## NEUP CINR R&D 23-29622

# Development of the Technical Bases to Support Flexible Siting of Microreactors based on Right-Sized Emergency Planning Zones (EPZ)

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Contributors: Patrick Dudas (Penn State), Nonna Sorokina (Penn State)

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- Project Overview
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- Community and Regulatory Engagement Plan
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# Project Overview - Objectives

- Objective: Providing the technical basis to support the application of a right-sized Emergency Planning Zone (EPZ), to **aid in the deployment of a microreactor research, development, and deployment (RD&D) platform at the Penn State University Park campus as proposed by the Post-Industrial Midwest and Appalachia (PIMA) Nuclear Alliance (NA).**
- **The proposed study will serve as a template to provide flexible siting in support of future microreactor deployments** that may be placed closer to demand centers and industrial facilities, thereby making them more economically competitive.
- This study will support the Level III PRA assessments by developing methods and models to improve the characterization of **post-accident near-field atmospheric dispersion of radionuclide particles for a generic microreactor.**
- Furthermore, by describing the site-specific risks, **PIMA-NA FRONTIER** can adopt a more rapid **licensing approach,** which allows the site license application to proceed separately from the design certification application of the microreactor.

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# Project Team and Contributors

- PSU
  - **PI: Saya Lee (NUCE)**
  - **Co-PI: Gretta Kellogg (AIMI)** & Two contributors for VR/XR and One contributor for Economic Impact
  - Two Contributors from AIMI and Business supporting Community Engagement
  - Four Contributors from the Office of Physical Plant (**OPP**): Two Licensing and Two Site Selection
  - Two Contributors from the Office of Government and Community Relations (**OGCR**)

- Pitt-Tech
  - **Co-PI: Sola Talabi – EPZ, Stakeholders Engagement, and Licensing**

- Westinghouse (**WEC**)
  - Michael Valore & Six contributors
  - Two for Radionuclides Inventory and Mechanical Source Terms
  - Two for Licensing
  - One for Business Model / Community Outreach
  - One for Communication

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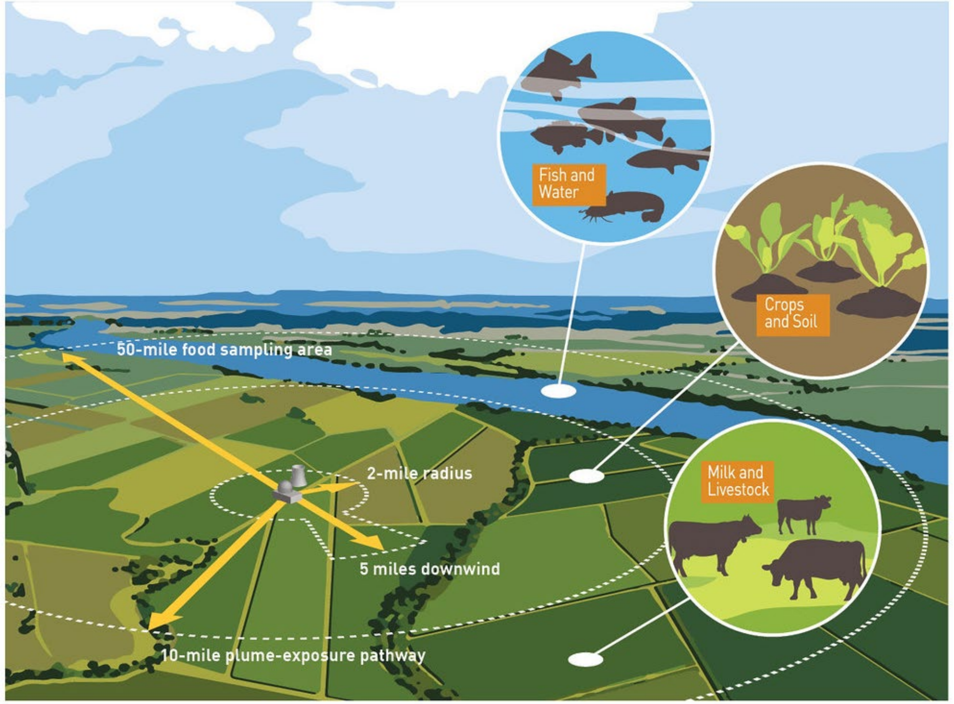
# Emergency Planning Zone (EPZ)

