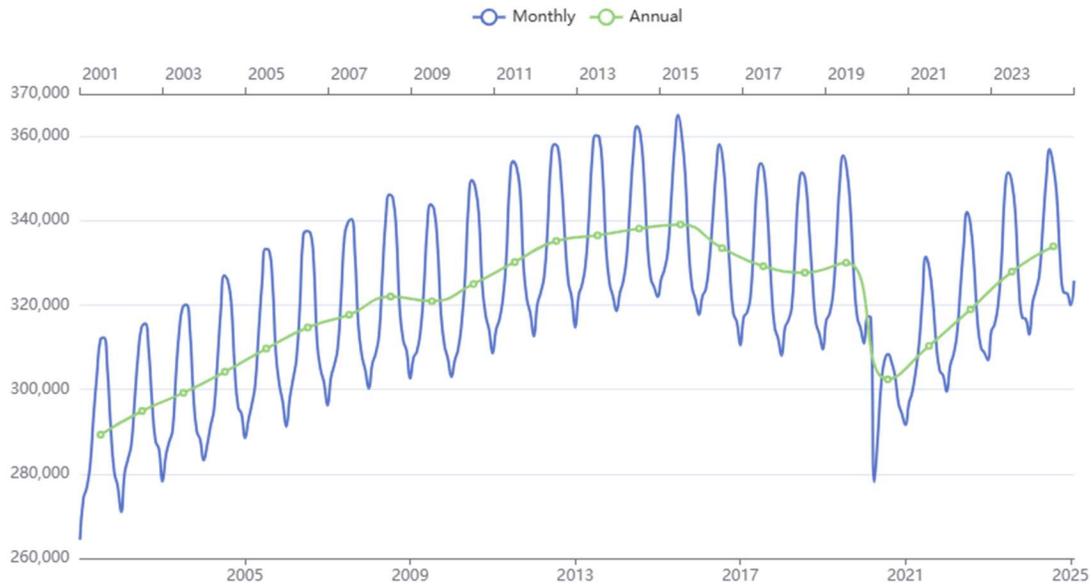


Figure 5. Alaska employment 2001–2024

(State of Alaska Department of Labor and Workforce Development 2025)

Alaska's working-age population (people aged 18–64) steadily declined for nine consecutive years, dropping from 479,000 in 2013 to 449,000 in 2022. This decline was primarily driven by two factors: negative net migration (more people leaving Alaska than arriving) and an aging population structure where the number of people turning 65 roughly equaled those turning 18. The decline was widespread across the state, affecting 26 of 30 boroughs and census areas, with Anchorage accounting for approximately 60% of the statewide reduction. Alaska's dependency ratio (non-working age people per 100 working-age people) increased to 64:100 in 2022, a burden not seen since the mid-1970s. Compared to other states, Alaska's 5.4% working-age population declined through 2021 was among the largest in the nation, with only West Virginia and Wyoming experiencing greater decreases. The COVID-19 pandemic exacerbated this trend, with working-age deaths increasing 40% above pre-pandemic levels (State of Alaska Department of Labor and Workforce Development 2003).

In addition to impact on overall employment, natural gas production also impacts overall socioeconomics with respect to balancing operational efficiency with investment in workforce wellbeing. For example, while anxiety and depression among gas and oil industry workers is comparable to that of the general population, long rotation schedules (56/28 day) have negative impacts on mental health, potentially leading to higher turnover and associated costs (Žeželj et al. 2019). Other studies have found increased physical health risks to natural gas workers. Yeoman et al. (2020) found that oil and gas extraction workers typically have some of the longest work hours across industries and a higher prevalence of smokeless tobacco use, excessive alcohol consumption, inadequate sleep, obesity, and inconsistent seat belt use compared to workers in other industries. These health risk factors have important socioeconomic implications for natural gas production communities since these workers face increased medical costs,

reduced productivity, and potentially shorter careers which impact both individual families and the broader community's economic stability. Increased healthcare utilization raises associated costs for both employees and employers (Yeoman et al. 2020).

2.4.13 Cultural Resources

Cultural resources in Alaska encompass the heritage and historical assets of both the Indigenous Alaska Native cultures and the pioneer settlers who came later. Alaska Native cultural resources include archaeological sites, traditional cultural properties, sacred places, language, oral traditions, subsistence practices, and crafts. These resources represent the diverse cultures of Alaska's Indigenous peoples, including Iñupiat, Yupik, Aleut, Athabaskan, Tlingit, Haida, and Tsimshian groups, each with their own distinct traditions and relationship to the land. Pioneer cultural resources reflect the more recent history of non-Native settlement, including Gold Rush era buildings, historic transportation routes, early industry sites, homesteads, and other physical remnants of frontier life (Gillispie 2018).

Cultural resources can be understood as physical attributes of interactions between humans and the human environment. The human environment is physical and non-physical, including property, social institutions, cultural uses of the biophysical environment, and religious practices. Cultural resources are comprised of locations, objects, subsistence, social practices, and the relationship of people with that environment (National Preservation Institute 2023). Current cultural sites are actively in use by local communities and may include structures, objects, and social and religious systems. Historical cultural sites are defined as “an area where human activity occurred, and artifacts remain” that are at least 50 years old (Kunce 2021).

“The definition of culture and how it relates to environmental management is hardly settled. There remains significant debate about proper characterizations of these relationships as important cultural factors can be easily missed. The complex interaction between culture and the environment exists within overlapping material and non-material domains. The cultural elements within the material sphere of the environment can include those of provisioning and regulating, such as subsistence activities or medicinal and religious practices. These practices often exist in a complementary relationship with non-material elements of culture such as spiritual enrichment, aesthetic experience, recreation, education and learning, and maintenance of social relations. However, these non-material experiences of culture may only exist in the presence of specific (material) cultural sites and the continuation of these practices depend on their preservation.” (Necefer et al. 2018).

Young et al. (2014) studied seabirds as an important cultural resource in the remote Pribilof Islands (St. Paul and St. George) in Alaska, even as actual subsistence practices decline. The study found overwhelming support for the cultural significance of seabirds among community members, with over 90% of respondents agreeing that seabirds are important to both Pribilofian and Aleut cultures. However, current seabird harvest levels remain low, with only about one-third of households reporting any reliance on seabird subsistence. The researchers documented a generational divide, with older residents valuing seabirds more highly than younger community members, suggesting a potential break in knowledge transfer. Many respondents associated seabird harvesting with family experiences, coming-of-age rituals, and ways children were taught to be valuable community members. Despite declining use, there was significant interest in preserving and expanding seabird knowledge, particularly on St. George, where 90%

of respondents wanted to learn more about seabirds. The researchers suggested that revitalizing interest through education could strengthen cultural connections and potentially support economic development through ecotourism in these communities facing challenging economic conditions.

Holton (2010) examined the influential "Native Peoples and Languages of Alaska Map" created by Michael Krauss in 1974. Krauss developed the map during the 1960s, interviewing speakers at the Alaska Native Hospital in Anchorage. He used linguistic science to map isoglosses (patterns of sound changes) that defined language boundaries, making subjective but informed decisions when these patterns crossed. The map represented an advancement over previous efforts by Shelikhov (1796), Verman (1863), Dall (1877), and Osgood (1936), which lacked linguistic detail. Naming languages presented additional challenges, as many names (like Yup'ik and Ahtna) derived from Native words but were not the indigenous terms for those languages, while others came from place names or neighboring languages, and some carried pejorative meanings later requiring change. The map served political and social functions during the Native language revitalization movement of the 1970s, facilitating the development of language education materials and helping establish enduring connections between Indigenous peoples and their traditional territories as Native languages face declining speaker populations. **Figure 6**, below, shows an updated map by Young et al. (2014).

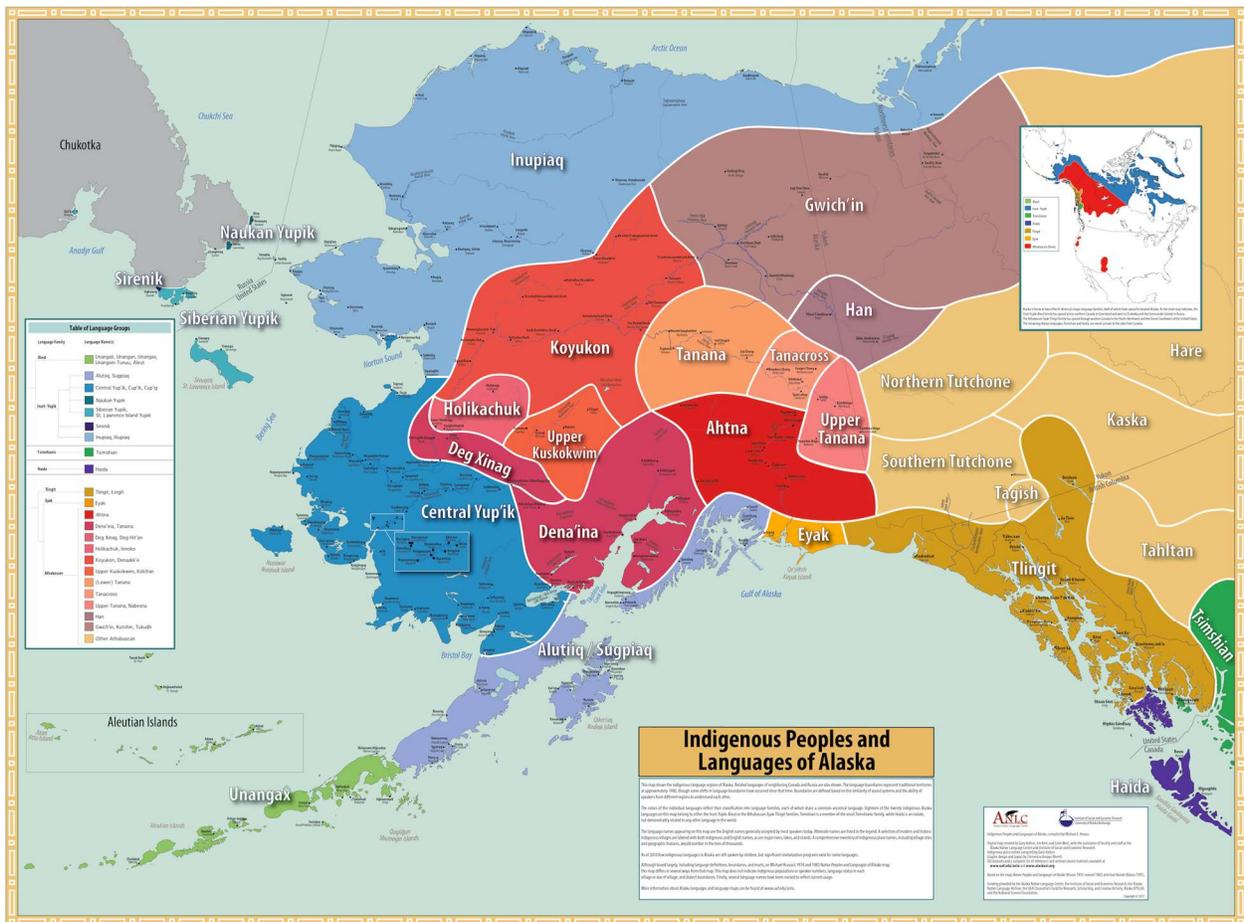


Figure 6. Indigenous peoples and languages of Alaska (Young et al. 2014)

Gillispie (2018) discusses the earliest confirmed inhabitants of Alaska belonged to the Eastern Beringian Tradition (14,000–12,000 years ago), arriving via the Beringia land bridge that connected Alaska to Northeast Asia during the late Pleistocene when continental ice sheets covered much of North America. These early inhabitants left evidence at sites like Swan Point in the Tanana River basin, which dates to at least 13,800 years ago. Over time, distinct cultural traditions developed across Alaska's various regions, including the American Paleo-arctic and Northern Paleoindian traditions, followed by the Northern Archaic Tradition (6,000–2,500 years ago) in interior regions, characterized by notched projectile points and adaptation to forest environments. Maritime adaptations evolved independently along Alaska's extensive coastlines, with the Paleo-marine Tradition in Southeast Alaska, the Paleo-Eskimo traditions in the Arctic and Bering Sea regions, the Anangula Tradition in the Aleutian Islands, and the Ocean Bay Tradition in the Gulf of Alaska. Later periods saw increasing social complexity, with the emergence of permanent settlements, elaborate material culture, social ranking, and evidence of warfare. Technological innovations included the transition from atlatls to bow and arrow technology in the Athabaskan Tradition (1,700 years ago to historic times), the development of sophisticated maritime hunting equipment, and the widespread adoption of ground slate technology in coastal regions. These diverse cultural patterns ultimately led to the formation of Alaska Native societies encountered by European explorers, including the Tlingit, Haida, Inupiat, Yupik, Aleut, and Alutiiq peoples, each possessing distinct cultural traditions deeply rooted in Alaska's prehistoric past.

2.4.13.1 Indigenous Perspectives and Traditional Knowledge

As of the 2020 Census, more than 20% of the Alaska population identifies as Alaskan Native or American Indian alone or in combination with other race/ethnicity options (Census Bureau and American Counts Staff 2021). Many distinct indigenous cultures exist in Alaska which can be “described geographically: Eyak, Tlingit, Haida, Tsimshian peoples live in the Southeast; the Inupiaq and St. Lawrence Island Yupik live in the north and northwest parts of Alaska; Yup'ik and Cup'ik Alaska Natives live in southwest Alaska; the Athabaskan peoples live in Alaska's interior; and Southcentral Alaska and the Aleutian Islands are the home of the Alutiiq (Sugpiaq) and Unangax peoples”(Alaska Federation of Natives 2023).

Protection of the general environment is important as interactions between people, animals, and the environment is important to Alaskan native religious practices. Traditional practices vary across the region, but are commonly rooted in the mediation between people, spirits, and animals. Also common is religious syncretism in native communities which experienced forms of colonialism and forced assimilation (University of Alaska Fairbanks Department of Tribal Governance 2023). Religious syncretism in Native Alaskan communities involves unique interactions between Protestant Christianity and Native Alaskan Religions. A Pew Research telephone poll on 310 Alaska adults report 62% of all Alaskan adults identify as Christian and 31% of Alaskan adults identify as Unaffiliated (Pew Research Center 2014a). While there are larger margins of error for such small sample sizes, these statistics are generally on-par with the wider American religious landscape, with around 70% of American Adults reporting Christian and 22% reporting Unaffiliated (Pew Research Center 2014b). In areas where traditional native religions are practiced, they may include aspects of animism combined with mainstream Christian religious practices.

Alaskan native communities are often at a disadvantage and disproportionately suffer from cultural, economic, and environmental change (Alaska Federation of Natives 2023). Native communities have rich

cultural values that interact with the physical environment in smaller groups of people in rural regions of Alaska. Alaskan native communities differ from the northwest Eskimos, southern peninsula Alutiiq, and the southeastern coast and more inland Indians. Since most communities rely heavily on access to safe, clean, and consistent subsistence fishing and hunting, environmental changes and human impacts severely affect native communities' food and resources (Alaska Federation of Natives 2023). Small rural communities in Alaska, especially Native communities, also struggle with access to education and training opportunities (Alaska Federation of Natives 2023). Outside of environmental concerns, "rising health costs due to high rates of diabetes and substance abuse among Native populations continue to challenge their cultural and economic survival" and "high energy costs for residential heating and electricity and a lack of infrastructure severely limit rural residents' cash income" (Alaska Federation of Natives 2023). Census data shows an increasing number of American Indians or Alaskan Natives living in urban areas than rural villages (Alaska Federation of Natives 2023).

Kawagley and Barnhardt (2007) found that Indigenous communities are impacted by government resource management decisions due to their deep cultural and spiritual connections to the land and traditional ecological knowledge. The study demonstrates this through examples like the Inupiaq whale hunters who balance subsistence hunting with industrial development, showing how government policies around resource extraction directly affect tribal ways of life and food security. There is a disconnect between Western scientific management approaches and Indigenous knowledge systems. The study also describes how government agencies often take a compartmentalized, specialized approach to resource management, while tribal perspectives emphasize interconnectedness and holistic understanding of ecosystems. For example, the study discussed how Native Alaskan observers noted comprehensive changes in marine ecosystems that specialized scientific studies missed by focusing on single species.

Dorantes and Brooks (2012) suggest that effective environmental protection requires bridging these different knowledge systems and ensuring tribal perspectives help shape policy, rather than tribes simply reacting to government actions that affect their resources and ways of life. Traditional ecological knowledge can help focus research efforts, provide valuable historical context that may be missing from limited scientific data, and reveal interconnections that might not be apparent through western scientific approaches alone. The authors emphasize that Alaska Native peoples are among those most directly affected by land management decisions in rural Alaska, making their involvement essential for developing plans that appropriately consider local impacts and perspectives. Meaningful participation from Alaska Native peoples may lead to better outcomes and increased local buy-in for conservation projects. Their involvement may help to ensure that management plans incorporate Indigenous perspectives and better represent rural public interests.

2.4.13.2 Regulatory Framework and Cost Implications

Kunce (2021) examined data from oil and gas fields in Wyoming spanning 1987–2004 finding a disparity exists in how cultural resource protection affects natural gas drilling costs between federal and private lands. On federal lands, each additional cultural site increases drilling costs substantially, approximately \$10,900 for shallow wells and up to \$32,100 for deeper wells. In contrast, cultural sites on private lands show no statistically significant impact on drilling costs. This difference emerges from varying regulatory requirements and enforcement practices. The study area, included cultural heritage dating from the Paleo-

Indian period (13,000 years ago) to the early 1950s, revealed that cultural resource presence increased net drilling costs by approximately \$114,000 on federal lands. Notably, 76% of the federal land drilling cost premium stems from biological and cultural resource protection requirements. The cost disparity between federal and private lands can be attributed to several factors. Federal land managers must legally identify and preserve Native American artifacts and historical sites, particularly those along original wagon trails. This requirement necessitates specific testing and archaeological excavation when drilling occurs within proximity to cultural sites. In contrast, private landowners may regard cultural artifacts as personal property and resisting archaeological surveys, resulting in less thorough documentation and protection of cultural sites on private lands. While these federal processes increase operational costs, they serve a protective function. The requirements for specific testing and archaeological excavation create a systematic approach to preserving cultural heritage sites during natural gas development.

2.4.13.3 Cultural and Environmental Impacts

Cultural resources are at risk of impacts from the construction of natural gas pipelines and from potential pipeline incidents which could damage or destroy existing nearby cultural structures or culturally important environmental areas, landscapes, sacred sites, plants, food sources, and buried objects. Necefer et al. (2018) found that the communities near natural gas pipelines are at risk of both health and cultural impacts due to the proximity of natural gas pipelines to sacred sites. The study noted that impacts to cultural resources were generally assessed on “economic valuation, willingness-to-pay, or related monetization methods” can be “incompatible with cultural values and may strip meaning or misrepresent the culture under consideration”. Many Indigenous communities are forced to weigh the benefits of new energy-development options against the loss of cultural resources. New energy developments may interfere with grazing lands, sacred sites, and certain plants, wildlife, and food. The study authors created a decision-making tool that assessed the impacts of energy-development options on natural resources and on Navajo cultural resources. The tool aids in the process of “meaningful conversation” with Indigenous communities about environmental and energy decisions. Users are given economic options for various new energy options and the certain landscapes that would be lost.

2.4.14 Recreation and Tourism

Travelers come to Alaska to see scenic landscapes and to experience nature immersion and wildlife encounters (Destination Analytics 2023). The typical visitor is affluent, married, and middle-aged, staying just over a week to explore the region. Nearly half of all visitors are repeat visitors. Most tourism activity centers around the Gulf of Alaska primarily in Juneau, Ketchikan, and Anchorage. Only 3% of visitors visited the Arctic region. Visitors’ primary activities are local cuisine, wildlife viewing, shopping, and outdoor activities like hiking. Domestic (U.S.) travelers make up 95% of all visitors to Alaska, while international visitors account for the remaining 5%, with Canadians representing 40% of the international segment. For transportation modes, cruise ships bring 43% of total visitors, while commercial airlines account for 55% of arrivals (Destination Analytics 2023).

Research has shown that oil and gas wells near recreation sites reduces visitation, particularly in the western regions of the United States (Rasch et al. 2018). Additional oil or gas wells within a 5-kilometer radius of a recreation site is associated with approximately six fewer annual visits to that site. This effect appears to be most pronounced in western states, where visitors often have higher expectations for

pristine natural settings. The impact of natural gas infrastructure extends beyond just well sites. Pipeline construction and maintenance create linear disturbances through natural areas that can fragment recreational trails, disrupt wildlife viewing opportunities, and alter the aesthetic qualities that many outdoor enthusiasts seek. The physical presence of pipelines, along with associated maintenance roads and cleared rights-of-way, can diminish the perceived naturalness of recreation areas and impact activities like hiking, camping, and nature photography (Rasch et al. 2018).

Natural gas development can affect recreation through multiple pathways. There are direct physical impacts from infrastructure development, including increased traffic, noise from operations, and visual impacts to the landscape. Studies have documented concerns about air and water quality near development sites, which can affect visitors' willingness to camp, fish, or engage in water-based recreation in these areas. The research suggests that these impacts vary depending on the regional context, visitors in more developed eastern regions appear more tolerant of industrial infrastructure compared to those in western regions where expectations for undeveloped landscapes are higher. The study indicates potential temporal displacement effects, where recreationists may shift their use patterns to avoid times of active development or maintenance. Some visitors may adapt their expectations and continue using areas with energy development, particularly in regions where such infrastructure is more common. The presence of energy workers may even create new patterns of recreation use in some areas, though this may displace traditional users seeking more pristine experiences (Rasch et al. 2018).

The economic implications of these impacts are complex. While natural gas development can generate revenue for local communities, reduced recreation visitation can affect tourism-based businesses and result in decreased recreation fees available to land managers for site maintenance and stewardship. The research indicates that careful consideration of these trade-offs is important when planning natural gas development near popular recreation areas. Mitigation strategies suggested include maintaining adequate buffers between recreation sites and gas infrastructure, minimizing visual impacts through creative pipeline routing and infrastructure placement, and carefully timing construction and maintenance activities to avoid peak recreation seasons. However, the effectiveness of these strategies varies by context and the specific recreation values being protected (Rasch et al. 2018).

Based on research by Price and Ronck (2018) tourism and natural gas development have a complex relationship that warrants careful consideration. The article discusses how oil and natural gas tourism sites in Texas tend to present a largely positive view of the industry while minimizing discussion of environmental impacts and risks. Notably, the research found that interpretive materials at these sites give minimal attention to pipeline infrastructure and associated controversies, which the authors identify as a "notable omission" given ongoing public debates about pipeline construction and safety. The tourism impacts of natural gas development appear to manifest in multiple ways. In some cases, former boomtowns have converted their industrial heritage into tourist attractions, creating museums and interpretive centers focused on the history of oil and gas extraction. However, these sites often present a nostalgic view that emphasizes economic benefits while downplaying long-term community impacts after resources are depleted. The research suggests that tourism related to natural gas tends to focus either on historical boomtown narratives or contemporary industry promotion, with little discussion of ongoing environmental and infrastructure challenges.

Regarding pipelines specifically, Price and Ronck (2018) indicate a gap in how tourism sites address this infrastructure. Despite pipelines being central to natural gas transportation and frequently featured in public debates, the analyzed tourism locations largely avoided discussing pipeline construction, safety concerns, or community impacts. Natural gas development can impact broader tourism potential in affected regions and while some communities have successfully leveraged their industrial heritage for tourism, questions remain about long-term sustainability and the balance between resource extraction and tourism development. Price and Ronck (2018) suggests a need for more research into how pipeline construction and natural gas infrastructure affect other forms of tourism in impacted areas and notes that most existing research on energy tourism focuses on historical sites rather than contemporary development impacts. This leaves a knowledge gap regarding how current natural gas operations, including pipeline construction and operation, influence tourism patterns and potential.

2.5 Summary and Discussion

Natural gas releases present multiple hazard pathways through fire, explosion, toxic exposure, and asphyxiation risks. The spatial and temporal characteristics of these hazards vary based on environmental conditions, with Alaska's climate creating distinct challenges for both hazard development and response capabilities. Environmental impacts of natural gas releases occur through various interconnected mechanisms. Air quality is affected by the release of methane and associated gases, while water quality suffers from dissolved gas effects and oxygen depletion. Vegetation experiences damage from hypoxia and thermal radiation from fires and explosions, while wildlife including marine and terrestrial experience direct exposure risks and habitat modification. Infrastructure affect bird species differently, with some showing significant behavioral disruptions or habitat avoidance while others demonstrate greater tolerance to these disturbances. While there are regulations to address the preservation and/or discovery of archaeological sites and historical resources, damage occurs before sites are discovered. Subsistence fishing and hunting disruption can affect food security in remote communities while pipeline infrastructure may be at risk due to vessel traffic while also serving as temporary reefs for marine life. The natural gas industry provides employment and economic stability to workers with employers balancing operational efficiency with investment in workforce wellbeing. Impacts to cultural resources in Alaskan Native communities require open communication when developing new pipeline infrastructure. Natural gas pipeline infrastructure and potential releases may impact tourism dollars for local economies that depend on these activities.

For developing qualitative rankings, the literature suggests considering the inherent vulnerability of different resources, their spatial and temporal relationship to infrastructure, and both acute and chronic exposure effects. The availability and effectiveness of mitigation measures must be weighed alongside the capacity for resource recovery post-exposure. These factors combine to create a multitude of considerations that must be carefully balanced in any evaluation. These findings provide a foundation for developing resource-specific vulnerability rankings (**Section 4.2.2**). The rankings must incorporate both the direct physical impacts of releases and the broader socioeconomic implications for affected communities. This approach will help ensure that risk assessments accurately reflect the full spectrum of potential impacts while acknowledging the complex interplay between environmental, social, and economic factors.

2.5.1 Research Needs

Conventional gas is found in geological formations where the gas flows easily and can be extracted using traditional vertical wells. Unconventional gas, by contrast, is trapped in formations such as shale, tight sandstone, or coal seams, and requires horizontal drilling and hydraulic fracturing. These fundamental differences in extraction methods create distinct exposure pathways that may lead to differing health and environmental impacts (Bamberger and Oswald 2012; Chambers et al. 2015; Clark et al. 2022).

While some research exists on acute environmental impacts from catastrophic pipeline failures (Scasta et al. 2023), there is limited understanding of how chronic, small-scale releases might affect ecosystem health over extended periods. The limited geographic variations in the selected studies make it difficult to understand how soil types, groundwater conditions, and ecological communities might respond differently given a natural gas pipeline release. While included research provides insights into vegetation damage mechanisms and soil chemistry changes (Hoeks 1972; Schollaert et al. 2020), there is limited long-term monitoring data regarding the recovery trajectories of complex ecosystem components like soil microbiota and tree canopies. The reviewed studies predominantly focus on urban environments (Schollaert et al. 2020) or specific forest types, leaving uncertainty about how these impacts manifest in coastal and estuarine settings with their unique soil conditions, vegetation types, and tidal influences. Reviewed literature is also lacking studies on the cascading effects through food webs and the potential impacts on marine organisms when natural gas releases occur in transition zones between terrestrial and aquatic environments. While Sanseverino et al. (2012) demonstrates methane-derived carbon's role in food webs, there is a lack of knowledge about the threshold between beneficial and harmful methane exposure levels. The research provides no standardized methodologies for measuring and comparing methane impacts across different marine environments, limiting our ability to make broad ecological assessments. Additionally, while Campbell et al. (2014) examines methane's effects in ice-covered waters, we know little about how these impacts might compound with other environmental stressors. In literature reviewed long-term studies tracking chronic methane exposure effects on marine ecosystems are particularly sparse. While some research exists on natural gas and methane exposure in marine environments, such as Knutsen and Serigstad's (2001) work on deep-water scenarios, our literature review found few studies focused on shallow-water environments characteristic of Cook Inlet and the North Slope Basin. This may either indicate limited investigation into the topic or suggest that natural gas releases in these environments produce minimal ecological impacts that do not necessitate extensive documentation.

Additional research is needed to improve our understanding of gas release impacts on marine and coastal birds as there is limited reviewed research on the effects of dry natural gas on birds. The reviewed literature largely assesses the impacts of unconventional gas, gas flaring, development activities, oil spills, and global warming (Ronconi et al. 2015; Russell 2005; Williams; et al. 2021). Research tends to focus on immediate behavioral responses, with minimal investigation into potential physiological changes or reproductive success impacts. We found little research on the effects of natural gas pipeline releases on marine mammals. The reviewed literature primarily focused on acute exposure events like oil spills or chronic exposure to persistent organic pollutants, while the potential impacts of methane and associated natural gas compounds remain largely unexplored. We lack information on chronic small-scale natural gas pipeline releases and spontaneous release events that may contain methane and VOCs including ethane, propane, butane, and various sulfur compounds. The fate and impact of these compounds in marine

environments, their bioaccumulation potential, and their physiological effects on marine mammals remain poorly understood. While studies have examined the atmospheric and water-quality impacts of natural gas releases, the biological impacts on terrestrial mammals, particularly through chronic low-level exposure remain sparse. Additional research on the potential ecological impacts of emissions from natural gas pipeline releases would help understand the effects on terrestrial mammals near pipeline structures.

