Appendix G

Summary of PHMSA Regulations and Accidental Release Dispersion Reports

Summary of PHMSA Regulations: CO_2 Pipelines
July 2024

Appendix G
Summary of PHMSA Regulations: CO_2 Pipelines

G.1 Is the project regulated by the Pipeline and Hazardous Materials Safety Administration, and if so, how is the project regulated?

Yes, the Otter Tail to Wilkin Carbon Dioxide (CO_2) Pipeline Project (project) is regulated by the Pipeline and Hazardous Materials Safety Administration (PHMSA) under Title 49 Code of Federal Regulations (CFR) Parts 190 and 195–199 concerning engineering, design, construction, safety, and operation of the project.

G.2 What is PHMSA, and what does it regulate?

PHMSA is a federal agency within the United States Department of Transportation (USDOT) that has statutory authority over pipeline engineering, design, construction, safety, and operation (see 49 CFR Parts 190, 195-199). PHMSA establishes the federal regulations for pipeline safety. It was created under the Special Programs Improvement Act (Public Law 108-426) of 2004. The mission of PHMSA is to protect people and the environment by advancing the safe transportation of energy products and other hazardous materials that are essential to our daily lives. There are two safety offices within PHMSA: the Office of Pipeline Safety and the Office of Hazardous Materials Safety.

PHMSA regulates the construction, operation, and maintenance of CO_2 pipelines. PHMSA defines CO_2 as "a fluid consisting of more than 90 percent carbon dioxide molecules compressed to a supercritical state" (49 CFR Section 195.2). Proposed rules and regulations (discussed below) will extend the regulations to pipelines transporting liquid and gas CO_2 as well. Extending PHMSA oversight to cover all forms of CO_2 will ensure that no new CO_2 pipelines lack safety standards and regulations.

G.3 Why does PHMSA regulation apply to the project?

In 1979, Congress enacted comprehensive safety legislation governing the transportation of hazardous liquids by pipeline, the Hazardous Liquids Pipeline Safety Act of 1979 (HLPSA; 49 United States Code 2001 et seq.). The HLPSA expanded the existing statutory authority for safety regulation. It also added civil penalty, compliance order, and injunctive enforcement authorities to the existing criminal sanctions. The HLPSA provides for a national hazardous liquid pipeline safety program with nationally uniform minimal standards and with enforcement administered through a federal-state partnership.

The HLPSA leaves to exclusive federal regulation and enforcement the "interstate pipeline facilities," or those used for the pipeline transportation of hazardous liquids in interstate or foreign commerce. For the remainder of the pipeline facilities, denominated "intrastate pipeline facilities," the HLPSA provides that the same federal regulation and enforcement will apply unless a state certifies that it will assume those responsibilities. A certified state must adopt the same minimal standards but may adopt additional more stringent standards so long as they are compatible. Therefore, in states that participate in the hazardous liquid pipeline safety program through certification, it is necessary to distinguish interstate and intrastate pipeline facilities.

Concerning the proposed CO_2 project, USDOT would consider this project to be an interstate pipeline facility and thus subject to PHMSA regulation.

G.3.1 Current PHMSA CO_2 Pipeline Regulations

Transportation of Hazardous Liquids by Pipeline (49 CFR Part 195) is broken down into the following subparts:

- Subpart A – General. This subpart prescribes safety standards and reporting requirements for pipeline facilities used in the transportation of hazardous liquids or carbon dioxide.
- Subpart B – Annual, Accident, and Safety-Related Condition Reporting. This part prescribes requirements for periodic reporting and for reporting of accidents and safety-related conditions.
- Subpart C – Design Requirements. This subpart prescribes minimum design requirements for new pipeline systems constructed with steel pipe and for relocating, replacing, or otherwise changing existing systems constructed with steel pipe. However, it does not apply to the movement of line pipe covered by 49 CFR Section 195.424.
- Subpart D – Construction. This subpart prescribes minimum requirements for constructing new pipeline systems with steel pipe and for relocating, replacing, or otherwise changing existing pipeline systems that are constructed with steel pipe. However, this subpart does not apply to the movement of pipe covered by 49 CFR Section 195.424.
- Subpart E – Pressure Testing. This subpart prescribes minimum requirements for the pressure testing of steel pipelines. However, this subpart does not apply to the movement of pipe under 49 CFR Section 195.424. Provisions include risk-based alternatives to pressure testing, test pressure, testing of components, test medium, pressure testing aboveground breakout tanks, testing of tie-ins, and records.
- Subpart F – Operation and Maintenance. This subpart prescribes minimum requirements for operating and maintaining pipeline systems constructed with steel pipe.
- Subpart G – Qualification of Pipeline Personnel. This subpart prescribes the minimum requirements for operator qualification of individuals performing covered tasks on a pipeline facility.
- Subpart H – Corrosion Control. This subpart prescribes minimum requirements for protecting steel pipelines against corrosion.

G.3.2 Status of Pending PHMSA Regulations for CO_2 Pipelines

On February 22, 2020, the Denbury Green Pipeline, a CO_2 pipeline in Satartia, Mississippi, experienced a rupture that caused 48 people to seek medical attention and many others to evacuate the release area (further discussed Chapter 8 of this Environmental Impact Statement [EIS]). As a result of this CO_2 pipeline failure, PHMSA announced in May 2022 that the agency will be taking various measures to strengthen CO_2 pipeline safety and steps to implement new safety and oversight measures to prevent future failures and/or mishandling of CO_2 pipeline failures (Docket No. PHMSA-2023-0013).[1]

On December 13–15, 2022, PHMSA held an informational public meeting addressing multiple safety topics. Among other things, PHMSA discussed with the public and industry how it is improving CO_2 pipeline safety by issuing advisory bulletins based on lessons learned from events like the pipeline failure that threatened the community of Satartia. This included discussion about calculating the potential impact radii for CO_2 pipeline releases. The overall purpose of the informational public meeting was to share safety information with the public and industry as well as gather input to inform future rulemaking decisions.

PHMSA received a letter from the Pipeline Safety Trust on February 17, 2023 (Docket No. PHMSA-2022-0125), formally requesting that PHMSA hold a public meeting on CO_2 pipeline safety and the announced rulemaking under RIN 2137-AF60.[2]

On May 31 and June 1, 2023, PHMSA held a public meeting and webcast on CO_2 pipeline safety.[3] The purpose of the May–June 2023 public meetings was to serve as an opportunity for pipeline stakeholders to help inform pipeline safety-related rulemaking decisions and share information surrounding CO_2 pipeline safety. Key stakeholders included the public, states, Tribal governments, other federal agencies, industry, and international regulators and/or organizations. Topics included the following:

- Safety expectations for pipeline operators
- General state of CO_2 pipeline infrastructure – current mileage and forecasts
- Federal and state jurisdictions and authorities
- Public awareness, engagement, and emergency notification
- Emergency equipment, training, and response
- Dispersion modeling
- Safety measures to address other constituents besides CO_2 in CO_2 pipelines
- Leak detection and reporting
- Geohazards
- Conversion to service
- Environmental justice

Speakers/participants included the following

- Public advocacy groups
- Pipeline operators
- Federal regulators
- Tribal governments
- States through the National Association of Pipeline Safety Representatives
- Other United States government agencies

Comments were allowed to be submitted for the meeting.

PHMSA intended to publish a Notice of Proposed Rulemaking (NPRM) in June 2024.[4] While not yet formally published in the *Federal Register*, the NPRM was submitted to the Office of the Secretary of Transportation in December 2023, and the date for the Office of Management and Budget completing its review is listed as May 1, 2024.[5] As of July 23, 2024, no new information is available from PHMSA, and PHMSA has not yet published the NPRM in the *Federal Register*.[6] The rulemakings chart of the Protecting Our Infrastructure of Pipelines and Enhancing Safety (PIPES) Act of 2020 was last updated by PHMSA on July 9, 2024, and states that the NPRM will be published in the *Federal Register* on August 10, 2024. A first draft of the new regulations from the agency is not expected before October 2024.[7] No date has been set for a prediction as to when the agency will have finalized rules in place.

G.4 What are CO_2 pipeline project mitigation strategies and measures to ensure public safety?

G.4.1 Measures Consistent with Proposed and Final Federal Rules

Since PHMSA has not formally initiated the Notice of Proposed Rulemaking process, proposed, new, or amended rules to current CO_2 pipeline regulations under 49 CFR Part 195 are not known at this time. PHMSA indicates the new rules and regulations will extend the regulations to pipelines transporting liquid and gas CO_2 as well, and that extending PHMSA oversight to cover all forms of CO_2 will ensure that no new CO_2 pipelines lack safety standards and regulations. As indicated above, PHMSA plans to publish a Notice of Proposed Rulemaking by August 10, 2024, and first drafts of any new regulations are not expected before October 2024. Therefore, discussion of mitigation strategies and measures to ensure public safety associated with any newly proposed (or final) PHMSA rules is not possible at this time. Chapter 3 of this EIS also discusses this topic.

Safety mitigation strategies and measures are further discussed and summarized in Chapter 8 of this EIS and in this Appendix G.

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[1] See PHMSA Announces New Safety Measures to Protect Americans From Carbon Dioxide Pipeline Failures After Satartia, MS Leak | PHMSA (dot.gov).

[2] See Federal Register :: Pipeline Safety: Carbon Dioxide Pipeline Safety Public Meeting. Accessed January 19, 2024.

[3] See Regulations.gov. Accessed January 19, 2024.

[4] See IN12169 (congress.gov). Accessed January 19, 2024.

[5] PHMSA. 2024. *Protecting Our Infrastructure of Pipelines and Enhancing Safety Act of 2020 Web Chart*. July 9. Accessed July 23, 2024. PIPES ACT 2020 Web Chart (dot.gov).

[6] PHMSA. 2022. *PHMSA Announces New Safety Measures to Protect Americans From Carbon Dioxide Pipeline Failures After Satartia, MS Leak*. May 26. Accessed November 2023. https://www.phmsa.dot.gov/news/phmsa-announces-new-safety-measures-protect-americans-carbon-dioxide-pipeline-failures.

[7] See https://www.eenews.net/articles/midwest-co2-pipeline-rush-creates-regulatory-chaos/#:~:text=PHMSA%E2%80%99s%20existing%20regulations%20cover%20pipelines%20carrying%20carbon%20dioxide%20in%20a%20%E2%80%9Csupercritical%E2%80%9D%20phase.