- Emergency planning zones (EPZs) are essential safety factors for nuclear facilities, where protective action plans, such as evacuation and sheltering

- NRC separates EPZ into Plume (PEPZ) and Ingestion (IEPZ)

- NUREG-0396 established the technical basis for the 10-mile (~16 km) PEPZ and 50-mile (~80km) IEPZ

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# EPZ sizing based on reactor thermal power level

A class 104 license for Research Reactors [ANSI/ANS 15.16]

| Authorized power level | Acceptable EPZ size |
|---|---|
| ≤2 MW | Operations boundary |
| >2 MW and ≤ 10 MW | 100 m |
| >10 MW and ≤ 20 MW | 400 m |
| >20 MW and ≤ 50 MW | 800 m |
| >50 MW | Will be determined on a case-by-case basis |

| Emergency zones (plume exposure pathway) | Whole body dose criteria | Dose evaluation period |
|---|---|---|
| U.S. | 10-50 mSv | 4 days |
| IAEA | 100 mSv | 7 days |
| Korea | 10 mSv | 2 days |
| Sweden | 20 mSv | 7 days |

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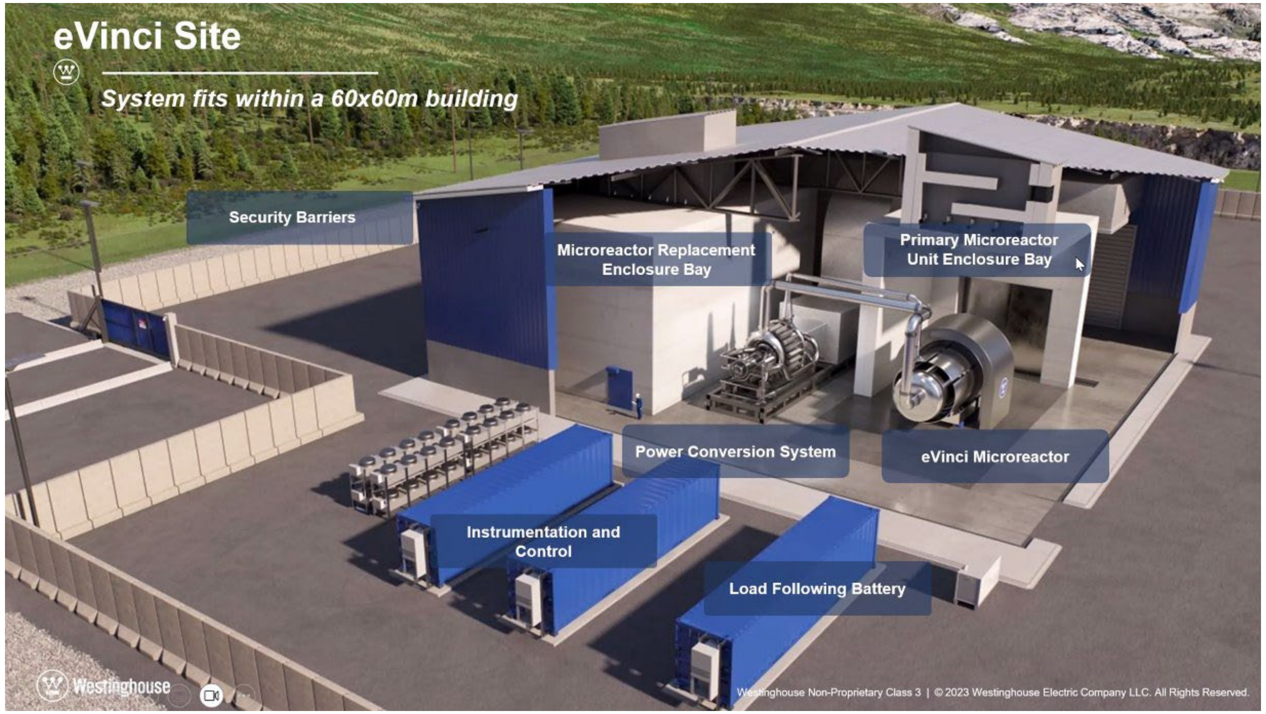
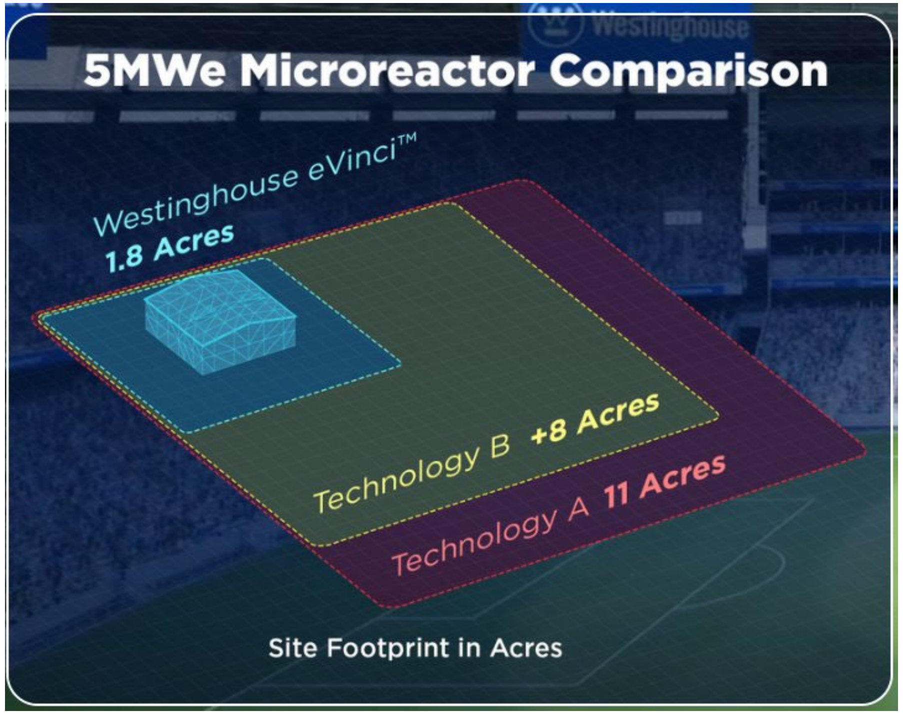
# Microreactor Siting