While numerous studies have examined air quality impacts from the oil and gas industry, many focus specifically on unconventional gas extraction (Bamberger and Oswald 2012; Carpenter 2016; Cushing et al. 2021), assess the industry as a whole (Alvarez et al. 2018), or focus on climate change (Alvarez et al. 2012; Littlefield et al. 2022). This research approach makes it challenging to isolate and evaluate the unique impacts of conventional natural gas operations. Studies reviewed frequently use proximity-based exposure assessments (Macey et al. 2014; McKenzie et al. 2017; Mitchell et al. 2015; Slizovskiy et al. 2015), which struggle to differentiate between natural gas pipeline emissions and other sources like industrial activities, vehicle exhaust, and agriculture. In addition, VOCs including BTEX compounds also come from various natural and human-made sources beyond natural gas production, complicating efforts to establish direct causation through proximity measurements alone. Research often focuses on immediate health effects rather than long-term impacts and chronic low-level exposures. Some studies examined indoor residential and commercial settings where natural gas is used for cooking and heating (Michanowicz et al. 2022b). Occupants in these enclosed environments likely experience higher exposure durations, but these spaces also contain combustion byproducts, making it difficult to attribute health effects specifically to natural gas itself rather than these byproducts. There is limited research on the long-term resilience of subsistence fishing communities following environmental contamination events, particularly regarding natural gas releases. Reviewed literature lacks analysis of how modern policy frameworks might create economic opportunities that complement rather than compete with traditional practices. There is insufficient research on the effectiveness of current consultation processes with Indigenous communities in preserving subsistence fishing rights and practices. There is also limited information on how fishing communities adapt their practices over time in response to pipeline infrastructure. Studies examining the long-term career trajectories of workers exposed to chronic low-level chemical exposure are lacking. There is minimal research on the economic implications of implementing enhanced safety protocols and their cost-benefit relationships to worker health outcomes. Reviewed research failed to examine natural gas-specific employment effects and extended studies of worker health and career outcomes. While one study examined cost implications of cultural resource protection, we found insufficient research on effective methods for balancing energy development with cultural preservation. Reviewed resources lacked information on the effectiveness of current regulatory frameworks in protecting cultural resources from natural gas-related impacts.

While Rasch et al. (2018) establish quantitative impacts on recreation site visitation, and Price and Ronck (2018) examine tourism narratives, important aspects of these relationships remain unexplored. The temporal dynamics of recreational displacement deserves examination, particularly regarding how visitor adaptation processes unfold over time and whether initial avoidance behaviors persist or evolve as communities become more accustomed to natural gas infrastructure. Understanding the differences between various types of recreational activities and their sensitivity to natural gas development could be beneficial. While Rasch et al. (2018) document general visitation declines, there's limited investigation into how specific activities may be differentially affected. The interaction between natural gas infrastructure and

specialized recreation activities could reveal important patterns. The economic dimension of recreation impacts requires more detailed investigation. Price and Ronck (2018) acknowledge potential trade-offs between energy development and tourism revenue but lack analysis of these competing economic forces. Reviewed literature was unable to quantify the long-term economic implications of reduced recreation access against the benefits of natural gas development, particularly in communities heavily dependent on outdoor recreation tourism. While artificial reef effects are documented, there is insufficient understanding of how these effects vary across different marine ecosystems and species assemblages. We found limited research on how different decommissioning approaches affect both fishing communities and marine ecosystems in the long term. While Rasch et al. (2018) suggests measures like maintaining buffers and timing construction around peak seasons, there's insufficient research evaluating these strategies' success in preserving recreation values. The lack of post-implementation studies makes it difficult to determine which approaches most effectively balance energy development with recreation interests.

3 Historical Incidences of Natural Gas Releases

The analyses presented in this report require pipeline infrastructure and incident data. This section describes the methods used to collect, aggregate, and validate these data, which include pipeline characteristics, historical release incidents, environmental conditions, location, and operational parameters associated with natural gas releases from pipelines. This discussion provides an indication of the quality of the data finally accepted for analysis in this study. In addition, it documents the various data sources which were reviewed and used for data throughout this report. All the natural gas pipeline release data and analysis presented in this report come from these databases. Further details about the specific data types, sources, and collection methodologies are provided in **Section 3.1**.

3.1 Available Datasets

Natural gas pipeline release data was collected and analyzed from multiple regulatory agencies to develop a comprehensive understanding of historical incidents in the OCS, state waters, and onshore. The datasets were carefully screened and evaluated to ensure analytical integrity while acknowledging inherent limitations in historical records. This section details the data selection process, key attributes retained for analysis, and important limitations that influenced the analytical approach.

3.1.1 reouData Selection

Data were first examined from three regulatory agencies: the U.S. Coast Guard's National Response Center (USCGNRC), PHMSA, and BSEE. These sources were selected based on their regulatory oversight responsibilities and standardized incident reporting requirements. Both PHMSA and BSEE have regulatory jurisdiction throughout the area examined, as well as incident report requirements in the case of a natural gas pipeline release. After examination of these incident reports, the data from PHMSA and BSEE were used. Each dataset provided unique insights while also offering opportunities for cross-validation of incident reports. The PHMSA data was used to gather causal factor breakdowns, while the BSEE data was used to calculate historical release rates.

Data quality control measures led to the exclusion of records with substantial missing or unknown fields to maintain analytical integrity. These measures are what led to the USCGNRC data being excluded, as many of the records were completely blank or had only one or two columns populated. It was also difficult to determine the relevancy of records to this study. BSEE’s data had no entries thrown out as the records were detailed and standardized throughout the years examined. PHMSA’s incident data varied throughout, as the data is based on scans of incident report forms. The forms starting in the year 2002 stored enough information to be useful, and as such the sections concerning PHMSA incident data begin in this year. This approach gives higher confidence in the resulting analyses and conclusions. Due to covering all three desired areas (OCS, state waters, and onshore), as well as being primarily pipeline focused, BSEE data in combination with the PHMSA mileage data was used for historical rate calculation. Due to having many more fields describing the various causes of releases, the PHMSA Gas Transmission and Gathering Annual data was used for the causal factor analysis. **Table 1** summarizes the incident data coverage by region for various periods. **Table 2** shows which data was used for which portions of this report.

Table 1. Dataset selection

| Source Agency | Description | OCS | State Waters | Onshore | Timeframe |
|---------------|---|-----|--------------|---------|-----------|
| PHMSA | Gas Transmission & Gathering Annual Data: Incident Data: Concerning pipeline releases of hazardous materials from either transmission or gathering pipelines. (PHMSA 2023b) | ✓ | ✓ | ✓ | 2002–2022 |
| PHMSA | Pipeline Mileage Data by Year (PHMSA 2023a) | ✓ | ✓ | ✓ | 1984–2022 |
| BSEE | BSEE Incident Data, Spills Archive: Data on past oil spills and incidents. (BSEE 2023) | ✓ | ✓ | ✓ | 1984–2022 |

Table 2. Dataset usage

| Dataset | Historical Rates (Section 3.2) | Causal Factor Analysis (Section 3.3) |
|------------------|--------------------------------|--------------------------------------|
| PHMSA - Incident | - | ✓ |
| PHMSA - Mileage | ✓ | - |
| BSEE - Incidents | ✓ | - |

The two datasets were filtered to focus on natural gas pipeline releases. Onshore, state waters, and OCS transmission pipeline data were retained to enable broader statistical analysis and trend identification between locations. Temporal restrictions were applied based on data quality and consistency considerations. Most notably, estimated release volumes were only systematically tracked by PHMSA after 2010, while human error categorization as a causal factor was standardized from 2001–2002 onwards.

Consequently, analyses involving release volumes or causal factors are temporally bounded by these temporal data limitations.

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3.1.2 Data Attributes

These datasets incorporated key attributes that enable comprehensive analysis of natural gas releases. These attributes can be grouped into several primary categories that provide context for understanding incident patterns and causal relationships.

Location and jurisdiction attributes (city, county, state, shore designation, and OCS status) were retained to enable categorization of releases as occurring in state waters, OCS, or onshore locations. These distinctions are crucial for understanding release patterns across different operating environments and jurisdictional boundaries. Federal waters designation was maintained to clearly delineate releases occurring within the OCS, while other geographic markers allow for regional analysis and identification of location-specific patterns.

Incident severity was captured through three metrics including fatalities, injuries, and incident duration (measured in hours and minutes until declared safe). These metrics were chosen as they provide quantifiable measures of impact and response effectiveness. The time-to-safety metric for natural gas releases tends to be longer than other hydrocarbon releases, as controlled bleed-out procedures are often employed as a safe mitigation strategy, whereas oil spills typically focus on immediate containment. While this skews the duration data higher for natural gas incidents, it was kept as an indicator of incident complexity and response requirements.

Causal factors were tracked through multiple related fields to enable detailed root cause analysis. Primary cause categories were supplemented with specific descriptive fields for key failure modes including corrosion (location and type), weather, mechanical failure, and human error. This approach to causal categorization allows for both event count analysis and mechanical failure assessment. The causal factors were specifically analyzed and categorized to facilitate translation from Gulf of America experience to Alaska OCS conditions - for instance, while hurricane damage is a substantial factor in the Gulf of America, the analogous extreme weather category was broadened to also include Alaska OCS-specific conditions like polar lows and subarctic remanent typhoons. Similarly, corrosion categorizations were maintained but will require different interpretation in Arctic conditions where low-temperature effects on materials must be considered. This discussion is continued at length in **3.4 Alaska OCS Causal Factors**.

Environmental conditions were captured through a series of weather-related fields including hurricanes, tropical storms, tornadoes, and other extreme weather events. These fields were included based on the assumption that weather patterns influence both the likelihood and severity of natural gas releases. While some weather categorizations may overlap, retaining multiple descriptors enables more nuanced analysis of weather impacts.

Infrastructure characteristics, particularly the pipeline type system classification (transmission, gathering, or distribution), were maintained to ensure proper scope boundaries for the analysis. For OCS and state waters operations, both gathering lines (connecting multiple wells to a central collection point) and transmission pipelines (carrying natural gas from offshore platforms to onshore facilities) were included due to their relevance to OCS operations. For onshore systems, only transmission pipelines were retained in the dataset, while distribution systems were excluded entirely as their operating conditions and regulatory requirements differ substantially from the OCS and state waters gathering and transmission systems that are the focus of this study. This distinction was crucial for maintaining consistency in the analysis and ensuring relevant comparisons could be made between Gulf of America and potential Alaska OCS operations.

3.1.3 Data Limitations

Several limitations affected both data collection and analysis methodologies. Field population consistency varied not only across the two data sources but also within the PHMSA dataset over time, as reporting forms and data collection methods evolved. PHMSA's incident reporting forms underwent several revisions, resulting in different fields being captured in different time periods, such as human error not being recorded as a causal factor until the 2001–2002 form revision. In cases where this uncertainty existed in field mapping between sources or across different versions of reporting forms, several mitigation strategies were employed. These strategies included narrowing down timeframes of analysis, broadening categories to accommodate varying detail levels, and excluding records with insufficient decipherable information.

The most important limitation stems from the limited incident records available from the Alaska OCS. The scarcity of historical natural gas release data from this region, due to a lack of any current OCS natural gas production, precluded standalone statistical analysis. To overcome this limitation, records from the Pacific OCS and Gulf of America OCS were incorporated to achieve statistical significance. While this approach provided sufficient data for meaningful analysis, it introduces two key considerations that required careful

The most important limitation stems from the limited incident records available from the Alaska OCS. The scarcity of historical natural gas release data from this region, due to a lack of any current OCS natural gas production, precluded standalone statistical analysis. To overcome this limitation, records from the Pacific OCS and Gulf of America OCS were incorporated to achieve statistical significance. While this approach provided sufficient data for meaningful analysis, it introduces two key considerations that required careful

treatment. The first consideration is that causal factor variations between regions may affect direct application of historical patterns. The second is that incident frequency expectations may differ due to distinct operating environments. These considerations are addressed in detail in **3.3 Natural Gas Pipeline Release Causal Factors** and **3.4 Alaska OCS Causal Factors**, where specific adjustment factors and regional variations are examined.

Temporal limitations also affected data availability and quality. Pre-1984 incident records lacked information including specific commodity identification between natural gas and other releases, fire and explosion occurrence data, ignition source information, and response procedure documentation. Due to these systematic data gaps, pre-1984 records were excluded from the analysis to maintain consistency and reliability in the findings. This temporal boundary ensures that all analyzed incidents include complete documentation of safety and operational factors.

3.1.4 Data Definitions – Locations

For the purposes of this report, we define several location-based terms to categorize gas pipeline releases. Onshore refers to a release that occurred on land, including inland water bodies. For the PHMSA and BSEE datasets, all releases logged as onshore were kept. This includes releases from the states in the Gulf of America, as well as California, but also includes releases from onshore transmission pipelines in landlocked states. It is worth noting that over 80% percent of the total onshore incidents were still from the Gulf of America OCS and Pacific OCS, but the other incidents were kept as there was no clear way to trim down the historical total of onshore mileage of transmission pipelines to just a subsection of states.

Offshore is an umbrella term referring to releases that occurred in marine waters, encompassing both state and federal waters. State Waters are those belonging to individual states, typically extending from the coastline to 3 miles (in most states) or up to 8 miles (in Texas and the west coast of Florida). OCS Waters refer to federal waters of the Outer Continental Shelf, extending from the seaward boundary of state waters out to 200 nautical miles from the coastline. Offshore has been scarcely used throughout this report, as the other terms give more clarity about release location. However, it is important to note that prior to 1999, many data sources did not distinguish between releases in state waters versus OCS waters, resulting in some combined statistics for these earlier time periods. When analyzing historical trends, this limitation in data granularity must be considered when interpreting offshore pipeline release statistics.

3.2 Historic Release Rates

The assessment of release rates requires analysis of two key variables: frequency and exposure. Frequency represents the quantifiable rate of occurrence within a specified time period. Exposure defines the operational extent to which these occurrences can take place. For pipeline natural gas release incidents, the exposure variable is measured in pipeline mile-years, while frequency is calculated as the number of documented incidents per mile-year. The analysis includes uncertainty factors to account for limitations in the historical incident data.

3.2.1 Frequency and Exposure Estimation

As mentioned in **3.1.1 reouData Selection**, the data used for this study tracks a detailed log of gas release incidents that occur to pipelines across the country. This data was used and categorized to create a historic release rate calculation, based on both frequency and exposure. Frequency was tracked by counting the number of relevant incident reports per year.

Exposure is a way to normalize the rate of occurrence across space in time. Exposure was calculated by taking the yearly number of pipeline-miles that were in use and vulnerable to having a potential leak. This data was tracked in detail by pipeline type (including gathering, transmission, and distribution) as well as pipeline location (OCS, state waters, or onshore). By dividing frequency by exposure, an estimate of historical release rates can be created. This rate can then be compared across the respective locations, and additional hazards, such as fire, ignition, and explosion, can also be analyzed.

3.2.2 Factors for Uncertainty

The rates calculated are rough estimates, based on data that was the best available. However, many natural gas releases have gone undetected or barely documented, so the rate may be an underestimate. On the other hand, it is also possible that the hazard rates for ignition and explosion occurring are an overestimate as these releases are much more threatening and noticeable, often leading to quick response and resolution. Natural gas can also be released alongside oil spills, but this is not always the case. This most often occurs in pipelines with three phase flow prior to processing, but this would not be the case with transmission pipelines with the exception of natural gas liquids. These types of events are almost always recorded as purely an oil spill in the data, and since no differentiation can be made between this type of spill and an oil spill that only released oil, they were excluded altogether.

3.2.3 Confidence Intervals

To estimate confidence intervals, ABSG assumes that gas release occurrences are a Poisson process. The Poisson distribution models the number of events to take place in a specified time interval when the events occur independently of each other and at a given rate. This is an ideal distribution for modeling independent release events due to the size of the dataset.

The Poisson process is defined by the parameter λ . When estimating λ using historical data, it can be assumed without loss of generality that the historically observed events all occur in a single time interval. In this simple case, the best estimate of λ is equal to the number of events observed, x . Confidence intervals for λ can then be computed using a variety of statistical estimates. Two of these estimates were used to calculate the 95% confidence intervals used in this report, based on recommendations found in Comparison of Confidence Intervals for the Poisson Mean (Kulkarni and Patil 2012):

$$\left(\frac{\chi^2_{(2x,0.05)}}{2}, \frac{\chi^2_{(2(x+1),0.95)}}{2} \right)$$

Equation 13. Garwood confidence estimate

$$((x-0.5) + Z_{0.05}\sqrt{(x-0.5)}, (x+0.5) + Z_{0.05}\sqrt{(x+0.5)})$$

Equation 14. Wald Continuity Correction (CC) confidence estimate

Equation 13 is an ideal estimate when $x = 4$ or more. **Equation 14** is ideal when $x = 2$ or less. **Equation 13** was used in the $x = 3$ case. When $x = 0$, the lower bound of the interval in **Equation 14** cannot be evaluated. Of course, the lower bound should be 0 in this case. After computing the confidence interval for λ , the results were then converted to spill rate confidence intervals by dividing by the exposure.

These results include a minor caveat related to the effect of hurricanes. Hurricanes tend to cause multiple releases at once as multiple platforms or pipelines are damaged simultaneously, which violates an assumption of the Poisson distribution that release occurrences are independent events. A more thorough analysis of the covariance of hurricane releases is beyond the scope of this analysis. In addition, the number of release occurrences during a hurricane can be hard to estimate. Multiplicative release reports and unreported releases can be difficult to track following a devastating storm. As such, hurricane release rates and their confidence intervals may not account for some data uncertainty.

3.2.4 Historic Release Rates

Release rates were calculated by dividing the number of incidents by the total active pipeline miles for each time period and region, then multiplying by 10,000 to normalize the rates of release per 10,000 miles of pipeline per year. The time periods (1984–1999, 2000–2005, 2006–2013, and 2014–2022) were selected based on changes in reporting requirements and environmental conditions, particularly hurricane activity in the Gulf of America. The time period of 1984–1999 is treated as the baseline period. For the periods heavily impacted by hurricanes (2000–2005 and 2006–2013), rates were calculated both including and excluding hurricane-related releases to better understand their impact on overall release frequencies. Confidence intervals were calculated using a 95% normal approximation based on the standard error of the observed rates. The consolidated dataset of yearly incident counts and exposed pipeline miles used for these calculations is provided in **Appendix A**. The following sections examine the specific rates and trends for onshore, state waters, and OCS environments.

3.2.4.1 Onshore Rates

The onshore release rate data in **Table 3** shows notable variations across different time periods from 1984 to 2022. During the earliest period (1984–1999), the base release rate was 2.12 releases per 10,000 pipeline miles per year, with relatively tight confidence bounds (2.00–2.24). This period serves as a useful baseline for comparing subsequent trends.

Table 3. Onshore historic release rates

| Source Agency | 1984–1999 | 2000–2005 | 2006–2013 | 2014–2022 |
|--|-----------|-----------|-----------|-----------|
| Including Hurricane Releases | - | - | - | - |
| Base Rate (releases per 10,000 pipeline mi. per year) | 2.12 | 2.50 | 3.00 | 1.97 |
| Lower Bound (95% Confidence) | 2.00 | 2.33 | 2.82 | 1.85 |
| Upper Bound (95% Confidence) | 2.24 | 2.67 | 3.18 | 2.09 |
| Excluding Hurricane Releases (Katrina, Rita, Ike, Gustav) | - | - | - | - |
| Base Rate (releases per 10,000 pipeline mi. per year) | - | 2.45 | 2.97 | 1.97 |
| Lower Bound (95% Confidence) | - | 2.24 | 2.77 | 1.85 |
| Upper Bound (95% Confidence) | - | 2.66 | 3.17 | 2.09 |

A gradual increase in onshore release rates is observed through the 2000–2005 and 2006–2013 periods, reaching a peak of 3.00 releases per 10,000 pipeline-miles annually in 2006–2013. This increasing trend may be partially attributed to the significant hurricane activity during these periods, particularly from hurricanes. When these hurricane-related releases are excluded from the 2000–2005 and 2006–2013 periods, the base rates decrease to 2.45 and 2.97 releases per 10,000 miles respectively, suggesting that while hurricanes contributed to elevated rates, there was still an underlying upward trend in non-hurricane related releases during these periods. In the data, 2014–2022 do not have any entries that were associated with hurricanes, so an adjustment was not performed. The most recent period (2014–2022) shows a marked improvement in release rates, with the base rate dropping to 1.97 releases per 10,000 miles annually, the lowest observed across all periods.

3.2.4.2 State Waters Release Rates

The release rates from state waters Error! Reference source not found. demonstrate notably different patterns and magnitudes compared to their onshore counterparts. Overall, pipeline release rates in state waters are substantially lower than onshore rates across all time periods.

Table 4. State waters historic release rates

| Source Agency | 1984–1999 | 2000–2005 | 2006–2013 | 2014–2022 |
|--|-----------|-----------|-----------|-----------|
| Including Hurricane Releases | - | - | - | - |
| Base Rate (releases per 10,000 pipeline mi. per year) | 0.13 | 0.21 | 0.55 | 0.15 |
| Lower Bound (95% Confidence) | 0.10 | 0.17 | 0.48 | 0.12 |
| Upper Bound (95% Confidence) | 0.16 | 0.25 | 0.62 | 0.18 |
| Excluding Hurricane Releases (Katrina, Rita, Ike, Gustav) | - | - | - | - |
| Base Rate (releases per 10,000 pipeline mi. per year) | - | 0.21 | 0.53 | 0.15 |
| Lower Bound (95% Confidence) | - | 0.15 | 0.45 | 0.12 |
| Upper Bound (95% Confidence) | - | 0.27 | 0.61 | 0.18 |

During the baseline period (1984–1999), pipelines in state waters experienced a relatively low release rate of 0.13 releases per 10,000 pipeline-miles annually. The tight confidence bounds (0.10–0.16) suggest consistent performance during this period. This rate increased moderately to 0.21 releases per 10,000 miles during 2000–2005, indicating a slight degradation in performance or possibly improved incident detection and reporting.

The most striking feature in the data for state waters is the spike in release rates during 2006–2013, where the rate more than doubled to 0.55 releases per 10,000 pipeline-miles annually. This dramatic increase coincides with the period of intense hurricane activity in the Gulf of America. However, even when excluding the major hurricane events, the base rate remains elevated at 0.53 releases per 10,000 pipeline-miles annually, suggesting that there may have been other factors beyond hurricane damage that contributed to the increased incident rate during this period. In the data, 2014–2022 do not have any entries that were associated with hurricanes, so an adjustment was not performed.

The most recent period (2014–2022) shows a substantial reduction in rates, with rates returning to near-historical levels at 0.15 releases per 10,000 miles annually. This represents a roughly 73% reduction from the 2006–2013 peak and may be due to implementation of lessons learned from the high-incident period, potentially including improved hurricane preparation protocols, enhanced structural designs, and more robust monitoring systems. The narrow confidence interval (0.12–0.18) indicates good consistency in recent performance.

3.2.4.3 OCS Release Rates

The OCS release rates in Error! Reference source not found. present a unique pattern distinct from both onshore and state waters trends, reflecting the particular challenges and evolving risk management

strategies in deepwater operations. The baseline period (1984–1999) mirrors that of state waters because the data do not distinguish between the two.

Table 5. OCS historic release rates

| Source Agency | 1984–1999 | 2000–2005 | 2006–2013 | 2014–2022 |
|--|-----------|-----------|-----------|-----------|
| Including Hurricane Releases | - | - | - | - |
| Base Rate (releases per 10,000 pipeline mi. per year) | 0.13 | 0.63 | 0.32 | 0.06 |
| Lower Bound (95% Confidence) | 0.10 | 0.56 | 0.27 | 0.04 |
| Upper Bound (95% Confidence) | 0.16 | 0.70 | 0.37 | 0.08 |
| Excluding Hurricane Releases (Katrina, Rita, Ike, Gustav) | - | - | - | - |
| Base Rate (releases per 10,000 pipeline mi. per year) | - | 0.46 | 0.32 | 0.06 |
| Lower Bound (95% Confidence) | - | 0.37 | 0.25 | 0.04 |
| Upper Bound (95% Confidence) | - | 0.55 | 0.39 | 0.08 |

An increase in release rates is observed during 2000–2005, where the rate peaked at 0.63 releases per 10,000 miles annually - nearly five times the baseline rate. This period coincides with notable hurricane activity, but notably, even when excluding major hurricane events, the rate remains elevated at 0.46 releases per 10,000 miles. This suggests that while hurricanes were a factor, other challenges such as increased deepwater development activity and associated learning curves may have contributed to the elevated rates.

The 2006–2013 period shows a substantial decrease in release rates, with rates dropping to 0.32 releases per 10,000 miles annually, both with and without hurricane-related incidents. This consistent rate regardless of hurricane inclusion suggests improved hurricane preparedness and response strategies may have been implemented following lessons learned from the previous period. In the data, 2014–2022 do not have any entries that were associated with hurricanes, so an adjustment was not performed.

The most recent period (2014–2022) shows another substantial decrease in release rates, with rates dropping to 0.06 releases per 10,000 miles annually - the lowest rate observed across all three operating environments (onshore, state waters, and OCS). This represents a 91% reduction from the 2000–2005 peak and likely reflects the maturation of deepwater operating practices, implementation of enhanced safety and monitoring systems, improved hurricane preparation protocols, more robust pipeline design standards, and comprehensive application of lessons learned from previous incidents. The narrow confidence interval (0.04–0.08) for this period indicates highly consistent performance and suggests that the improvements implemented produce reliable results.

3.2.5 Explosion and Ignition Historical Rates

The historical rates of hazardous outcomes (explosion and/or ignition) in Error! Reference source not found. following natural gas releases were calculated using BSEE incident data from 2006–2022, with data segmented into two time periods: 2006–2013 and 2014–2022. Earlier BSEE data was excluded from this analysis due to inconsistent or nonexistent reporting of ignition and fire outcomes in historical records. The analysis examined rates across three distinct operating environments: OCS, state waters, and onshore operations.

Table 6. Historic explosion and ignition occurrence rates

| Location | 2006–2013 Total Event Count | 2006–2013 Ignition, Explosion Count | 2006–2013 Ignition, Explosion Percentage | 2014–2022 Total Event Count | 2014–2022 Ignition, Explosion Count | 2014–2022 Ignition, Explosion Percentage |
|--------------|-----------------------------|-------------------------------------|--|-----------------------------|-------------------------------------|--|
| OCS | 15 | 0 | 0.00% | 30 | 2 | 6.67% |
| State Waters | 141 | 15 | 10.64% | 80 | 10 | 12.50% |
| Onshore | 800 | 64 | 8.00% | 1,028 | 158 | 15.37% |

In OCS operations, the percentage of hazardous outcomes increased from 0% in 2006–2013 (zero incidents out of 15 total releases) to 6.67% in 2014–2022 (2 incidents out of 30 total releases). Operations in state waters demonstrated relatively consistent hazard frequencies, with rates of 10.60% (15 incidents out of 141 releases) in 2006–2013 and 12.50% (10 incidents out of 80 releases) in 2014–2022. Onshore facilities showed the highest frequency rates, increasing from 8.00% (64 incidents out of 800 releases) in 2006–2013 to 15.37% (158 incidents out of 1,028 releases) in 2014–2022.

The most statistically robust rates come from the onshore environment due to the larger number of total incidents. The state waters and OCS environments have more limited datasets, with 30 total OCS incidents and 221 state waters incidents across both time periods. Based on the available historical data, a 6.67% ignition probability rate is calculated for OCS operations. This rate represents the most recent empirical evidence (2014–2022 period) and falls between the historical minimum (0%) and the rates observed in other operating environments.

The limited number of OCS releases (30 total incidents) introduces potential statistical uncertainty in the calculated 6.67% ignition rate. With such a small sample size, two ignition events may overstate the actual ignition probability. For comparison, if just one ignition event had occurred instead of two during the same period, the calculated rate would be 3.33%.

3.3 Natural Gas Pipeline Release Causal Factors

Pipelines on the OCS are vulnerable to a range of factors that can trigger gas releases. Causal factors are the primary circumstances or conditions that directly lead to an incident such as a pipeline failure. These include environmental conditions, infrastructure integrity issues, operational errors, and external interference. Each of these contributing elements can lead to incidents ranging from minor leaks to catastrophic ruptures in natural gas pipelines. Broad categories were made based on causes listed in

PHMSA incident data throughout the years examined. These causal factor categories identified in the Pipeline and Hazardous Materials Safety Administration (PHMSA) data from 2002–2022 include:

- Hurricanes and Weather
- Equipment and Mechanical Failure
- Corrosion
- Human Error
- Third-Party Events, External Factors, and Collisions

It is worth noting that since most of the data analyzed was from the Gulf of America region, each factor's rate was adjusted when analyzing the Alaska OCS. This is discussed at greater detail later in the report in **Table 10** in **Section 4.2.4 Adjustment Factor Calculation**.