Updated Aerial and Thermal Dispersion Report:
Otter Tail to Wilkin CO2 Pipeline Project
July 21, 2024 (Allied Solutions)

Aerial and Thermal Dispersion Analysis: Otter Tail to Wilkin Carbon Dioxide Pipeline Project
MN Docket No.: PL-22-422

1-11-2024
Updated for Final EIS July 21, 2024

Prepared by:

ALLIED SOLUTIONS

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1. Executive Summary

Allied Solutions verified the aerial dispersion analysis that Summit Carbon Solutions (the applicant) conducted on the Otter Tail to Wilkin CO_2 Pipeline by duplicating their input data and running the analysis in CANARY, a software package used specifically for calculating aerial dispersion impact of a product release from a pipeline. We also created our own assumptions and input data and ran our own analysis using CANARY, then we compared our results to the applicant's results.

Our analysis generated larger impact areas than the applicant's analysis (11.1 feet greater at 15,000 parts-per-million (ppm) and 107.9 feet greater at 40,000 ppm). We investigated the reasons for the differences and concluded that the applicant's process was valid, but we used more conservative assumptions and more targeted levels of concern.

The applicant also conducted an analysis of the effects of terrain using a software package called FLO-2D, which did not materially impact their CANARY-generated results. FLO-2D, however, does not account for windbreaks. Furthermore, engineers at FLO-2D reported that the software cannot account for gaseous mixing—a key component in aerial dispersion—and is not intended to be used for aerial dispersion analyses. Therefore, we recommend using computational fluid dynamics (CFD) software to determine if windbreaks and terrain would materially affect the aerial dispersion impact area of a potential release from the potential Otter Tail to Wilkin CO_2 Pipeline and determine how long impacted areas would remain hazardous.

2. Introduction

Allied Solutions (hereinafter referred to as "Allied," "us," "we," or "our") created this report for HDR Engineering, Inc. (hereinafter referred to as "HDR," "the client," or "client"), on behalf of the State of Minnesota, Department of Commerce, Environmental Review and Analysis (EERA) unit. In it, we describe our methodology for completing an aerial and thermal dispersion analysis for the Otter Tail to Wilkin CO_2 Pipeline project and summarize the results.

We also validated a previous aerial dispersion analysis conducted by the applicant, Summit Carbon Solutions (hereinafter referred to as "the applicant"). The applicant submitted the inputs and outputs of said aerial dispersion as part of an effort to gain a permit from the State of Minnesota to build the Otter Tail to Wilkins pipeline.

3. Definitions

Table 1. Definition of Terms

Acronym or Term	Definition
CANARY	Software used to determine the impact of various HVL releases on the surrounding area. CANARY integrates multicomponent thermodynamics into a time-varying fluid release simulation. These simulations account for two-phase flow, flash vaporization, and aerosol formation, as well as liquid rainout. Vaporization from liquid pools takes into account pool spreading, heat transfer effects, and impoundment.
CDC	Centers for Disease Control and Prevention

Acronym or Term	Definition
CFD	Computational fluid dynamics
CO_2	Carbon dioxide
Levels of Concern (LOCs)	A threshold value of a hazard (toxicity, flammability, thermal radiation, or overpressure); usually, the value above which a threat to people or property exists
NOAA	National Oceanic and Atmospheric Administration
Product	Synonymous with “products in the pipeline'”
Valve Segment	A segment of pipeline that is between two valves
VCE	Vapor cloud explosion

4. Methodology

In this section, we describe the methodology, software, and analyses we use for all aerial and thermal dispersion analyses.

NOTE: In this analysis, we did not consider terrain and vegetation when calculating impact area. Terrain and vegetation are considered in a separate computational fluid dynamics (CFD) analysis noted in the Reference section.

4.1 Software and General Analyses

We perform aerial dispersion analyses using CANARY software, which was designed by engineers at Quest Consultants, Inc. The software uses a multi-component thermodynamics model to determine the potential outcomes following a hazardous liquid release. Our Integrity Engineers who perform these analyses are trained and qualified by Quest to use CANARY.

CANARY software is an industry standard for aerial and thermal dispersion analysis. See Appendix C for an overview of aerial dispersion software available on the market.

These are the types of analyses we perform with CANARY software to check for potentially hazardous conditions:

- Area impact of vapor cloud;
- Flammable area impact of vapor cloud;
- Vapor cloud explosion area impact; and
- Jet fire and pool fire area of impact.

5. Project-Specific Methodology and Data

For this project, we completed an aerial and thermal analysis of the proposed Otter Tail to Wilkin CO_2 pipeline and validated the aerial dispersion analysis conducted by the applicant.

5.1 Aerial and Thermal Analysis

We used the data in Tables 2 and 7 (see Appendix A) to perform the area impact analyses for this project. Table 7 lists the specific variables we used for our analysis.

Because CO_2 is not flammable, we did ***not*** conduct the following analyses:

- Flammable area impact of vapor cloud;
- Vapor cloud explosion area impact; and
- Jet fire and pool fire area of impact.

We performed an aerial dispersion analysis of the proposed project pipeline rights-of-way, keeping the worst-case scenario in mind.

The Levels of Concern (LOCs) we chose for the project are 40,000 ppm (the NIOSH-defined limit of "immediately dangerous to life or health" (IDLH)) and 30,000 ppm (the NIOSH short-term exposure limit (STEL)). STEL is the maximum time-weighted average concentration a person could be exposed to over a 15-minute period without injury.

Evidence presented by the CDC suggests that longer exposures to higher concentrations can produce signs of intoxication but not death or permanent impact to health. Regardless, to be conservative, we have selected the CDC-recommended IDLH level of 40,000 ppm.

We selected these LOCs because they are useful exposure milestones typically presented by the CDC to inform the public of relevant exposure limits.

Table 2. Project-Specific Analysis Information

Product	Analyses Performed	LOC (ppm)
CO_2	Vapor cloud analysis	30,000
		40,000

NOTE: We conducted modeling in CANARY based on the assumption that the product was pure CO_2, not a mixture of CO_2 and other components, because:

- The introduction of even fractions of a percent of other product components can interfere with CANARY's ability to accurately model the result due to software model constraints; and
- Modeling pure CO_2 produces more conservative results.

5.2 Applicant's Aerial Dispersion Analysis

We vetted the applicant's aerial dispersion analysis of the proposed Otter Tail to Wilkin CO_2 pipeline. The applicant used the data in Tables 3 and 8 (Appendix A) to perform the area impact analyses. Table 3 lists the analyses they conducted and the CO_2-specific LOCs they used. Table 8 in Appendix A lists the project-specific data they used.

Table 3. Applicant Project-Specific Analysis Information

Product	Analyses Performed	LOC (ppm)
CO_2	Vapor cloud analysis	15,000
		40,000
		80,000

NOTE: The applicant modeled their analysis in CANARY using a mixture of CO_2 and other components such as nitrogen (0.0047 molar fraction) and oxygen (0.002 molar fraction). This can interfere with CANARY's ability to accurately model the result due to software model constraints, per Quest Consultants.

6. Results

Since the environment where the pipeline would be located can vary greatly in terms of temperature and humidity (see Table 9 in Appendix B), we ran models for both the hottest part of the year and the coldest part of the year, along with the associated humidity levels, to determine worst-case impact distance. Table 10 (Appendix B) shows the data we used for reasonable worst-case scenarios.

Based on our modeling of release impact distances using the highest and lowest reasonable temperatures and associated humidities (Table 10), we chose a reasonable worst-case temperature of -22.1 °F and a humidity level of 74.3%.

Table 4 shows the impact distances for CO_2 at different concentrations.

There is a reasonable chance that the pipeline will need to be shut in during pipeline operations, which would leave CO_2 trapped in the pipeline for an undetermined amount of time. If the CO_2 stays above 1,200 psi, it stays in a supercritical state. If the CO_2 is allowed to depressurize below 1,200 psi, the operator runs the risk of CO_2 phasing to a mixture of gas and liquid—an operational condition to avoid.

Table 4. Impact Distances for CO2 at Different Concentrations

Pipeline	Pipeline Diameter (in)	Segment Length (mi)	Pressure (psi)	Maximum Impact Distance at 40,000 ppm[1] (ft)	Maximum Impact Distance at 30,000 ppm[2] (ft)	Maximum Impact Distance at 15,000 ppm[3] (ft)
Otter Tail to Wilkins CO_2	4[4]	13.9	2,197.89	617.5	701.6	910.1

[1] 40,000 ppm is the immediately dangerous to life or health (IDLH) limit.

[2] 30,000 ppm is the National institute for Occupational Safety and Health (NIOSH) short-term exposure limit (STEL). The NIOSH STEL is the maximum time-weighted average concentration a person could be exposed to over a 15-minute period without injury.

[3] 15,000 ppm is half of the NIOSH STEL. We used it to compare with the applicant LOCs.

[4] A 4-inch nominal diameter pipeline has an outside diameter of 4.5 inches.

6.1 Evaluation of Applicant's Aerial Dispersion Analysis

Using applicant-provided data (see Table 8), Allied ran the CANARY model and verified the applicant-provided impact distances (see Table 5).

Table 5. Applicant Provided LOCs and Associated Impact Distances

Product	Analyses Performed	LOC (ppm)	Maximum Impact Distance (ft)
CO_2	Vapor cloud analysis	15,000	896.0
		40,000	509.6

Also, the applicant used a software package called FLO-2D to model the aerial dispersion over terrain. However, from information supplied by the applicant, it appears that the FLO-2D analysis did not affect the impact distances produced using CANARY.

7. Discussion and Recommendations

Our analysis resulted in greater potential impact distances than the applicant-calculated impact distances. To understand what could contribute to this discrepancy, see the differences in project-specific values in Table 6.

Table 6. Differences in Project-Specific Values Contributing to Discrepancies in Potential Impact Distances

Attribute	Applicant Value Used	Allied Value Used	Comment
Wind Speed (mph)	5	4	Slower wind speeds tend to extend impact distances. See Table 7 for more information.
Product Temperature Before Rupture (°F)	30	-20	It is our opinion that this should be the colder temperature based on the last five years of weather data at Fergus Falls, Minnesota. See Appendix B for more information.
Relative Humidity	71%	88.7%	It is our opinion that this should be the higher value based on the last five years of weather

Attribute	Applicant Value Used	Allied Value Used	Comment
			data at Fergus Falls, Minnesota. See Appendix B for more information.
Air Temperature (°F)	3.2	-22.1	It is our opinion that this should be the colder temperature based on the last five years of weather data at Fergus Falls, Minnesota. See Appendix B for more information.
Angle of CO_2 Release from Horizontal	5 degrees	19 degrees	Quest Consultants recommend 19 degrees because it generates the worst-case scenario with their models. Angles less than 19 degrees tend to be unrealistically conservative and generate a greater area of impact than is practical.
Dispersion Coefficient Averaging Time (min)	1	Same as the Rupture Release time (60 minutes)	In general, when this value is less than the release time, it generates an artificially greater potential impact distance. In general, matching the rupture release time is standard.
Valve Segment Length (ft)	105,600.69	73,392.0	The different valve segment lengths do not materially affect the impact distance.
Rupture Placement Along the Valve Segment	About 1/8 downstream of the center of the valve segment	Equidistant from both ends of the valve segment	The different rupture locations do not materially affect the impact distance.