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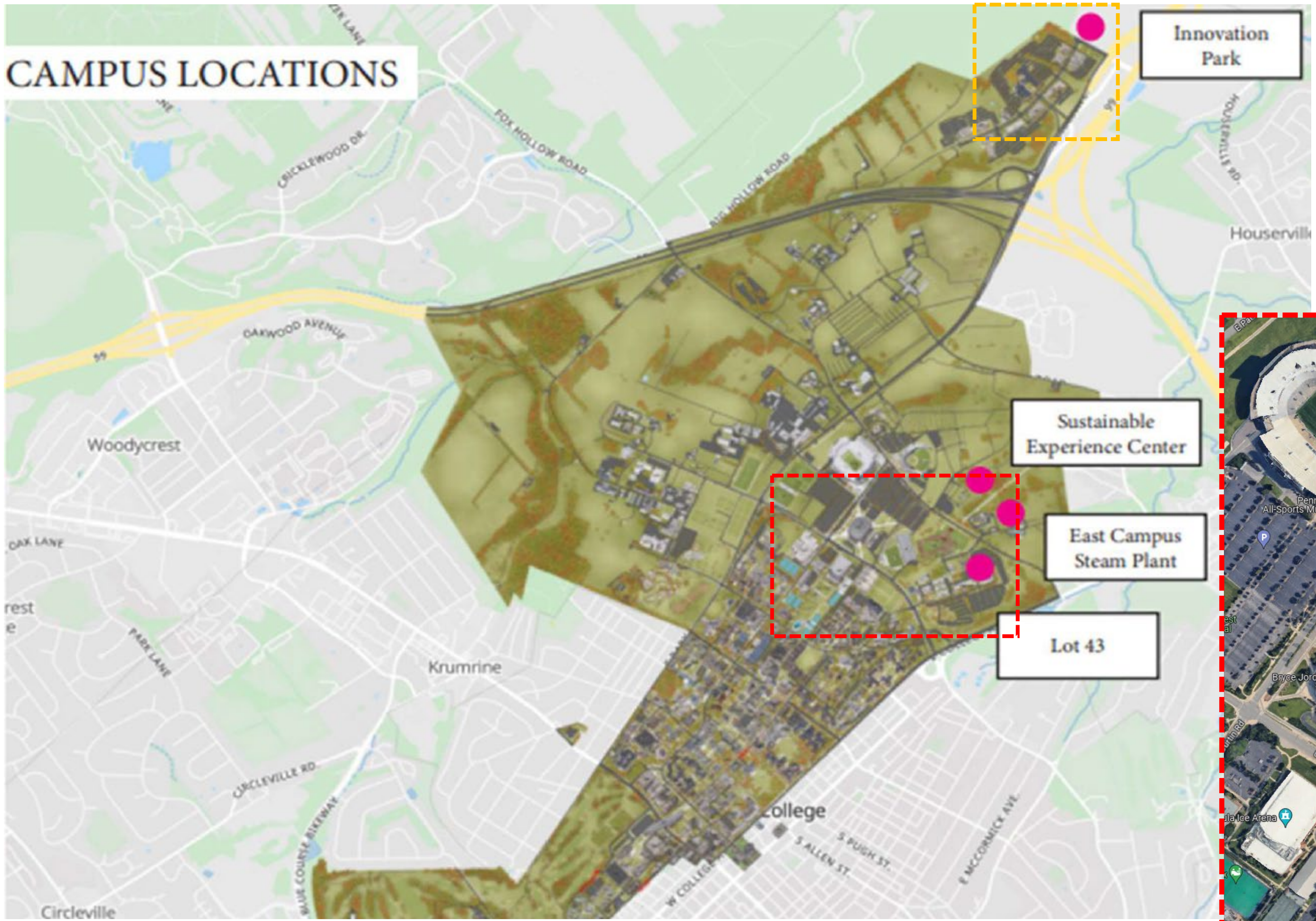