3.3.1 Weather and Hurricane

Weather-related events represent a significant source of natural gas releases in the Gulf of America OCS, with hurricanes being the primary driver of these incidents. Analysis of data from 2002–2022 (**Figure 7**) shows substantial variation in annual event counts, largely corresponding to major hurricane activity in the region. The data clearly demonstrates the outsized impact of major hurricane seasons. The year 2005, which saw both Hurricanes Katrina and Rita make landfall, recorded 65 weather-related releases - the highest annual total in the dataset. Similarly, 2008 saw 36 releases coinciding with Hurricanes Ike and Gustav. Outside of major hurricane years, weather-related releases typically range from 5 to 15 incidents annually, with an average of 8 releases per year during non-hurricane seasons.

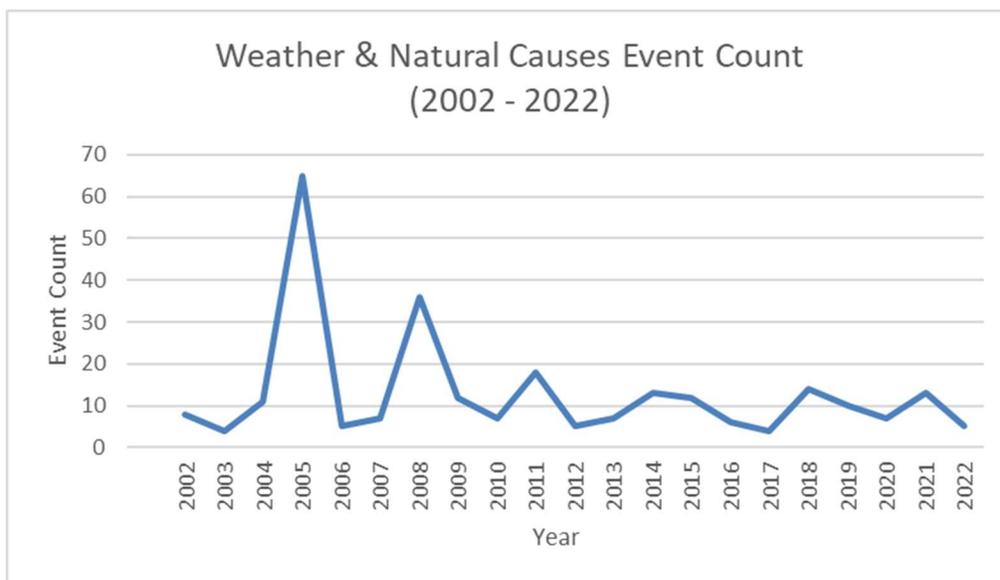


Figure 7. Weather and natural cause event count

The period from 2004 to 2008 particularly highlights the impact of severe storms on natural gas infrastructure. During this timeframe, five major hurricanes (Ivan, Katrina, Rita, Gustav, and Ike) contributed to significantly elevated release numbers. However, improved industry standards for facility and pipeline design, along with enhanced storm preparedness protocols (American Petroleum Institute

2017), have helped reduce the vulnerability of offshore infrastructure to severe weather events. This is evidenced by the relatively stable and lower release rates seen in recent years, even during active hurricane seasons.

While hurricanes do not occur in the Alaska OCS, polar lows - characterized by hurricane-force winds and severe weather conditions - could potentially cause similar infrastructural damage. However, available Alaska OCS data contains no documented natural gas releases associated with polar low events. This is due in part to the current lack of gas production and natural gas pipelines in the Alaska OCS. Additionally, polar lows in the Beaufort and Chukchi seas occur less frequently than Gulf of America hurricanes and typically exhibit less severe conditions. The calculated rate for weather-related events in the Gulf of America has averaged approximately 1 event per 10,000 pipeline-miles per year since 2010. However, given the reduced frequency and severity of extreme weather events similar to strong hurricanes in the Alaska OCS, this rate would require substantial downward adjustment for Arctic and subarctic risk assessments.

3.3.2 Equipment and Mechanical Failure

Equipment failure represents one of the most significant causal factors for natural gas releases in the Gulf of America OCS, with event counts increasing over time (**Figure 8**). Analysis of historical data reveals that equipment failure-related releases have increased substantially, from an average of 30 incidents per year in the 2002–2011 period to over 60 incidents annually in recent years (2018–2022). These failures can manifest in various ways throughout pipeline systems. Connection failures most frequently occur at the source or end of the pipeline where it meets the platform or onshore facility, while material failures can occur along the entire pipeline. Common mechanical failures include issues with bends, bolts, connectors, fittings, clamps, joints, valves, and other pipeline features (Det Norske Veritas 2021). The increasing event count in failures may be attributed to aging infrastructure in the Gulf of America OCS, as many facilities and pipelines reach or exceed their original design lifespans. Additionally, throughout the years more pipeline miles have been added to operation, likely contributing to the increase in event count.

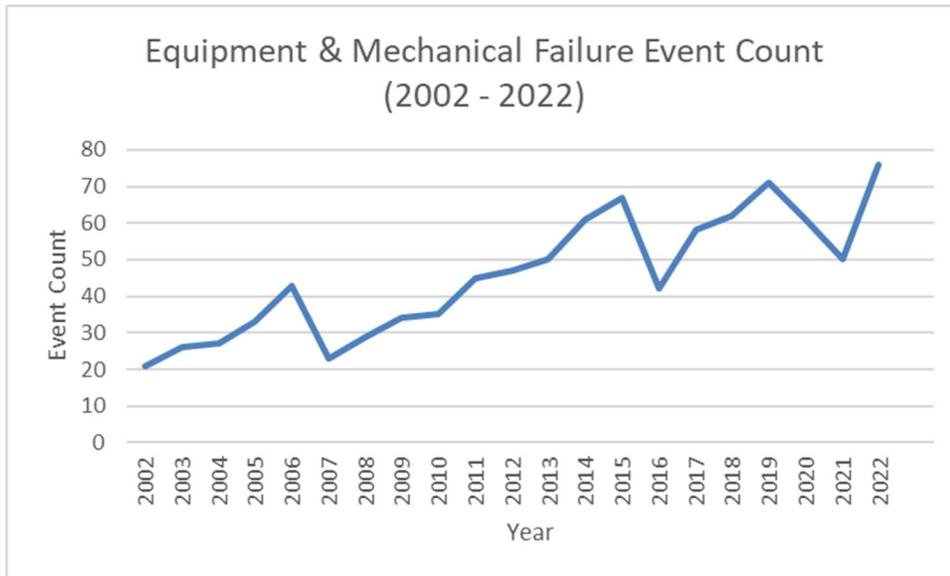


Figure 8. Equipment and mechanical failure event count

When considering the Alaska OCS, equipment failure rates are likely to remain constant or increase compared to Gulf of America rates due to several additional stress factors. Extreme low temperatures significantly affect material properties and performance, while ice forces can create additional structural stress on equipment and infrastructure. These environmental conditions can lead to accelerated wear, which is compounded by limited accessibility for maintenance and repairs during winter months. It is worth noting that since the design criteria for Arctic pipelines require burial, these rates may be overestimated as burial will likely provide protection from exposure to the environment. Overall, these concerns have prompted BSEE and BOEM to require more frequent auditing of mechanical integrity on the Alaska OCS than on the Gulf of America OCS (81 FR 46478 2016). These Arctic and subarctic-specific causal factors are discussed further in **Section 3.4 Alaska OCS Causal Factors**.

3.3.3 Human Error

Human error has been specifically tracked as a causal factor for natural gas releases since 2002, providing over two decades of consistent data for analysis (**Figure 9**). During this period, human error-related releases have demonstrated remarkable stability, averaging 22 incidents per year with a standard deviation of 4 incidents. This stability persists despite significant changes in technology, operational procedures, and industry practices over the same timeframe. The annual data shows minor fluctuations but no significant long-term trends, with peaks of 29 incidents in both 2004 and 2014, and a low of 13 incidents in 2009.

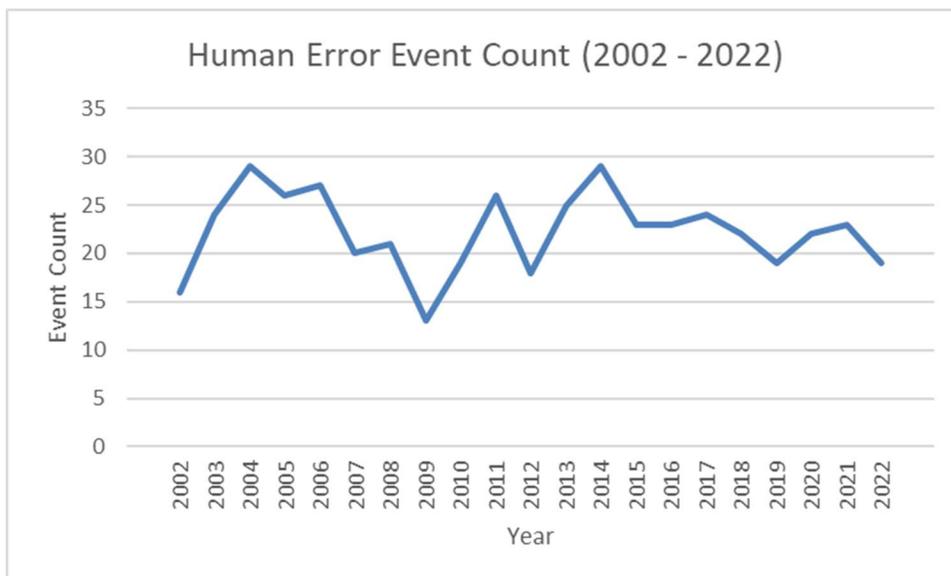


Figure 9. Human error event count

One notable characteristic of human error-related releases is their typically smaller volume compared to other causal factors. This can be attributed to faster detection and response times, as personnel are usually present to identify and address the release immediately. Additionally, human error incidents occur more frequently on platforms than pipelines, likely due to the higher level of direct human interaction with equipment and systems on platforms.

Looking ahead to Alaska OCS operations, it is hard to say how release rates caused by human error will change. Research is mixed, with some studies indicating that extreme cold environments can negatively impact cognitive performance and physical dexterity (Balindres et al. 2016). More recent studies have contradicted this by finding that the Alaska North Slope onshore has lower spill rates than the Gulf of America OCS (Robertson and Campbell 2020). The combination of adverse weather conditions, extended periods of darkness, and the psychological challenges of working in remote Arctic and subarctic locations are unique factors that may cause changes in the frequency of human error.

3.3.4 Corrosion and Erosion

Corrosion and erosion represent persistent challenges for natural gas pipeline integrity in the Gulf of America OCS (**Figure 10**). Analysis of data from 2002–2022, when standardized reporting was implemented, reveals that corrosion-related releases have fluctuated significantly while maintaining a relatively stable long-term average of 27 incidents per year.

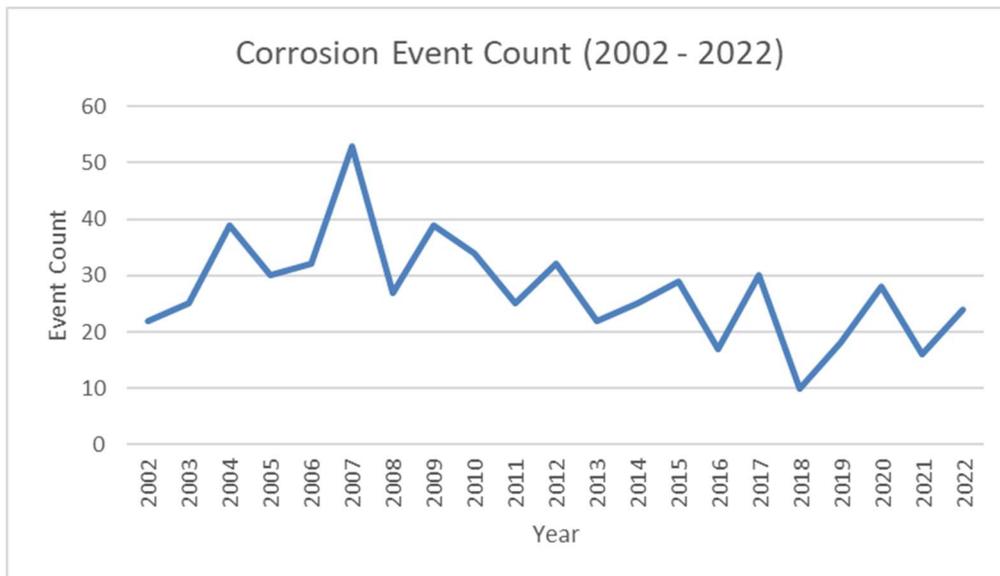


Figure 10. Corrosion event count

The data shows notable variation in annual incident rates, with peaks of 53 releases in 2007 and 39 releases in both 2004 and 2009. However, recent years (2018–2022) have shown a slight decline, averaging 18 incidents annually. This reduction may be attributed to improved corrosion prevention technologies, enhanced monitoring systems, and more frequent inspection protocols.

Corrosion-related releases can occur through multiple mechanisms. Internal corrosion typically results from the presence of water and corrosive compounds within the pipeline, while external corrosion occurs due to environmental exposure and degradation of protective coatings. Both types can lead to wall thinning and eventual failure, often manifesting as small to medium-sized releases. In some cases, corrosion acts as a precursor to more severe mechanical failures, particularly when combined with other stressors such as external forces or pressure fluctuations (National Research Council 1994).

When considering the Alaska OCS environment, corrosion risks present a complex challenge. While lower temperatures generally slow chemical reaction rates, potentially reducing some forms of corrosion, the Arctic and subarctic environments introduce unique corrosion mechanisms. The presence of salt-laden ice, temperature cycling, and different microbial populations may create distinct corrosion patterns not commonly observed in the Gulf of America. Additionally, limited accessibility for inspection and maintenance during winter months may allow corrosion issues to progress further before detection and intervention are possible.

3.3.5 Third-Party Impacts and External Factors

Most external impact incidents involve either anchor strikes or fishing gear interactions with pipelines (**Figure 11**). These typically occur when vessels unknowingly drag anchors or trawling nets across pipeline corridors. External and third-party impacts represent a notable but declining source of natural gas releases in the Gulf of America OCS. Analysis focusing on data from 2002 onwards, when PHMSA

standardized its incident classification system, shows a clear downward trend in these types of releases over the past two decades.

From 2002 to 2022, the data shows an initial rise to an average 30 events in the mid to late 2000's (2005–2009), before the event count number fell and stabilized to around 11 releases annually in recent years (2018–2023). The first half of this period (2002–2011) averaged just under 23.5 incidents per year, while the second half (2012–2023) saw this number drop to an average of 11.5 incidents annually, representing a nearly 50% reduction in event count.

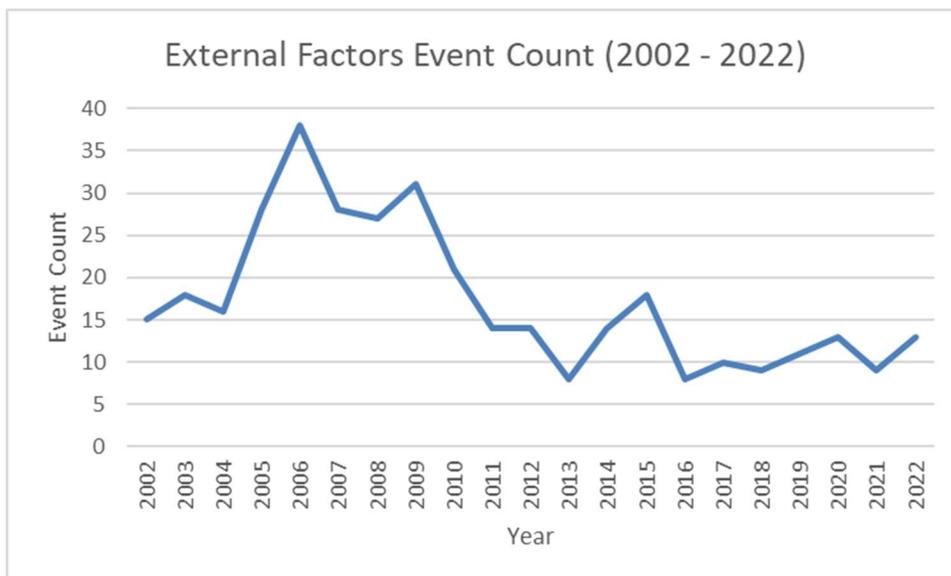


Figure 11. External factors event count

This substantial reduction may be attributed to several factors, including, but not limited to, improved vessel tracking technology, better marking of pipeline locations, increased use of pipeline burial in high-traffic areas, and enhanced maritime safety protocols. The implementation of Automatic Identification System (AIS) requirements for vessels and more accurate GPS navigation systems has particularly helped reduce accidental encounters between vessels and offshore infrastructure.

While these incidents represent a persistent risk in the heavily trafficked waters of the Gulf of America, their potential impact in the Alaska OCS is expected to be minimal. The significantly lower vessel traffic volumes in Arctic waters, combined with fewer miles of exposed pipeline due to burial requirements for ice protection, substantially reduce the risk of external impacts. Additionally, restricted commercial fishing activities in the Alaska OCS and limited seasonal accessibility for vessel operations further minimize the potential for such incidents. These factors suggest that external impact rates from Gulf of America data should be greatly lessened when applied to Cook Inlet's subarctic waters and should be adjusted to near-zero when applied to the Beaufort Sea's Arctic waters. However, this adjustment should be periodically reviewed as Arctic and subarctic maritime traffic patterns may change with increasing ice-free periods and potential new shipping routes.

3.4 Alaska OCS Causal Factors

The Arctic and subarctic environments in the Alaska OCS present distinct challenges for natural gas pipeline operations that differ significantly from conditions in the Gulf of America and Pacific OCS regions. The harsh climate, remote locations, and unique environmental conditions require innovative approaches to pipeline design, construction, and maintenance to prevent natural gas releases. This section analyzes seven key risk factors focused on how Arctic and subarctic conditions affect pipeline integrity and operational safety.

Arctic and subarctic weather and low temperatures fundamentally affect pipeline materials and maintenance capabilities for surface pipelines. Ice-related hazards, including ice forces and gouging, can directly damage pipeline infrastructure. Seabed deformation mechanisms such as strudel scouring and upheaval buckling pose structural challenges unique to these regions. Additionally, thaw settlement from permafrost degradation creates long-term risks for pipeline stability. While standard pipeline integrity threats from the Gulf of America and Pacific OCS regions remain relevant, conditions present in the Alaska OCS introduce additional complexity to these risks. The following sections examine how each risk factor influences pipeline integrity and natural gas release potential, considering both immediate physical threats and long-term operational challenges. This analysis provides context for developing appropriate design standards, monitoring protocols, and risk mitigation strategies for natural gas pipeline operations in the Alaska OCS.

3.4.1 Background

Offshore oil and gas development and activities are relatively new to the Alaska OCS, and the scientific community is still researching the relationships between and challenges to the industry and the environment. Further research is needed on the geography, climate, and challenges of the Alaska OCS region. Scientists are developing models to understand the potential impacts of offshore activities on the environment and the influences of the environment on offshore development. Some of these models focus on the Arctic and subarctic environments themselves, such as sea ice modeling (Jones and Worster 2014), or the relationships between the atmosphere, ice, and ocean as in the Louvain-La-Neuve single-category model and the Los Alamos multicategory model (Roy et al. 2015).

Other scientific research takes a more applied approach and considers how these environments are influenced or how influences develop, often with a focus on the oil and gas industry. Throughout all this research, consideration of how both the environment of the Arctic and Subarctic regions and oil and gas industry are changing is necessary. Understanding the natural environment and its challenges in the Alaska OCS is crucial to preventing, mitigating, and responding to natural gas releases. Because the number of natural gas releases is limited in the Arctic and Subarctic, a global analysis of historical natural gas release incidents may provide insight to the probability of such events occurring (Nuka Research and Planning Group and Pearson Consulting 2010). The international nature of the issue requires consideration of research and data from other nations with similar regional and regulatory environments to the Alaska OCS. This report considers international sources that can lend insight to the US on modeling sea ice, estimating natural gas release occurrence rates, and structural design.

3.4.2 Arctic and Subarctic Climate Considerations

The following sections describe conditions that are inherent to the Arctic and subarctic climate. These conditions will influence the causal factors of Gulf of America and Pacific releases and will make gas releases in the Arctic and subarctic more or less likely compared to those in the Gulf of America and Pacific.

3.4.2.1 Arctic and Subarctic Weather

Adverse weather conditions in the Arctic and subarctic present unique risks for natural gas releases from pipelines and other infrastructure. While traditional hurricanes do not form in the Alaska OCS, similar storms called "arctic hurricanes" or "polar lows" occur frequently (Smirnova et al. 2015). These storms bring blizzard conditions and low-pressure systems. A study of the Nordic and Barents seas documented 637 polar lows across 14 extended winter seasons (Smirnova et al. 2015). In November 2011, western Alaska experienced a polar low with winds reaching 93 miles per hour, comparable to a Category 1 hurricane, with storm surge equivalent to a Category 3 hurricane (NOAA 2011). Recent research on polar low frequency shows uncertainty regarding climate change impacts. While early studies suggested declining frequency with warming seas (Zahn and Storch 2010), current literature is less conclusive (Smirnova et al. 2015). Additional research is needed to project storm frequencies in specific Arctic areas (Romero and Emanuel 2017). These storms can directly impact pipeline integrity through physical forces and create hazardous working conditions that increase human error risks (Orimolade et al. 2017).

Wave height poses another significant concern for pipeline infrastructure. As of 2016, wave heights in the Alaska OCS reached 4.9 m during storms, with projected increases as sea ice coverage decreases. Studies indicate the Arctic Ocean may be ice-free by 2050, leading to more severe wave conditions (Waseda et al. 2017). The combination of reduced sea ice protection and increased wave heights will require enhanced pipeline design and installation standards (Erikson et al. 2022; Kasper et al. 2023).

The Arctic and subarctic's high latitudes creates additional operational challenges through limited daylight in winter and constant daylight in summer (Det Norske Veritas 2012). The Beaufort Sea high pressure system influences wind patterns, affecting both operations and pipeline stress loads (Serreze and Barrett 2011). Communication and navigation systems face disruption from electromagnetic interference and limited infrastructure, complicating emergency response capabilities (Canadian Coast Guard 2012; Clement et al. 2013). These factors must be considered in pipeline monitoring and maintenance planning.

3.4.2.2 Low Temperatures

The extremely low temperatures on the surface of both the Arctic and subarctic create unique challenges for natural gas pipeline operations and maintenance. These conditions affect both infrastructure integrity and human performance during inspection and repair activities. Low temperatures significantly impact material properties of pipelines and increase the risk of operational errors during maintenance procedures. The harsh environment impairs manual tasks through cold-related discomfort and reduced dexterity, potentially compromising pipeline maintenance quality (Det Norske Veritas 2012). Research shows that human error probabilities increase substantially in cold and harsh working environments, particularly during complex technical procedures. The primary concern is reduced cognitive performance in extreme

cold, which can undermine even well-trained staff capabilities during important pipeline operations (Balindres et al. 2016). These human factors must be carefully considered in pipeline maintenance scheduling and emergency response planning.

3.4.3 Ice Forces

As the Arctic and subarctic climates continue to change, the presence of sea ice will be more unpredictable. This is emphasized in November, when the forming of sea ice begins, and in June to July, when it begins to break apart. Recent trends show decreasing multi-year ice across the Alaska OCS region. While newer, thinner ice is more prone to movement and drifting, it typically exerts less force during interactions with infrastructure (Juricke et al. 2013). NASA satellite imagery shows the most rapid sea ice retreat in the Beaufort Sea region, where sea ice coverage has significantly decreased from historical levels to 4.64 million km² in 2017 (Hansen 2017). The relationship between sea ice and pipeline infrastructure requires careful consideration in design and operation. While much research has focused on ice interactions with surface structures and vessels (Zhou et al. 2018), understanding ice forces on subsea pipelines remains important. Engineering studies are examining how different design approaches can better withstand ice loads under varying conditions (Ranta et al. 2018). The age and thickness of ice significantly affect the forces exerted on infrastructure (Juricke et al. 2013), requiring flexible design approaches to accommodate changing Arctic and subarctic conditions.

The risk of natural gas releases from ice force damage can be mitigated through appropriate pipeline routing, burial depth requirements, and structural design considerations. However, these mitigation strategies must account for the evolving nature of Arctic and subarctic ice conditions and potential changes in ice behavior over infrastructure lifespans.

3.4.4 Ice Gouging

Ice gouging occurs when sea ice keels penetrate and scour the seabed. This phenomenon poses a significant risk to natural gas pipelines installed on the seabed (Barrette 2011). In the Beaufort Sea region, documented gouge depths range from 2 to 3.5 m (McGonigal and Barrette 2018), with some ice keels impacting depths up to 15 m (Arndt et al. 2014). Traditional stress-based pipeline design approaches are inadequate for these conditions. Instead, strain-based principles are being adopted for pipelines to account for material deformation under ice forces (Paulin and Caines 2016). This design philosophy recognizes that Arctic and subarctic pipelines experience higher strain from ground movement, unsupported spanning, and seismic loading compared to Gulf of America installations (Gao et al. 2010). The Liberty pipeline project exemplifies this approach, incorporating 100-year and 1,000-year gouge depth predictions in its design criteria (Hilcorp Alaska LLC 2017).

Pipeline burial provides some protection against ice gouging but cannot completely eliminate the risk. Ice keels weighing between 85,000 and 292,000 tons (Bruneau et al. 1977) can create gouges up to five m deep and several kilometers long, potentially affecting even buried pipelines through soil displacement. While current standards and requirements may not fully address these risks (Barrette 2011), emerging mitigation strategies such as ice towing show promise (Yulmetov and Løset 2017). However, the unpredictability of sea ice movement continues to pose challenges for pipeline integrity management in Arctic and subarctic waters.

3.4.5 Strudel Scouring

Strudel scouring presents a unique hazard to Arctic and subarctic natural gas pipelines when flood water drains through vertical holes in sea ice, creating powerful downward jets that erode the seabed. This phenomenon is most prevalent during spring thaws when river floodwater encounters landfast sea ice (Hilcorp Alaska LLC 2017; USACE 1999). The erosive force of strudel scours can compromise pipeline integrity by removing supporting seabed material (Barrette 2011). This loss of support can trigger pipeline oscillation, lateral buckling, or general overstress conditions. While complete pipeline exposure is possible but unlikely, even partial exposure increases vulnerability to other environmental forces (Hilcorp Alaska LLC 2017).

Current understanding of strudel scouring effects on pipelines remains limited compared to traditional scour mechanisms studied in the Gulf of America, such as hurricane-induced sediment movement (Teague et al. 2006). Standard equilibrium calculations for pipeline scour, based on Gulf of America conditions, do not account for Arctic and subarctic-specific factors like ice presence and low temperatures (Luan et al. 2015). The Liberty pipeline project highlighted this knowledge gap, incorporating specific strudel scour risk assessments for Arctic conditions (Hilcorp Alaska LLC 2017). Additional research is needed to develop appropriate pipeline design requirements for Arctic and subarctic conditions where strudel scouring poses a significant risk of natural gas releases (Carpenter 2017).

3.4.6 Upheaval Buckling

Natural gas pipelines in the Alaska OCS face complex forces from surrounding ocean conditions, seabed characteristics, and internal pressures that can lead to upheaval buckling. While buckling risks exist in all OCS regions, Arctic and subarctic conditions present heightened concerns due to variable seabed conditions, extreme temperature fluctuations, and specialized construction material requirements. High-pressure natural gas pipelines experience significant axial expansion, creating compressive loads that can cause upward bending away from the seabed (Maltby 1993). Karampour et al. (2013) identified three primary upheaval buckling scenarios based on pipeline bend location and seabed topography. While both upheaval and lateral buckling can occur, upheaval buckling presents a greater risk of pipeline failure and subsequent gas releases. Pipeline imperfections, whether from initial installation or seabed irregularities, can increase buckling risk (Adebanjo and Simms 2016). These irregularities may result from landslides, lateral spreading, or seismic settlement (O'Rourke and Liu 2012).

While the Beaufort Sea region, particularly near Camden Bay, shows some seismic activity, overall seismic risk is lower than in other oil and gas producing regions. Cook Inlet, however, has a notable amount of seismic activity. Due to this, lessons from other regions, such as Japan's incorporation of seismic considerations into pipeline design following a 2007 earthquake (Shinkai et al. 2012), may provide valuable insights for Alaska OCS pipeline design standards.

3.4.7 Thaw Settlement

Pipeline-generated heat can cause permafrost melting, leading to thaw settlement that threatens pipeline integrity. When permafrost melts beneath pipelines, the loss of structural support can result in pipeline collapse or damage, potentially leading to natural gas releases (Pullman et al. 2007). This risk extends

beyond terrestrial pipelines to subsea infrastructure where offshore permafrost exists. This interaction between pipelines and permafrost creates complex challenges in Arctic and subarctic environments. Warming seas and pipeline heat contribute to permafrost thaw, which can release both ancient and modern methane from frozen formations (Sparrow et al. 2018). These releases can cause seabed upheaval or form depressions where frozen gases were previously trapped, creating additional stresses on pipeline infrastructure. Pipeline design and construction in Arctic and subarctic conditions must account for these unique permafrost-related risks (Oswell 2011).