In general, the applicant's methodology and results are valid, but they could have been more conservative in their modeling parameters and LOCs. The main concern is the impact distance at the 40,000-ppm concentration level. Allied calculated 617.5 ft and the applicant calculated 509.6 ft. Even though the applicant uses the more conservative impact distance at the 15,000-ppm concentration LOC to make certain determinations, the 30,000-ppm and 40,000-ppm level LOCs are more meaningful because they have a larger effect on the health and wellbeing of those impacted by a potential pipeline rupture.

There are slight terrain changes along the rights-of-way, in addition to windbreaks designed to interrupt the wind that carries CO_2. It seems appropriate to take into consideration those factors when determining the reasonable worst-case impact from a potential rupture. The applicant uses FLO-2D to attempt that analysis. However, FLO-2D only considers terrain, not windbreaks or other flora. Also, according to engineers at FLO-2D, their software is meant to model liquid releases (single-phase flow) or liquid releases with sediment, which they refer to as "2-phase flow."

Furthermore, engineers at FLO-2D maintain that said software cannot account for gaseous mixing—a key component in aerial dispersion—and is not intended to be used for aerial dispersion analyses. As Allied did not attempt to account for windbreaks and terrain and the use of FLO-2D is not appropriate for terrain modeling of gaseous releases, we recommend using a computational fluid dynamics (CFD) software to determine if windbreaks and terrain materially affect a potential release.

Performing a CFD analysis would not only provide better insight into the effect of terrain and local windbreaks, it would also show how long LOCs would be exceeded at various impact distances away from the pipeline. The time aspect of impact is very important because many NIOSH limits are based on exposure time at different limits. Exposure times associated with different concentration levels and impact distances are some of the most important aspects of aerial dispersion analysis. Again, we recommend using CFD software to determine the exposure time associated with various NIOSH exposure limits.

8. References

We performed this analysis in conjunction with the following reports:

- Single Line CFD Analysis – Proposed Otter Tail to Wilkin CO_2 Pipeline Project – Report v0.pdf
- Reports and documents supplied by the applicant.

Appendix A – Project-Specific Data

Table 7 describes the project-specific data we used to conduct the analysis.

Table 7. Project-Specific Data

Attribute	Used For	Value Used	Source	Justification
Wind Speed (mph)	Momentum jet dispersion model VCE momentum jet dispersion model	4	Allied Solutions	4.47 mph is endorsed by Quest Consultants to produce reasonable worst-case conditions when using their software. We used a slightly lower value for additional conservatism.
Product Temperature Before Rupture (°F)	All models	-20	Allied Solutions	Due to a measured soil temperature at burial depth being subzero[5] and the existence of aboveground valve sets, this temperature should be nearly the same as the air temperature.
Wind Speed Measurement Height (ft)	Momentum jet dispersion model VCE momentum jet dispersion model	32.81 (10 m)	Allied Solutions	Endorsed by Quest Consultants to produce reasonable worst-case conditions when using their software
Wind Stability Class	Momentum jet dispersion model VCE momentum jet dispersion model	Class F	Allied Solutions	A laminar wind condition that produces the largest impact long distances away from the pipeline
Relative Humidity	All models	88.7%	Allied Solutions	Selected from analysis in Appendix B
Air Temperature (°F)	All models	-22.1	Allied Solutions	Selected from analysis in Appendix B

[5] NOAA. Soil Temperature Maps by Depth: History data in CSV. Data retrieved 12/15/2023. https://www.weather.gov/ncrfc/LMI_SoilTemperatureDepthMaps.

Attribute	Used For	Value Used	Source	Justification
Surrounding Surface Roughness (in)	All models	6 (0.007 m)	Allied Solutions	Selected to provide the reasonably largest impacted area by assuming the smoothest onshore surfaces the CANARY software can offer
CO_2 Pressure (psi)	All models	2,197.89	Applicant Provided	Applicant-provided data adjusted for altitude
Release Duration (min)	All models	60	Allied Solutions	Sufficient time to fully depressurize a valve segment (If we find it insufficient, we increase it until results verify that it is sufficient)
Rupture Release Point (ft)	All models	0	Allied Solutions	Indicates the worst case of pipe at ground level and unburied
Angle of CO_2 Release from Horizontal	All models	19 degrees	Allied Solutions	The angle of release Quest Consultants recommend because it generates the worst-case scenario with their models
Dispersion Coefficient Averaging Time (min)	Momentum jet dispersion model VCE momentum jet dispersion model	Same as the Rupture Release time	Allied Solutions	Must be the same as the Rupture Release Time or results cannot be trusted
Impoundment?	All models	No	Allied Solutions	No impoundment generates the worst case
Max Flow Rate (lbs/sec)	All models	13.34	Applicant Provided	Applicant-provided data
Pipe Diameter (in)	All models	4.5	Applicant Provided	Applicant-provided data plus 0.5 inches for conservatism
Rupture Diameter (in)	All models	Same as pipe diameter to simulate a full guillotine rupture	Applicant Provided	Applicant-provided data

Attribute	Used For	Value Used	Source	Justification
Valve Segment Length (ft)	All models	73,392	Applicant Provided	Result from running CANARY on all pipeline segments provided by Applicant. The segment that generated the largest impact area starts at the valve at milepost 4.8 and ends at the valve at milepost 18.7.
Rupture Placement Along the Valve Segment	All models	Equidistant from both ends of the valve segment	Allied Solutions	Provides accurate answers considering how the various models work
Isolation Valve Closure Time (min)	All models	10	Applicant Provided	Applicant-provided data

Table 8. Applicant Project-Specific Data

Attribute	Value Used
Wind Speed (mph)	5
Product Temperature Before Rupture (°F)	30
Wind Speed Measurement Height (ft)	32.81 (10 m)
Wind Stability Class	Class F
Relative Humidity	71%
Air Temperature (°F)	3.2
Surrounding Surface Roughness (in)	6 (0.007 m)
CO_2 Pressure (psi)	2,197.89

Attribute	Value Used
Release Duration (min)	60
Rupture Release Point (ft)	0
Angle of CO_2 Release from Horizontal	5 degrees
Dispersion Coefficient Averaging Time (min)	1
Impoundment?	No
Max Flow Rate (lbs/sec)	13.34
Pipe Diameter (in)	4.03
Rupture Diameter (in)	Same as pipe diameter to simulate a full guillotine rupture
Valve Segment Length (ft)	105,600.69
Rupture Placement Along the Valve Segment	About 1/8 downstream of the center of the valve segment
Isolation Valve Closure Time (min)	10

Appendix B – Finding Reasonable Worst-Case Values for Humidity and Air/Ground Conditions

To use humidity and air/ground temperature inputs that generate a reasonable worst-case scenario, we reviewed temperature and humidity data for Fergus Falls, Minnesota for the last five years: 12-17-2018 through 12-17-2023[6] (see Table 9).

Table 9. Descriptive Weather Statistics for Fergus Falls 12-17-2018 through 12-17-2023

Attribute	Minimum Value	Maximum Value	Median Value
Air Temperature (°F)	-34.6	98.6	43.9
Relative Humidity (%)	27.4	99.8	75.3

To find the reasonable worst-case temperature and humidity, we test reasonable high and low temperatures with their associated humidities to see which ones produce the reasonable worst-case impact scenario.

Finding Low Temperature and Humidity Values

To determine the reasonable worst-case scenario low temperature and humidity values for our model, we reviewed the temperature and humidity data for Fergus Falls, Minnesota for the last five years: 12-17-2018 through 12-17-2023.

There were 196 days on which the temperature at Fergus Falls dropped below zero during the last five years. The vast majority of the coldest temperatures were above -25.2 °F. Figure 1 shows the number of days the minimum temperature was in each range of below-zero temperatures. For example, the minimum temperature was in the range of -11.1 °F to -6.4 °F for a total of 37 days between 12-17-2018 and 12-17-2023.

[6] Visual Crossing. Total Weather Data: History & forecast data in CSV or JSON. Data retrieved 12/18/2023. https://www.visualcrossing.com/weather-data

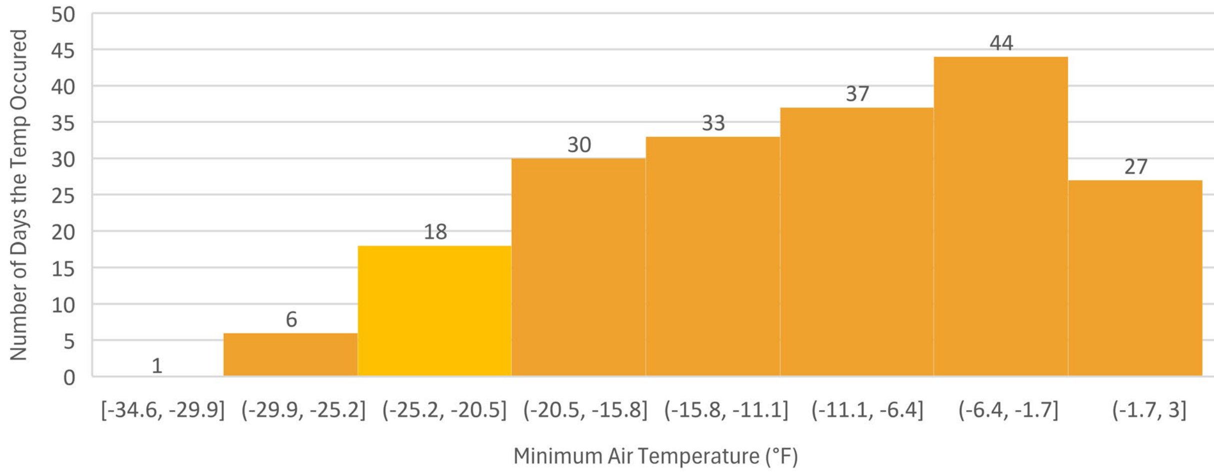

Figure 1. Number of Days Minimum Temperature Was Below Zero in Fergus Falls 12-17-2018 through 12-17-2023

We chose -25.2 and -20.5 °F as the reasonable worst-case temperature range to use for this project. We did not choose the extreme worst-case temperatures, which occur extremely seldom (0.4% of the time). For the 18 cases where the temperature was within the chosen reasonable worst-case scenario range, we averaged the high and low of the range to come up with a single value: -22.9 °F.