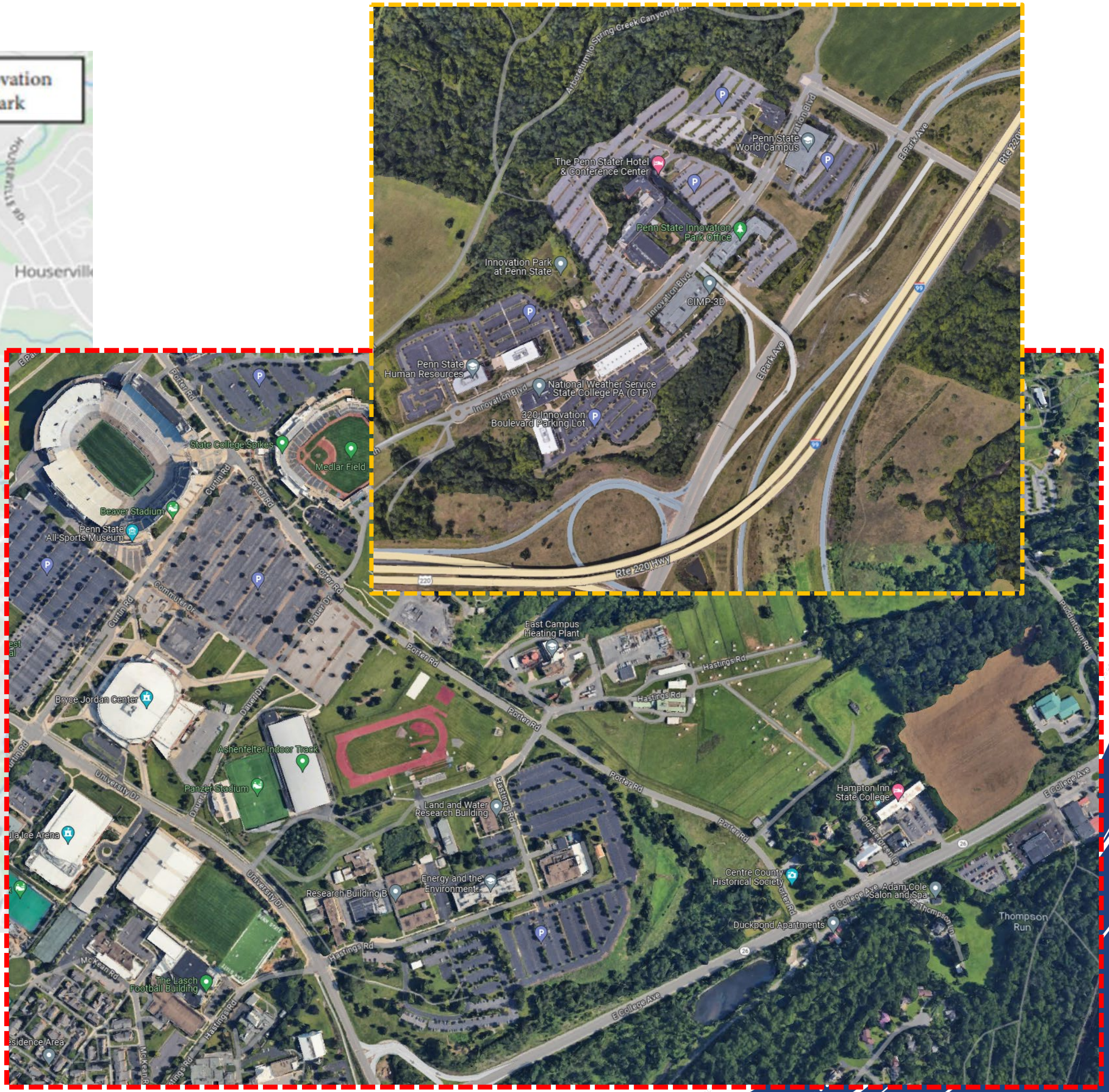
# Penn State Site-Specific Study Candidates 2025



