Determination of Potential Impact Radius for CO_2 Pipelines using Machine Learning Approach

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Agenda

- Background
- Project Outline
- Project Progress
- Summary and Discussion
- Q&A

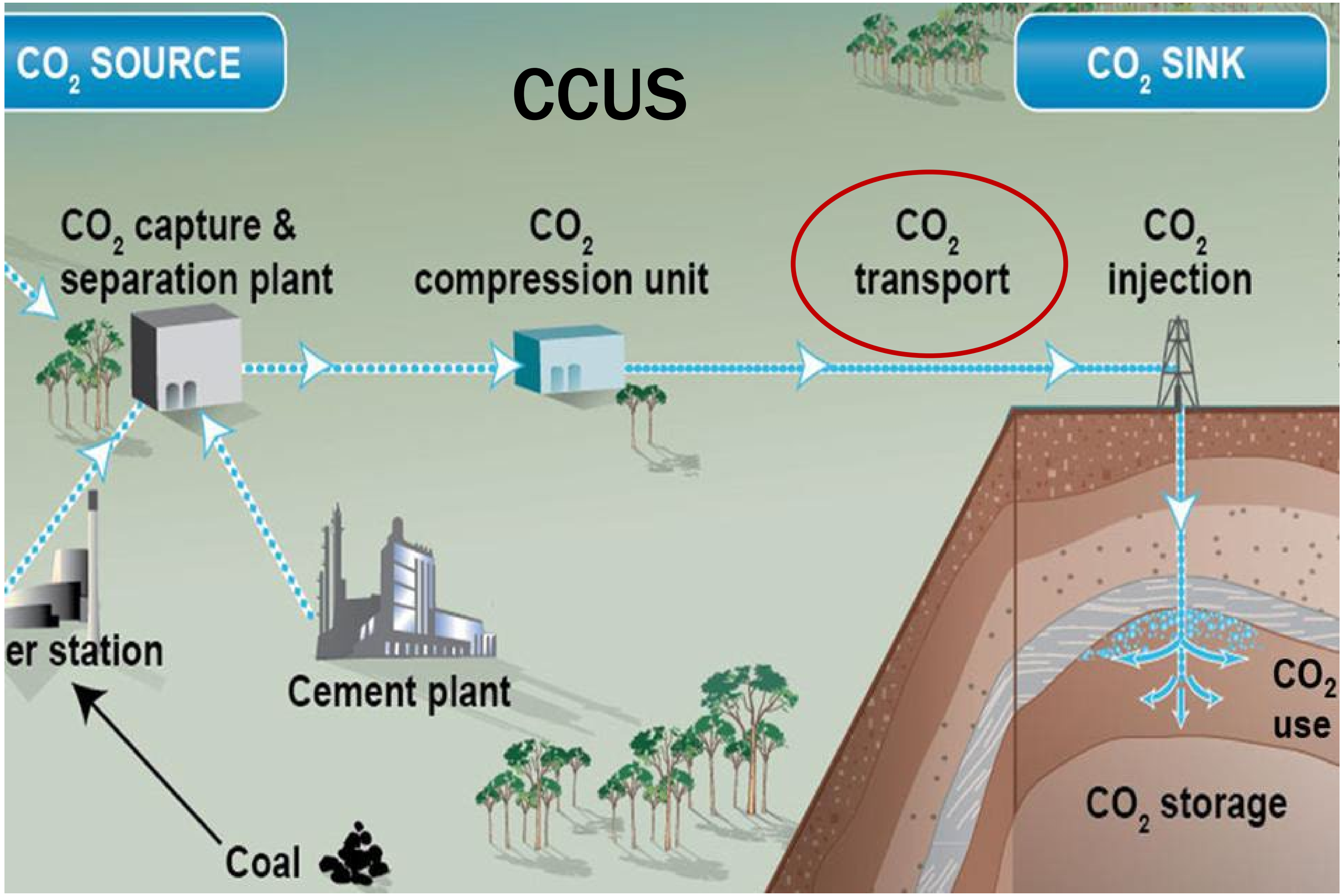
1. Background

Carbon Capture, Utilization and Storage

<u>2035 Goal</u>: reduce greenhouse gas emissions and aim for net zero by 2035.

<u>Carbon Capture</u>: achieve 14% of the global greenhouse gas emission reductions needed by 2050.

<u>CO_2 Transport</u>: ~50 CO_2 pipelines currently operating in the US.



1. Background

- **Satartia, Mississippi Incident (2020)**
  - A *24-inch* pipeline carrying liquefied CO_2 ruptured.
  - The pipeline was built through **hilly, rugged terrain**. Saturated with rain, soil around the pipeline slid, causing a pipe weld to break and releasing CO_2.
  - A plume of CO_2 rolled toward the village of 50 people. Emergency personnel evacuated about 200 residents, and 45 people sought medical attention.

- **PHMSA** Announces New Safety Measures to Protect Americans From CO_2 Pipeline Failures, seeking solutions to advance the safe operation of CO_2 pipelines.

- PHMSA's regulations in 49 CFR 192.903 identify **PIR for <u>natural gas pipelines</u>**.