Offshore permafrost distribution varies significantly across the Alaska OCS. In the Beaufort Sea region, subsea permafrost is concentrated near the shoreline in waters less than 20 m deep (Ruppel et al. 2017). The Yamal Peninsula demonstrates how permafrost can extend to the ocean floor, highlighting risks for both coastal and offshore pipelines (Sojtaric 2014). However, the Chukchi Sea region shows less permafrost presence, largely due to shoreline retreat patterns (Harper 1978). Understanding these regional variations is crucial for pipeline routing and design to minimize thaw settlement risks throughout the Alaska OCS.

4 Methodology

This study employs two independent methodological approaches to assess natural gas pipeline releases in the Alaska OCS, a quantitative modeling approach and a qualitative impact assessment framework. The quantitative component utilizes computational modeling to predict release volumes, rates, and gas behavior from pipeline failures. The qualitative framework evaluates potential environmental and social impacts based on historical release data and resource vulnerability assessments. While these approaches examine the same phenomenon, they generate complementary rather than integrated results, providing decision-makers and general scientists with a comprehensive understanding of both the hazard frequency, severity, area impacted, and potential consequences of natural gas releases.

4.1 Quantitative Release Modeling

The quantitative analysis employs a suite of computational models to predict the physical behavior of natural gas releases from subsea pipelines. This modeling approach tracks the gas from its initial release at a pipeline breach through its rise in the water column and eventual atmospheric dispersion. The analysis utilizes the Minerals Management Service (MMS) Worst Case Discharge (WCD) Pipeline Gas Release Computer Model (WCDgas) to simulate subsea releases. This is followed by the application of a Gaussian plume model, utilizing the Briggs rural dispersion coefficients, which estimates the atmospheric dispersion of methane following a subsea release and subsequent emergence at the water surface. These models provide specific predictions about release volumes, rates, plume characteristics, and gas concentrations that can inform engineering and safety decisions.

4.1.1 Model Framework

The quantitative analysis utilizes the WCDgas to simulate the behavior of gas discharges from seafloor pipelines. The model is capable of analyzing both worst-case pipeline rupture scenarios and smaller

diameter punctures. The primary model inputs consist of pipeline configuration and characteristics, fluid properties, releases or break specifications, environmental conditions, and operational parameters.

The model architecture integrates three primary components. The Release Module determines the initial gas release rate at the seafloor rupture point. The Near Field Module then models the movement of the gas as it travels from the seafloor through the water column to the surface. These components are linked through a Graphical User Interface that connects them with the necessary databases and allows for user interaction with the system. The main component used is the Discharge Module, which gives an estimate of total volume of gas released, as well as some other relevant release statistics.

The WCDgas model provides the necessary source term data for understanding the initial release. However, to fully assess potential hazards, the fate of the gas after reaching the water surface must also be evaluated. Once the methane emerges at the sea surface, additional modeling is required to predict how it disperses in the atmosphere and to identify potential hazard zones. This next analytical step requires the application of appropriate atmospheric dispersion techniques suitable for coastal environments.

To estimate the atmospheric dispersion of methane following a subsea release and subsequent emergence at the water surface, a Gaussian plume model was employed, utilizing the Briggs rural dispersion coefficients. This approach is appropriate for estimating behavior of released light (passive) gas releases, like methane, in open areas such as coastal regions. The Gaussian plume model assumes a steady, continuous release and allows prediction of downwind concentrations. In this case in particular, the model was used to estimate the downwind and crosswind extent of the vapor cloud, to the lower flammability limit concentration.

The necessary inputs for simulation of a given scenario are shown in **Table 7**. A multitude of combinations of inputs were used for each scenario to perform sensitivity analysis based on a selection of these input fields. Further information on the values that may change in the input fields is provided in **Appendix C: Scenario Matrices**, as well as **Section 4.2.3 in Table 9**, **Section 4.4.1 in Table 11**, and **Section 4.4.2 in Table 12**.

Table 7. Model input fields

| Category | Input Fields |
|-----------------------------------|--|
| Gas Composition | <ul style="list-style-type: none">• Fraction of each component in the gas• Mol weight for each component• Liquid Densities |
| Flow Inlet Properties | <ul style="list-style-type: none">• Depth• Total Gas Flow Rate• Fluid Temperature• Closing / Shut-In Time |
| Pipeline or Riser Segment | <ul style="list-style-type: none">• Length• Inside Diameter• Roughness coefficient• Heat Transfer coefficient• Ambient Temperature |
| Pipe Connector or Junction | <ul style="list-style-type: none">• Depth |
| Outlet | <ul style="list-style-type: none">• Depth• Fluid Pressure• Closing / Shut-In Time |
| Leak Properties | <ul style="list-style-type: none">• Distance from Upstream Endpoint• Nominal Pipeline Diameter• Water Depth |

4.1.2 Model Limitations

Several limitations constrain the pipeline network modeling capabilities. The system can only model single "tree" pipeline networks where all branches converge toward a single outlet point at the root. Closed re-circulating loops cannot be included in the network configuration. The model is restricted to analyzing one release point at a time. Each branch of the pipeline network is limited to 100 segments, and the system can accommodate a maximum of five junction points. At each junction, no more than five pipeline segments can be connected. All pipeline objects within the model must maintain direct connections to either junctions or connectors. The overall network is constrained to a maximum of 50 branches, which was not an issue for the pipeline systems that were modeled. Additionally, the model does not consider the possibility of a release starting and remaining undetected or the release continuing due to it being inaccessible. Nor does it consider a scenario such as the Cook Inlet release that spanned from December 2016–April 13, 2017 in which the pipeline would have been shut in but had continued operation leading to a continued natural gas release in order to avoid an oil spill.

The simplified Gaussian plume model with Briggs rural dispersion coefficients is used to estimate the extent of flammable vapor from a ground-level point source in a coastal setting. Conservative meteorological parameters were selected to ensure a protective estimate of vapor dispersion. The model assumes steady-state conditions, uniform wind direction and speed, and flat, unobstructed terrain with

low surface roughness typical of rural or coastal environments. Building effects, terrain variations, and temporal changes in meteorological conditions are not considered. Additionally, the model does not account for complex coastal meteorology or water surface interactions. These simplifications may result in conservative estimates of vapor extent, but they provide a transparent and reproducible basis for worst-case scenario planning in the absence of detailed site-specific data.

4.1.3 Gas Behavior Calculations

The model employs several sophisticated algorithms to predict gas behavior throughout the release event. The pipeline release calculations utilize the Peng Robinson Equation of State to determine gas properties under varying conditions. This equation accounts for choking effects and fluid flow behavior while incorporating changes in pressure and temperature throughout the system. The calculations also consider both frictional losses and hydrostatic pressure drops within the pipeline network.

SL Ross Environmental Research Ltd et al. (2009) notes that the bubble plume modeling component is based on Fanneløp's general solution for underwater gas releases. This mathematical framework accounts for the variation in gas volume with changing hydrostatic pressure as the gas rises through the water column. The model assumes isothermal expansion conditions and calculates key plume variables including the radius of the plume, vertical velocity, and rise time to the surface. These calculations provide information about the behavior and dispersal of a subsea pipeline gas release (SL Ross Environmental Research Ltd et al. 2009).

The Briggs rural dispersion coefficients were selected to approximate the horizontal and vertical dispersion in a coastal setting, where surface roughness is low. For this assessment, the release was modeled as a ground-level (water-level) point source. A stability class of E and wind speed of 3 m/s were chosen to provide a relatively conservative estimate of the extent of flammable vapor.

The simplified Gaussian plume approach with Briggs rural coefficients offers distinct advantages to more sophisticated models such as the EPA's Offshore and Coastal Dispersion Model (OCD) model. This method requires less computational resources and input data, making it ideal for assessments where comprehensive meteorological information is unavailable. Its straightforward, transparent calculations can be easily verified, and when paired with conservative parameters (stability class E, low wind speed). For specific applications like determining methane flammability zones, the added complexity of OCD may not significantly improve accuracy, especially when dealing with uncertain coastal conditions where simpler models with conservative assumptions may better manage unknowns.

4.1.4 Release Scenario Testing

To systematically evaluate the range of potential natural gas releases, a comprehensive scenario matrix was developed examining multiple release variables and conditions. This structured approach allows for a thorough assessment of how different pipeline configurations, operational parameters, and environmental conditions influence release characteristics.

The scenario development process centered on three fundamental variables that significantly impact release behavior. First, the analysis considered multiple breach configurations ranging from small pinholes

(1/4-inch diameter) to complete guillotine breaks spanning the full pipeline diameter. Intermediate sizes were also evaluated to provide thorough coverage of potential breach scenarios. Second, the location of the breach along the pipeline was systematically varied, as this affects both the release dynamics and response capabilities. Locations near the upstream inlet (within first 10% of pipeline length), at the pipeline midpoint (45–55% of length), and near the downstream outlet (within last 10% of length) were analyzed. Finally, different release detection and response timing scenarios were evaluated, including quick detection with 10-minute response, delayed detection with 30-minute response, and extended undetected releases with 2-hour response times.

This methodical scenario development approach serves multiple purposes within the broader analysis framework. It enables identification of credible scenarios for detailed impact assessment, provides insight into how release characteristics vary with different breach configurations, and supports development of detection and response recommendations. The scenario matrix also shows the emissions rate and category, which were constructed as estimates for the potential area impacted by the dispersion for each scenario. The scenario matrix for the scenarios are available in **Appendix C: Scenario Matrices**.

4.2 Qualitative Impact Assessment

The qualitative component provides a structured framework for evaluating potential environmental and social impacts from natural gas releases. This approach begins with an analysis of the onshore, state waters, and OCS historical release rates from **Section 3.2.4** which are adjusted to reflect Alaska OCS conditions. The framework then assesses potential impacts across 12 resource categories using a seven-point scale ranging from negligible to major effects. This systematic assessment considers factors such as geographic location, seasonal patterns, and resource vulnerability to provide a comprehensive evaluation of potential consequences.

4.2.1 Historical Rate Analysis

The qualitative component of the methodology begins with an analysis of historical release rates. These rates are adjusted downward to reflect the specific conditions of the Alaska OCS environment. The adjustment process considers several factors including differences in infrastructure age, maintenance practices, and environmental conditions between the Alaska OCS and the Gulf of America and Pacific OCS. The adjusted rates are then combined with hazard analysis to create a comprehensive risk profile.

4.2.2 Resource Impact Framework

A systematic framework has been developed to assess potential impacts on various resources of concern. The assessment uses a seven-point scale ranging from N/A (not applicable) to Major impacts. This scale provides sufficient granularity to differentiate between varying levels of impact while maintaining practical usability. The N/A designation is reserved for scenarios where specific resource-location combinations are not possible, such as impacts to terrestrial mammals from releases in offshore waters. **Table 8** details the different classifications and their perceived meanings.

Table 8. Ranking classifications

| Ranking | Definition | Numerical Value |
|-----------------------------|--|------------------------|
| Not Applicable (N/A) | Impact cannot occur due to spatial separation or lack of pathway | 0 |
| Negligible | Effects are below detection limits or without natural variation | 0.125 |
| Negligible to Minor | Effects are detectable but localized and brief | 0.188 |
| Minor | Effects are detectable, localized, and short-term | 0.25 |
| Minor to Moderate | Effects may extend beyond local area or immediate timeframe | 0.375 |
| Moderate | Effects are substantial but not severe | 0.5 |
| Moderate to Major | Effects approach severe levels in either space or time | 0.75 |
| Major | Effects are severe, long-lasting, or widespread | 1 |

The framework evaluates impacts across twelve distinct resource categories that align with BOEM's environmental assessment requirements. Each resource category is assessed independently based on its unique characteristics and vulnerabilities. The resource categories include physical, biological, and socioeconomic resources. All these resource categories are covered at depth in the literature review, and the literature review heavily influenced the rating each resource received at each location.

4.2.2.1 Air Quality

Offshore releases of natural gas present Minor to Moderate impacts without ignition due to the rapid dispersion of methane in open marine environments, though seasonal variations in Alaska can lead to temporary accumulation under winter ice before spring ventilation. When ignition occurs offshore, impacts increase to Moderate as combustion produces additional pollutants including carbon dioxide, carbon monoxide, nitrogen oxides, and particulate matter, with dispersion patterns heavily influenced by marine atmospheric conditions and Alaska's unique seasonal temperature inversions.

Onshore releases similarly rate as Minor to Moderate without ignition, reflecting documented increases in respiratory issues near release sites, though impacts remain localized due to natural gas's tendency to rise and disperse rapidly in the atmosphere. Ignited onshore releases are rated as Moderate due to the increased production of combustion pollutants combined with Alaska's challenging topography and strong temperature inversions that can trap emissions in valleys or low-lying areas, particularly during winter months when atmospheric mixing is limited. For additional reasoning as to why these levels were selected, please refer to **2.4.1 Air Quality**.

4.2.2.2 Water Quality

Natural gas releases in offshore environments are ranked as negligible for both ignited and unignited scenarios, primarily because methane's low solubility and buoyant properties cause it to rise through the water column with minimal dissolution - though studies show approximately 1% dissolves during ascent. For onshore releases, the negligible ranking reflects that natural gas pipeline releases typically have

minimal interaction with water bodies, and in cases where gas does contact water, its low solubility and tendency to rapidly surface limits water quality impacts.

Even in Alaska's unique seasonal conditions where winter ice cover can temporarily trap methane under ice, these accumulations dissipate rapidly during spring break up with no lasting effects on water quality. The potential for dissolved methane to create localized hypoxic conditions exists but remains temporary and highly localized due to natural gas's strong tendency to surface and disperse. This temporary nature and limited spatial extent of any impacts supports the negligible ranking across all scenarios and locations. For additional reasoning as to why these levels were selected, please refer to **2.4.2 Water Quality**.

4.2.2.3 Coastal and Estuarine Habitats

Offshore natural gas releases are ranked as negligible due to methane's strong buoyant properties which cause it to rise rapidly through the water column with minimal interaction with benthic habitats. In ignited scenarios, the ranking increases slightly to negligible to minor to account for potential localized thermal effects on surface waters and temporary disruption to coastal organisms from the combustion event, though these impacts remain brief and spatially limited.

Onshore releases near coastal areas are ranked as negligible for unignited scenarios since natural gas's tendency to rise and disperse means minimal interaction with coastal habitats. However, when ignition occurs, the ranking increases to moderate to major for onshore releases due to the potential for sustained fires that can damage coastal vegetation through direct burning and heat stress, create lasting changes to soil chemistry in the burn zone, and potentially trigger cascading effects through coastal food webs. These impacts can persist for several years, particularly in areas closest to the ignition point where soil conditions remain significantly altered. For additional reasoning as to why these levels were selected, please refer to **2.4.4 Coastal and Estuarine Habitats** Coastal and Estuarine Habitats.

4.2.2.4 Fish and Invertebrates

Offshore natural gas releases are ranked as negligible to minor both in unignited and ignited scenarios due to methane's rapid rise through the water column, though brief localized impacts can occur through temporary oxygen depletion as methane-oxidizing bacteria consume dissolved gas. These effects remain highly localized and short-term, as gas dispersion and water circulation quickly restore normal conditions.

Onshore releases are ranked as negligible since natural gas typically has minimal interaction with aquatic habitats due to its buoyant properties and rapid atmospheric dispersion. The ranking remains negligible in ignited scenarios as thermal impacts would be largely confined to the immediate burn area with limited potential to affect aquatic systems unless the release occurs directly adjacent to water bodies, in which case any impacts would remain brief and localized. For additional reasoning as to why these levels were selected, please refer to **2.4.5 Fish and Motile Invertebrates**.

4.2.2.5 Birds

Marine and coastal birds face negligible impacts from unignited offshore gas releases due to the rapid dispersion of gas at the water surface, with no documented direct effects from methane exposure. When ignition occurs, the ranking increases to minor as birds may be temporarily attracted to the flame and

bright illumination, potentially leading to increased energy expenditure from circling behavior and minor collision risks, though these effects remain localized and brief.

Onshore releases without ignition are ranked as negligible since natural gas quickly disperses upward and dilutes in the atmosphere. However, ignited releases increase to minor impact levels due to potential thermal effects and behavioral disruption from flames and illumination, particularly during nighttime or low-visibility conditions when birds may be attracted to the light source, though these effects typically remain localized to the immediate area of the release. For additional reasoning as to why these levels were selected, please refer to **2.4.6 Marine/coastal Birds**.

4.2.2.6 Marine Mammals

Offshore natural gas releases are ranked as negligible for unignited scenarios since marine mammals can easily avoid the localized gas plume, and methane's rapid rise through the water column limits exposure potential. When ignition occurs, the ranking increases to negligible to minor to account for possible behavioral disturbance from surface flames and noise, though these effects remain brief and spatially limited as marine mammals can readily avoid the area.

Marine mammals are ranked as not applicable (N/A) for onshore releases since there is no exposure pathway between terrestrial gas releases and marine species. This ranking remains N/A even in ignited scenarios as thermal and noise effects from onshore fires would not extend significantly into marine habitats where these species occur. For additional reasoning as to why these levels were selected, please refer to **2.4.7 Marine Mammals**.

4.2.2.7 Terrestrial Mammals

Onshore unignited natural gas releases are ranked as negligible since terrestrial mammals can readily detect and avoid areas of gas accumulation, and methane's rapid upward dispersion limits the potential for significant exposure. However, when ignition occurs, the ranking increases to moderate to major due to the potential for direct mortality from thermal effects, habitat destruction in the burn zone, and behavioral displacement from the immediate burn area due to noise, light, heat, and possible fire.

For offshore releases, impacts to terrestrial mammals are ranked as not applicable (N/A) since there is no exposure pathway between marine gas releases and land-based species. This ranking holds true for both ignited and unignited scenarios as effects from offshore releases would not extend significantly into terrestrial habitats where these species occur. For additional reasoning as to why these levels were selected, please refer to **2.4.8 Terrestrial Mammals**.

4.2.2.8 Recreation, Tourism, and Sports Fishing

Offshore natural gas releases are ranked as negligible in unignited scenarios since methane's rapid dispersion limits impacts to recreational activities, though brief localized interruptions to boating or fishing may occur in the immediate release area. When ignition occurs, the ranking increases to minor due to temporary access restrictions around the burn zone and potential displacement of fish that could affect sports fishing success, though these effects remain spatially and temporally limited.

Onshore releases are ranked as negligible without ignition as natural gas quickly disperses upward with minimal impact on recreational activities. However, when ignition occurs, the ranking increases to minor due to temporary access restrictions around the burn zone, potential trail closures, and visual impacts that may briefly affect recreation and tourism experiences in the immediate area. For additional reasoning as to why these levels were selected, please refer to **2.4.11 Commercial and Recreational Fisheries** and **2.4.14 Recreation and Tourism**.

4.2.2.9 Communities and Subsistence

Offshore natural gas releases are ranked as negligible without ignition and minor with ignition, reflecting the limited impact on marine-based subsistence activities. The rapid dispersion of methane and minimal interaction with marine resources ensure that community impact remains minimal. Even in ignited scenarios, disruptions are brief and localized, with potential temporary effects on marine hunting and fishing practices that do not fundamentally alter community resource access or traditional subsistence patterns.

Onshore releases present more nuanced implications for communities and subsistence practices. Without ignition, impacts are negligible to minor, primarily due to natural gas's rapid upward dispersion and limited interaction with community resources. When ignition occurs, the impact increases to minor, reflecting potential temporary disruptions to land-based subsistence activities. These impacts could include brief displacement from traditional hunting and gathering areas, but hunting and gathering areas are not generally near pipelines. Additionally, short-term interruptions to resource access may occur, and localized changes in habitat may temporarily affect traditional subsistence harvesting patterns. For additional reasoning as to why these levels were selected, please refer to **2.4.10 Subsistence** and **2.4.13 Cultural Resources**.

4.2.2.10 Economy

Offshore natural gas releases are ranked as negligible without ignition, reflecting the limited direct economic impacts due to the rapid dispersion of gas and typically brief duration of such events. When ignition occurs, the ranking increases to negligible to minor, accounting for potential temporary disruptions to offshore activities, possible damage to nearby infrastructure, and short-term restrictions on maritime transportation or industrial activities in the immediate area. However, these effects remain localized and temporary, with minimal broader economic consequences given the typically rapid response and containment of such events.

Onshore releases are similarly ranked as negligible without ignition since natural gas quickly disperses upward with minimal economic disruption beyond very localized and temporary access restrictions or brief operational interruptions. In ignited scenarios, the ranking increases to negligible to minor, reflecting potential damage to local infrastructure, temporary business disruptions in the immediate area, and possible short-term impacts to transportation corridors or industrial activities. These economic impacts, while potentially more concentrated than offshore events due to proximity to infrastructure and business centers, remain relatively limited in both spatial and temporal scope, with effects typically resolving once the release is contained and any damaged infrastructure is repaired. For additional reasoning as to why these levels were selected, please refer **2.4.12 Employment and Income**.

4.2.2.11 Commercial Fishing

Offshore natural gas releases are ranked as negligible without ignition since methane's rapid dispersion through the water column and at the surface creates minimal disruption to commercial fishing activities. The primary impact is brief, localized access restrictions around the release point for safety purposes. When ignition occurs, the ranking increases to minor, reflecting more substantial temporary exclusion zones around the burning gas plume, potential changes in fish behavior or distribution patterns near the incident, and possible brief interruptions to fishing operations in the immediate area. These effects remain temporary and spatially limited, allowing fishing activities to resume once the release is controlled.

Onshore releases are ranked as negligible without ignition since natural gas's rapid upward dispersion means minimal interaction with marine resources or fishing operations. In ignited scenarios, the ranking increases slightly to negligible to minor, primarily accounting for potential impacts to fishing access points, processing facilities, or transportation routes if the release occurs near coastal infrastructure supporting commercial fishing operations. However, these effects typically remain highly localized and temporary, with minimal direct impact on marine resources or broader fishing activities. The slightly lower ranking for onshore versus offshore ignited releases reflects the reduced potential for direct interaction with fishing operations and marine resources. For additional reasoning as to why these levels were selected, please refer to **Section 2.4.11 Commercial and Recreational Fisheries**.

4.2.2.12 Archaeological and Historic Resources

Offshore natural gas releases are ranked as negligible without ignition since methane's rapid rise through the water column and minimal dissolution creates no lasting physical or chemical impacts to submerged archaeological resources or historic sites. When ignition occurs, the ranking increases slightly to negligible to minor, accounting for potential thermal effects on surface historic resources (such as historic vessels) in the immediate area of the burn, though such impacts would be extremely rare given typical exclusion zones and the brief duration of most events. The surface-oriented nature of natural gas releases means minimal interaction with seafloor cultural resources.

Onshore releases are likewise ranked as negligible in unignited scenarios due to natural gas's rapid atmospheric dispersion and lack of chemical interaction with archaeological materials or historic structures. In ignited scenarios, the ranking increases to negligible to minor, reflecting the potential for thermal damage to nearby historic structures or archaeological sites, particularly those constructed of combustible materials. However, these impacts remain highly localized to the immediate burn area and are typically preventable through standard emergency response protocols that prioritize protection of identified cultural resources. The slightly higher potential for impacts in onshore versus offshore scenarios reflects the greater likelihood of proximity to documented archaeological and historic sites. For additional reasoning as to why these levels were selected, please refer to **Section 2.4.9 Archaeological and Historic Resources** and **Section 2.4.13 Cultural Resources**.

4.2.3 Weighting Factors

In addition to the ranking of resources, several parameters affect the final impact assessment. These factors are all listed in **Table 9**.

Table 9. Weighted factors

| Factor | Input |
|-----------------------------------|---|
| Geographic Location | Beaufort Sea, Chukchi Sea, Cook Inlet |
| Pipeline Diameter | Pipeline Diameter in inches (Inputs include 4, 6, 8, and 12 in) |
| Pipeline Length, Location | Breakdown of miles in OCS, state waters, and onshore |
| Gas Composition | Classification of gas inside the pipeline as dry or wet gas |
| Predicted Project Lifetime | Predicted number of years of operation for the pipeline project |

4.2.4 Adjustment Factor Calculation

The process of adapting Gulf of America incident rates to Arctic and subarctic conditions required careful consideration of how each causal factor would be affected by the change in operating environment. The analysis began with establishing baseline frequencies for each causal factor using Gulf of America historical data from 2004–2023. This analysis used the same data as was used in **3.2 Historic Release Rates**. Equipment failure accounted for 35% of incidents, weather/natural causes for 25%, other/external factors for 34%, and human error for 6% of total incidents.

An adjustment factor was then applied to each causal factor based on expected changes in the Arctic and subarctic environments. Equipment failure and human error were assigned adjustment factors of 1.0, indicating these causal factors are likely to maintain similar frequencies. Weather and natural causes received an adjustment factor of 0.15, reflecting the reduced frequency of severe storms in the Arctic and subarctic compared to hurricane activity in the Gulf of America. Other and external factors, primarily consisting of third-party vessel impacts, were assigned a factor of 0.002 due to significantly reduced maritime traffic. **Table 10** summarizes the calculation of the aggregated causal factor adjustment factor.

Table 10. Adjustment factor calculation

| Causal Factor | Event Count | Percent of Releases | Adjustment Factor | Weighted Adjustment |
|-------------------------------|---------------|---------------------|-------------------|---------------------|
| Equipment Failure | 4,161 | 35% | 1 | 0.345 |
| Human Error | 731 | 6% | 1 | 0.061 |
| Other/External Factors | 4,126 | 34% | 0.002 | 0.001 |
| Weather/Natural Causes | 3,042 | 25% | 0.15 | 0.038 |
| Aggregate | 12,060 | 100% | N/A | 0.444 |

The weighted combination of these adjustments resulted in an overall factor of 0.444 for Arctic operations. Given the distinct operational characteristics of different regions in the Alaska OCS, this factor was further refined. Cook Inlet, with its higher vessel traffic and developed infrastructure, was assigned a rounded adjustment factor of 0.5. The Beaufort and Chukchi seas, with minimal vessel traffic and more extreme conditions, were assigned a more conservative factor of 0.4. This methodology provides a systematic approach to translating Gulf of America incident rates to Alaska OCS conditions while accounting for regional variations in operational risk factors.

4.2.5 Release Size Estimate Adjustment

As mentioned, the main limitation of this analysis was the availability of pipeline natural gas release data, especially for releases occurring in Alaska. In an effort to improve gas release volume estimates, we randomly selected 100 offshore pipelines in the Gulf of America and used modeling software to simulate natural gas releases, ensuring that the release sizes matched historical estimates from past incidents.

To adapt these simulations for the Alaska OCS, we adjusted key environmental and pipeline parameters, including water depth, water temperature, and pipeline diameter. These adjustments were necessary to account for the different conditions in Alaska compared to the Gulf of America. We then re-simulated the natural gas releases under these new conditions and tracked the changes in gas release volume. The Sankey chart showing these changes as well as a table showing size breakdown are shown in **Appendix E**.

It is important to note that while no release technically qualified as "Extreme" in Alaska after the adjustments, one release was retained as "Extreme" to better simulate real-life scenarios. This approach ensures that the model remains more reflective of potential extreme events.

4.2.6 Hazard Integration

The qualitative assessment incorporates scenarios involving ignition, fire, and explosion. These scenarios are weighted according to their calculated hazard rates. The assessment considers both the probability of these events and their potential consequences for each resource category.

4.3 Model Integration

To better understand potential Alaska OCS natural gas releases, this study integrated physical modeling using WCDgas with historical Gulf of America pipeline data analysis. This integration allowed for more accurate Alaska release volume predictions while maintaining realistic operational parameters from actual pipeline systems. The integration process began with the selection of 100 representative pipeline segments from the Gulf of America OCS historical database. These segments provided real-world pipeline diameters, flow rates, operating pressures, emergency shutdown times, and gas compositions. These operational parameters were maintained as baseline characteristics for the Alaska analysis, as they represent proven, functional pipeline systems.

These Gulf of America segments were then "adapted" for Alaska OCS conditions by modifying key physical parameters while maintaining their operational characteristics. Water depths were adjusted to match bathymetry in the Alaska OCS, and ambient water temperatures were modified to reflect these conditions. Where necessary, pipeline diameters were adjusted to align with proposed Alaska OCS infrastructure specifications, though these adjustments were minimal to maintain the validity of the operational parameters. WCDgas simulations were then run for each adapted segment to generate Alaska OCS-specific predictions. These simulations produced expected release volumes, release durations, gas plume characteristics, and surface expression parameters that reflect conditions in the Alaska OCS. This approach maintains the operational realism of actual pipeline systems while accounting for the unique physical conditions of the Alaska OCS.

The results provide more accurate predictions of potential release volumes in the Alaska OCS compared to simple scaling of historical Gulf of America data, as the WCDgas model properly accounts for several key factors. While the findings of this part of the study will be discussed later in the report, it is worth noting that this process yielded a different expected release size distribution.

4.4 Scenario Development

Representative scenarios were developed to demonstrate the application of both models, using the Liberty Development Project as a template. The hypothetical Liberty Development, proposed for the Beaufort Sea OCS, provides realistic pipeline configurations and operating conditions that are likely to be replicated in future Alaska OCS developments. The scenarios mirror Liberty's subsea pipeline specifications, proposed water depths, and environmental conditions while incorporating variations to test model sensitivity.