# Penn State Site Candidates Update


State College Map

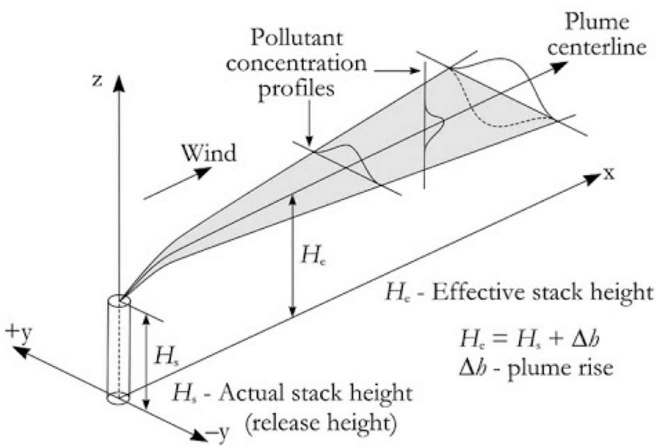
# Near-Field Atmospheric Dispersion

- Near-Filed Atmospheric Transport and Dispersion (ATD)
  - Field measurements,
  - Wind tunnel measurements,
  - Particle tracking based on computational fluid dynamics (CFD), and
  - Empirical models such as Gaussian Plume Models

$$C(x,y,z,H) = \frac{Q}{2\,\pi\sigma_y\sigma_z u}\exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]\left\{\exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right]+\exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right]\right\}\exp\left[-\frac{\lambda x}{u}\right]DF(x)$$

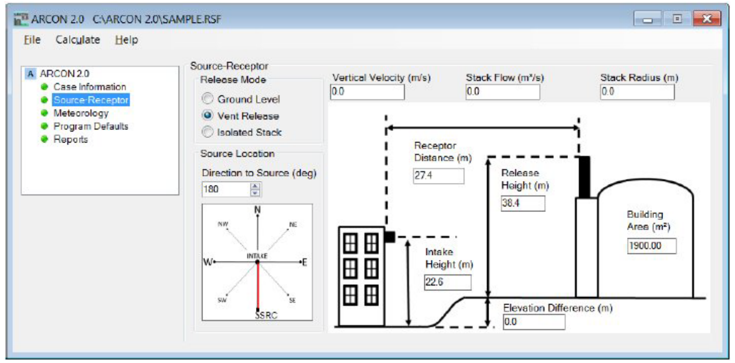
Treats **crosswind** ($\boldsymbol{\sigma_y}$) and **vertical** ($\boldsymbol{\sigma_z}$) dispersion as a Gaussian distribution based on weather stability classes