In the weather dataset we used, there isn't a recorded measurement of -22.9 °F. The closest temperature recorded was in February 2021—a minimum temperature of -22.1 °F, which was associated with a relative humidity of 74.3%. We used those values as the low temperature and humidity values for this project.

Note About Temperature at Pipe Depth

It is our understanding that the applicant will install its proposed pipeline at a depth of 54 inches (measured from top of pipe). Normally, this would provide considerable insulation from the ambient temperature aboveground. However, we looked at soil temperature data from NOAA[7] and discovered that over the last two years, the coldest soil reading of the year at 40 inches deep differed from the coldest ambient temperatures by only a few degrees Fahrenheit. Since colder temperatures in Minnesota can penetrate so deeply into the ground, the installation depth of the pipeline does far less to insulate it from colder temperatures than in other parts of the country. Therefore, to be conservative, we chose the coldest air temperatures as the basis for a worst-case scenario rather than modifying those temperatures to approximate below-ground temperatures.

Finding High Temperature and Humidity Values

To determine the reasonable worst-case scenario high temperature and humidity values for our model, we reviewed the temperature and humidity data for Fergus Falls, Minnesota for the last five years: 12-17-2018 through 12-17-2023.

[7] NOAA. Soil Temperature Maps by Depth: History data in CSV. Data retrieved 12/15/2023. https://www.weather.gov/ncrfc/LMI_SoilTemperatureDepthMaps.

When evaluating the 606 days on which the maximum temperature at Fergus Falls was above 70 degrees[8] during the last five years, we saw that the vast majority of the hottest temperatures were below 87.4 °F. Figure 2 shows the number of days the maximum temperature was in each range of above 70-degree temperatures. For example, the maximum temperature was in the range of 80.2 °F to 82.6 °F for a total of 143 days between 12-17-2018 and 12-17-2023.

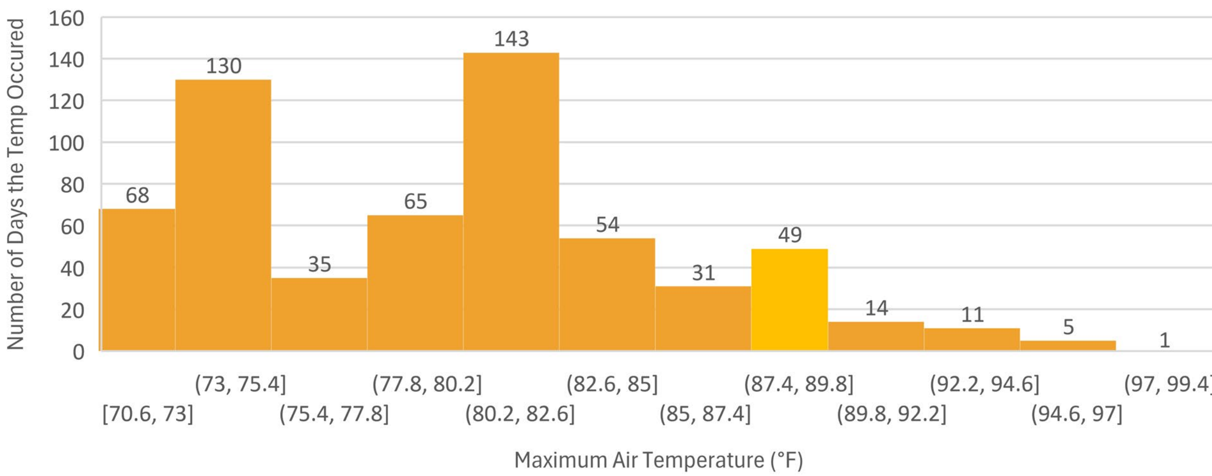

Figure 2. Number of Days Maximum Temperature Was Above 70 degrees in Fergus Falls 12-17-2018 through 12-17-2023

We chose 87.4 to 89.8 °F as the reasonable worst-case temperature. We did not choose the extreme worst-case temperatures, which occur extremely seldom (1.7% of the time). For the 49 cases where the temperature was within the chosen reasonable worst-case scenario range, we averaged the high and low of the range to come up with a single value: 88.6 °F.

In the weather dataset we used, there isn't a recorded measurement of 88.6 °F. The closest temperature was recorded in June 2019—a maximum temperature of 88.7 °F, which was associated with a relative humidity of 55.5%. We used those values as the high temperature and humidity values for this project.

Finding Final Reasonable Temperature and Humidity Values

Table 10 shows the high and low Fergus Falls temperatures and associated humidity values we used for our analysis.

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[8] Days with temperatures above 70 degrees are temperatures within roughly 30 degrees of the maximum temperatures in the dataset used for this project. This range was chosen to mirror the range chosen in the previous section which looked at temperatures roughly within 30 degrees of the coldest temperature recorded.

Table 10. High and Low Temperatures with Humidity Levels Used in Our Analysis

Attribute	Minimum Value	Maximum Value
Air Temperature (°F)	-22.1	88.7
Relative Humidity (%)	74.3	55.5

These are not the extreme worst-case temperatures and humidities, because we are not trying to represent a "sky is falling" scenario. Instead, we are trying to base our analysis on a "reasonable" worst-case scenario.

To that end, we used the other model variables in Appendix A, along with the variables in Table 10, to run CANARY and determine which set of temperature and relative humidity variables create a larger area of impact from a potential release. With all other variables being equal, the lowest temperature and its associated humidity level created a larger area of impact.

Appendix C – Overview of Available Aerial Dispersion Software and CANARY Validation

Overview of Available Aerial Dispersion Software

Aerial dispersion modeling plays a crucial role in assessing the environmental impact of and potential risks associated with the release of hazardous substances into the atmosphere. Additionally, aerial dispersion modeling is typically completed for proposed CO_2 pipeline projects as part of engineering, design, and other compliance requirements of the Pipeline and Hazardous Materials Safety Administration (PHMSA).

Various software tools have been developed to simulate and predict the dispersion patterns of pollutants. Such simulations help users conduct emergency response planning, assess risk, and comply with applicable regulations. As the demand for accurate and reliable dispersion modeling increases, it's important to continuously compare aerial dispersion modeling software packages, their functionality and limitations, and user reviews and feedback.

In this report, we provide a brief overview of the three most common, non-CFD[9] software packages—CANARY, ALOHA, and CHARM—all of which can be used to conduct aerial dispersion analyses of liquid CO_2 pipeline releases as the CO_2 rapidly decompresses to a heavier-than-air gas. Please note that CFD and non-CFD software are not designed to quantify risk or conduct risk analysis. Rather, they are tools for establishing potential impacts and limits of said impacts, which is only one element of risk analysis.

CANARY, a software tool developed by Quest, is a multi-component thermodynamics model that determines potential outcomes following a liquid CO_2 release. CANARY provides the means for a qualified user to model the development of a variety of toxic, flammable, explosive, and radiant energy releases. CANARY is used for siting buildings and planning for pipeline and rail transport of highly volatile hazardous liquids such as liquid CO_2. Use of CANARY is commonplace in the pipeline industry.

ALOHA, which stands for Areal Locations of Hazardous Atmospheres, is a software tool developed by the National Oceanic and Atmospheric Administration (NOAA) to model the dispersion of hazardous chemicals in the atmosphere. ALOHA is used for emergency response planning, risk assessment, and decision support in the event of accidental chemical releases.

CHARM, which stands for Complex Hazardous Air Release Model, is a modeling program developed and maintained by Dr. Mark Eltgroth. It calculates and predicts the dispersion and concentration of airborne vapor and particle plumes from released chemicals. CHARM also predicts the footprints of thermal radiation, overpressures, and particle deposition. CHARM is used for evaluating the impact of hazard liquid releases, designing emergency response plans, and implementing training programs.

There are many technical pros and cons related to each software package. However, in this overview, we present high-level distinctions.

[9] Computational fluid dynamics (CFD) is the branch of applied science that concerns the analysis of flow, turbulence, and pressure distribution of liquids and gases, and their interaction with structures. It also helps predict fluid flow, mass transfer, chemical reactions, and related phenomena.

Pros:

- All three software packages accurately model CO_2 aerial dispersions of volatile hazardous liquid releases – for which they were designed.
- CANARY has a long and vetted history in the pipeline industry—so much so that some major pipeline operators have it written into their standards that they will use only CANARY when modeling aerial dispersions.
- ALOHA is free and has an extensive library of chemicals and levels of concern.
- CHARM has a "pseudo-CFD" capability to incorporate terrain in dispersion models.

Cons:

- All three software packages require special training to use them correctly (that is, an untrained individual could pick up any of the three software packages, input data, and receive what looks like a reasonable answer but it would be wrong).
- CANARY does not incorporate terrain into its dispersion modeling capabilities.
- ALOHA can only model a limited number of basic situations and requires significant amounts of personnel time to run large numbers of simulations. ALOHA also doesn't take terrain into account.
- CHARM has difficulty coupling the heavier-than-air modeling with the lighter-than-air modeling in some cases, which can affect the accuracy of the initial release for some products.

Combining these factors with our professional experience, Allied chooses to primarily use CANARY for aerial dispersion modeling. CANARY is widely used and accepted in the pipeline industry, and other software packages can be used in conjunction with CANARY to include the effects of terrain and other objects if necessary. In addition, since the applicant used CANARY to perform their aerial dispersion analysis, Allied chose to use CANARY when validating the applicant's results. Using the same software also allowed us to more easily compare the results of the applicant's analysis to our own independent analysis.

CANARY Validation and Verification

Quest verifies the release and dispersion models contained in the QuestFOCUS package (the predecessor to CANARY by Quest), which were reviewed in a United States Environmental Protection Agency (EPA)–sponsored study[10] and an American Petroleum Institute (API)–sponsored study[11]. In both studies, the authors evaluated the QuestFOCUS software on technical merit (appropriateness of models for specific applications) and how well the model predicted specific releases. One conclusion the authors drew in both studies was that the dispersion software tended to overpredict the extent of the gas cloud travel, resulting in too large a cloud when compared to the test data (i.e., a conservative approach).

[10] TRC (1991), Evaluation of Dense Gas Simulation Models. Prepared for the U.S. Environmental Protection Agency by TRC Environmental Consultants, Inc., East Hartford, Connecticut, 06108, EPA Contract No. 68-02-4399, May 1991.