- To develop a rapid, universally applicable tool to assess the consequences of accidental CO_2 dispersion from high-pressure pipelines and determine the **PIR for <u>CO_2 pipelines</u>**.

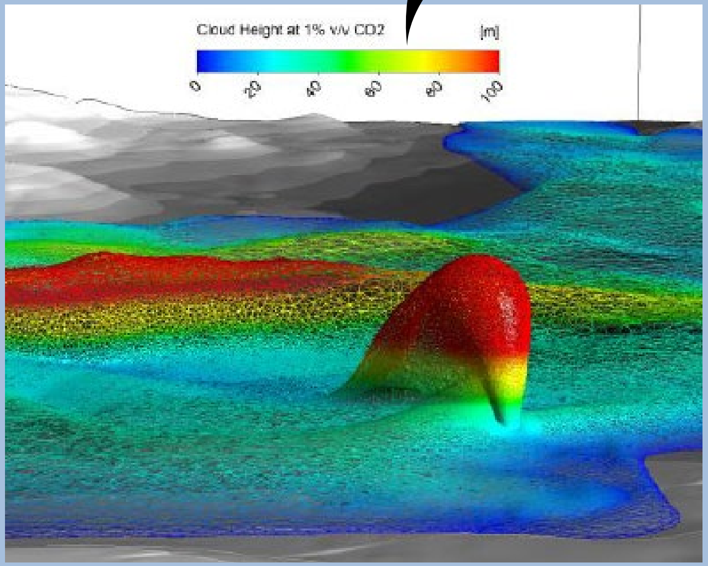
2. Project Outline

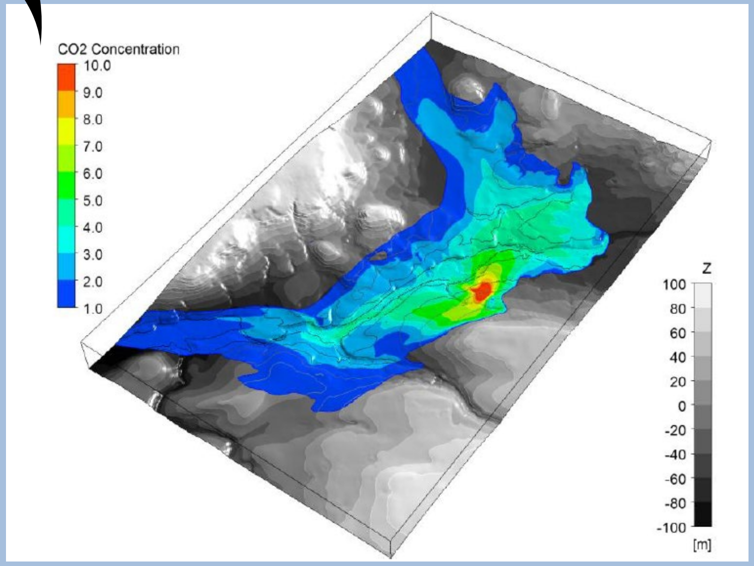
- **Pipeline characteristics**
- **Terrain information**
- **Weather conditions**

→ **Machine learning based prediction model** → **PIR**

Computational Fluid Dynamics

ANSYS Fluent





Woolley, R. M., Fairweather, M., Wareing, C. J., Falle, S. A. E. G., Mahgerefteh, H., Martynov, S., Brown, S., Narasimhamurthy, V. D., Storvik, I. E., Sælen, L., Skjold, T., Economou, I. G., Tsangaris, D. M., Boulougouris, G. C., Diamantonis, N., Cusco, L., Wardman, M., Gant, S. E., Wilday, J., . . . Jamois, D. (2014). CO2PipeHaz: Quantitative Hazard Assessment for Next Generation CO2 Pipelines. Elsevier Science B.V., Amsterdam.