**Gaussian Plume model**



# EPZ – Atmospheric Dispersion Code

- ARCON



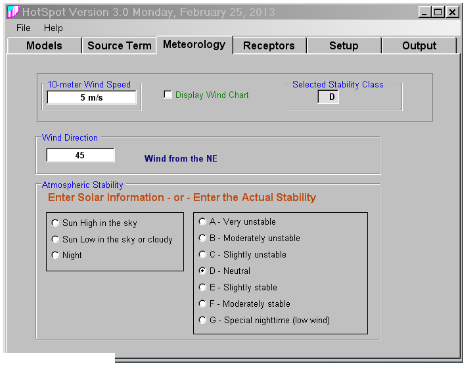

Atmospheric Relative CONcentration in Building Wakes

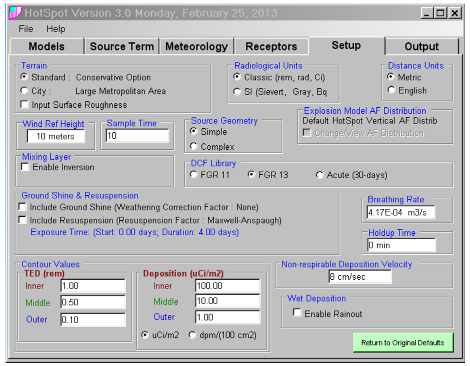
Code developed for the NRC, used to calculate $\chi/Q$ in support to habitability assessment

Valid for near-field distances (>10 m) range

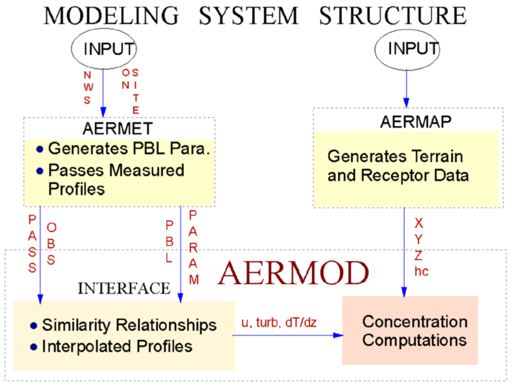
Incorporates building wake effects

- HotSpot Heath Physics



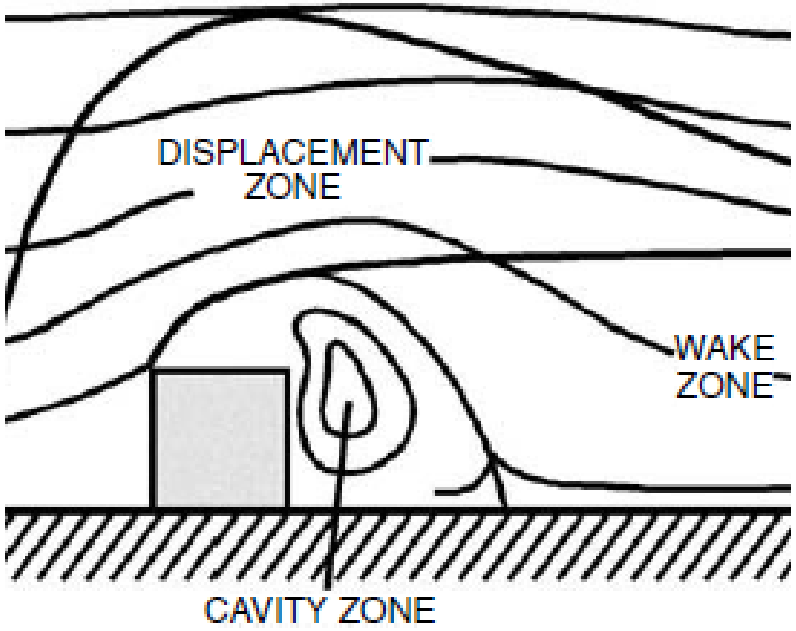

- AERMOD



# Building Wake & Meandering

Tall buildings and other structures will disturb the flow of air, creating three main zones of flow:

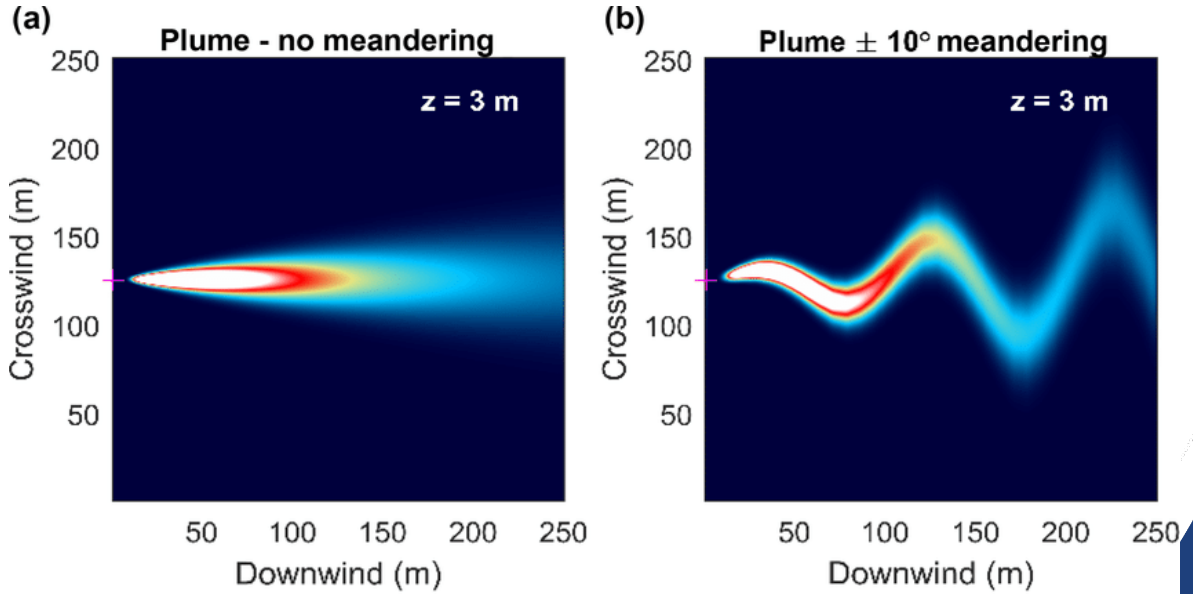
- Displacement Zone
- Wake Zone
- Cavity Zone




Plume meander should be consider when:

Low wind speeds ≤ 6 m/s

For distances ≤ 800 m and stability classes D, E, F, and G (NRC, 1983)




(Caulton, Dana R. et al., 2018)

# ARCON Gaussian Plume model

$$\frac{\chi}{Q} = \frac{1}{\pi \sigma_y \sigma_z U} \exp\left[-0.5\left(\frac{y}{\sigma_y}\right)^2\right] \exp\left[-0.5\left(\frac{h_e - h_i}{\sigma_z}\right)^2\right]$$

$$\Sigma_y = \left(\sigma_y^2 + \Delta\sigma_{y1}^2 + \Delta\sigma_{y2}^2\right)^{1/2}$$

$$\Sigma_z = \left(\sigma_z^2 + \Delta\sigma_{z1}^2 + \Delta\sigma_{z2}^2\right)^{1/2}$$

Sub-script 1: Low wind speed (or wind meandering)

Sub-script 2: Building wake

$$\Delta\sigma_{y1}^2 = 9.13\text{x}10^5\left[1-\left(1+\frac{\text{x}}{1000\text{U}}\right)\exp\left(-\frac{\text{x}}{1000\text{U}}\right)\right]$$

$$\Delta\sigma_{z1}^2 = 6.67\text{x}10^2\left[1-\left(1+\frac{\text{x}}{100\text{U}}\right)\exp\left(-\frac{\text{x}}{100\text{U}}\right)\right]$$

$$\Delta\sigma_{y2}^2 = 5.24\text{x}10^{-2}U^2A\left[1-\left(1+\frac{\text{x}}{10\sqrt{A}}\right)\exp\left(-\frac{\text{x}}{10\sqrt{A}}\right)\right]$$

$$\Delta\sigma_{z2}^2 = 1.17\text{x}10^{-2}U^2A\left[1-\left(1+\frac{\text{x}}{10\sqrt{A}}\right)\exp\left(-\frac{\text{x}}{10\sqrt{A}}\right)\right]$$