[11] [Hanna, S. R., D. G. Strimaitis, and J. C. Chang (1991), Hazard Response Modeling Uncertainty (A Quantitative Method), Volume II, Evaluation of Commonly-Used Hazardous Gas Dispersion Models. Study cosponsored by the Air Force Engineering and Services Center, Tyndall Air Force Base, Florida, and the American Petroleum Institute; performed by Sigma Research Corporation, Westford, Massachusetts, September, 1991]

Finally, the authors of a third study prepared for the Minerals Management Service (Chang, et al., 1998) reviewed models for use in modeling routine and accidental releases of flammable and toxic gases. CANARY by Quest received the highest possible ranking in the science and credibility categories. In addition, the report recommends CANARY by Quest for use when evaluating toxic and flammable gas releases.[12]

[12] Chang, Joseph C., Mark E. Fernau, Joseph S. Scire, and David G. Strimaitis (1998), A Critical Review of Four Types of Air Quality Models Pertinent to MMS Regulatory and Environmental Assessment Missions. Mineral Management Service, Gulf of Mexico OCS Region, U.S. Department of the Interior, New Orleans, November 1998.

Computational Fluid Dynamics Report
Otter Tail to Wilkin CO2 Pipeline Project
January 15, 2024

Addendum for Supplemental Modeling:
Otter Tail to Wilkin CO2 Pipeline Project
July 11, 2024

(Allied Solutions)

COMPUTATIONAL FLUID DYNAMICS ANALYSIS: OTTER TAIL TO WILKIN CARBON DIOXIDE PIPELINE PROJECT
MN DOCKET NO. PL-22-422

1/15/2024

(With Addendum to Computational Fluid Dynamics Analysis: Otter Tail to Wilkin CO2 Pipeline Project, July 11, 2024)

PREPARED BY:

ALLIED SOLUTIONS

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1. Introduction

Allied Solutions (hereinafter referred to as “Allied,” “we,” “us,” or “our”) conducted a computational fluid dynamics (CFD) analysis for HDR Engineering, Inc. (hereinafter referred to as “HDR,” “you,” “your,” “the client,” or “client”) on behalf of the State of Minnesota, Department of Commerce, Environmental Review and Analysis (EERA) unit. In this report, we describe our methodology for completing a CFD analysis for the proposed Otter Tail to Wilkin CO_2 Pipeline Project and summarize the results.

Please note that this CFD analysis shows how elevation and windbreaks can affect an aerial dispersion model and does not give an absolute impact distance for every case that might arise along the pipeline. While we chose reasonable worst-case conditions and modeling factors where practical, weather conditions can vary in unpredictable ways. The reader must interpret the results of the CFD analysis in conjunction with the Single Line Aerial Dispersion Analysis – Proposed Otter Tail to Wilkin CO2 Pipeline Project – Report (1/11/2024) (AD Report). The reader should not consider this report as an independent set of quantitative results.

Addendum: In response to public comments received on the Draft Environmental Impact Statement (EIS) for the project, specifically comments on Appendix G of the Draft EIS (“Computational Fluid Dynamics Analysis: Otter Tail to Wilkin Carbon Dioxide Pipeline Project, MN Docket No. PL-22-422”), Allied performed supplemental CFD modeling which is presented after section 8 herein.

2. Background

We documented our aerial dispersion analysis for the proposed Otter Tail to Wilkin CO_2 Pipeline Project in the AD Report. One of our key recommendations was to supplement the aerial dispersion analysis with this CFD analysis to account for windbreaks and slight terrain changes along the rights-of-way. HDR and EERA accepted that recommendation, and this report is the result.

3. Definitions

Table 1. Definition of Terms

Acronym or Term	Definition
Computational Fluid Dynamics (CFD)	A branch of fluid mechanics that uses numerical analysis and computer software to analyze and solve problems that involve fluid flows
Digital Elevation Model (DEM)	A 3D computer graphical representation of elevation data to represent terrain
Levels of Concern (LOCs)	A threshold value above which a hazard may exist (e.g., toxicity, flammability, thermal radiation, or overpressure); usually, the value above which a threat to people or property exists
United States Geological Survey (USGS)	A scientific agency that studies the landscape of the United States, its natural resources, and the natural hazards that threaten it to support decision-making about environmental, resource, and public safety issues

4. Methodology

In this section, we describe the methodology, software, and analyses we use for the CFD analysis for the proposed Otter Tail to Wilkin CO_2 Pipeline Project. We included terrain and windbreaks representative of those present in the pipeline project area and analyzed their influence on the impact of a potential CO_2 pipeline rupture. We analyzed four different scenarios as described below.

The Level of Concern (LOC) we chose for the project is 30,000 ppm (the NIOSH short-term exposure limit (STEL)). STEL is the maximum time-weighted average concentration a person could be exposed to over a 15-minute period without injury.

4.1 Scenario 1: Standard Aerial and Thermal Dispersion Analysis

This is our baseline analysis, for which we used a reasonable worst-case scenario. (See the AD Report). Since this analysis is our baseline scenario it does not take terrain or windbreaks into account so the other scenarios could be compared to this baseline scenario to show the difference between terrain vs. no terrain and windbreak vs. no windbreak on the impact distance.

4.2 Scenario 2: CFD with Terrain

In this analysis, we take into account terrain representative of the proposed project right-of-way (referred to as RA-South in the draft Environmental Impact Statement) — flat terrain (0.4% average grade slope running the entirety of the project area). We used the same assumptions and data we used in the first scenario. We compared the results of this scenario to the results of the first scenario to determine what effect modeled terrain has on a potential CO_2 release impact distance.

4.3 Scenario 3: CFD with Windbreak 50 feet from the Rupture

In this analysis, we don't take terrain into account and assume the CO_2 released from the pipeline arcs into the air and hits a windbreak before it hits the ground.

4.4 Scenario 4: CFD with Windbreak 500 feet Downwind of the Rupture

In this analysis, we don't take terrain into account and assume the CO_2 released from the pipeline arcs into the air, settles back to the ground, and then hits a windbreak.

In Scenarios 3 and 4, we use Darcy's Law[1] to calculate the pressure drop through the windbreak. Darcy's Law can be expressed as:

$$q = -\frac{k}{\mu L}\Delta p$$

Where q is the total mass flow rate of the gas flowing through the windbreak, k is the permeability of the windbreak, μ is the dynamic viscosity of the gas[2], L is the depth of the windbreak, and Δp is the pressure drop through the windbreak. Using this formula, we can enhance the CFD model to account for how a CO_2

[1] Darcy's law describes the flow of a fluid, including gases, through a porous medium such as a windbreak.
[2] The dynamic viscosity of the gas is calculated at each time increment the CFD model is running based on the mass fraction of air and CO_2 and the temperature at the associated point in time.

release can approach and pass through a windbreak using porosity and permeability values for trees typically used in windbreaks (see Table 2).

4.5 Software Used

We performed CFD analyses using COMSOL software version 6.1, which is a multiphysics finite element analysis modeling software with a CFD module. COMSOL is a finite element analysis, solver, and simulation software package for various physics and engineering applications, especially coupled phenomena and multiphysics. COMSOL is designed by engineers at COMSOL, Inc. which was founded in 1986 in Stockholm, Sweden.

We used CANARY software to create Scenario 1, as we reported in the AD Report. CANARY was designed by engineers at Quest Consultants, Inc. CANARY uses a multi-component thermodynamics model to determine the potential outcomes following a hazardous liquid release.

5. Project Data

For Scenario 1, we used the results of the independently modeled results from the AD Report.

For the elevation data in Scenario 2, we downloaded an 8-meter (1/3 arc-second) accurate digital elevation model (DEM) surrounding the proposed project area[3] from the United States Geological Survey (USGS), which is the most granular DEM available for the project area. The specific area we chose for Scenario 2 traversed a highway embankment and an irrigation ditch, which were representative of elevation changes along the proposed project right-of-way (RA-South).

To model the windbreaks in Scenarios 3 and 4, we reviewed actual windbreaks along the proposed project right-of-way. While there was variability in the windbreaks surveyed, we chose conifers approximately 40 feet tall with green vegetation 20 feet in diameter, which seemed to approximate the windbreaks average height and diameter. To be conservative, we assumed a single row of trees.

In the CFD model, we approximated this windbreak with a wall 40 feet tall, 20 feet deep, and 400 feet wide that has the wind porosity properties shown in Table 2. Four hundred feet is just wider than the widest part of the reasonable worst-case CO_2 release we modeled in the AD Report. We used that width to negate any effects that could arise from a dispersion going around a windbreak so that we could focus on how a release could penetrate a windbreak. Also, a 400-foot windbreak width is a good representation of the windbreaks in the project area. Table 2 shows the CO_2 and windbreak properties we used in our analysis.

[3] USGS. GIS data download application. Data retrieved 01/09/2024. https://www.usgs.gov/the-national-map-data-delivery/gis-data-download

Table 2. CO_2 and Windbreak Properties Used

Attribute (units)	Value	Comment
Diffusion coefficient for CO_2 in air (cm^2 per second)[1]	0.139	Used to calculate the total mass moving through the windbreak
Windbreak porosity (unitless)[2]	0.95	Is equal to $1 - \frac{tree\ volume}{total\ volume}$
Windbreak permeability (meters)[2]	1×10^{-13}	We used a more liberal number than what was reported in the cited source, which makes the windbreaks in this analysis more permeable.
Plant area density[3]	60%	Lower end of winter protection and upper end of wind erosion design recommendations; consistent with local windbreak design

[1] See Pritchard, D. and Currie, J. Diffusion of coefficients of carbon dioxide, nitrous oxide, ethylene and ethane in air and their measurement. *European Journal of Soil Sciences*. Volume 33 (Issue 2), June 1982. https://doi.org/10.1111/j.1365-2389.1982.tb01757.x

[2] See Figure 5 in Koch, K., Samson, R., Siegfried, D. Experimental and computational aerodynamic characterization of urban trees. *Biosystems engineering*. Volume 190, February 2020. https://doi.org/10.1016/j.biosystemseng.2019.11.020

[3] See AF Note 36, page 2 in USDA. Windbreak Density: Rules of thumb for Design. *Agroforestry Notes*. September 2007.

6. Results

Using the methodology and data we have described, we found that elevation changes along the proposed project right-of-way did not affect the impact distance of potential CO_2 in a significant way. The dispersion impact area was approximately 300 feet wide and 700 feet long (see Figure 1). Figures 2 and 3 visualize the dispersion impact area for both Scenarios 3 and 4 which did affect the impact distance significantly.