PIR: CO_2 Critical Concentrations

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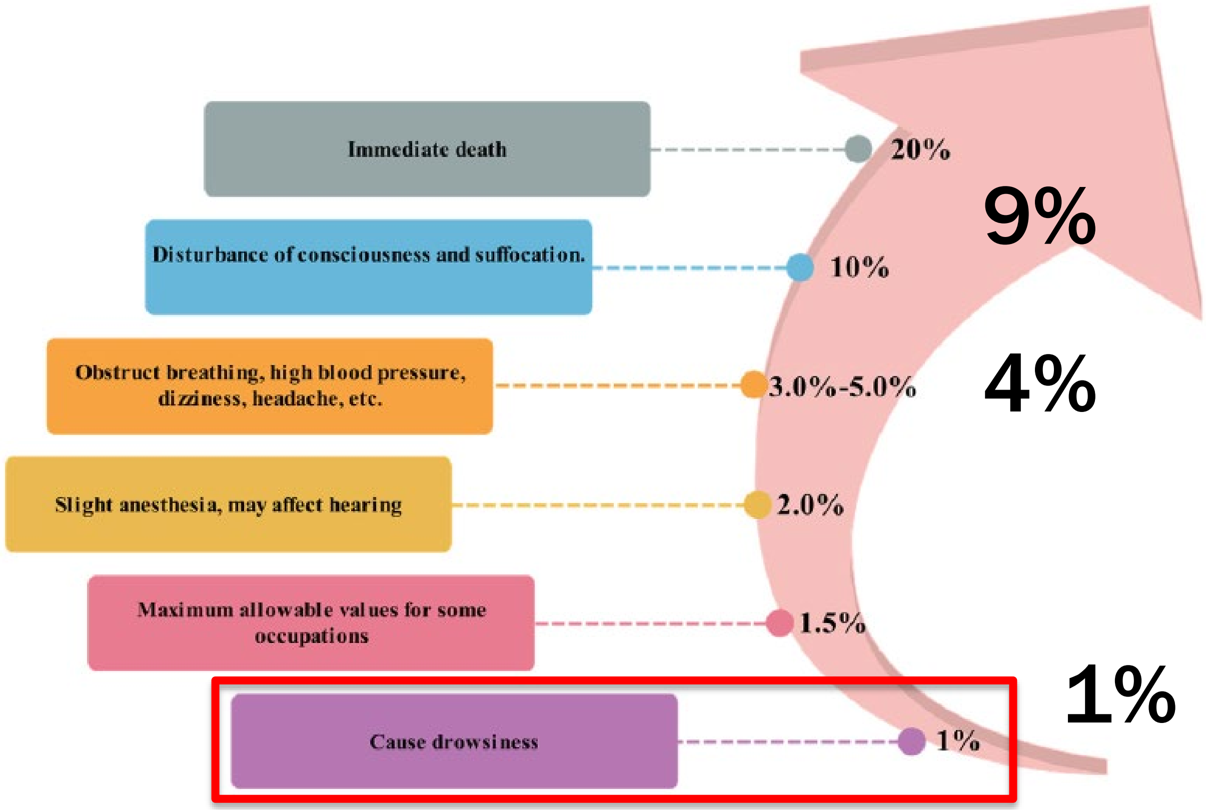
Although CO_2 is **neither toxic nor flammable**, its asphyxiant nature with the **catastrophic release** from a pipeline rupture could pose a significant threat to the people in the vicinity.

- LC_{Lo}(5 mins): **90,000 ppm**
- Adjusted 0.5-hr LC (CF): 49,500 ppm
- IDLH: **40,000 ppm**
  - **LC_{Lo}**: The lowest concentration of a material in air reported to have caused the death.
  - **Adjusted 0.5-hr LC**: The adjusted concentration to 30 minutes exposure.
  - **IDLH**: A condition that poses a threat of exposure to airborne contaminants when that exposure is likely to cause death or immediate or delayed permanent adverse health effects or prevent escape from such an environment (based on a 30-minute exposure duration)



Lu, H. et al., Carbon Dioxide Transport via Pipelines: A Systematic Review. *J. Clean. Prod.* **2020**, *266*, 121994.

3. Project Progress - CFD

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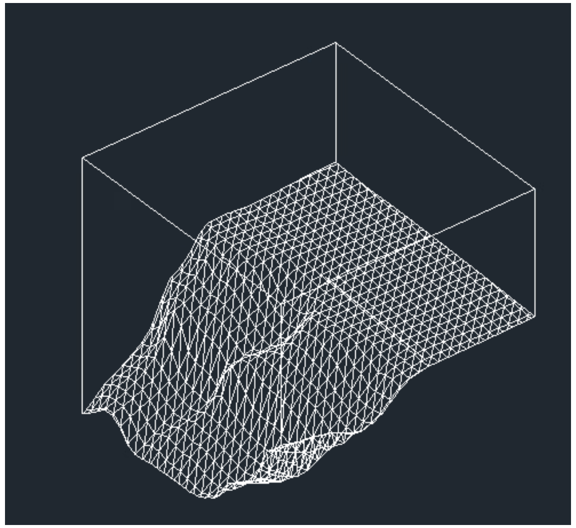