The baseline scenario utilizes a pipeline configuration similar to Liberty's proposed subsea pipeline system. Additional scenarios examine varying diameter pipelines to account for potential future developments as well as the fuel lines that run in parallel from the shore to the platforms. Environmental conditions in the scenarios reflect those documented in Liberty's Development and Production Plan, including seasonal water temperatures, ice conditions, water depths ranging from shallow near-shore to deeper Alaska OCS locations, current patterns typical of the Beaufort Sea, and meteorological conditions characteristic of the region.

For the quantitative model, scenarios were developed to test various release points along the pipeline length, ranging from shallow near-shore locations to deeper waters. Each location was modeled with both pipeline ruptures and smaller punctures to understand how release characteristics vary with depth and breach type. Operating parameters such as pressure, flow rates, and shutdown times were based on Liberty's proposed specifications but varied systematically to understand their influence on release volumes and rates.

For the qualitative assessment, scenarios were constructed to examine how geographic location and seasonal timing affect potential resource impacts. These scenarios consider variations in biological resource presence, subsistence activities, and ice conditions throughout the year. While based on Liberty's location in the Beaufort Sea, additional scenarios examine potential developments in the Chukchi Sea and Cook Inlet to provide comparative analysis across different Alaska OCS regions.

4.4.1 Scenario One: Single Platform to Shore Pipeline

This baseline scenario represents a simplified version of the Liberty Development Project's subsea pipeline system, providing a foundation for understanding gas releases in Arctic conditions. The pipeline system consists of a single production platform located in the Beaufort Sea connected to an onshore processing facility via a subsea pipeline running along the seabed as shown in **Figure 12**.



Figure 12. Scenario One pipeline diagram

The main pipeline used was a replica of Liberty Offshore Alternative 4a, a pipeline in the Beaufort Sea with a diameter of 6 inches and a length of 7.7 miles, shown in **Table 11**. Depth, water temperature, gas composition, and pipeline diameter were kept static while a variety of hole sizes, close in times, and release locations were tested for sensitivity analysis (BOEM 2018).

Table 11. Scenario One parameters

| Parameter | Value |
|-----------------------|------------------------|
| Pipeline Diameter | 6 inches |
| Length | 7.7 miles, 1.5 onshore |
| Design Lifetime | 24 years |
| Burial Depth | 7–10 ft |
| Operating Pressure | 1,400 psig |
| Operating Temperature | -5 to 5 °C |

4.4.2 Scenario Two: Multiple Pipelines Merge to Shore

This scenario used a triple inlet scenario with a pipeline junction as shown in **Figure 13**, based in Cook Inlet. Pipeline information was similar to that of other Alaska OCS projects.

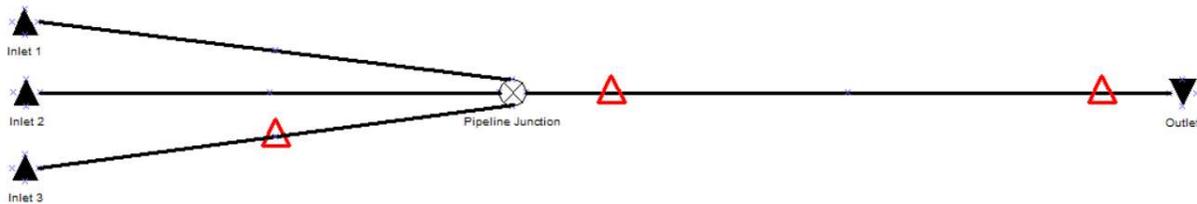


Figure 13. Scenario Two pipeline diagram

This figure shows the pipeline diagram, as well as representations of the three release locations that were examined. This is not to scale, but provides a useful visual of the scenario. Many factors thought to be commonplace across the Alaska OCS were kept the same as Scenario One or slightly edited for differences between Cook Inlet and the Beaufort Sea, as shown in **Table 12**. An exception to this was burial depth, as pipelines in Cook Inlet are not trenched and buried. As such, this parameter was removed.

However, these changes were not the focus of the study because they either have been researched or were kept constant so that other features could be examined. This included gas composition, pipeline diameter, hole size selection, close in time selection, and operating pressure.

Table 12. Scenario Two parameters

| Parameter | Value |
|-----------------------|------------------------|
| Pipeline Diameter | 6 inches |
| Length | 5.1 miles, 0.6 onshore |
| Design Lifetime | 30 years |
| Operating Pressure | 1,400 psig |
| Operating Temperature | -5 to 5 °C |
| Pipeline Diameter | 6 inches |

5 Results

5.1 Scenario One

5.1.1 Quantitative Results

A series of 27 simulations were conducted examining gas releases from the pipeline configuration described in **Section 3**. The scenario matrix for this Scenario is available in **Appendix C: Scenario Matrices**. The simulations systematically varied hole size (0.25 inch, 2 inch, and 6 inch with 6 inch representing a full rupture), close-in time (600, 1,800, and 7,200 s), and distance from the pipeline endpoint (1,000, 6,000, and 11,400 m) to characterize potential release volumes.

The relationship between hole size and close-in time reveals a distinct pattern of increasing divergence (**Figure 14**). At short close-in times (600 seconds), all hole sizes result in similar release volumes around 900 Mcf. However, as close-in time extends, larger holes (2 and 6 inch) show substantially higher release volumes compared to the 0.25-inch hole. By 7,200 seconds, the 6-inch hole releases approximately 1,530 Mcf compared to 1,015 Mcf for the 0.25-inch hole, representing a 51% increase. This suggests that rapid detection and response is particularly critical for larger breach scenarios.

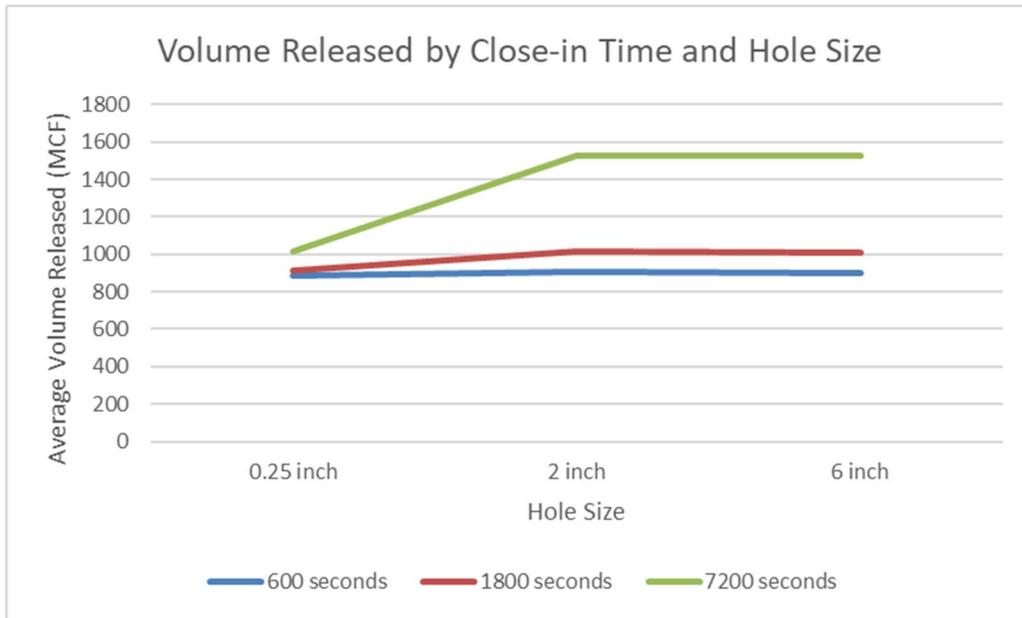


Figure 14. Scenario One volume released with varied close-in time and hole size

Analysis of hole size versus distance reveals a consistent inverse relationship between release volume and distance from the endpoint (**Figure 15**). This relationship is most pronounced for larger hole sizes, where releases at 1,000 m average 1,200 Mcf compared to 1,070 Mcf at 1,1400 m for 6-inch holes. The 0.25-inch hole shows less sensitivity to location, with only a 7% difference in release volume across the full distance range. This suggests that pipeline pressure profiles have a greater influence on release dynamics for larger breaches.

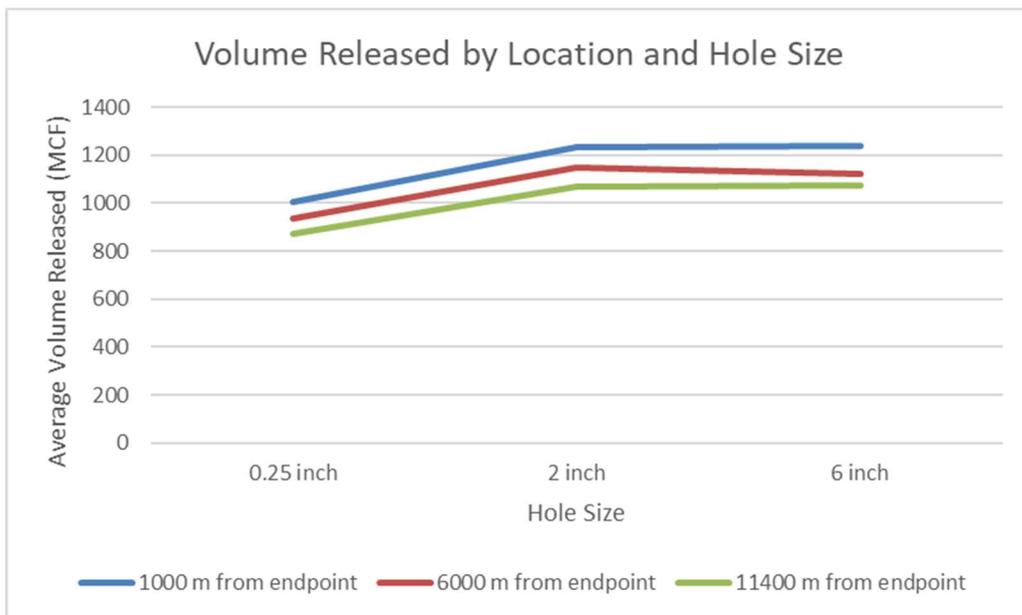


Figure 15. Scenario One volume released with varied release location and hole size

The interaction between close-in time and distance demonstrates that location effects become more significant with extended release durations (**Figure 16**). At 600 s, release volumes vary by less than 10% across all distances. However, at 7,200 s, releases at 1,000 m result in volumes approximately 15% higher than those at 11,400 m. This indicates that distance-related pressure effects compound over longer release durations, making rapid response particularly important for breaches near the pipeline endpoint.

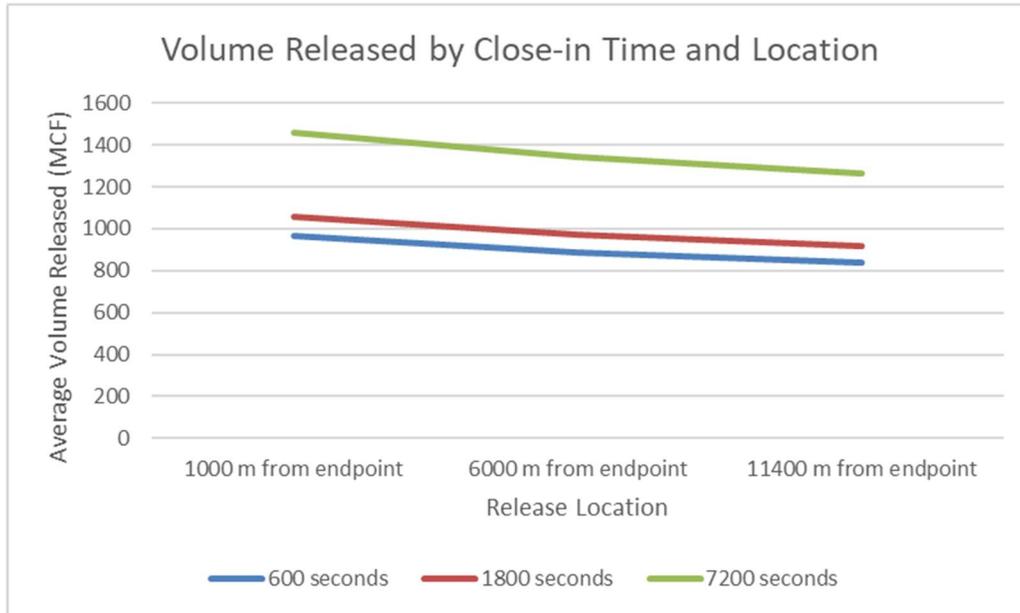


Figure 16. Scenario One volume released with varied close-in time and release location

These relationships highlight the complex interactions between release parameters and emphasize the importance of both release detection capabilities and breach characteristics in determining final release volumes. The analysis suggests that rapid detection and response systems would be most beneficial for larger breaches located near the pipeline endpoint, where release volumes show the highest sensitivity to extended close-in times.

Dispersion modeling was used to understand the hazard areas associated with each of the 27 releases that were modeled for Scenario One. **Table 13** shows the dispersion areas based on the emissions rates implied by the modeled releases and release times. Additional details are provided in **Appendices C and F**.

Table 13. Dispersion area

| Emissions Rate Category | Dispersion Area (m ³) | Count |
|-------------------------|-----------------------------------|-------|
| Low | 6,678 | 9 |
| Medium | 13,769 | 9 |
| High | 28,806 | 9 |

5.1.2 Qualitative Results

The qualitative assessment examined potential impacts across 12 environmental and socioeconomic resource categories. A relative scoring system was developed to compare impacts across these categories based on the hypothetical Liberty Development's Alternative 4a pipeline configuration (shown in **Table 14, Figure 17**).

Table 14. Scenario One relative risk by resource

| Resource | Relative Risk Score |
|--|----------------------------|
| Air Quality | 13.3 |
| Water Quality | 4.3 |
| Coastal and Estuarine Habitats | 6.7 |
| Fish and Invertebrates | 4.8 |
| Birds | 4.8 |
| Marine Mammals | 0.7 |
| Terrestrial Mammals | 5.9 |
| Recreation, tourism, and sports fishing | 4.8 |
| Communities and Subsistence | 6.3 |
| Economy | 4.5 |
| Commercial Fishing | 4.5 |
| Archaeological and historic resources | 4.5 |

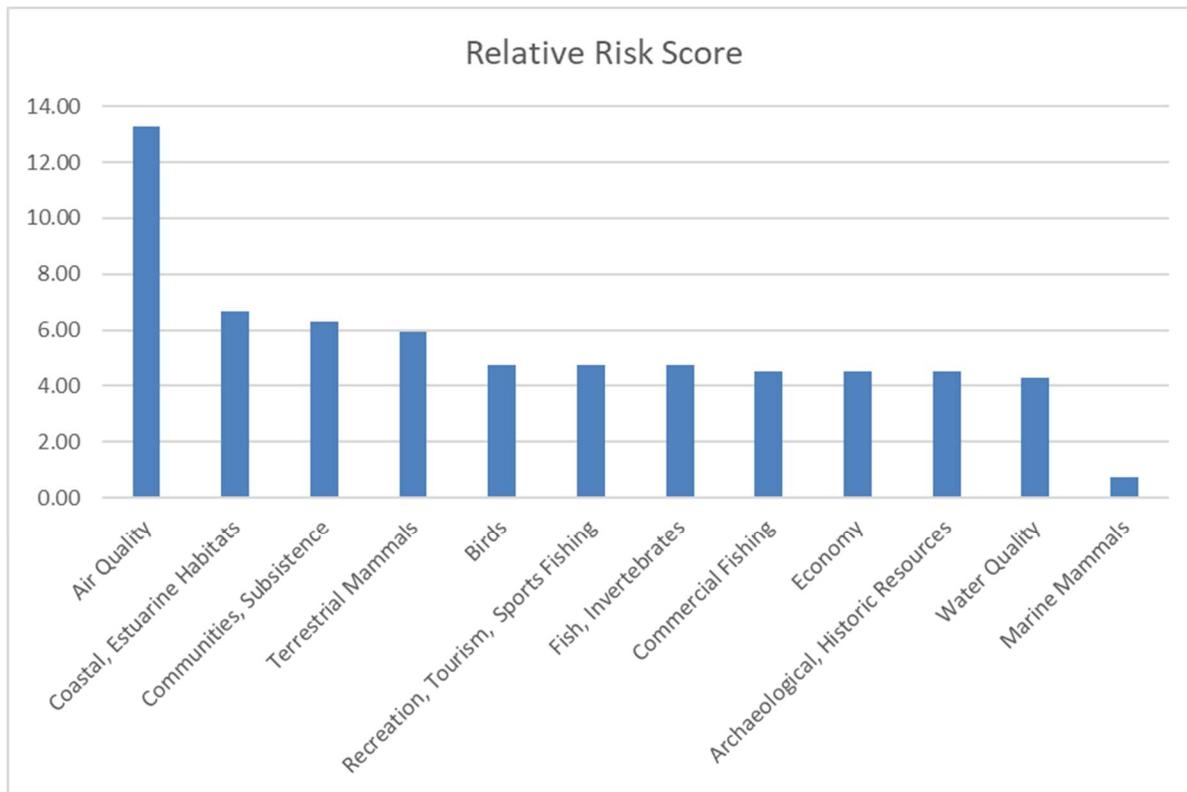


Figure 17. Scenario One relative risk score by resource

The assessment categorized impacts into four distinct risk levels, using air quality impacts as the baseline for minor risk classification. Air quality, with a score of 13.3, represents the highest potential impact level observed in the analysis, though this still falls within minor risk parameters given the rapid atmospheric dispersion characteristics of natural gas. This establishes an upper boundary for potential environmental impacts from pipeline releases in this configuration. Two resources demonstrated negligible-minor risk levels: coastal and estuarine habitats (6.7) and communities and subsistence activities (6.3). While these scores indicate slightly elevated concern compared to other categories, they remain well below the threshold for minor impacts, suggesting limited environmental and social consequences.

The majority of evaluated resources fell within the negligible risk category, with scores clustering between 4.5 and 5.9. This group includes terrestrial mammals (5.9), followed by a cluster of resources scoring 4.8: fish and invertebrates, birds, and recreation activities. A second cluster at 4.5 includes economic impacts, commercial fishing, and archaeological resources considerations. This consistency across diverse resource categories suggests that natural gas releases pose very limited risks to most environmental and socioeconomic resources. The lowest risk level, classified as minimal risk, includes water quality (4.3) and marine mammals (0.7). Marine mammals showed particularly low susceptibility to pipeline releases, likely due to their mobility and limited exposure pathways. Water quality impacts remain minimal due to the rapid rise of natural gas through the water column and limited dissolution. This rapid rise is in part due to the shallow depths of the Beaufort Sea, further minimizing the time that the natural gas spends in the water.

This comprehensive risk assessment framework demonstrates that natural gas pipeline releases in this configuration pose minimal environmental and socioeconomic risks overall. Even the highest impact category falls within minor risk parameters, while most resources cluster in the negligible risk category.

5.2 Scenario Two

5.2.1 Quantitative Results

A series of 27 simulations were conducted examining gas releases from a complex pipeline network in Cook Inlet consisting of three inlet lines converging at a junction, followed by a 5,000 m pipeline to the outlet. The scenario matrix for this Scenario is available in **Appendix C: Scenario Matrices**. The simulations systematically varied hole size (0.25, 2, and 6 inch diameter), close-in time (600, 1,800, and 7,200 s), and location (500 m from outlet, 1,000 m from junction, and 200 m from Inlet 3) to characterize potential release volumes.

The relationship between hole size and close-in time reveals distinct patterns based on release location (**Figure 18**). At short close-in times (600 s), releases 500 m from the outlet show moderate variation by hole size, ranging from 766 Mcf (0.25-inch) to 907 Mcf (6-inch). However, by 7,200 seconds, the difference becomes more pronounced, with the 6-inch hole releasing 3,290 Mcf compared to 932 Mcf for the 0.25-inch hole - a 253% increase. This divergence is less dramatic for releases near Inlet 3, suggesting network topology influences hole size sensitivity.

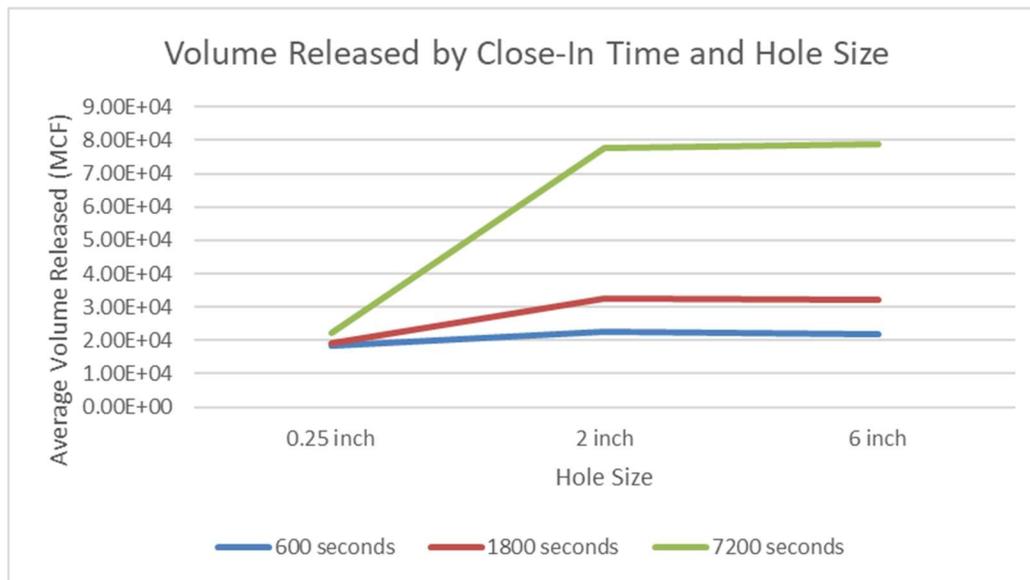


Figure 18. Scenario Two volume released with varied close-in time and hole size

Analysis of hole size versus location demonstrates the impact of network configuration on release volumes (**Figure 19**). For 6-inch holes, releases near the outlet average 3,290 Mcf compared to 2,130 mcd near Inlet 3 at 7,200 s. This 54% difference reflects the additional flow paths available downstream of the junction. The effect diminishes for smaller holes, with 0.25-inch releases showing only a 35% difference between locations, indicating that network effects are more pronounced for larger breaches.

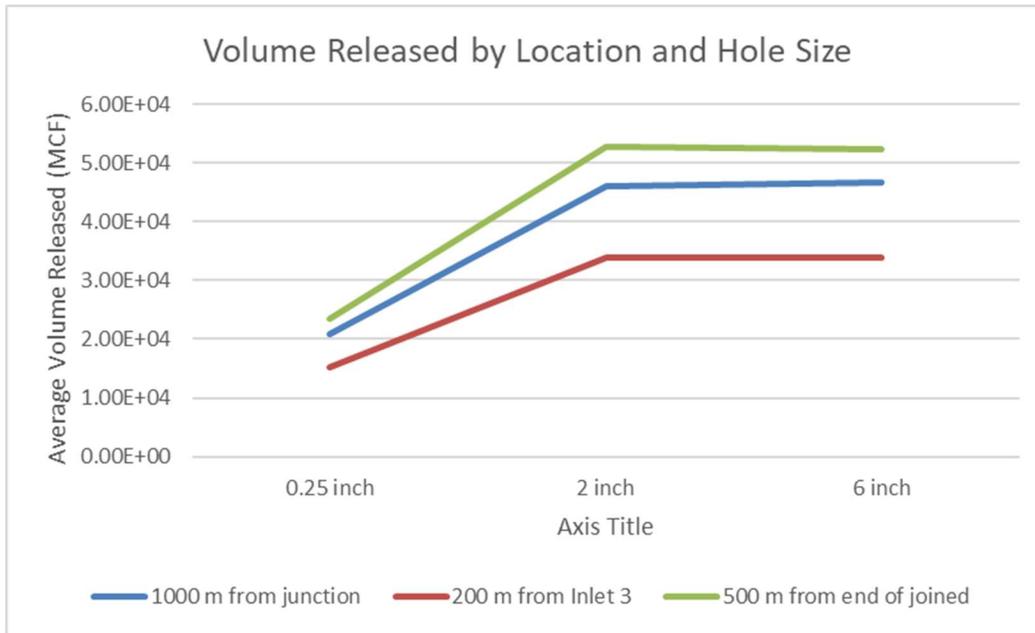


Figure 19. Scenario Two volume released with varied release location and hole size

The interaction between close-in time and location reveals increasing divergence over time (**Figure 20**). At 600 s, the difference between outlet-proximate and Inlet 3 releases averages 64% across all hole sizes. By 7,200 s, this location effect increases to 54–253% depending on hole size, demonstrating that network topology influences become more significant with extended release durations.

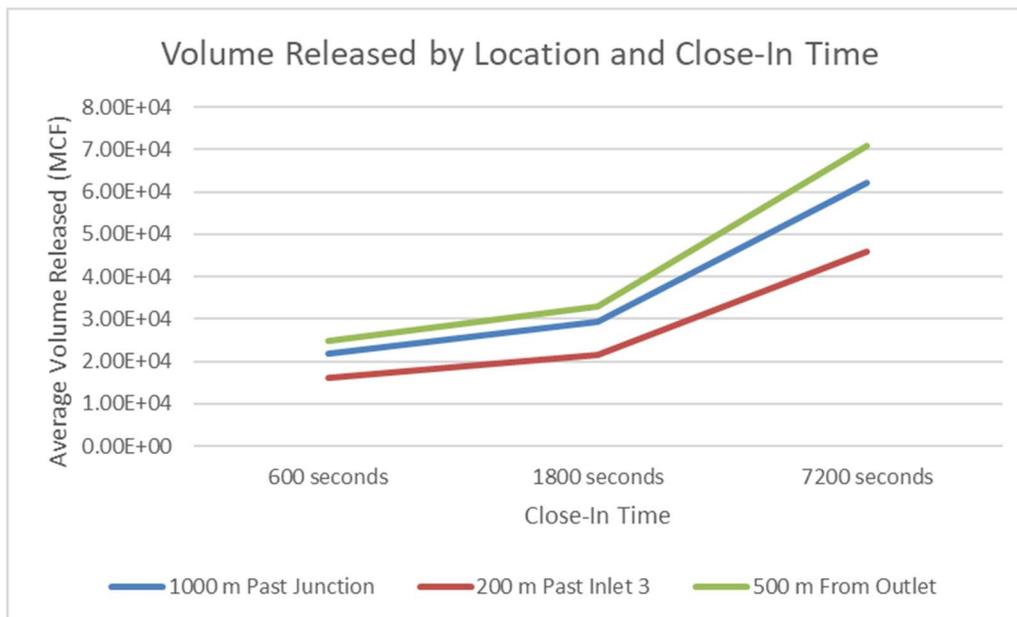


Figure 20. Scenario Two volume released with varied close-in time and release location

These relationships highlight how pipeline convergence points affect release dynamics and emphasize the importance of both release detection capabilities and network topology in determining final release

volumes. The analysis suggests that detection and response systems should prioritize breaches downstream of pipeline junctions, where multiple flow paths contribute to substantially higher release volumes.

Dispersion modeling was used to understand the hazard areas associated with each of the 27 releases that were modeled for Scenario Two. **Table 15** shows the dispersion areas based on the emissions rates implied by the modelled releases and release times. Additional details are provided in **Appendices C and F**.

Table 15. Dispersion area

| Emissions Rate Category | Dispersion Area (m ³) | Count |
|-------------------------|-----------------------------------|-------|
| Low | 6,678 | 10 |
| Medium | 13,769 | 9 |
| High | 28,806 | 8 |

5.2.2 Qualitative Results

The qualitative assessment examined potential impacts across 12 environmental and socioeconomic resource categories. A relative scoring system was developed to compare impacts across these categories based on the Cook Inlet pipeline configuration with three converging inlets (shown in Error! Reference source not found.16, **Figure 21**).