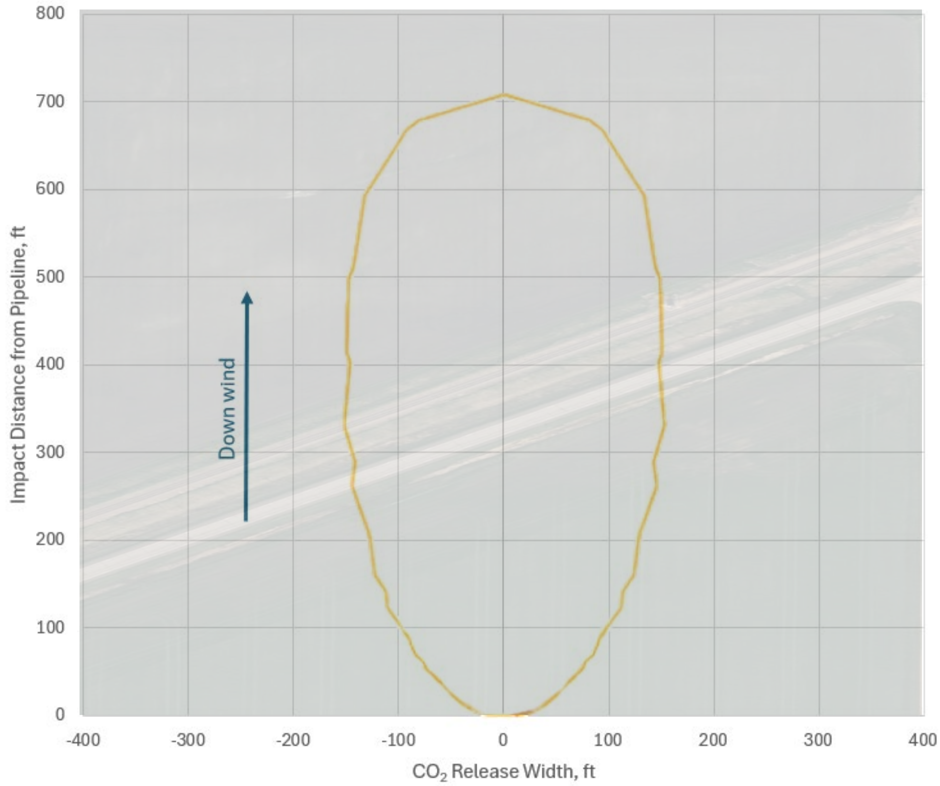

Figure 1. CO_2 Impact Area from a Potential Rupture for 30,000 ppm at 10 Feet Above the Ground for Scenario 2

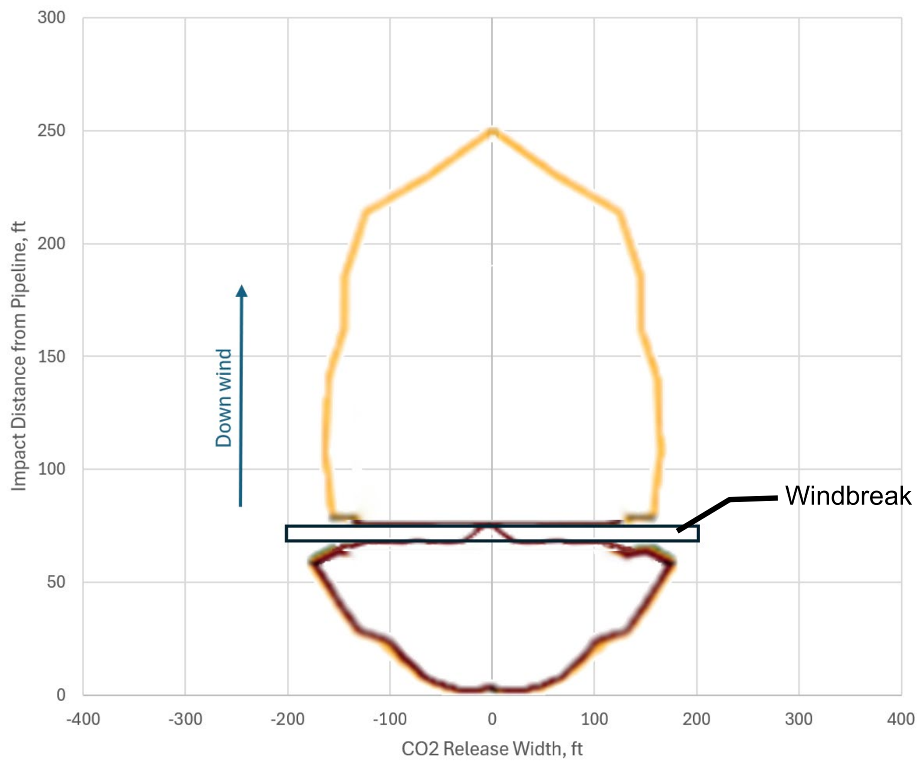

Figure 2. CO_2 Impact Area from a Potential Rupture for 30,000 ppm at 10 Feet Above Ground for Scenario 3

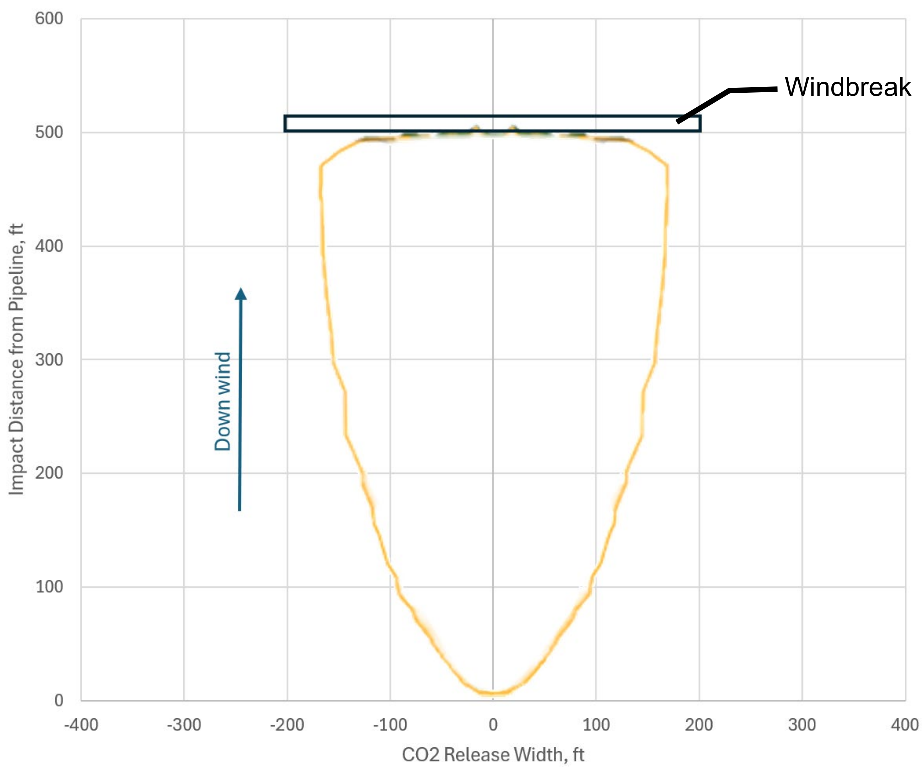

Figure 3. CO_2 Impact Area from a Potential Rupture for 30,000 ppm at 10 Feet Above Ground for Scenario 4

Table 3 shows the impact distances for the four scenarios, plus the time in seconds and minutes it takes to reach the maximum impact distance from the pipeline centerline, and the time it takes for the release to dissipate below 30,000 ppm.

Table 3. Comparison of Impact Distances for Different Scenarios for a LOC of 30,000 ppm

Scenario	Maximum Impact Distance (ft)	Time it Takes to Reach Maximum Impact Distance (sec (min))	Comment	Time it Takes for the Release to Dissipate Below 30,000 ppm (sec (min))[1]
Scenario 1: CANARY-only model	702	146 (2.4)	Baseline scenario	N/A[2]
Scenario 2: CFD with terrain	711	151 (2.5)	Terrain only adds 1.2% to the impact distance	234 (3.9)
Scenario 3: CFD with windbreak 50 feet downwind	253	108 (1.8)	Significant CO_2 transfer through windbreak. However, the windbreak absorbs most of the energy from the release.	157 (2.6)
Scenario 4: CFD with windbreak far 500 feet downwind	500	129 (2.2)	No CO_2 goes beyond the wind break at the 30,000-ppm concentration.	182 (3)

[1] Assumes all of the release is beneath 30,000 ppm from source to maximum impact distance.

[2] CANARY cannot calculate how long it takes for a release to dissipate.

As the data in Table 3 shows, windbreaks decrease the impact distance of the modeled CO_2 release in Scenario 1.

7. Discussion

When analyzing the results in Table 3, there are a few things to keep in mind:

1. We modeled one row of windbreak. If a windbreak has more rows, which is usually the case in the project area, the impact distances will be much shorter.
2. We assumed the windbreaks were intact and had uniform density from top to bottom. Wind break variation would affect CO_2 release impact distances.
3. In Scenario 3, where the CO_2 release comes out of the ground and then hits the windbreak before it settles back on the ground, the product would most likely freeze and accumulate on that windbreak. This would most likely decrease the permeability of the windbreak and make it more wall-like than what we modeled, which would decrease the CO_2 release impact distance even more than what we show in Table 3.

4. We used conifers as our windbreak because that is what is present along the project right-of-way and because they generally provide the most protection from the wind closer to the ground.

Figure 2 shows that in Scenarios 2 through 4, the CO_2 clouds form and disperse rapidly. Based on that information, we can make the following conclusion:

- A full rupture results in impacts too quickly for an early warning device, such as an oxygen detector, to be effective.

Finally, regardless of the scenario, the time it takes for the 30,000-ppm concentration CO_2 release to dissipate is very short—less than 4 minutes. In fact, the total time of the entire event would be less than 7 minutes in a worst-case scenario.

8. References

We performed this analysis in conjunction with the following reports and documents:

- Single Line Aerial Dispersion Analysis - Otter Tail to Wilkin CO_2 Pipeline Project – Report (1/11/2024)

Addendum – Supplemental Modeling

Addendum created July 11, 2024.

In response to public comments regarding the " Computational Fluid Dynamics Analysis: Otter Tail to Wilkin Carbon Dioxide Pipeline Project MN Docket No. PL-22-422" report dated January 15, 2024 (Appendix G of the Draft EIS), Allied performed supplemental CFD modeling to address concerns about the effect of:

- Wind speeds of less than 4 mph,
- Wind applied to the analysis after all of the CO_2 has evacuated the pipeline, and
- A worst-case surface roughness value equal to ice on the ground during winter conditions.