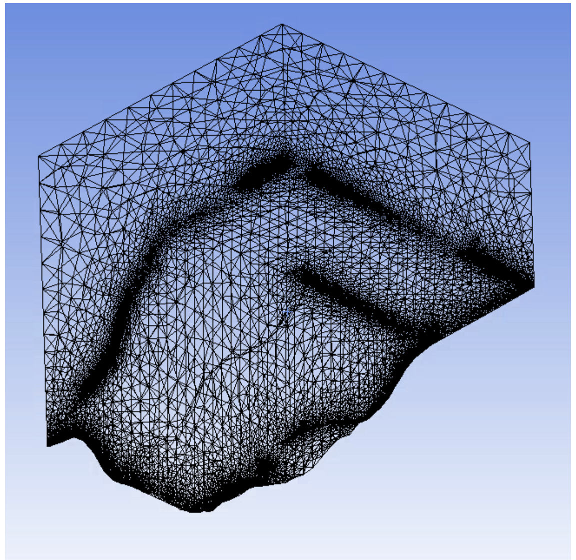

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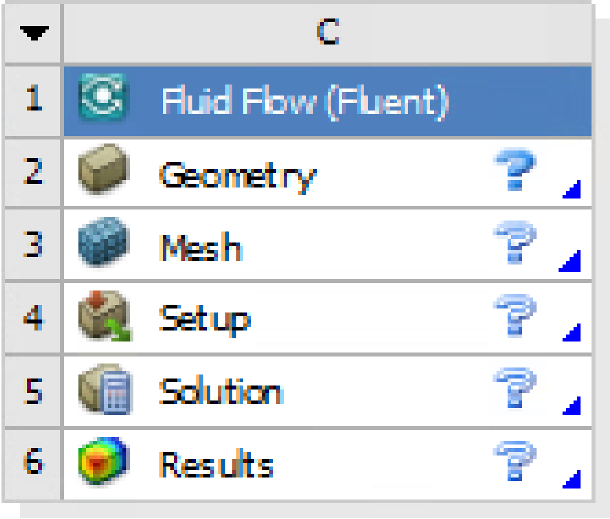
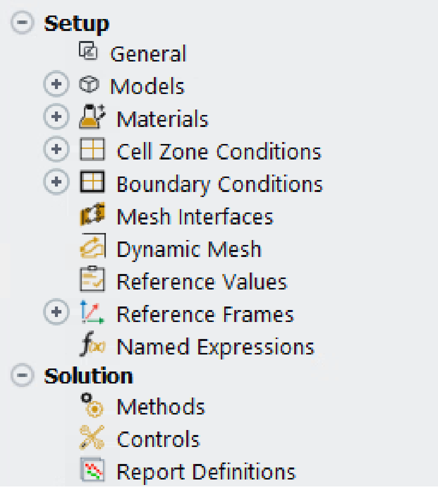
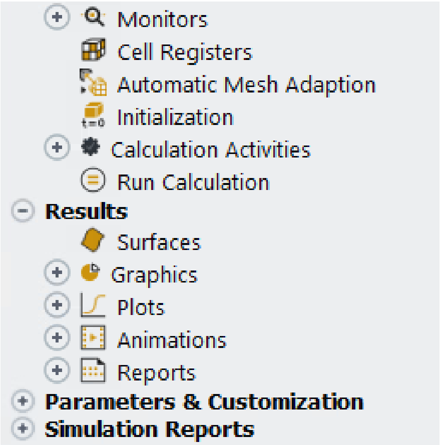
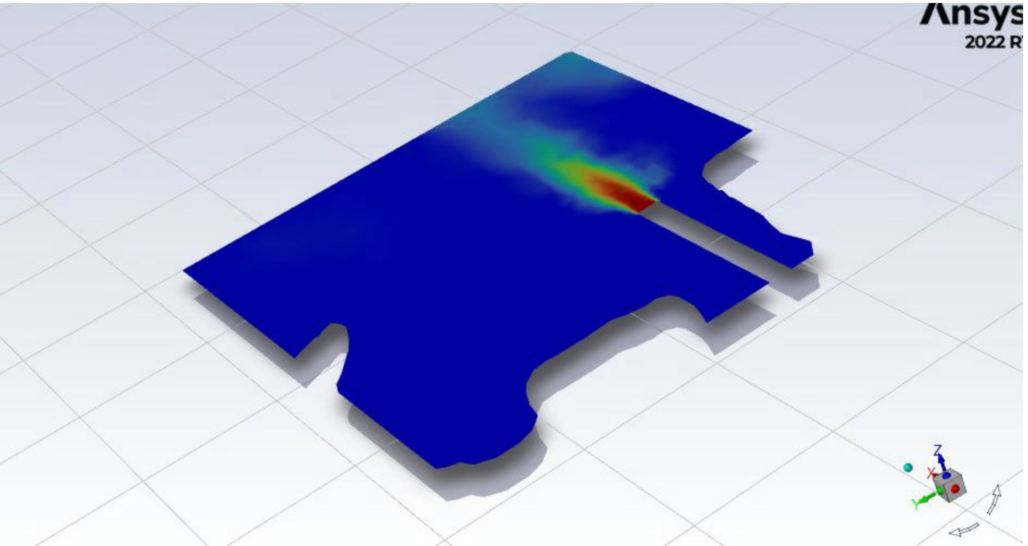


Fluid Flow (Fluent)







CFD Model Validation

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CO2PIPETRANS
BP Test 8

Table 4
Predicted versus observed flow rates and UDM source-term data (BP tests).