Table 16. Scenario Two relative risk by resource

| Resource | Relative Risk Score |
|---|---------------------|
| Air Quality | 10.3 |
| Water Quality | 3.3 |
| Coastal and Estuarine Habitats | 4.8 |
| Fish and Invertebrates | 3.6 |
| Birds | 3.6 |
| Marine Mammals | 1.1 |
| Terrestrial Mammals | 3.7 |
| Recreation, tourism, and sports fishing | 3.6 |
| Communities and Subsistence | 4.6 |
| Economy | 3.5 |
| Commercial Fishing | 3.5 |
| Archaeological and historic resources | 3.5 |

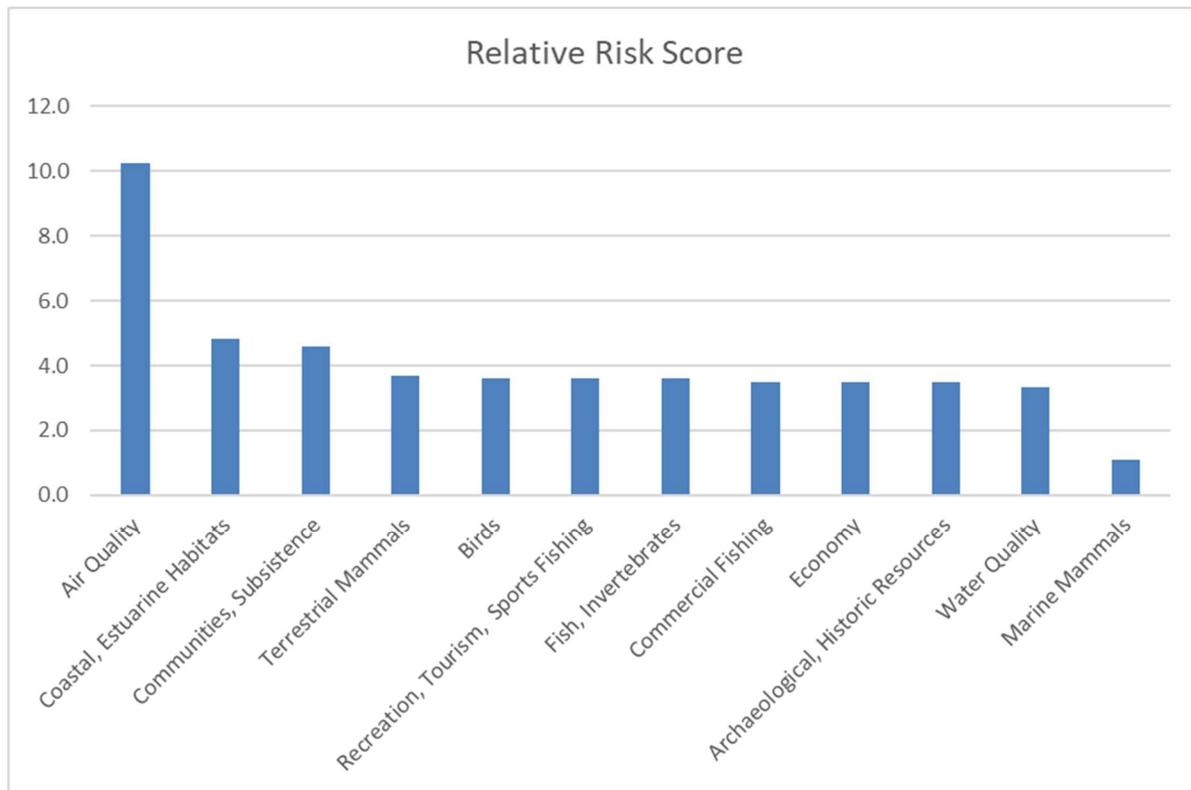


Figure 21. Scenario Two relative risk score by resource

The assessment categorized impacts into four distinct risk levels, using air quality impacts as the baseline for minor risk classification. Air quality, with a score of 10.25, represents the highest potential impact level observed in the analysis, though this represents a 23% reduction compared to the single pipeline configuration discussed in **5.1 Scenario One**. This lower score likely reflects the distributed nature of the network, which tends to limit maximum release volumes at any single point.

Coastal and estuarine habitats (4.81) demonstrated the second-highest risk level, followed closely by communities and subsistence activities (4.59). These scores represent significant reductions of 28% and 27% respectively compared to the single pipeline configuration, suggesting that the network topology helps mitigate peak environmental and social impacts.

The majority of evaluated resources clustered tightly in the negligible risk category, with scores ranging from 3.47 to 3.70. This group includes terrestrial mammals (3.70), birds and recreation activities (both 3.63), fish and invertebrates (3.62), followed by a cluster of resources scoring 3.47–3.48: commercial fishing, economy, archaeological resources, and - considerations. This tight clustering, combined with the overall lower scores compared to the single pipeline configuration, suggests that the network design helps distribute and minimize potential impacts across most resource categories.

The lowest risk level includes water quality (3.31) and marine mammals (1.10). While maintaining their position as lowest-risk categories, both showed slightly elevated scores compared to the single pipeline

configuration (increases of 23% and 57% respectively). This may reflect the increased geographic spread of potential release points in the network configuration.

This comprehensive risk assessment framework demonstrates that while the three-inlet network configuration maintains the same general pattern of relative risks between resources, it tends to moderate extreme scores, reducing peak impacts while slightly elevating minimum impacts. This suggests that network topology can be an important factor in overall risk mitigation strategies.

The results demonstrate complex relationships between hole size, close-in time, and release location can influence gas release volumes from pipeline networks. The most striking finding is the strong interaction between hole size and close-in time, particularly for larger breaches. While small holes (0.25-inch) show relatively stable release volumes across different close-in times, larger holes (2-inch and 6-inch) exhibit dramatically increasing volumes with extended release durations. This relationship appears to be fundamentally different between simple and complex pipeline networks.

In the single pipeline configuration (Scenario One), the maximum divergence between 0.25-inch and 6-inch holes reached 51% at 7200 s. However, in the complex network configuration (Scenario Two), this divergence increased to 253% under similar conditions, highlighting how network topology can amplify the effects of breach size. This suggests that rapid detection and response systems become even more critical in complex pipeline networks.

The influence of release location reveals important distinctions between simple and complex pipeline configurations. In the single pipeline scenario, distance from the endpoint showed a consistent inverse relationship with release volume, driven primarily by pressure profile effects. However, the complex network demonstrated more nuanced location effects, particularly around junction points where multiple flow paths converge. Analysis of location effects revealed a striking 54% increase in release volumes for large holes (6-inch) near the outlet compared to upstream locations in the complex network configuration. This substantial difference was notably less pronounced in the single pipeline configuration. The amplified effect in complex networks appears to be driven by several key factors. Junction points, where multiple flow paths converge, create zones of elevated risk due to the cumulative contribution of interconnected pipelines. The network topology itself can amplify these location-based effects, particularly at convergence points where pressure and flow dynamics become more complex.

The qualitative assessment of environmental impacts revealed nuanced patterns in how pipeline configuration influences potential consequences across different resource categories. Both simple and complex network scenarios maintained consistent risk hierarchies, with air quality impacts consistently emerging as the highest concern.

6 Conclusions

The results demonstrate complex relationships between hole size, close-in time, and release location can influence gas release volumes from pipeline networks. The most striking finding is the strong interaction between hole size and close-in time, particularly for larger breaches. While small holes (0.25-inch) show relatively stable release volumes across different close-in times, larger holes (2-inch and 6-inch) exhibit

dramatically increasing volumes with extended release durations. This relationship appears to be fundamentally different between simple and complex pipeline networks.

In the single pipeline configuration (Scenario One), the maximum divergence between 0.25-inch and 6-inch holes reached 51% at 7200 s. However, in the complex network configuration (Scenario Two), this divergence increased to 253% under similar conditions, highlighting how network topology can amplify the effects of breach size. This suggests that rapid detection and response systems become even more critical in complex pipeline networks.

The influence of release location reveals important distinctions between simple and complex pipeline configurations. In the single pipeline scenario, distance from the endpoint showed a consistent inverse relationship with release volume, driven primarily by pressure profile effects. However, the complex network demonstrated more nuanced location effects, particularly around junction points where multiple flow paths converge. Analysis of location effects revealed a striking 54% increase in release volumes for large holes (6-inch) near the outlet compared to upstream locations in the complex network configuration. This substantial difference was notably less pronounced in the single pipeline configuration. The amplified effect in complex networks appears to be driven by several key factors. Junction points, where multiple flow paths converge, create zones of elevated risk due to the cumulative contribution of interconnected pipelines. The network topology itself can amplify these location-based effects, particularly at convergence points where pressure and flow dynamics become more complex.

The qualitative assessment of environmental impacts revealed nuanced patterns in how pipeline configuration influences potential consequences across different resource categories. Both simple and complex network scenarios maintained consistent risk hierarchies, with air quality impacts consistently emerging as the highest concern.

6.1 Limitations

The analysis and findings presented in this report are subject to several key limitations that must be considered when interpreting and applying the results. The primary limitation stems from the limited availability of comprehensive natural gas release data from offshore pipelines. While detailed documentation exists for oil spills, natural gas releases are often under-reported or documented with incomplete information. Critical data fields such as release volumes, duration, and environmental conditions are frequently omitted from incident reports. This data scarcity impacts the statistical robustness of the analysis and introduces uncertainty into the derived occurrence rates.

A substantial limitation arises from the geographic distribution of the available data. Approximately 99% of the pipeline incident data comes from the Gulf of America OCS with minimal representation from the Alaska OCS. The stark differences in environmental conditions, operational challenges, and causal factors between these regions introduces uncertainty when extrapolating Gulf of America -based findings to Alaska. While adjustment factors were developed to account for these regional differences, the lack of Alaska-specific release data reduces confidence in these adjustments, particularly when considering the unique Alaska conditions that are not present in the Gulf of America dataset.

The available scientific literature examining natural gas releases from offshore and onshore pipelines is sparse compared to oil spill research. This limitation is particularly acute for Arctic and subarctic environments like the Alaska OCS. Key knowledge gaps exist regarding the behavior of natural gas releases under Alaska OCS conditions, environmental impacts on Alaska marine ecosystems, effects on subsistence resources and communities, and long-term consequences of releases on permafrost and ice-covered waters. The limited research base makes it difficult to validate assumptions and compare findings against other studies.

The temporal coverage of the analysis presents another limitation. Our dataset primarily spans recent decades, which may not fully capture the evolution of pipeline technology, regulatory requirements, and industry practices. The rapid pace of technological advancement in pipeline design, monitoring systems, and leak detection capabilities means that historical incident rates may not accurately reflect current risk levels.

These limitations highlight the need for improved data collection and reporting practices specific to natural gas releases. More comprehensive incident documentation, including detailed environmental conditions and release characteristics, would strengthen future analyses. Additionally, expanded research into gas release behavior and impacts under Alaska conditions would help validate modeling assumptions and improve our understanding of potential consequences. Despite these limitations, this analysis represents the most comprehensive assessment possible with currently available data and provides valuable insights for risk assessment and management in the Alaska OCS region.

6.2 Future Research Implications

The limitations identified in this analysis, combined with the evolving nature of Arctic oil and gas development, suggest several key areas for future research. Primary among these is the critical need for research examining how natural gas releases behave in Arctic conditions. Specific focus should be placed on gas plume dynamics in ice-covered waters, interaction between released gas and various ice conditions/formations, effects of low temperatures on release rates and dispersion patterns, and validation of existing gas dispersion models for Arctic conditions. These fundamental studies would provide a stronger foundation for risk assessment and response planning in Arctic environments.

Improved methodologies for detecting and quantifying natural gas releases in Arctic environments represent another crucial research need. Future work should focus on developing remote sensing techniques suitable for Arctic conditions, real-time monitoring systems that can function reliably in extreme environments, and the integration of multiple detection technologies to improve accuracy. Additionally, standardized protocols for release volume estimation need to be established to ensure consistent and reliable data collection across the industry. Environmental impact assessment presents a third major area requiring additional research focus. While this study has examined available data on environmental impacts, knowledge gaps remain regarding both immediate and long-term effects of natural gas releases in Arctic environments. Future studies should investigate effects on Arctic marine ecosystems and species, the interaction between gas releases and permafrost stability, impacts on ice formation and stability, and the influence on local atmospheric conditions.

The modeling approaches developed in this study could be enhanced through future research efforts. Particular attention should be given to validating and refining the adjustment factors developed for translating Gulf of America release rates to Arctic conditions. This could include detailed case studies of actual releases in Arctic environments, laboratory experiments simulating Arctic conditions, and the development of more sophisticated mathematical models incorporating Arctic-specific parameters. Statistical analysis methods could be improved through the development of more robust datasets specific to Arctic pipeline operations. Future research should focus on establishing standardized reporting protocols for natural gas releases, implementing comprehensive monitoring programs in Arctic regions, and developing methods to account for the unique challenges of data collection in remote Arctic locations. This would help address the current limitations in data availability and quality.

Finally, climate change implications deserve specific attention in future research efforts. As Arctic conditions continue to evolve, studies should examine how changing environmental conditions might affect pipeline integrity, release behavior, and environmental impacts. This research should include modeling of future scenarios under different climate projections, assessment of emerging risks due to changing Arctic conditions, and development of adaptive management strategies for pipeline operations in a changing Arctic and subarctic environment.

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Appendix A: Cook Inlet and North Slope Lease and Pipeline Maps

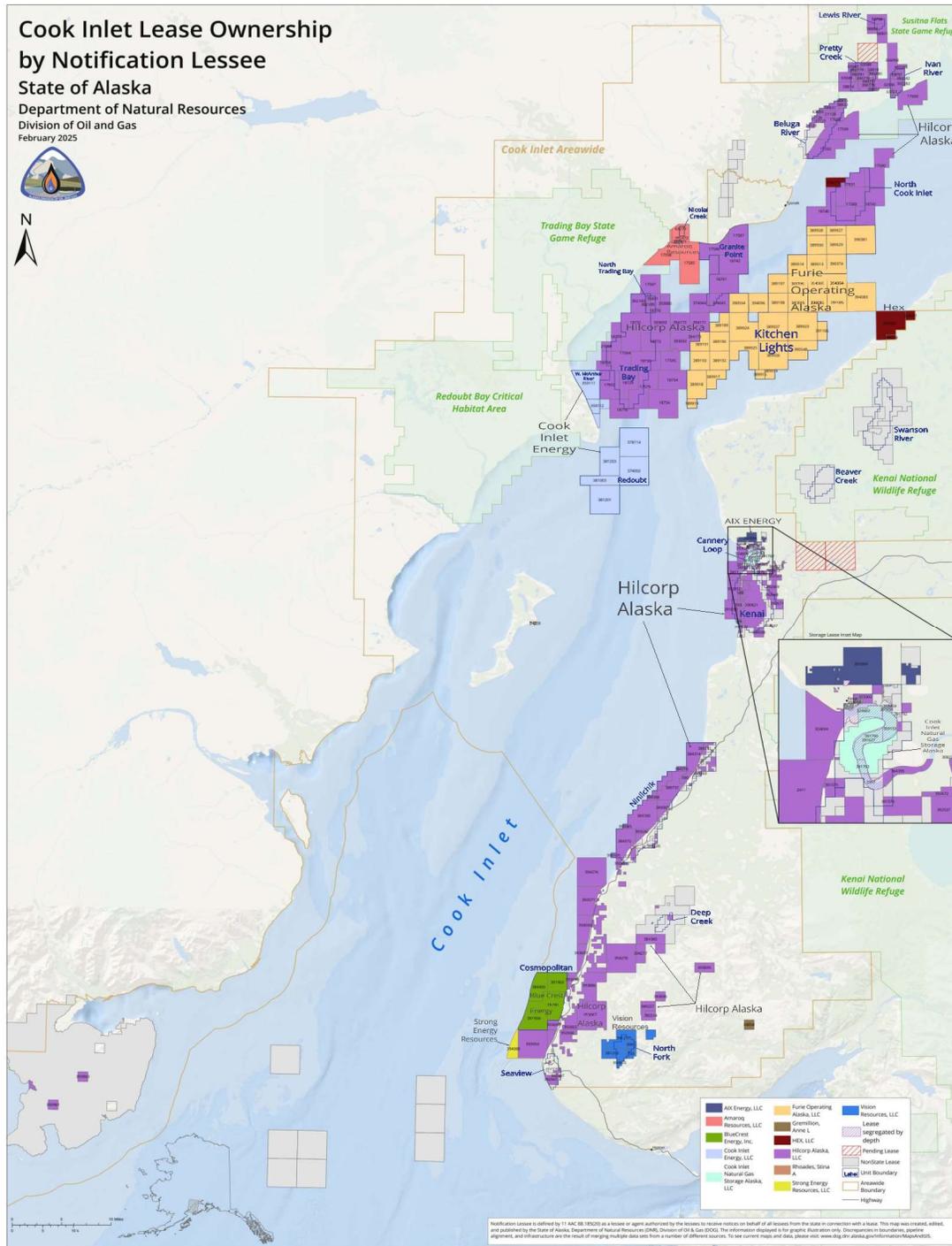


Figure A-22. 2025 Cook Inlet Lease Ownership by Notification Lessee (2025)

Available at <https://dog.dnr.alaska.gov> (State Pipeline Coordinators Section 2022a; 2025a)

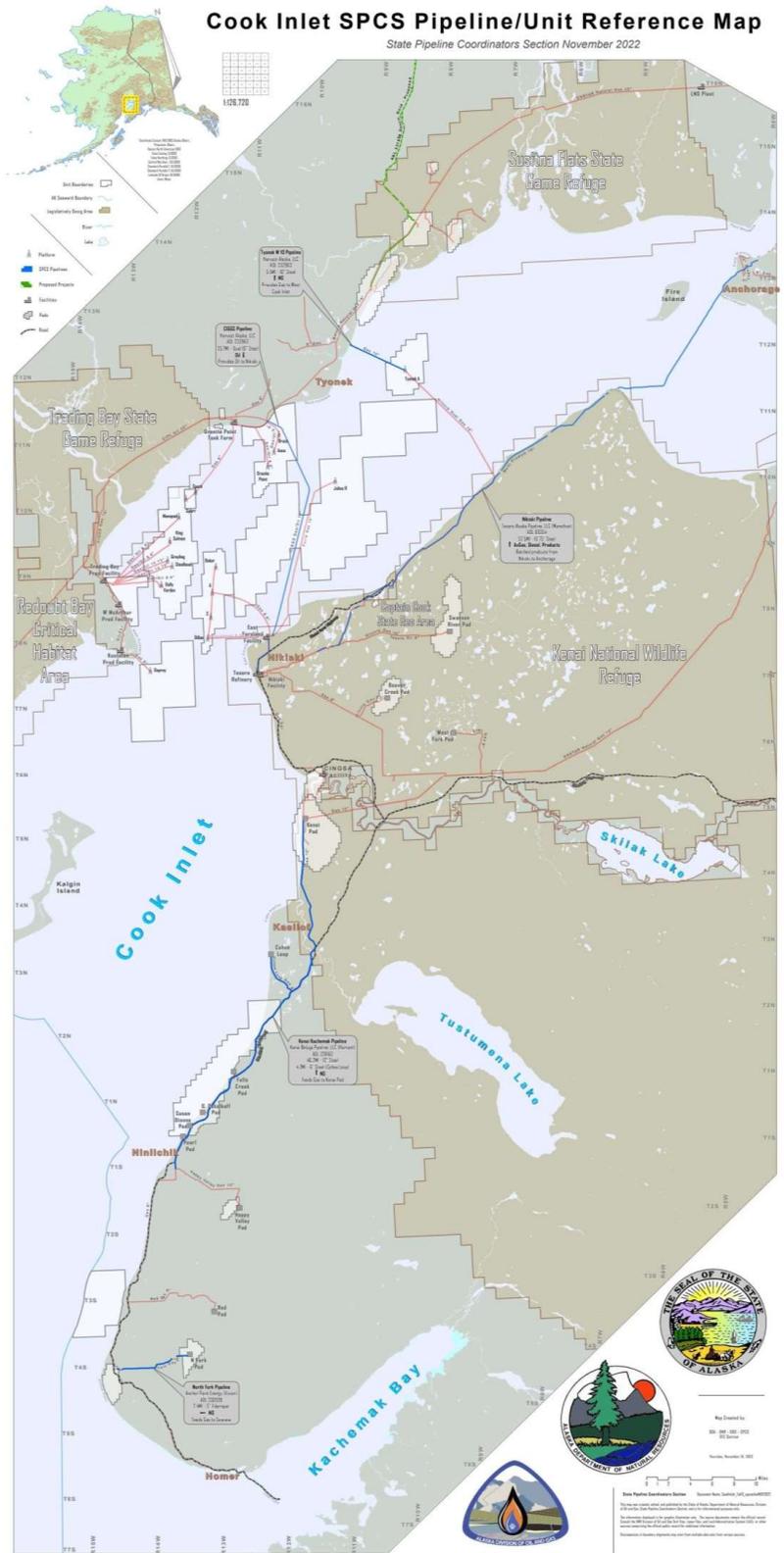


Figure A-23. Cook Inlet Pipeline/Unit Reference Map (2022)

Available at <https://dog.dnr.alaska.gov> (State Pipeline Coordinators Section 2022a)

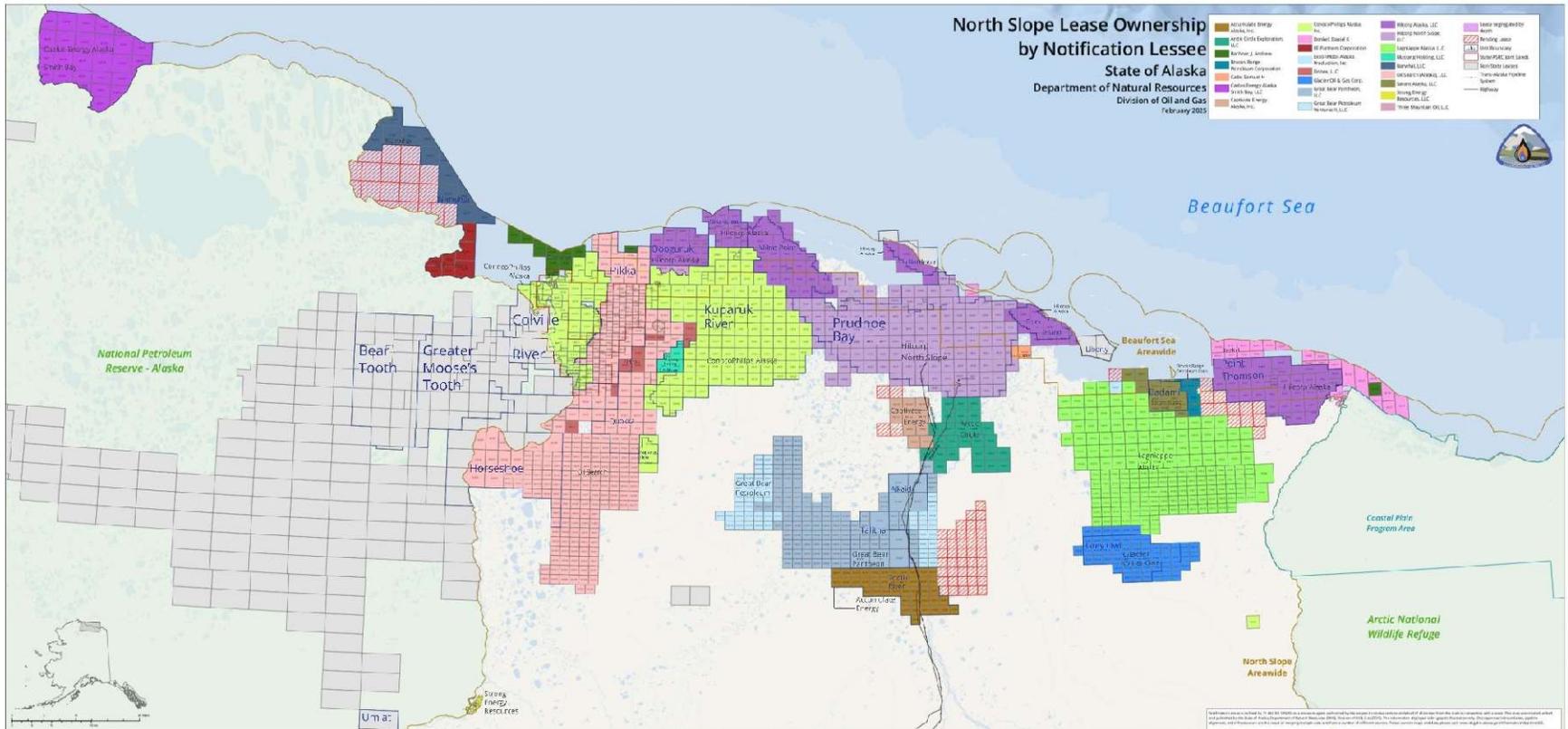


Figure A-24. North Slope Lease Ownership by Notification Lessee (2025)

Available at <https://dog.dnr.alaska.gov> (State Pipeline Coordinators Section 2025b)

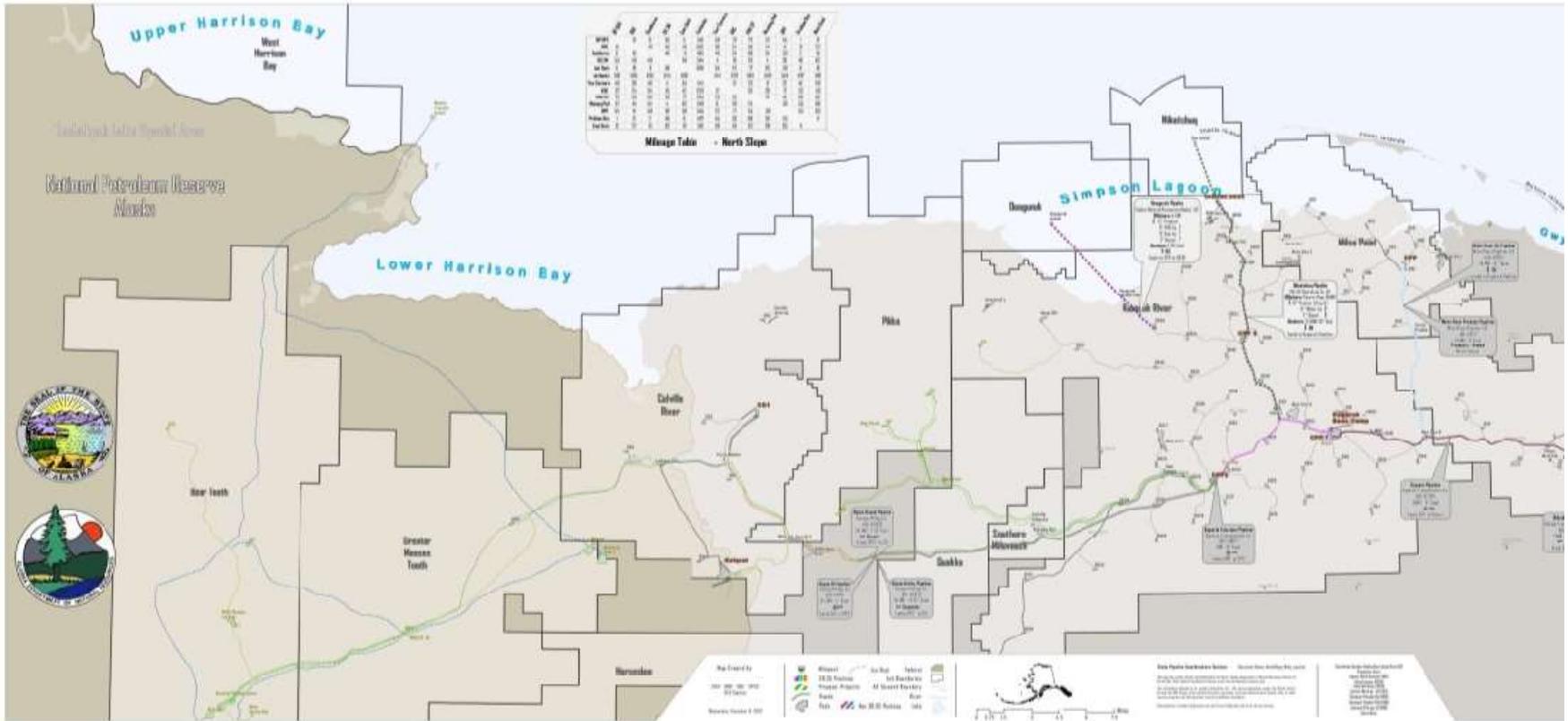


Figure A-25. North Slope Pipeline/Unit Reference Map (2022) Left

Available at <https://dog.dnr.alaska.gov> (State Pipeline Coordinators Section 2022b)

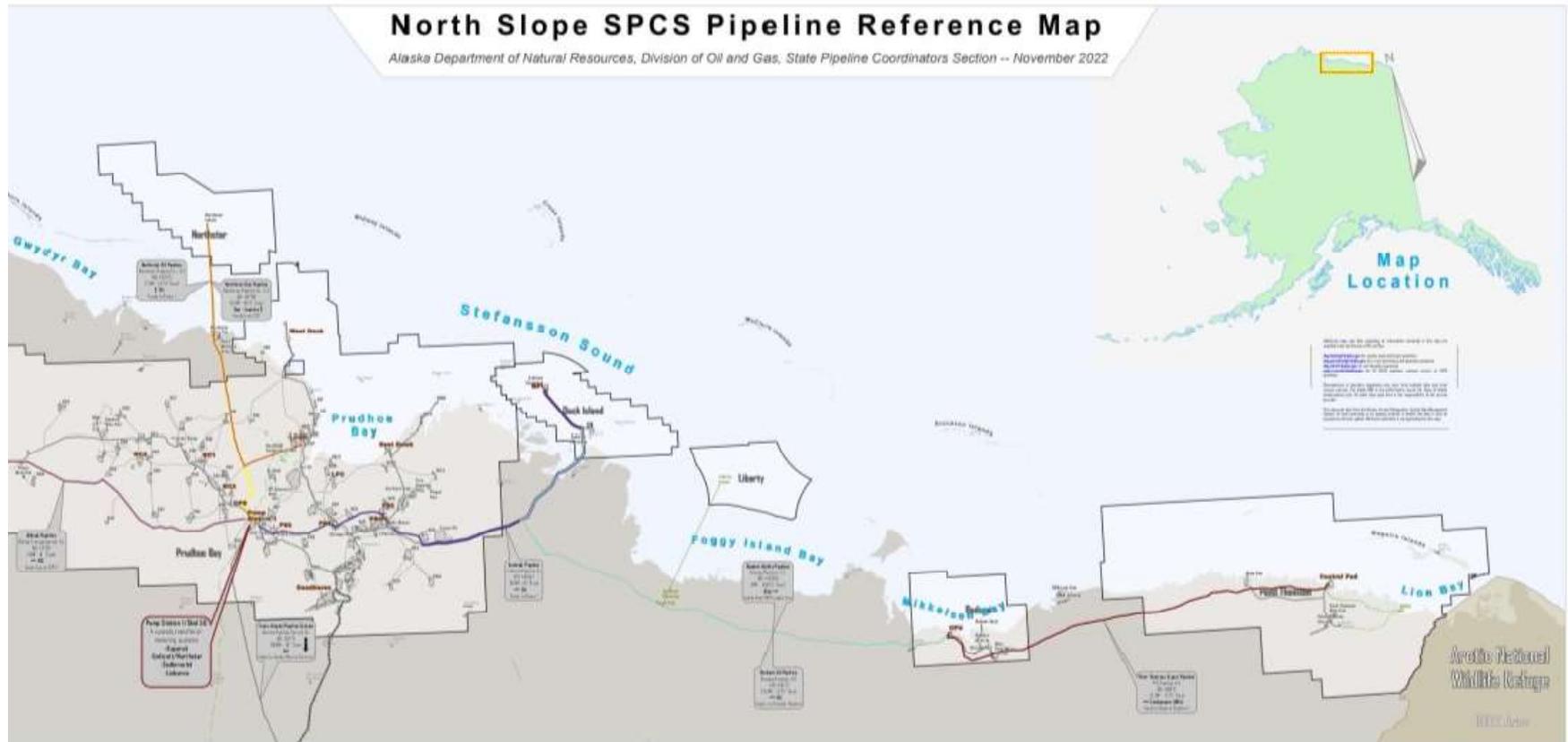


Figure A-26. North Slope Pipeline/Unit Reference Map (2022) Right

Available at <https://dog.dnr.alaska.gov> (State Pipeline Coordinators Section 2022a; 2022b)

Appendix B: Consolidated Natural Gas Release Counts and Exposed Pipeline Miles by Year

The data source used for this part of the calculation distinctly listed location as either: OCS, Offshore, or Onshore. Due to this breakdown, as well as the fact that offshore is not always less than OCS, it was assumed that Offshore refers to state waters and OCS to the Outer Continental Shelf. Additionally, pipeline mileage was not specified as either state waters or OCS so the mileage number is shared between both.