In this addendum, we describe our methodology for completing this supplementary CFD analysis for the proposed Otter Tail to Wilkin CO_2 Pipeline Project, summarize the results, and compare the results to the results in the January 15, 2024, report.

Methodology

For an explanation of the CFD software we used, see the above Section 4.5 of the original report.

For this model, we chose the same assumptions, input data, and conditions used in Scenario 3, in the January 15, 2024, report with some exceptions. Section 4.3 of the original report outlined the following conditions and assumptions: Terrain was not taken into account and the CO_2 released from the pipeline arced into the air and hit a windbreak before it hit the ground. The windbreak was 50 feet from the rupture. The exceptions used in this model are as follows:

- **Exception 1 –** We removed the windbreak. From the results in the original report, we found that terrain along the proposed rights-of-way did not materially affect the impact distance associated with a CO_2 concentration of 30,000 ppm. Therefore, Scenario 3 is a reasonable model to use if we remove the windbreak, because Scenario 3 doesn't consider terrain.
- **Exception 2 –** We adjusted the surrounding surface roughness (ground roughness) from 0.007 meters to 0.00001 meters. We did that to address the concern noted in comments that the model should mimic the snow and ice on the ground of the proposed rights-of-way in the winter. We chose a surface roughness commensurate with the conditions found on an ice-skating rink—near zero roughness—as a highly conservative estimate of ground roughness in winter conditions.
- **Exception 3 –** We varied the wind speed between 1 mph and 4 mph addressing the concern noted in comments that the model should take into consideration wind speeds of less than 4 mph. This addendum CFD model shows the effect those lower wind speeds have on impact distance of a CO_2 dispersion.
- **Exception 4 –** The final concern noted in comments we addressed in this addendum CFD model is if the CO_2 is released during a potential rupture with zero wind influencing the dispersion cloud and then, after a time, the wind picks up and carries the dispersion downwind. To address this concern, we tested those conditions in the model.

Analysis and Results

First, using the surrounding surface roughness associated with an ice-skating rink (0.00001 meters) and a wind speed of 1 mph, we determined the wind delay that maximizes the impact distance by running the

CFD model with the spread of wind time delays in Table 4. This covered all significant wind delay scenarios. Table 4 also shows the modeling results associated with the various wind delay scenarios.

Table 4. Comparison of Impact Distances for Different Wind Delay Scenarios for a LOC of 30,000 ppm at 1 mph Constant Windspeed

Wind Delay (seconds)	Comment	Maximum Impact Distance (ft)	Time to Reach Maximum Impact Distance (sec (min))	Time to Dissipate Below 30,000 ppm (sec (min))[1]
0	We chose a 0-second delay so that the "wind delay equals zero" scenario could complement the results in the original report.	671	188 (3.1)	277 (4.6)
10	We chose a 10-second delay because the original aerial dispersion results show that the bulk of the carbon dioxide leaves the pipe in that amount of time.	650	191 (3.2)	281 (4.7)
95	We chose a 95-second delay because the original aerial dispersion results show that almost all the carbon dioxide leaves the pipe in that amount of time.	515	401 (6.7)	590 (9.8)

[1] Assumes the concentration of the release is below 30,000 ppm from source to maximum impact distance.

Second, using the zero-wind delay in Table 4 that resulted in the largest impact distance (671 feet), we then determined what wind speed would create the maximum impact distance by running the CFD model with the varying wind speeds shown in Table 5. These wind speeds were all equal to or less than 4 mph to address commenters' concerns with the initial modeling results included in the Draft EIS.

Table 5. Comparison of Impact Distances for Wind Speed Scenarios with 4 mph or Less for a LOC of 30,000 ppm with a Wind Delay of Zero

Wind Speed (mph)	Maximum Impact Distance (ft)	Time to Reach Maximum Impact Distance (sec (min))	Time to Dissipate Below 30,000 ppm (sec (min))[1]	Comment
1	671	188 (3.1)	277 (4.6)	Same as the first row in Table 4 above. Repeated here for comparison to other wind speeds.
2	702	182 (3.0)	265 (4.4)	

Wind Speed (mph)	Maximum Impact Distance (ft)	Time to Reach Maximum Impact Distance (sec (min))	Time to Dissipate Below 30,000 ppm (sec (min))[1]	Comment
3	736	177 (3.0)	251 (4.2)	
4	769	144 (2.4)	231 (3.9)	
4	711	151 (2.5)	234 (3.9)	For comparison, these are the results from Scenario 2 in Table 3 of the above original report, which is the maximum impact distance from the original report.[2]

[1] Assumes the concentration of the release is below 30,000 ppm from source to maximum impact distance.

[2] Note that we used a surface roughness value of 0.007 meters, which is different from the 0.0001 meters surface roughness value we used in this supplemental modeling.

Comparison to Original Results

When reviewing the results in Table 5, we found that the new CFD model parameters did not cause significant changes in the impact distance of a CO_2 release. The maximum impact distance in the original modeling was 711 feet. The maximum impact distance under the low wind and low roughness exceptions of this supplemental modeling was 769 feet.

The results of the 4 mph scenarios in Table 5 demonstrate an 8.2% increase (58 feet) in impact distance if we use a surface roughness associated with an ice-skating rink (0.00001 meters) versus a surface roughness associated with short-cut grass (0.007 meters). A surface roughness of 0.007 meters is the industry standard and what we used in the original CFD model.

Ice-skating rink roughness, which has near-zero friction, does not normally occur in nature. This roughness is unrealistic for the proposed right-of-way because it does not take snow and other environmental conditions into consideration. However, this roughness provides an upper limit for the modeled potential impact distance of a 30,000 ppm CO_2 cloud. Also, we did not consider vegetation (crops, grass, bushes, etc.) in the CFD modeling we conducted for this addendum, which would reduce the potential impact distance.

Finally, Scenarios 3 and 4 in the original report show that windbreaks virtually stop CO_2 dispersions, and the results of the supplemental modeling do not change this observation.

CO2 Pipeline Sensitivity Analysis Report:
Otter Tail to Wilkin CO2 Pipeline Project
January 16, 2024
(Allied Solutions)

CO_2 PIPELINE SENSITIVITY ANALYSIS REPORT: OTTER TAIL TO WILKIN CARBON DIOXIDE PIPELINE PROJECT

MN DOCKET NO.: PL-22-422

1-16-2024

PREPARED BY:

ALLIED SOLUTIONS

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1. Introduction

Carbon capture and storage (CCS) and other industrial processes require transportation of carbon dioxide (CO_2) through pipelines. Ensuring the safe operation of these pipelines is of paramount importance to protect people, animals, and the environment. To understand the dynamics of CO_2 pipeline ruptures and identify critical factors that influence the release and dispersion of CO_2, experienced subject matter experts are engaged to conduct a sensitivity analysis.

Allied Solutions, INC (hereinafter referred to as "Allied," "we," "us," or "our") conducted such a sensitivity analysis for HDR Engineering, Inc., on behalf of the State of Minnesota, Department of Commerce, Environmental Review and Analysis (EERA) unit on the Proposed Otter Tail to Wilkin CO_2 Project. In this report, we describe our methodology for completing a CO_2 sensitivity analysis and summarize the results.

Please note that this analysis shows how various weather and operational parameters can affect the impact distance of an aerial dispersion model. While we chose reasonable weather conditions and modeling factors consistent with the proposed project and the area it is in, the reader must interpret the results of this report in conjunction with the two reports in the References section below. The reader should not consider this report as an independent set of quantitative results.

2. Background

The increasing emphasis on mitigating greenhouse gas (GHG) emissions has led to the development of technologies like CCS, which is the process of capturing CO_2 with special equipment, subjecting it to high pressure to turn it into a liquid (called a "supercritical" state), and transporting it to underground storage sites. When we conduct a sensitivity analysis on those proposed pipelines, it allows us to inform the public and decisionmakers when considering the impact a CO_2 pipeline could have in the unlikely event of a rupture.

3. Definitions

TABLE 1. DEFINITIONS OF TERMS

Acronym or Term	Definition
CANARY	Software used to determine the impact of various HVL releases on the surrounding area; integrates multicomponent thermodynamics into a time-varying fluid release simulation, which accounts for two-phase flow, flash vaporization, aerosol formation, and liquid rainout
CO_2	Carbon dioxide
Highly Volatile Liquid (HVL)	Per 49 CFR §195.2, a hazardous liquid that will form a vapor cloud when released to the atmosphere and that has a vapor pressure exceeding 276 kPa (40 psia) at 37.8 °C (100 °F)
Level of Concern (LOCs)	A threshold value above which a hazard may exist (e.g., toxicity, flammability, thermal radiation, or overpressure); usually, the value above which a threat to people or property exists

Acronym or Term	Definition
Machine Learning	A computer system that learns and adapts without following explicit instructions by using algorithms and statistical models to analyze and draw inferences from patterns in data
Root Mean Square Error (RMSE)	The proportion of the variance in the output of a regression model that can be explained by the inputs; a value closer to 1 indicates a model where the inputs more accurately predict the output
multiple R squared	A goodness-of-fit measure for linear regression models; a value of 0 to 1 indicates the percentage of the variance in the dependent variable that the independent variables explain collectively, with 1 being a perfect fit
Sensitivity Analysis	A method of analysis that determines how different values of multiple inputs affect a particular output under a given set of assumptions
Valve Segment	A segment of pipeline between two valves

4. Software and Techniques Used

To conduct the sensitivity analysis, we used an aerial dispersion software package—CANARY—and machine learning, which is a method for determining patterns and relationships between inputs and outputs.

4.1 CANARY

CANARY is an aerial dispersion analysis software designed by engineers at Quest Consultants, Inc. This software uses a multi-component thermodynamics model to determine the potential outcomes following a hazardous liquid release. Integrity engineers who perform these analyses must be trained and qualified by Quest to use CANARY.

4.2 Machine Learning

We used machine learning to display the relationship between the inputs and outputs from CANARY. Machine learning is a computer system that learns and adapts without following explicit instructions by using algorithms and statistical models to analyze and draw inferences from patterns in data. We first normalized the data in terms of a standard deviation to prepare the data for modeling. We then used a gradient-boosted regression tree[1] to create a model to fit the data.

5. Levels of Concern

We used the National Institute of Occupational Safety and Health (NIOSH) exposure limits as levels of concern (LOCs). The Centers for Disease Control and Prevention's NIOSH Pocket Guide to Chemical Hazards provides exposure limits for a wide range of chemicals stemming from documented cases and research, which creates an industry-accepted clearinghouse of chemical safety information.