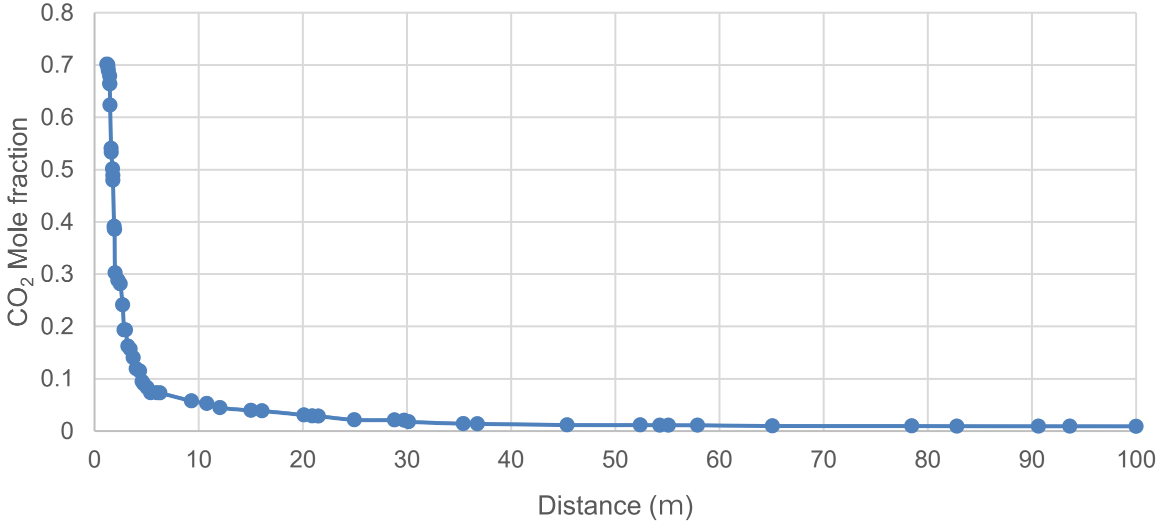
	Test1	Test 2	Test3	Test 5	Test6	Test 11	Test 8	Test 8R	Test 9
Discharge rate									
DISC initial discharge rate (kg/s)	8.84	10.98	9.988	50.75	3.21	7.03	4.19	3.90	6.86
DISC/TVDI discharge rate (kg/s) (averaged over first 20 s for tests 8.8R,9)	8.84	10.98	9.988	50.75	3.21	7.03	4.01	3.73	6.25
Observed discharge rate (kg/s) (averaged over first 20 s for tests 8.8R,9)	–	11.41	9.972	41.17	3.50	7.12	4.07	3.80	6.05
Deviation predicted from observed	7.8%	−3.9%	0.16%	+23%	−8.2%	−1.1%	−1.5%	−1.8%	+3.4%
Final (post-expansion) state (UDM input)									
Discharge rate (kg/s) (from experiments)	8.2	11.41	9.988	41.17	3.50	7.12	4.07	3.80	6.05
Temperature (K) (DISC output)	194.6	194.1	194.26	194.4	193.8	194.1	198.2	204.8	194.1
Solid fraction (–) (DISC output)	0.397	0.403	0.384	0.399	0.397	0.330	0	0	0.154
Velocity (m/s) (DISC output)	156.7	189.8	179.2	191.7	191.3	154.2	466.5	472.8	289.0

Table 1
Experimental conditions for BP CO_2 tests.

Input	Test1	Test2	Test3	Test5	Test6	Test11	Test8	Test8R	Test9	Input for models
Discharge data										
Steady-state/transient	Steady	Steady	Steady	Steady	Steady	Steady	Trans.	Trans.	Trans.	–
Storage phase	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid	Vapour	Vapour	Vapour	DISC,TVDI
Storage pressure (barg)	103.4	155.5	133.5	157.68	156.7	82.03	157.76	148.7	154.16	DISC,TVDI
Storage temperature (°C)	5	7.84	11.02	9.12	9.48	17.44	147.12	149.37	69.17	DISC,TVDI
Vessel volume (m^3)	–	–	–	–	–	–	6.3	6.3	6.3	TVDI
Orifice diameter (mm)	11.94	11.94	11.94	25.62	6.46	11.94	11.94	11.94	11.94	DISC,TVDI
Orifice length (mm)	46.78	46.78	46.78	72.41	47.79	46.78	46.78	46.78	46.78	–
Release duration (s)	60	59	60	40	120	58	120	132	179	–
Ambient data										
Ambient temperature (°C)	14.2	7.5	10.6	5.8	6.1	11.6	11.19	11.1	8.2	DISC,TVDI,UDM
Ambient pressure (mbara)	999.4	958.2	972.5	985.4	938.4	960.2	957.99	957.1	958.9	DISC,TVDI,UDM
Relative humidity (%)	74.4	96	95.8	96.7	1	94	100	100	99.9	DISC,TVDI,UDM
Wind direction (degrees)	322.4	265.6	288.8	278.6	299	270.8	269.3	270	270.7	UDM uses 270°
Wind speed (m/s)	4	3.44	3.37	5.13	2.20	5.99	4.71	0.76	4.04	UDM

Witlox, H. W. M., Harper, M., Oke, A., & Stene, J. (2014). Phast validation of discharge and atmospheric dispersion for pressurised carbon dioxide releases. Journal of Loss Prevention in the Process Industries, 30, 243-255. 10.1016/j.jlp.2013.10.006

CFD Model Validation



Distance (m)	Experiment	Simulation
5	8.22%	**8.80%**
10	3.36%	**4.55%**
20	1.85%	**2.64%**
40	1.49%	**1.24%**

Liu, X., Godbole, A., Lu, C., Michal, G., & Venton, P. (2014). Source strength and dispersion of CO2 releases from high-pressure pipelines: CFD model using real gas equation of state. Applied Energy, 126, 56-68. 10.1016/j.apenergy.2014.03.073

3. Project Progress – CFD Inputs

Related Factors for CFD Inputs:

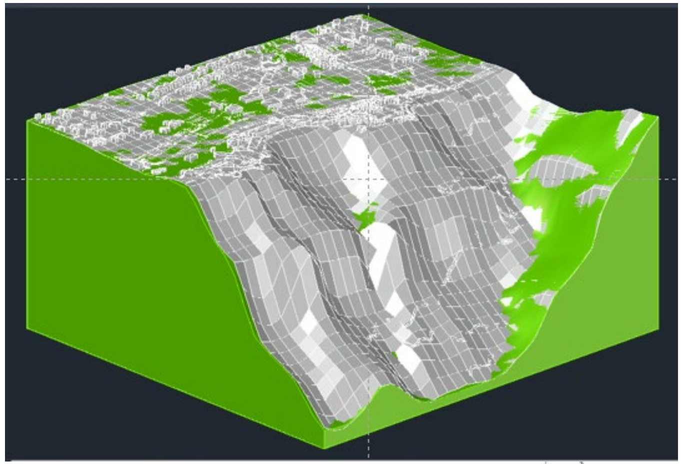
- Applicable **terrain types** for the CO_2 pipelines (CADMAPPER)
- **Corresponding design of CO_2 pipeline:** pipeline characteristics, temperature, pressure, diameters, flow rate (Operating data)
- **Weather** (Wind speed and air temperature)

Expected CFD Outputs:

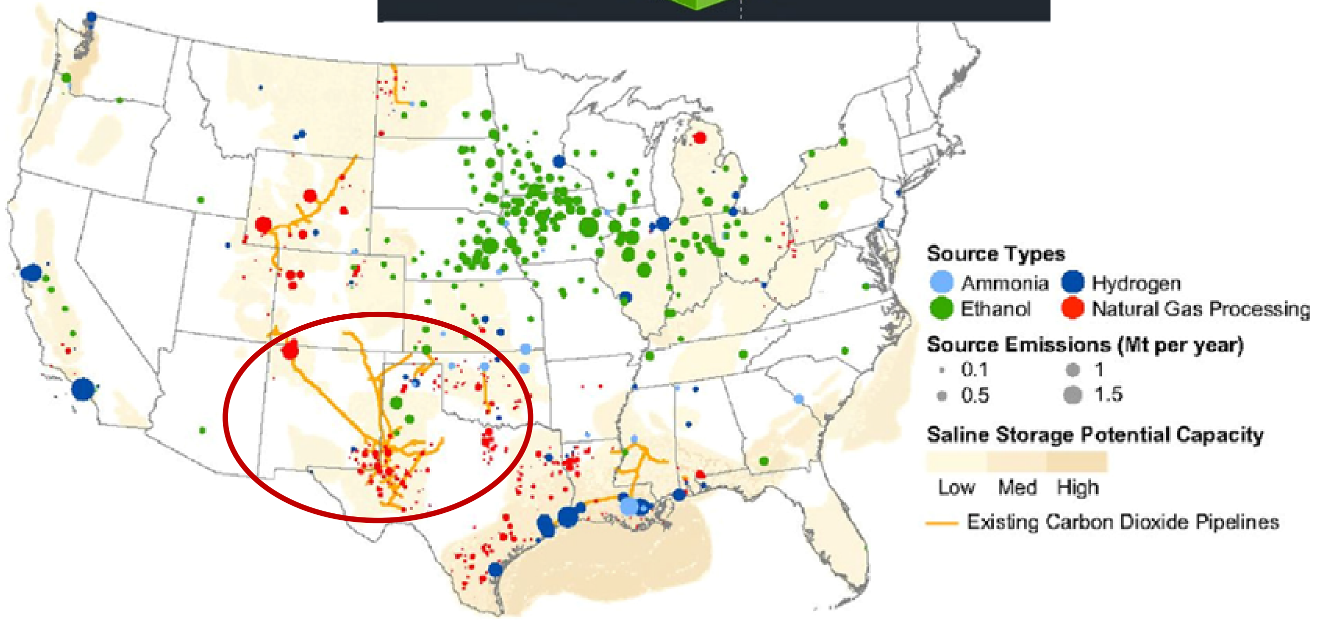
- CO_2 concentrations at distances from the pipeline with different conditions
- PIR

Terrains

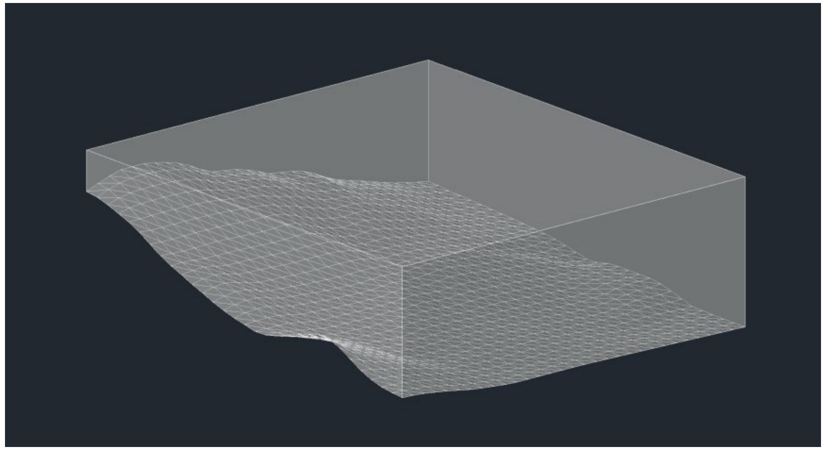
With the help from **AutoCAD Architecture**, the **realistic terrain** could be established to conduct the further CFD simulations.