Table B-17. Consolidated natural gas release counts and exposed pipeline miles by year

| Year | OCS | State Waters | Onshore | Pipeline Miles - Onshore | Pipeline Miles - Offshore |
|------|-----|--------------|---------|--------------------------|---------------------------|
| 1984 | 5 | 1 | 79 | 277,601 | 7,353 |
| 1985 | 13 | 1 | 115 | 282,745 | 7,719 |
| 1986 | 6 | 1 | 76 | 280,667 | 9,291 |
| 1987 | 8 | 3 | 59 | 284,235 | 7,622 |
| 1988 | 7 | 5 | 77 | 275,931 | 7,886 |
| 1989 | 15 | 5 | 83 | 279,728 | 8,198 |
| 1990 | 16 | 0 | 73 | 283,815 | 8,110 |
| 1991 | 5 | 2 | 64 | 285,295 | 8,567 |
| 1992 | 17 | 2 | 55 | 283,071 | 8,397 |
| 1993 | 11 | 2 | 82 | 285,043 | 8,220 |
| 1994 | 15 | 13 | 53 | 293,438 | 8,107 |
| 1995 | 15 | 3 | 46 | 288,846 | 8,101 |
| 1996 | 8 | 7 | 62 | 277,861 | 6,811 |
| 1997 | 8 | 6 | 59 | 287,745 | 6,625 |
| 1998 | 15 | 10 | 74 | 295,601 | 7,108 |
| 1999 | 2 | 7 | 45 | 290,042 | 6,017 |
| 2000 | 7 | 5 | 68 | 293,716 | 5,241 |
| 2001 | 3 | 10 | 74 | 284,452 | 5,541 |
| 2002 | 17 | 4 | 61 | 296,794 | 6,205 |
| 2003 | 8 | 5 | 84 | 295,402 | 6,090 |
| 2004 | 29 | 7 | 86 | 296,944 | 6,057 |
| 2005 | 59 | 10 | 113 | 294,800 | 5,668 |
| 2006 | 21 | 11 | 113 | 293,705 | 6,619 |
| 2007 | 24 | 18 | 89 | 294,938 | 6,127 |
| 2008 | 36 | 10 | 94 | 297,267 | 5,914 |
| 2009 | 21 | 12 | 96 | 298,964 | 5,596 |

| Year | OCS | State Waters | Onshore | Pipeline Miles - Onshore | Pipeline Miles - Offshore |
|-------------|------------|---------------------|----------------|---------------------------------|----------------------------------|
| 2010 | 0 | 30 | 86 | 299,360 | 5,447 |
| 2011 | 0 | 21 | 107 | 299,730 | 5,328 |
| 2012 | 0 | 24 | 92 | 298,612 | 4,769 |
| 2013 | 1 | 15 | 96 | 298,378 | 4,490 |
| 2014 | 0 | 22 | 120 | 297,901 | 3,923 |
| 2015 | 0 | 16 | 133 | 297,334 | 3,831 |
| 2016 | 0 | 8 | 88 | 297,055 | 3,298 |
| 2017 | 0 | 21 | 105 | 297,578 | 3,156 |
| 2018 | 1 | 3 | 113 | 298,520 | 3,105 |
| 2019 | 0 | 7 | 122 | 298,907 | 3,430 |
| 2020 | 11 | 0 | 120 | 298,834 | 2,836 |
| 2021 | 11 | 3 | 97 | 298,748 | 2,778 |
| 2022 | 7 | 0 | 130 | 298,023 | 2,774 |

Appendix C: Scenario Matrices

Table B-18. Scenario One

| Hole Size (in) | Location | Release Time (seconds) | Release Volume (MCF) | Emission Rate (kg / sec) | Emission Rate Category |
|----------------|------------------------|------------------------|----------------------|--------------------------|------------------------|
| 0.25 | 1,000 m from endpoint | 1,800 | 978.11 | 60.02 | Medium |
| 0.25 | 11,400 m from endpoint | 1,800 | 847.46 | 52.00 | Medium |
| 0.25 | 6,000 m from endpoint | 1,800 | 907.49 | 55.68 | Medium |
| 0.25 | 1,000 m from endpoint | 600 | 953.39 | 175.50 | High |
| 0.25 | 11,400 m from endpoint | 600 | 826.27 | 152.10 | High |
| 0.25 | 6,000 m from endpoint | 600 | 886.30 | 163.15 | High |
| 0.25 | 1,000 m from endpoint | 7,200 | 1,087.57 | 16.68 | Low |
| 0.25 | 11,400 m from endpoint | 7,200 | 942.80 | 14.46 | Low |
| 0.25 | 6,000 m from endpoint | 7,200 | 1,009.89 | 15.49 | Low |
| 2 | 1,000 m from endpoint | 1,800 | 1,091.10 | 66.95 | Medium |
| 2 | 11,400 m from endpoint | 1,800 | 946.33 | 58.07 | Medium |
| 2 | 6,000 m from endpoint | 1,800 | 1,013.42 | 62.18 | Medium |
| 2 | 1,000 m from endpoint | 600 | 971.05 | 178.75 | High |
| 2 | 11,400 m from endpoint | 600 | 843.93 | 155.35 | High |
| 2 | 6,000 m from endpoint | 600 | 903.95 | 166.40 | High |
| 2 | 1,000 m from endpoint | 7,200 | 1,641.95 | 25.19 | Low |
| 2 | 11,400 m from endpoint | 7,200 | 1,419.49 | 21.78 | Low |
| 2 | 6,000 m from endpoint | 7,200 | 1,525.42 | 23.40 | Low |
| 6 | 1,000 m from endpoint | 1,800 | 1,094.63 | 67.17 | Medium |
| 6 | 11,400 m from endpoint | 1,800 | 949.86 | 58.28 | Medium |
| 6 | 6,000 m from endpoint | 1,800 | 988.70 | 60.67 | Medium |
| 6 | 1,000 m from endpoint | 600 | 971.05 | 178.75 | High |
| 6 | 11,400 m from endpoint | 600 | 847.46 | 156.00 | High |
| 6 | 6,000 m from endpoint | 600 | 875.71 | 161.20 | High |
| 6 | 1,000 m from endpoint | 7,200 | 1,645.48 | 25.24 | Low |
| 6 | 11,400 m from endpoint | 7,200 | 1,426.55 | 21.88 | Low |
| 6 | 6,000 m from endpoint | 7,200 | 1,500.71 | 23.02 | Low |

Per Section 2.4.3.2, the dispersion area LFL

Table B-19. Scenario Two

| Hole Size (in) | Location | Release Time (seconds) | Release Volume (MCF) | Emission Rate (kg / sec) | Emission Rate Category |
|----------------|--------------------------|------------------------|----------------------|--------------------------|------------------------|
| 0.25 | 500 m from end of joined | 7,200 | 932 | 14.3 | Low |
| 0.25 | 1,000 m from junction | 7,200 | 819 | 12.5666667 | Low |
| 0.25 | 200 m from Inlet 3 | 7,200 | 604 | 9.2625 | Low |
| 0.25 | 500 m from end of joined | 600 | 766 | 141.05 | High |
| 0.25 | 1,000 m from junction | 600 | 678 | 124.8 | High |
| 0.25 | 200 m from Inlet 3 | 600 | 498 | 91.65 | Medium |
| 0.25 | 500 m from end of joined | 1,800 | 798 | 48.9666667 | Low |
| 0.25 | 1,000 m from junction | 1,800 | 703 | 43.1166667 | Low |
| 0.25 | 200 m from Inlet 3 | 1,800 | 516 | 31.6333333 | Low |
| 2 | 500 m from end of joined | 7,200 | 3,273 | 50.2125 | Medium |
| 2 | 1,000 m from junction | 7,200 | 2,857 | 43.8208333 | Low |
| 2 | 200 m from Inlet 3 | 7,200 | 2,115 | 32.4458333 | Low |
| 2 | 500 m from end of joined | 600 | 946 | 174.2 | High |
| 2 | 1,000 m from junction | 600 | 826 | 152.1 | High |
| 2 | 200 m from Inlet 3 | 600 | 607 | 111.8 | High |
| 2 | 500 m from end of joined | 1,800 | 1,367 | 83.85 | Medium |
| 2 | 1,000 m from junction | 1,800 | 1,190 | 73.0166667 | Medium |
| 2 | 200 m from Inlet 3 | 1,800 | 879 | 53.95 | Medium |
| 6 | 500 m from end of joined | 7,200 | 3,294 | 50.5375 | Medium |
| 6 | 1,000 m from junction | 7,200 | 2,913 | 44.6875 | Low |
| 6 | 200 m from Inlet 3 | 7,200 | 2,129 | 32.6625 | Low |
| 6 | 500 m from end of joined | 600 | 907 | 167.05 | High |
| 6 | 1,000 m from junction | 600 | 823 | 151.45 | High |
| 6 | 200 m from Inlet 3 | 600 | 590 | 108.55 | High |
| 6 | 500 m from end of joined | 1,800 | 1,342 | 82.3333333 | Medium |
| 6 | 1,000 m from junction | 1,800 | 1,201 | 73.6666667 | Medium |
| 6 | 200 m from Inlet 3 | 1,800 | 872 | 53.5166667 | Medium |

Table B-20. Scenario One and Two dispersion areas

| Emission Rate Category | Category Upper Limit (Kg/m3) | Dispersion Area (m2) |
|-------------------------------|-------------------------------------|-----------------------------|
| Low | 50 | 6,678 |
| Medium | 100 | 13,769 |
| High | 200 | 28,806 |

Fire Radius: = 241 feet → **16,961.97 square meters**

Appendix D: Data Attributes

Table B-21. PHMSA dataset

| Category | Description |
|----------------------------|--|
| Incident Identification | Unique identifiers and timestamps for the incident (e.g., REPORT_NUMBER, RPTID, REPORT_RECEIVED_DATE, IYEAR, IDATE, I HOUR). |
| Operator Information | Details about the operator (e.g., OPERATOR_ID, NAME, OPSTREET, OPCITY, OPSTATE, OPZIP). |
| Location Information | Geographic details of the incident (e.g., LATITUDE, LONGITUDE, ACCITY, ACCOUNTY, ACSTATE, ACZIP, ON_OFF_SHORE). |
| Facility Information | Information about the pipeline or facility involved (e.g., PIPE_FAC_NAME, SEGMENT_NAME, PIPE_TYPE, PIPE_DIAMETER, PIPE_WALL_THICKNESS). |
| Material Details | Information about the materials involved (e.g., MATERIAL_INVOLVED, MATERIAL_DETAILS, PIPE_COAT, PIPE_COATING_TYPE). |
| Release Details | Details about the type and extent of the release (e.g., COMMODITY_RELEASED_TYPE, UNINTENTIONAL_RELEASE, INTENTIONAL_RELEASE, RELEASE_TYPE). |
| Fatalities and Injuries | Counts and indicators for fatalities and injuries (e.g., FATALITY_IND, NUM_EMP_FATALITIES, NUM_GP_FATALITIES, INJURY_IND, NUM_EMP_INJURIES). |
| Property Damage | Estimated costs and property damage details (e.g., PRPTY, EST_COST_PROP_DAMAGE, EST_COST_EMERGENCY). |
| Shutdown and Restart | Information about shutdowns and restarts (e.g., SHUTDOWN_DUE_ACCIDENT_IND, SHUTDOWN_DATETIME, RESTART_DATETIME). |
| Fire and Explosion | Indicators and details for fire and explosions (e.g., IGNITE_IND, EXPLODE_IND, HOW_EXTINGUISHED). |
| Evacuation Details | Information about evacuations (e.g., NUM_PUB_EVACUATED, EVAC_REASON, EVAC_REASON_TEXT). |
| Pressure and Flow | Pressure and flow details (e.g., ACCIDENT_PSIG, MAOP, GAS_FLOW_IN_PIPE_IN_MCF). |
| Inspection and Testing | Inspection and testing details (e.g., INTERNAL_INSPECTION_IND, HYDRTST_MOST_RCNT_YEAR, DIRECT_ASMNT_CONDUCTED). |
| Corrosion Factors | Details about corrosion causes and types (e.g., GALVANIC_CORROSION_IND, ATMOSPHERE_CORROSION_IND, MICROBIOLOGICAL_CORROSION_IND). |
| Weather and Natural Causes | Details about weather-related factors (e.g., NATURAL_FORCE_TYPE, EARTH_SUBTYPE, HEAVY_RAINS_SUBTYPE, NF_HURRICANE_IND). |
| External Factors | Information about external causes (e.g., EX_PARTY_TYPE, EXCAVATOR_IND, VEHICLE_SUBTYPE, OSF_OTHER_DETAILS). |
| Human Error | Indicators of human-related causes (e.g., INVEST_INCORRECT_ACTION_IND, INVEST_FATIGUE_IND, IO_NOT_INSTALLED_PROPERLY_IND). |
| Equipment Failure | Details about equipment-related failures (e.g., EQ_FAILURE_TYPE, CONTROL_VALVE_IND, PRESSURE_REGULATOR_IND). |

| Category | Description |
|----------------------------------|---|
| Pipeline Design and Construction | Information about pipeline design and construction issues (e.g., PWF_DESIGN_IND, PWF_CONSTRUCTION_IND, PWF_INSTALLATION_IND). |
| Environmental Impact | Indicators of environmental effects (e.g., WILDLIFE_IMPACT_IND, FISH_AQUATIC_IMPACT_IND, BIRDS_IMPACT_IND). |
| Investigation Details | Status and findings of investigations (e.g., INVESTIGATION_STATUS, CAUSE, CAUSE_DETAILS). |
| Communication | Details about communication during the incident (e.g., COMMUNICATION_STATE_FED_IND, PARTY_INITIATED_COMMUNICATION). |
| Narrative and Comments | Free-text fields for additional details (e.g., NARRATIVE, UNKNOWN_TEXT, CAUSE_DETAILS_TEXT). |
| Contact Information | Contact details for preparers and local contacts (e.g., PREPARER_NAME, PREPARER_EMAIL, LOCAL_CONTACT_NAME). |

Table B-22. BSEE dataset

| Attribute | Description |
|--------------------------|--|
| YEAR | Year in which the release occurred |
| NAME | Pipeline or facility name |
| CITY | Nearest city to the release location |
| COUNTY | County where release occurred (if applicable) |
| STATE | State nearest to the release location |
| SHORE | Indicator if release occurred in onshore or offshore environment |
| OCS | Indicator if release occurred in Outer Continental Shelf waters |
| COMMODITY RELEASED | Type of substance gas released (filtered for natural gas) |
| TYPE COMMODITY DETAILS | Additional details on the released substance |
| FEDERAL LAND NOT OCS | Indicator if release occurred on federal land not on OCS |
| ITYPE | Incident type classification |
| FATALITIES | Number of fatalities resulting from the incident |
| INJURIES | Number of injuries resulting from the incident |
| HOURS TILL DECLARED SAFE | Time in hours until the site was declared safe |
| MINS UNTIL DECLARED SAFE | Time in minutes until the site was declared safe |
| CAUSE | Primary cause code for the release |
| CAUSE DESCRIPTION | Detailed description of the release cause |

| Attribute | Description |
|---------------------------|--|
| CATEGORY | Classification category of the release |
| TRANSMISSION OR GATHERING | Pipeline system type (transmission or gathering) |
| ENVIRONMENT | Environmental conditions at time of release |
| LOCATION OF CORROSION | Specific location of corrosion if applicable |
| CAUSE OF CORROSION | Specific cause of corrosion if applicable |
| CONSTRUCTION DEFECT | Indicator if construction defect was present |
| EARTH MOVE | Indicator if earth movement contributed |
| EARTH MOVE DESCRIPTION | Description of earth movement if applicable |
| FLOODS | Indicator if flooding contributed |
| FLOODS DESCRIPTION | Description of flooding if applicable |
| TEMPER_TEXT | Temperature-related information |
| THIRD PARTY/OPERATOR | Indicator if third party or operator involved |
| FIRE/EXPLOSION | Indicator if fire or explosion occurred |
| EXPLODE | Indicator if explosion occurred |
| EXTREME WEATHER | Indicator if extreme weather was a factor |
| HURRICANE | Indicator if hurricane was involved |
| TROPICAL STORM | Indicator if tropical storm was involved |
| TORNADO | Indicator if tornado was involved |
| OTHER EXTREME WEATHER | Indicator if other extreme weather was involved |

Appendix E: Region-Based Release Size Adjustment Sankey Chart

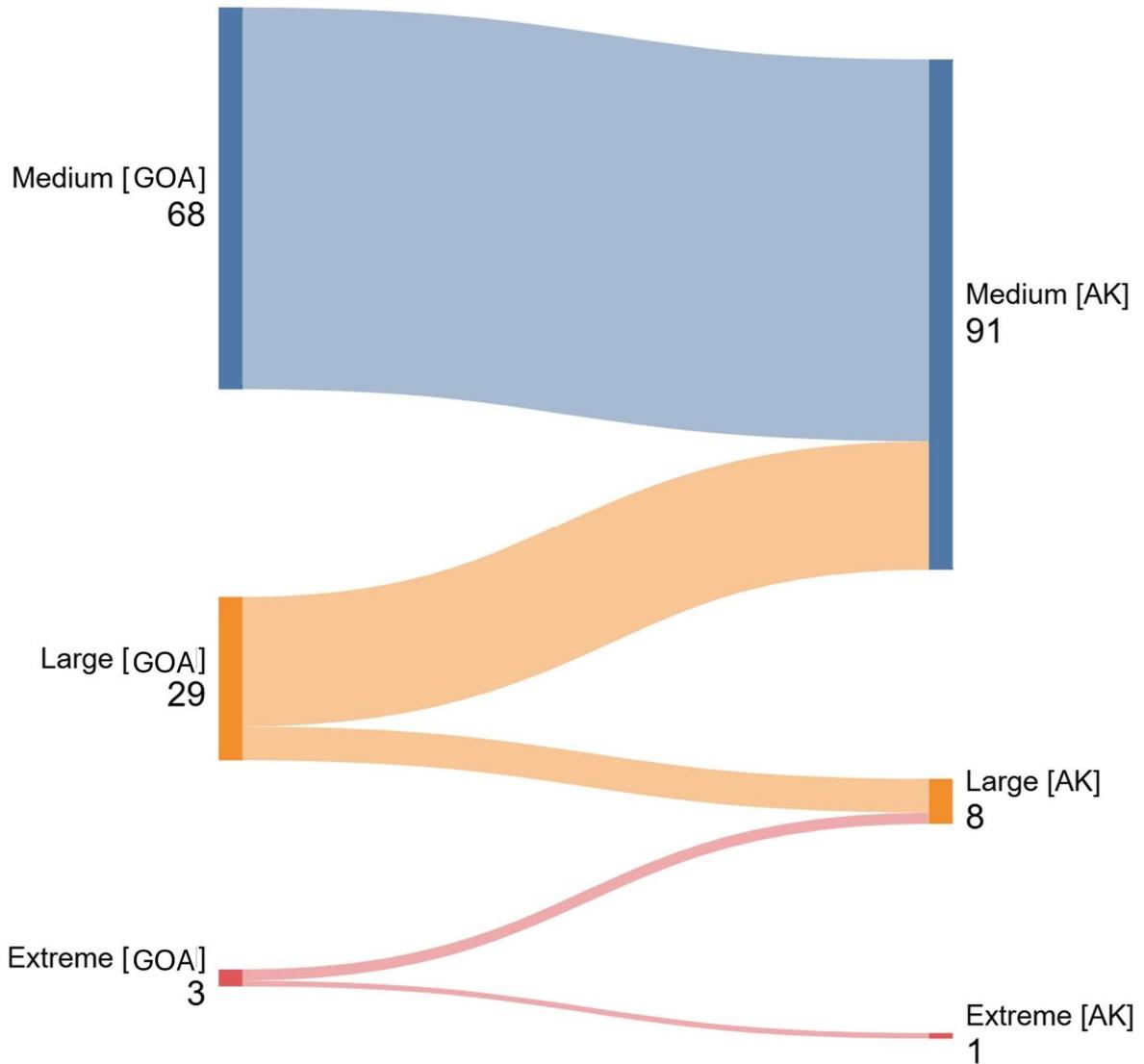


Figure B-27. Region-based release size adjustment Sankey chart

| Size Category | Size Range (MCF) |
|---------------|------------------|
| Medium | >3,000–20, 000 |
| Large | >20,000–100,000 |
| Extreme | >100,000 |

Appendix F: Dispersion Model Output

Low Emission Rate Calculations:

Gaussian Dispersion for Methane Release

Scenario Parameters

| | |
|------------------------------------|---|
| Release rate | $Q := 50 \cdot \frac{\text{kg}}{\text{sec}}$ |
| Release height | $h_s := 0 \text{ m}$ |
| Topography (urban=0, rural=1) | $\text{topo} := 1$ |
| Wind speed | $u_{10} := 3 \cdot \frac{\text{m}}{\text{sec}}$ |
| Stability category (0=A, ..., 5=F) | $\text{stab} := 4$ |
| Receptor height | $z := 0 \text{ m}$ |

Functions for Briggs Urban and Rural Dispersion Coefficients

$$\text{BRy} := \begin{pmatrix} 0.22 & 10^{-4} & -0.5 \\ 0.16 & 10^{-4} & -0.5 \\ 0.11 & 10^{-4} & -0.5 \\ 0.08 & 10^{-4} & -0.5 \\ 0.06 & 10^{-4} & -0.5 \\ 0.04 & 10^{-4} & -0.5 \end{pmatrix} \quad \text{BRz} := \begin{pmatrix} 0.20 & 0.0 & 1 \\ 0.12 & 0.0 & 1 \\ 0.08 & 2 \cdot 10^{-4} & -0.5 \\ 0.06 & 15 \cdot 10^{-4} & -0.5 \\ 0.03 & 3 \cdot 10^{-4} & -1.0 \\ 0.016 & 3 \cdot 10^{-4} & -1.0 \end{pmatrix} \quad \text{BUy} := \begin{pmatrix} 0.32 & 4 \cdot 10^{-4} & -0.5 \\ 0.32 & 4 \cdot 10^{-4} & -0.5 \\ 0.22 & 4 \cdot 10^{-4} & -0.5 \\ 0.16 & 4 \cdot 10^{-4} & -0.5 \\ 0.11 & 4 \cdot 10^{-4} & -0.5 \\ 0.11 & 4 \cdot 10^{-4} & -0.5 \end{pmatrix} \quad \text{BUz} := \begin{pmatrix} 0.24 & 10 \cdot 10^{-4} & 0.5 \\ 0.24 & 10 \cdot 10^{-4} & 0.5 \\ 0.20 & 0.0 & 1.0 \\ 0.14 & 3 \cdot 10^{-4} & -0.5 \\ 0.08 & 15 \cdot 10^{-4} & -0.5 \\ 0.08 & 15 \cdot 10^{-4} & -0.5 \end{pmatrix}$$

$$B_y(\text{top}) := \text{BUy}(\text{top} = 0) + \text{BRy}(\text{top} = 1)$$

$$\sigma_y(\text{sc}, \text{top}, x) := B_y(\text{top})_{\text{sc},0} \cdot x \left(1.0 + B_y(\text{top})_{\text{sc},1} \frac{x}{\text{m}} \right)^{B_y(\text{top})_{\text{sc},2}}$$

$$B_z(\text{top}) := \text{BUz}(\text{top} = 0) + \text{BRz}(\text{top} = 1)$$

$$\sigma_z(\text{sc}, \text{top}, x) := B_z(\text{top})_{\text{sc},0} \cdot x \left(1.0 + B_z(\text{top})_{\text{sc},1} \frac{x}{\text{m}} \right)^{B_z(\text{top})_{\text{sc},2}}$$

Exponents Used in Adjusting Wind Speed

| | Rural | Urban | |
|--------|-------|-------|---|
| $p :=$ | 0.07 | 0.15 | A |
| | 0.07 | 0.15 | B |
| | 0.10 | 0.20 | C |
| | 0.15 | 0.25 | D |
| | 0.35 | 0.30 | E |
| | 0.55 | 0.30 | F |

Function for Wind Speed at Any Height

$$u(\text{sc}, \text{top}, u_{10}, h) := \left[u_{10} \left(\frac{h}{10 \cdot \text{m}} \right)^{P_{\text{sc}, \text{top}}} \cdot (h \geq 10 \cdot \text{m}) \right] \cdot \left[u_{10} \left(\frac{h}{10 \cdot \text{m}} \right)^{P_{\text{sc}, \text{top}}} \geq 1 \cdot \frac{\text{m}}{\text{sec}} \right] + u_{10} \cdot (h < 10 \cdot \text{m})$$

Gaussian Dispersion Function for Downwind Concentration

$$C_{g1}(QR, sc, top, u_{10}, x, h) := \frac{QR}{2 \cdot \pi \cdot \sigma_y(sc, top, x) \cdot \sigma_z(sc, top, x) \cdot u(sc, top, u_{10}, h)}$$

$$C_{g2}(sc, top, x, y, z, h) := e^{-\frac{y^2}{2 \cdot (\sigma_y(sc, top, x))^2}} \cdot \left[e^{-\frac{(z-h)^2}{2 \cdot (\sigma_z(sc, top, x))^2}} + e^{-\frac{(z+h)^2}{2 \cdot (\sigma_z(sc, top, x))^2}} \right]$$

$$C_g(QR, sc, top, u_{10}, x, y, z, h) := C_{g1}(QR, sc, top, u_{10}, x, h) \cdot C_{g2}(sc, top, x, y, z, h)$$