[1] Gradient-boosted regression trees (GBRT) are a flexible, non-parametric, statistical learning technique for classification and regression; used to accurately fit models to data.

For this project we used the CO_2-specific toxic LOC of 15,000 ppm, which is half of 30,000 ppm (the NIOSH short-term exposure limit[2] (STEL). This value generates the largest amount in variability in impact distances of the LOCs used in the Single Line Aerial Dispersion Analysis (see the References section). We need the LOC so that we have a way to compare the impact of the various scenarios we modeled.

6. Models Used

The toxic area impact of a CO_2 vapor cloud is the area in which the ground-level toxic vapor concentration is predicted to be hazardous. We use CANARY's momentum jet dispersion model to predict the downwind travel of a toxic gas or aerosol momentum jet release. The model requires LOCs (see the Levels of Concern section of this report) and the variables listed in Table 2 (see Appendix A) to run an analysis of the toxic area impact.

The output of this analysis is the impact distance from the pipeline that a potential CO_2 release could reach (in feet).

7. Analysis

We performed this sensitivity analysis on a representative pipeline transporting supercritical CO_2 by 1) using a basic set of input variables that can influence a dispersion; 2) modeling a wide range of CO_2 ruptures by differing the basic set of variables as inputs; and 3) using machine learning to display the sensitivity of input variables to the outputs of the impacted area of a potential CO_2 pipeline rupture.

The representative pipeline we modeled has a broader range of the same properties of the proposed project, so this analysis is valid in the context of the proposed project and potential weather it may be subjected to.

7.1 Declaring Input Variables

For this project, we analyzed the relationship between certain inputs and the resulting potential impact of a CO_2 rupture. We chose these inputs based on practical variable ranges[3] appropriate for the project area:

- Four different wind speeds
- Four different air and ground surface temperatures
- Four different pipeline pressures
- Five different volumes of CO_2 released, based on diameter and length of the pipeline[4]
- Four different relative humidities

[2] The NIOSH STEL is the maximum time-weighted average concentration a person could be exposed to over a 15-minute period without injury.
[3] The variable ranges selected were slightly larger than the expected operational and weather conditions the proposed project would be affected by.
[4] The five pipeline segment volumes are based on the Otter Tail to Wilkin CO2 Pipeline Project pipeline segments.

In our experience, these are the core influential input variables. See Appendix A for a list of all the variables we used.

7.2 Modeling CO_2 Ruptures

We used the values in Table 2 (see Appendix A) to build CANARY input files, and the CANARY software itself to generate 1,208 individual models (i.e., all permutations of all the input variables we chose).

7.3 Using Machine Learning to Show Model Sensitivity

We used the inputs and outputs from the previous section to create a "learning dataset" for machine learning (ML) to model the sensitivity. Using a gradient-boosted regression tree, we generated a model that fit the data by 97%[5]—meaning the model closely fits the CANARY software's ability to produce results over the range of input values used in this analysis. Keep in mind that the range of inputs used in this analysis covers the weather and operational conditions this proposed project will be subjected to as provided in the Single Line Aerial Dispersion Analysis (see the References section).

We then used the ML model to obtain the sensitivity of the inputs to the output (impact distance). Figure 1 shows the attribute set we considered (inputs) and the range of potential positive and negative effects that all inputs can have on the impact from a potential CO_2 rupture. Green is a positive impact, meaning it reduces the size of the CO_2 rupture, whereas red is a negative impact, meaning the CO_2 impact was increased.

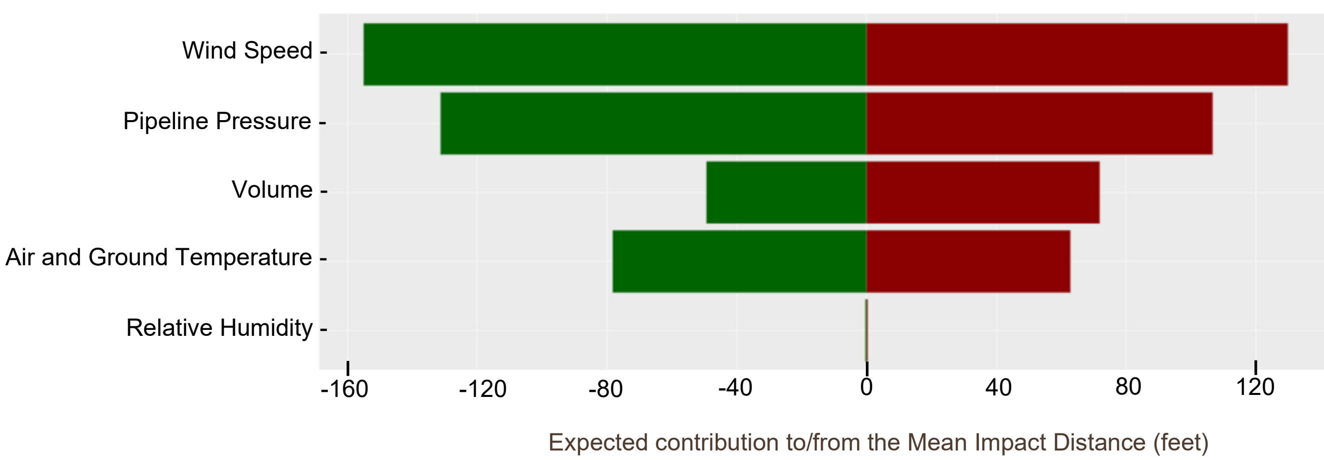

FIGURE 1. SENSITIVITY RANGE OF AERIAL DISPERSION ATTRIBUTES ON POTENTIAL CO_2 RUPTURE AREA

8. Discussion and Conclusions

The multiple R squared score and the RSME of the gradient-boosted regression tree (see footnote 5 on the previous page) demonstrates that ML generated a model that very closely represents the 1,280 CANARY aerial dispersion models, which show that wind speed has the biggest impact on a potential CO_2 rupture

[5] The model has a multiple R squared value of 0.97 and a RSME value of 48 with a mean of 661.

for the proposed project—from nearly negative 160 feet to more than positive 120 feet. What this means is that wind speed can add up to 120 feet of impact distance above and beyond the mean impact distance we calculated for the 1,280 models, or it can decrease the impact distance by up to 160 feet. It's common knowledge in the oil and gas industry that wind speed has a significant influence on aerial dispersion impact distance, so this result is consistent with industry knowledge or experience.

Pipeline pressure has the second largest impact on the amount (mass) of CO_2 immediately released from a potential rupture. The higher the pipeline pressure, the higher the density (mass per volume) of CO_2, released. The higher the density released, the less likely it is to dissipate over time because more density means greater concentration. Likewise, the lower the pressure, the less the density. The less the density, the more quickly the release can dissipate over time.

One other point to note is that volume, like pressure, also affects the amount of CO_2 immediately released from a rupture. What the ML model shows, however, is though volume matters, it doesn't matter as much as wind speed and pipeline pressure.

Also of note is that humidity does not materially contribute to the impact distance. Comparatively, temperature is much more important.

Perhaps the biggest takeaway is how the dynamic relationship of the five input variables simultaneously affect the impact distance. In other words, if all five variables are included in the same ML model, Figure 1 shows how much influence each input has on the mean impact distance. For example, if we were to take out one of the input variables, the remaining input variables may affect the impact distance in a significantly different way because of the complex relationships between all the input variables.

Finally, Figure 1 shows the *range* of influence the input variables have on the mean impact distance. In other words, given the input variables we used with data ranges in Table 2, wind speed can affect the mean impact distance anywhere from nearly negative 160 feet to more than positive 120 feet, making it the most influential input variable we tested. It also means that, in certain cases, wind speed doesn't affect the mean impact distance at all; zero is one of the impact distances between negative 160 ft and positive 120 feet.

9. References

We performed this analysis in conjunction with the following reports:

- Single Line Aerial Dispersion Analysis - Otter Tail to Wilkin CO2 Pipeline Project - Report (1/11/2024).pdf

Single Line CFD Analysis – Proposed Otter Tail to Wilkin CO_2 Pipeline Project – Report (1/15/2024).pdf

Appendix A – Project-Specific Data

Table 2 describes the project-specific data we used to conduct the analysis.

TABLE 2. PROJECT-SPECIFIC DATA

Attribute	Value Used	Justification
Wind Speed[1] (mph)	2, 4.33, 6.67, 9	4.47 mph is endorsed by Quest Consultants to produce reasonable worst-case conditions when using their software; we chose these values based on typical weather patterns for the project area
Wind Speed Measurement Height (ft)	32.81 (10 m)	Endorsed by Quest Consultants to produce reasonable worst-case conditions when using their software
Wind Stability Class	Class F	A laminar wind condition that produces the largest affect to impacted areas away from the pipeline
Relative Humidity[1]	20, 46.67, 73.33, 100%	Based on weather typical in the project area
Air/Ground Temperature[1] (°F)	-30,13.33, 56.67,100	Based on weather typical in the project area
Surrounding Surface Roughness (in)	6 (0.007 m)	Provides the reasonably largest impacted area by assuming the smoothest onshore surface the CANARY software offers
CO_2 Pressure[1] (psi)	1,100, 1,465.96, 1,831.93, 2,197.89	Based on the data for the proposed pipeline the applicant provided for the proposed project
Release Duration (min)	60	Sufficient time to fully depressurize a valve segment
Rupture Release Point (ft)	0	Indicates the worst-case scenario of pipe at ground level and unburied
Angle of CO_2 Release from Horizontal	19 degrees	The angle of release Quest Consultants recommend because it generates the worst-case scenario with their models

Attribute	Value Used	Justification
Dispersion Coefficient Averaging Time (min)	Same as the Rupture Release time	Must be the same as the Rupture Release Time or results may be suspect
Impoundment?	No	Generates the worst-case scenario for any given pipeline release
Max Flow Rate (lbs/sec)	10.36	Based on the data for the proposed pipeline that the applicant provided for the proposed project
Pipe Diameter[1] (in)	4	Based on the data for the proposed pipeline that the applicant provided for the proposed project
Rupture Diameter (in)	Same as pipe diameter to simulate a full guillotine rupture	Assumes a total guillotine rupture by setting this value to the same diameter of the pipeline
Valve Segment Length[1] (miles)	4.8, 13.9, 1.6, 7.4, 0.7	Measurements of the pipeline segments on the proposed pipeline
Rupture Placement Along the Valve Segment	Equidistant from both ends of the valve segment	Provides accurate answers considering how the various models work
Isolation Valve Closure Time (min)	10	Typical closure time for hazardous liquids pipelines

[1] We chose these values to produce a set of normalized inputs for modeling. Also, we chose the values because they are reasonably representative of the project area.