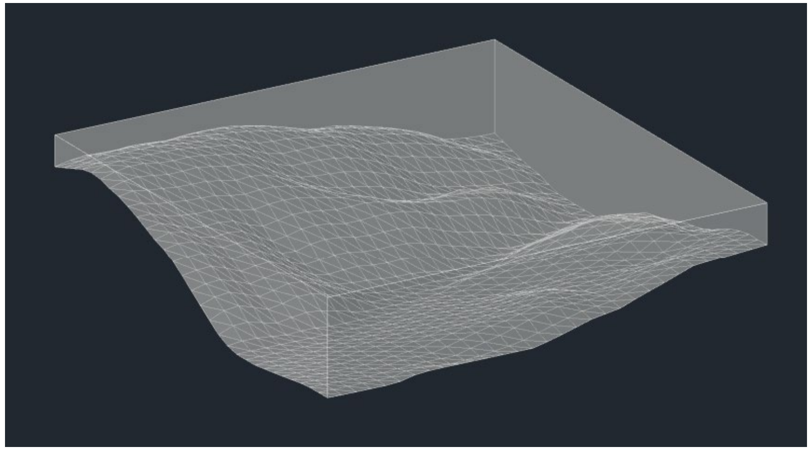
U.S. Regions with Large-scale CO_2 Pipeline Systems in Operation	Miles of Pipeline
Permian Basin (W. TX, NM, and S. CO)	2,600
Gulf Coast (MS, LA, and E. TX)	740
Rocky Mountains (N. CO, WY, and MT)	730
Mid-Continent (OK and KS)	480
Other (ND, MI, Canada)	215



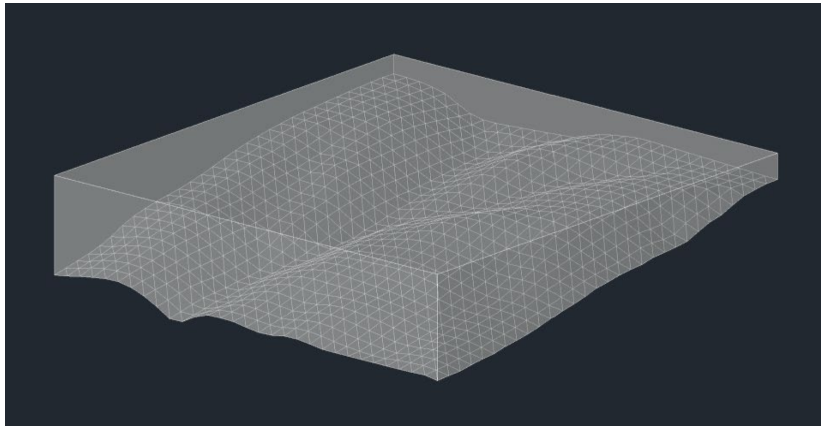
Terrains



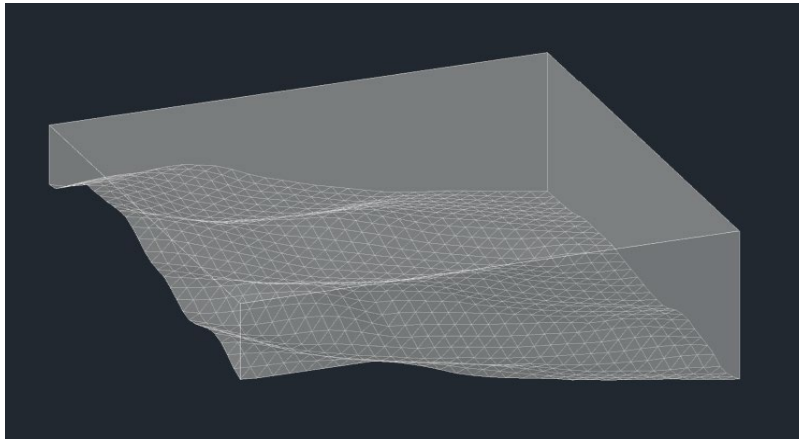
Raton, New Mexico



Vernal, Utah



Calistoga, California



Walsenburg, Colorado

CO_2 Pipeline Characteristics

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Maximum and minimum pressure range of different categories of CO_2 pipeline.