Gaussian Dispersion Function Cloud Width

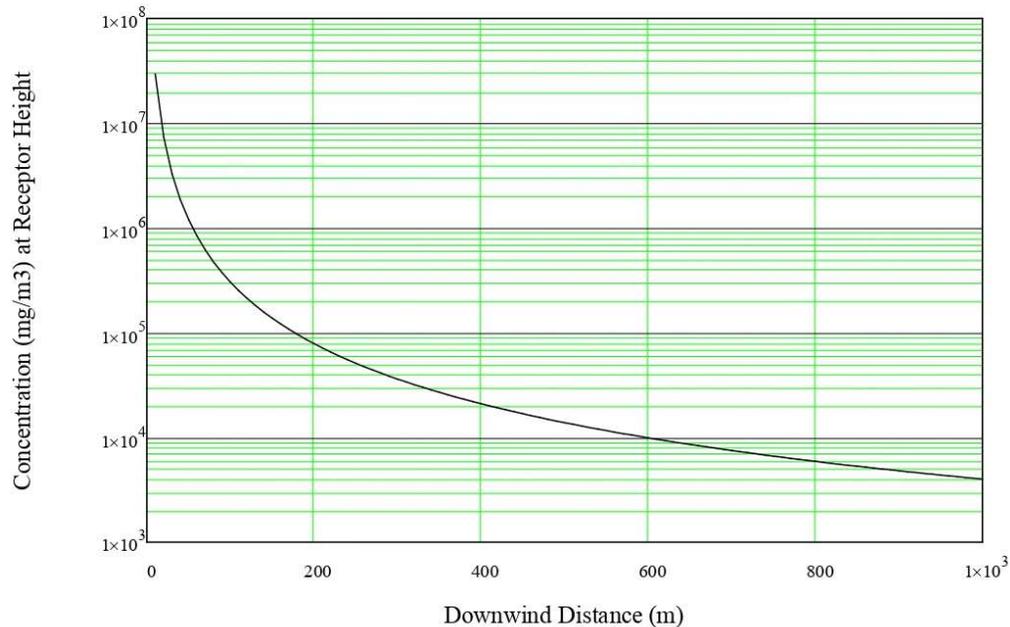
$$W_{g1}(TE, sc, top, x) := 2 \cdot TE \cdot \pi \cdot \sigma_y(sc, top, x) \cdot \sigma_z(sc, top, x)$$

$$W_{g2}(QR, sc, top, u_{10}, x, z, h) := \frac{u(sc, top, u_{10}, h)}{QR \cdot \left[\exp\left[\frac{-1}{2} \cdot \frac{(z-h)^2}{\sigma_z(sc, top, x)^2}\right] + \exp\left[\frac{-1}{2} \cdot \frac{(z+h)^2}{\sigma_z(sc, top, x)^2}\right] \right]}$$

$$W_g(TE, QR, sc, top, u_{10}, x, z, h) := \left(\sigma_y(sc, top, x) \cdot \sqrt{-2 \cdot \ln(W_{g1}(TE, sc, top, x) \cdot W_{g2}(QR, sc, top, u_{10}, x, z, h))} \right)$$

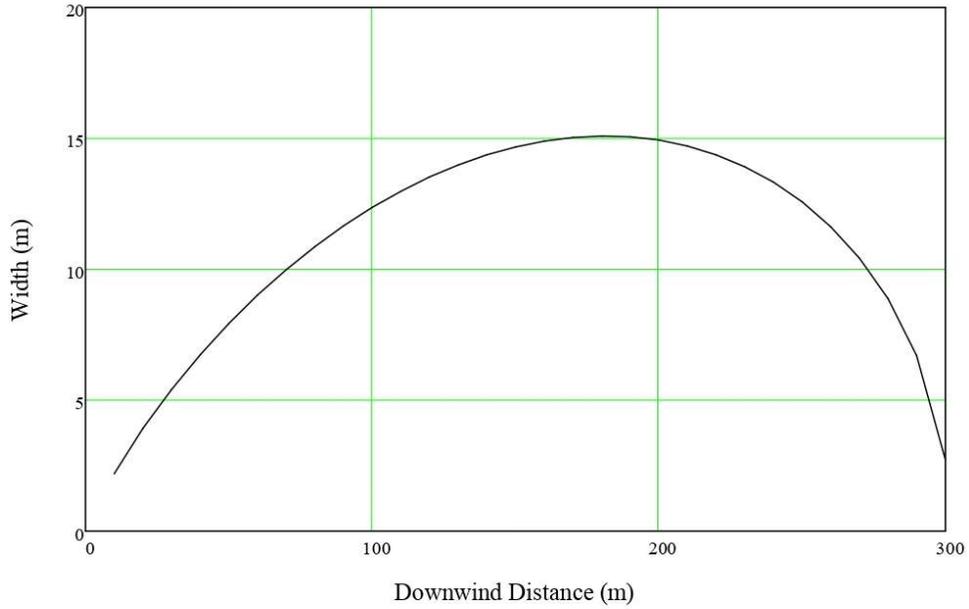
Cloud Concentrations

$$x_{max} := 1000\text{-m} \quad i := 1..100 \quad d_i := i \cdot \frac{x_{max}}{100} \quad C_i := C_g(Q, stab, topo, u_{10}, d_i, 0\text{-m}, z, h_s)$$



Cloud Width to LFL Concentration

LFL $TE := 3.58 \cdot 10^4 \frac{\text{mg}}{\text{m}^3}$ Widths to plot $W_i := W_g(TE, Q, \text{stab}, \text{topo}, u_{10}, d_i, z, h_s)$



| | 0 |
|----|-----|
| 0 | 0 |
| 1 | 10 |
| 2 | 20 |
| 3 | 30 |
| 4 | 40 |
| 5 | 50 |
| 6 | 60 |
| 7 | 70 |
| 8 | 80 |
| 9 | 90 |
| 10 | 100 |
| 11 | 110 |
| 12 | 120 |
| 13 | 130 |
| 14 | 140 |
| 15 | ... |

d =

| | 0 |
|----|--------|
| 0 | 0 |
| 1 | 2.198 |
| 2 | 3.916 |
| 3 | 5.408 |
| 4 | 6.736 |
| 5 | 7.931 |
| 6 | 9.01 |
| 7 | 9.985 |
| 8 | 10.865 |
| 9 | 11.654 |
| 10 | 12.359 |
| 11 | 12.981 |
| 12 | 13.522 |
| 13 | 13.984 |
| 14 | 14.368 |
| 15 | ... |

W =

Area of LFL Footprint

$j := 1..30$

$\text{Area} := 2 \cdot d_i \cdot \sum_j W_j$

$\text{Area} = 6678 \text{ m}^2$

Medium Emission Rate Calculations:

Gaussian Dispersion for Methane Release

Scenario Parameters

| | |
|------------------------------------|---|
| Release rate | $Q := 100 \cdot \frac{\text{kg}}{\text{sec}}$ |
| Release height | $h_s := 0 \cdot \text{m}$ |
| Topography (urban=0, rural=1) | topo := 1 |
| Wind speed | $u_{10} := 3 \cdot \frac{\text{m}}{\text{sec}}$ |
| Stability category (0=A, ..., 5=F) | stab := 4 |
| Receptor height | $z := 0 \cdot \text{m}$ |

Functions for Briggs Urban and Rural Dispersion Coefficients

$$\text{BRy} := \begin{pmatrix} 0.22 & 10^{-4} & -0.5 \\ 0.16 & 10^{-4} & -0.5 \\ 0.11 & 10^{-4} & -0.5 \\ 0.08 & 10^{-4} & -0.5 \\ 0.06 & 10^{-4} & -0.5 \\ 0.04 & 10^{-4} & -0.5 \end{pmatrix} \quad \text{BRz} := \begin{pmatrix} 0.20 & 0.0 & 1 \\ 0.12 & 0.0 & 1 \\ 0.08 & 2 \cdot 10^{-4} & -0.5 \\ 0.06 & 15 \cdot 10^{-4} & -0.5 \\ 0.03 & 3 \cdot 10^{-4} & -1.0 \\ 0.016 & 3 \cdot 10^{-4} & -1.0 \end{pmatrix} \quad \text{BUy} := \begin{pmatrix} 0.32 & 4 \cdot 10^{-4} & -0.5 \\ 0.32 & 4 \cdot 10^{-4} & -0.5 \\ 0.22 & 4 \cdot 10^{-4} & -0.5 \\ 0.16 & 4 \cdot 10^{-4} & -0.5 \\ 0.11 & 4 \cdot 10^{-4} & -0.5 \\ 0.11 & 4 \cdot 10^{-4} & -0.5 \end{pmatrix} \quad \text{BUz} := \begin{pmatrix} 0.24 & 10 \cdot 10^{-4} & 0.5 \\ 0.24 & 10 \cdot 10^{-4} & 0.5 \\ 0.20 & 0.0 & 1.0 \\ 0.14 & 3 \cdot 10^{-4} & -0.5 \\ 0.08 & 15 \cdot 10^{-4} & -0.5 \\ 0.08 & 15 \cdot 10^{-4} & -0.5 \end{pmatrix}$$

$$B_y(\text{top}) := \text{BUy} \cdot (\text{top} = 0) + \text{BRy} \cdot (\text{top} = 1)$$

$$\sigma_y(\text{sc}, \text{top}, x) := B_y(\text{top})_{\text{sc},0} \cdot x \cdot \left(1.0 + B_y(\text{top})_{\text{sc},1} \cdot \frac{x}{\text{m}} \right)^{B_y(\text{top})_{\text{sc},2}}$$

$$B_z(\text{top}) := \text{BUz} \cdot (\text{top} = 0) + \text{BRz} \cdot (\text{top} = 1)$$

$$\sigma_z(\text{sc}, \text{top}, x) := B_z(\text{top})_{\text{sc},0} \cdot x \cdot \left(1.0 + B_z(\text{top})_{\text{sc},1} \cdot \frac{x}{\text{m}} \right)^{B_z(\text{top})_{\text{sc},2}}$$

Exponents Used in Adjusting Wind Speed

| | | | |
|------|-------|-------|---|
| | Rural | Urban | |
| p := | 0.07 | 0.15 | A |
| | 0.07 | 0.15 | B |
| | 0.10 | 0.20 | C |
| | 0.15 | 0.25 | D |
| | 0.35 | 0.30 | E |
| | 0.55 | 0.30 | F |

Function for Wind Speed at Any Height

$$u(\text{sc}, \text{top}, u_{10}, h) := \left[u_{10} \cdot \left(\frac{h}{10 \cdot \text{m}} \right)^{P_{\text{sc}, \text{top}}} \cdot (h \geq 10 \cdot \text{m}) \right] \cdot \left[u_{10} \cdot \left(\frac{h}{10 \cdot \text{m}} \right)^{P_{\text{sc}, \text{top}}} \geq 1 \cdot \frac{\text{m}}{\text{sec}} \right] + u_{10} \cdot (h < 10 \cdot \text{m})$$

Gaussian Dispersion Function for Downwind Concentration

$$C_{g1}(QR, sc, top, u_{10}, x, h) := \frac{QR}{2 \cdot \pi \cdot \sigma_y(sc, top, x) \cdot \sigma_z(sc, top, x) \cdot u(sc, top, u_{10}, h)}$$

$$C_{g2}(sc, top, x, y, z, h) := e^{-\frac{y^2}{2 \cdot (\sigma_y(sc, top, x))^2}} \cdot \left[e^{-\frac{(z-h)^2}{2 \cdot (\sigma_z(sc, top, x))^2}} + e^{-\frac{(z+h)^2}{2 \cdot (\sigma_z(sc, top, x))^2}} \right]$$

$$C_g(QR, sc, top, u_{10}, x, y, z, h) := C_{g1}(QR, sc, top, u_{10}, x, h) \cdot C_{g2}(sc, top, x, y, z, h)$$

Gaussian Dispersion Function Cloud Width

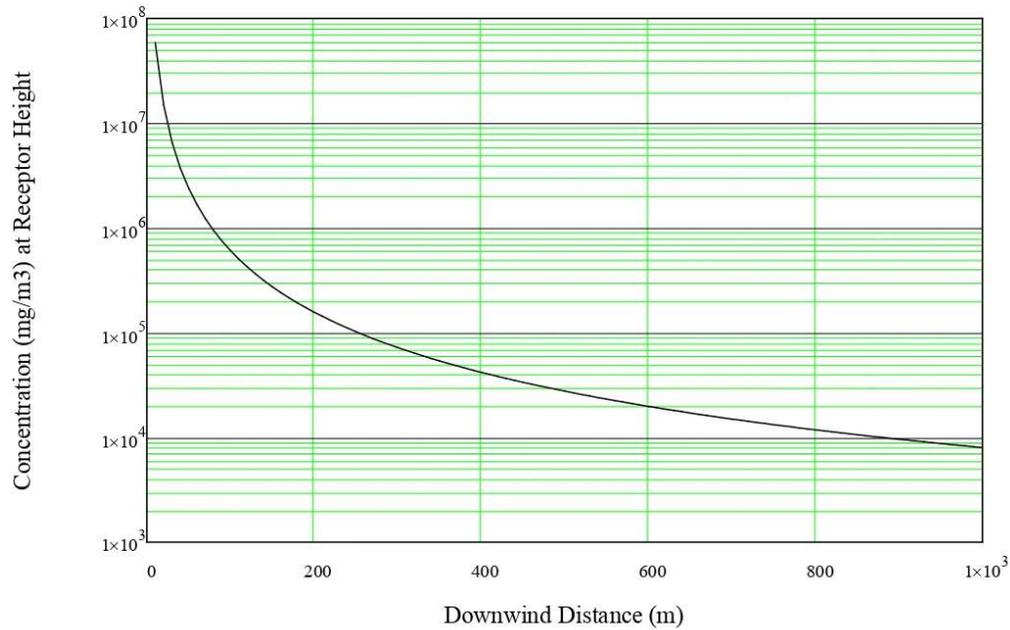
$$W_{g1}(TE, sc, top, x) := 2 \cdot TE \cdot \pi \cdot \sigma_y(sc, top, x) \cdot \sigma_z(sc, top, x)$$

$$W_{g2}(QR, sc, top, u_{10}, x, z, h) := \frac{u(sc, top, u_{10}, h)}{QR \cdot \left[\exp\left[\frac{-1}{2} \cdot \frac{(z-h)^2}{\sigma_z(sc, top, x)^2}\right] + \exp\left[\frac{-1}{2} \cdot \frac{(z+h)^2}{\sigma_z(sc, top, x)^2}\right] \right]}$$

$$W_g(TE, QR, sc, top, u_{10}, x, z, h) := \left(\sigma_y(sc, top, x) \cdot \sqrt{-2 \cdot \ln(W_{g1}(TE, sc, top, x) \cdot W_{g2}(QR, sc, top, u_{10}, x, z, h))} \right)$$

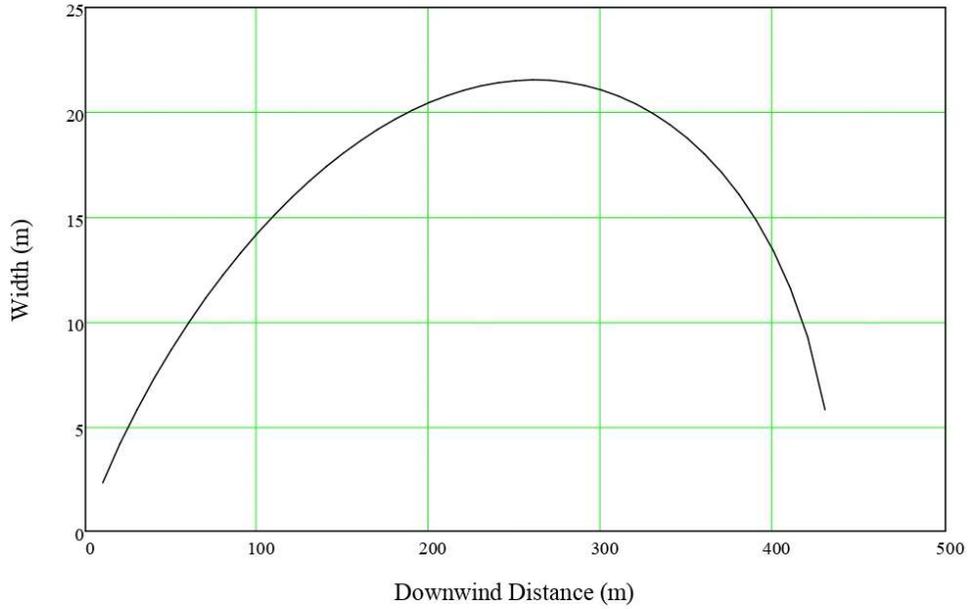
Cloud Concentrations

$$x_{max} := 1000\text{-m} \quad i := 1..100 \quad d_i := i \cdot \frac{x_{max}}{100} \quad C_i := C_g(Q, stab, topo, u_{10}, d_i, 0\text{-m}, z, h_s)$$



Cloud Width to LFL Concentration

LFL $TE := 3.58 \cdot 10^4 \frac{\text{mg}}{\text{m}^3}$ Widths to plot $W_i := W_g(TE, Q, \text{stab}, \text{topo}, u_{10}, d_i, z, h_s)$



| | |
|-------|------|
| | 0 |
| 0 | 0 |
| 1 | 10 |
| 2 | 20 |
| 3 | 30 |
| 4 | 40 |
| 5 | 50 |
| 6 | 60 |
| d = 7 | 70 m |
| 8 | 80 |
| 9 | 90 |
| 10 | 100 |
| 11 | 110 |
| 12 | 120 |
| 13 | 130 |
| 14 | 140 |
| 15 | ... |

| | |
|-------|----------|
| | 0 |
| 0 | 0 |
| 1 | 2.309 |
| 2 | 4.162 |
| 3 | 5.807 |
| 4 | 7.303 |
| 5 | 8.678 |
| 6 | 9.952 |
| W = 7 | 11.135 m |
| 8 | 12.236 |
| 9 | 13.262 |
| 10 | 14.218 |
| 11 | 15.107 |
| 12 | 15.933 |
| 13 | 16.698 |
| 14 | 17.404 |
| 15 | ... |

Area of LFL Footprint

$j := 1..43$

$\text{Area} := 2 \cdot d_i \cdot \sum_j W_j$

$\text{Area} = 13769 \text{ m}^2$

Large Emission Rate Calculations:

Gaussian Dispersion for Methane Release

Scenario Parameters

| | |
|------------------------------------|---|
| Release rate | $Q := 200 \cdot \frac{\text{kg}}{\text{sec}}$ |
| Release height | $h_s := 0 \cdot \text{m}$ |
| Topography (urban=0, rural=1) | topo := 1 |
| Wind speed | $u_{10} := 3 \cdot \frac{\text{m}}{\text{sec}}$ |
| Stability category (0=A, ..., 5=F) | stab := 4 |
| Receptor height | $z := 0 \cdot \text{m}$ |

Functions for Briggs Urban and Rural Dispersion Coefficients

$$\text{BRy} := \begin{pmatrix} 0.22 & 10^{-4} & -0.5 \\ 0.16 & 10^{-4} & -0.5 \\ 0.11 & 10^{-4} & -0.5 \\ 0.08 & 10^{-4} & -0.5 \\ 0.06 & 10^{-4} & -0.5 \\ 0.04 & 10^{-4} & -0.5 \end{pmatrix} \quad \text{BRz} := \begin{pmatrix} 0.20 & 0.0 & 1 \\ 0.12 & 0.0 & 1 \\ 0.08 & 2 \cdot 10^{-4} & -0.5 \\ 0.06 & 15 \cdot 10^{-4} & -0.5 \\ 0.03 & 3 \cdot 10^{-4} & -1.0 \\ 0.016 & 3 \cdot 10^{-4} & -1.0 \end{pmatrix} \quad \text{BUy} := \begin{pmatrix} 0.32 & 4 \cdot 10^{-4} & -0.5 \\ 0.32 & 4 \cdot 10^{-4} & -0.5 \\ 0.22 & 4 \cdot 10^{-4} & -0.5 \\ 0.16 & 4 \cdot 10^{-4} & -0.5 \\ 0.11 & 4 \cdot 10^{-4} & -0.5 \\ 0.11 & 4 \cdot 10^{-4} & -0.5 \end{pmatrix} \quad \text{BUz} := \begin{pmatrix} 0.24 & 10 \cdot 10^{-4} & 0.5 \\ 0.24 & 10 \cdot 10^{-4} & 0.5 \\ 0.20 & 0.0 & 1.0 \\ 0.14 & 3 \cdot 10^{-4} & -0.5 \\ 0.08 & 15 \cdot 10^{-4} & -0.5 \\ 0.08 & 15 \cdot 10^{-4} & -0.5 \end{pmatrix}$$

$$B_y(\text{top}) := \text{BUy} \cdot (\text{top} = 0) + \text{BRy} \cdot (\text{top} = 1)$$

$$\sigma_y(\text{sc}, \text{top}, x) := B_y(\text{top})_{\text{sc}, 0} \cdot x \cdot \left(1.0 + B_y(\text{top})_{\text{sc}, 1} \cdot \frac{x}{\text{m}} \right)^{B_y(\text{top})_{\text{sc}, 2}}$$

$$B_z(\text{top}) := \text{BUz} \cdot (\text{top} = 0) + \text{BRz} \cdot (\text{top} = 1)$$

$$\sigma_z(\text{sc}, \text{top}, x) := B_z(\text{top})_{\text{sc}, 0} \cdot x \cdot \left(1.0 + B_z(\text{top})_{\text{sc}, 1} \cdot \frac{x}{\text{m}} \right)^{B_z(\text{top})_{\text{sc}, 2}}$$

Exponents Used in Adjusting Wind Speed

| | Rural | Urban | |
|--------|-------|-------|---|
| $p :=$ | 0.07 | 0.15 | A |
| | 0.07 | 0.15 | B |
| | 0.10 | 0.20 | C |
| | 0.15 | 0.25 | D |
| | 0.35 | 0.30 | E |
| | 0.55 | 0.30 | F |

Function for Wind Speed at Any Height

$$u(\text{sc}, \text{top}, u_{10}, h) := \left[u_{10} \left(\frac{h}{10 \cdot \text{m}} \right)^{P_{\text{sc}, \text{top}}} \cdot (h \geq 10 \cdot \text{m}) \right] + \left[u_{10} \left(\frac{h}{10 \cdot \text{m}} \right)^{P_{\text{sc}, \text{top}}} \geq 1 \cdot \frac{\text{m}}{\text{sec}} \right] + u_{10} \cdot (h < 10 \cdot \text{m})$$

Gaussian Dispersion Function for Downwind Concentration

$$C_{g1}(QR, sc, top, u_{10}, x, h) := \frac{QR}{2 \cdot \pi \cdot \sigma_y(sc, top, x) \cdot \sigma_z(sc, top, x) \cdot u(sc, top, u_{10}, h)}$$

$$C_{g2}(sc, top, x, y, z, h) := e^{-\frac{y^2}{2 \cdot (\sigma_y(sc, top, x))^2}} \cdot \left[e^{-\frac{(z-h)^2}{2 \cdot (\sigma_z(sc, top, x))^2}} + e^{-\frac{(z+h)^2}{2 \cdot (\sigma_z(sc, top, x))^2}} \right]$$

$$C_g(QR, sc, top, u_{10}, x, y, z, h) := C_{g1}(QR, sc, top, u_{10}, x, h) \cdot C_{g2}(sc, top, x, y, z, h)$$

Gaussian Dispersion Function Cloud Width

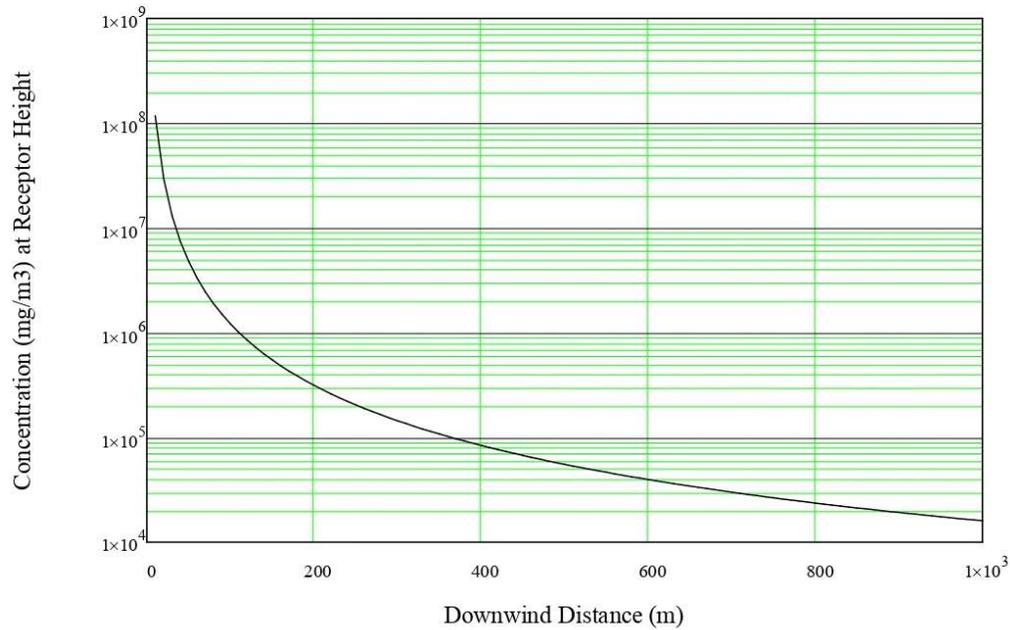
$$W_{g1}(TE, sc, top, x) := 2 \cdot TE \cdot \pi \cdot \sigma_y(sc, top, x) \cdot \sigma_z(sc, top, x)$$

$$W_{g2}(QR, sc, top, u_{10}, x, z, h) := \frac{u(sc, top, u_{10}, h)}{QR \cdot \left[\exp\left[\frac{-1}{2} \cdot \frac{(z-h)^2}{\sigma_z(sc, top, x)^2}\right] + \exp\left[\frac{-1}{2} \cdot \frac{(z+h)^2}{\sigma_z(sc, top, x)^2}\right] \right]}$$

$$W_g(TE, QR, sc, top, u_{10}, x, z, h) := \left(\sigma_y(sc, top, x) \cdot \sqrt{-2 \cdot \ln(W_{g1}(TE, sc, top, x) \cdot W_{g2}(QR, sc, top, u_{10}, x, z, h))} \right)$$

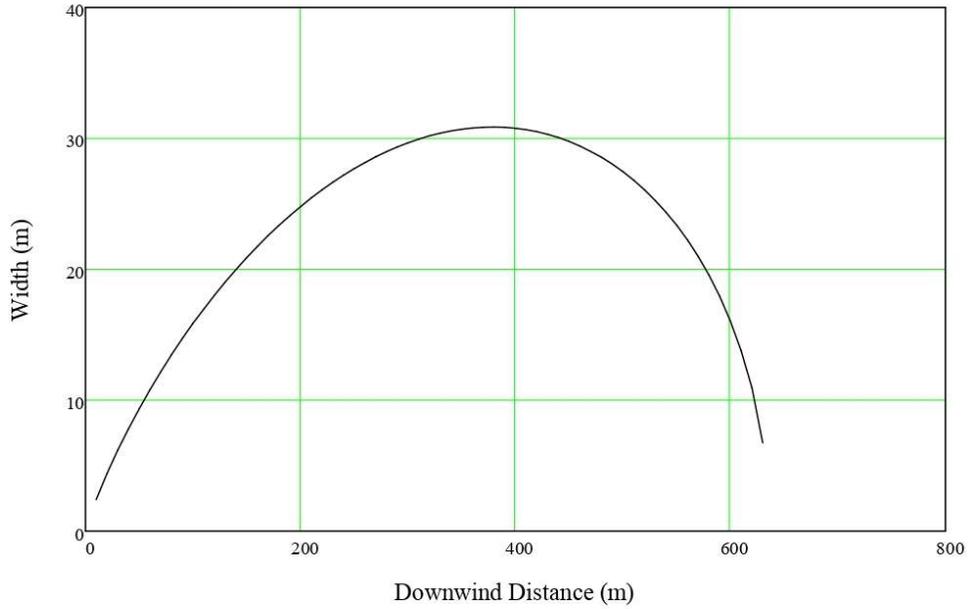
Cloud Concentrations

$$x_{max} := 1000\text{-m} \quad i := 1..100 \quad d_i := i \cdot \frac{x_{max}}{100} \quad C_i := C_g(Q, stab, topo, u_{10}, d_i, 0\text{-m}, z, h_s)$$



Cloud Width to LFL Concentration

LFL $TE := 3.58 \cdot 10^{-4} \frac{\text{mg}}{\text{m}^3}$ Widths to plot $W_i := W_g(TE, Q, \text{stab}, \text{topo}, u_{10}, d_i, z, h_s)$



| | |
|-------|------|
| | 0 |
| 0 | 0 |
| 1 | 10 |
| 2 | 20 |
| 3 | 30 |
| 4 | 40 |
| 5 | 50 |
| 6 | 60 |
| d = 7 | 70 m |
| 8 | 80 |
| 9 | 90 |
| 10 | 100 |
| 11 | 110 |
| 12 | 120 |
| 13 | 130 |
| 14 | 140 |
| 15 | ... |

| | |
|-------|----------|
| | 0 |
| 0 | 0 |
| 1 | 2.414 |
| 2 | 4.395 |
| 3 | 6.181 |
| 4 | 7.828 |
| 5 | 9.366 |
| 6 | 10.812 |
| W = 7 | 12.177 m |
| 8 | 13.469 |
| 9 | 14.695 |
| 10 | 15.861 |
| 11 | 16.969 |
| 12 | 18.024 |
| 13 | 19.029 |
| 14 | 19.984 |
| 15 | ... |

Area of LFL Footprint

$j := 1..63$

$\text{Area} := 2 \cdot d_i \cdot \sum_j W_j$

$\text{Area} = 28806 \text{ m}^2$



U.S. Department of the Interior (DOI)

DOI protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors the Nation's trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities.



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BOEM's mission is to manage development of U.S. Outer Continental Shelf energy, mineral, and geological resources in an environmentally and economically responsible way.

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The mission of the Environmental Studies Program is to provide the information needed to predict, assess, and manage impacts from offshore energy and marine mineral exploration, development, and production activities on human, marine, and coastal environments. The proposal, selection, research, review, collaboration, production, and dissemination of each of BOEM's Environmental Studies follows the DOI Code of Scientific and Scholarly Conduct, in support of a culture of scientific and professional integrity, as set out in the DOI Departmental Manual (305 DM 3).