Design parameter	High	Medium	Low
Maximum pressure (MPa)	15.1–20.0	9.8–14.5	2.1–4.0
Minimum pressure (MPa)	7.2–15.1	3.1–3.5	0.3–1.0

- **Pressure: 1-20 Mpa**
- **Diameter: 4-30 inch**
- **Flow rate: 50-1300 MMcfd**

Exhibit 4 Permian Basin CO_2 transportation pipelines

Scale	Pipeline	Operator	Location	Length (mi)	Diameter (in)	Estimated Flow Capacity (MMcfd)
Large-Scale Trunk-lines	Cortez	Kinder Morgan	TX	502	30	1,300
	Sheep Mtn	Oxy Permian	TX	408	24	590
	Bravo	Oxy Permian	NM, TX	218	20	380
	Canyon Reef Carriers	Kinder Morgan	TX	170	16	220
	Centerline	Kinder Morgan	TX	113	16	220
	Central Basin	Kinder Morgan	TX	143	16	220
Smaller-Scale Distribution Systems	Este I - to Welch, Tx	ExxonMobil, et al	TX	40	14	180
	Este II - to Salt Crk Field	Oxy Permian	TX	45	12	130
	Means	ExxonMobil	TX	35	12	130
	North Ward Estes	Whiting	TX	26	12	130
	Slaughter	Oxy Permian	TX	35	12	130
	Mabee Lateral	Chevron	TX	18	10	110
	Val Verde	Oxy Permian	TX	83	10	110
	Rosebud	Hess	NM	50*	12	100*
	Anton Irish	Oxy Permian	TX	40	8	80
	Dollarhide	Chevron	TX	23	8	80
	Llano	Trinity CO_2	NM	53	12	80
	North Cowden	Oxy Permian	TX	8	8	80
	Pecos County	Kinder Morgan	TX	26	8	80
	Pikes Peak	Oxy Permian	TX	40	8	80
	W. Texas	Trinity CO_2	TX, NM	60	12	80
	Comanche Creek	Oxy Permian	TX	120	6	70
	Cordona Lake	XTO	TX	7	6	70
	El Mar	Kinder Morgan	TX	35	6	70
	Wellman	Trinity CO_2	TX	25	6	70
	Adair	Apache	TX	15	4	50
	Ford	Kinder Morgan	TX	12	4	50

National Energy Technology Institute. (2015). A Review of the CO_2 Pipeline Infrastructure in the U.S.

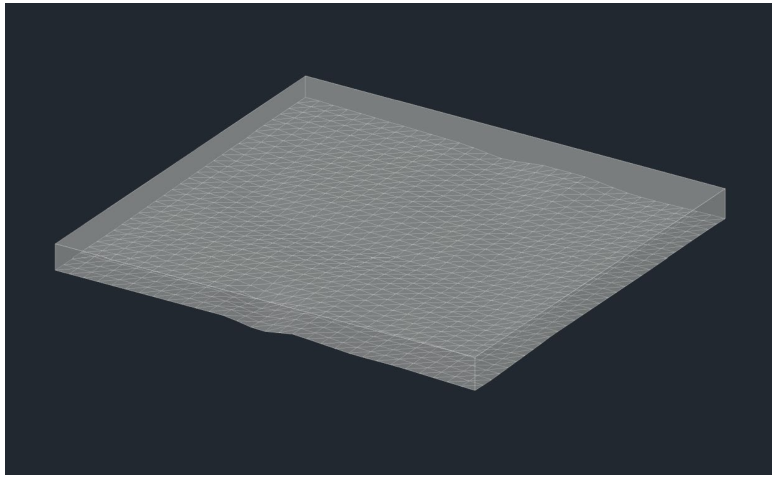
MMcfd: Million cubic feet per day

3. Project Progress - Case Studies

	Variable	High	Medium	Low
Pipeline characteristics	Pressure (MPa)	20	10	1
	Diameter (inch)	30	16	4
	Flow rate (MMcfd)	1300	600	30
Weather conditions	Wind speed (mph)	25	15	1
	Temperature (°F)	100	50	0

National Energy Technology Institute. (2015). A Review of the CO2 Pipeline Infrastructure in the U.S.

CFD Model for Case Studies



Terrain: Monticello, Mississippi

C	1%	4%	9%
Case 1	210 m	10 m	6 m
Case 2	1810 m	450 m	155 m

Variable	Case 1	Case 2
Pressure (MPa)	20	20
Diameter (inch)	4	30
Flow rate (MMcfd)	30	1300
Wind speed (mph)	1	1
Temperature (°F)	60	60

National Energy Technology Institute. (2015). A Review of the CO2 Pipeline Infrastructure in the U.S.

4. Summary and Discussion

- **Current machine learning tool should account for**
  - Local geography: Terrain type
  - Pipeline characteristics: Diameter, flow rate, and operating pressure
  - Weather: Wind speed and local ambient temperature

- The PIR will differentiate between areas with **minor (1%), medium (4%), and severe (9%)** health consequences from full pipeline ruptures.

- A CO_2 pipelines **dispersion database**.

- A user-friendly **web app or mobile app** will be developed.

4. Summary and Discussion

- **Discussion**
  - Any recommendations about weather conditions
  - Ground surface or roughness
  - CO_2 operating temperature
  - Technology to be integrated into this project

- **Terminology**: Potential Impact Radius (PIR) vs Potential Impact Distance (PID)

- **Future Work**
  - Machine learning model validation
  - Expect functions for software available for publics

Thank You!

Questions & Discussion