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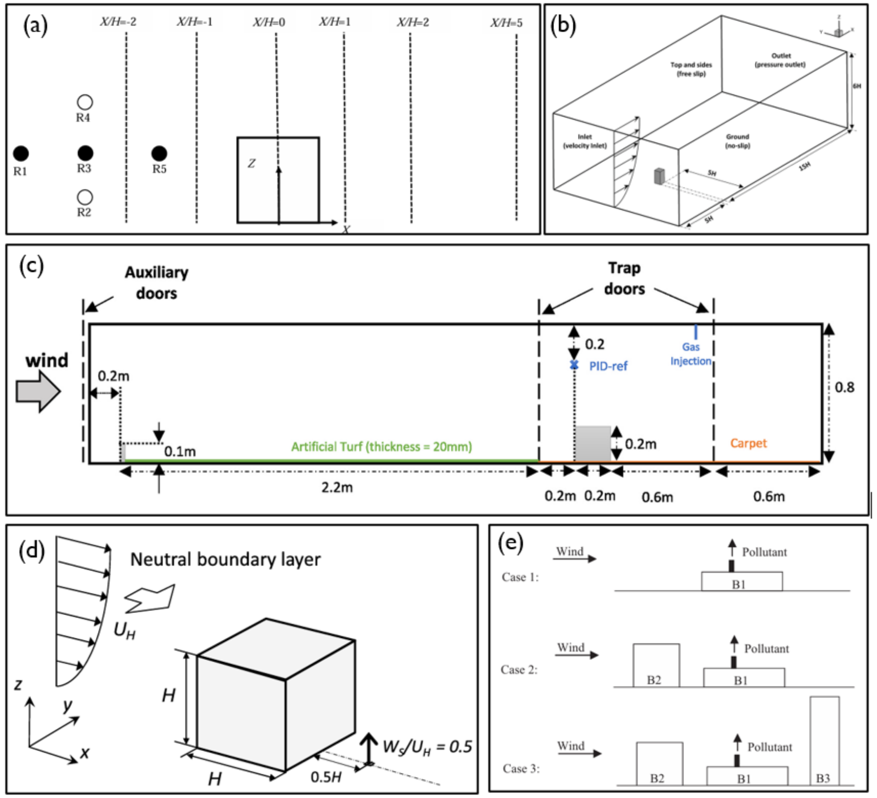
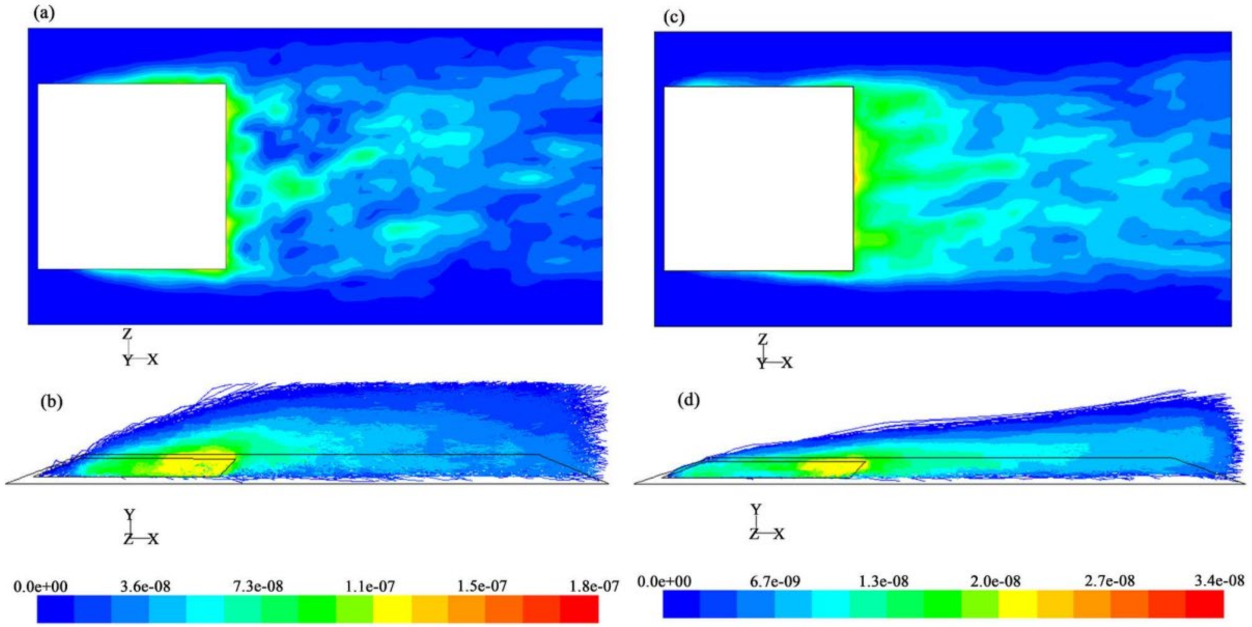
# Existing CFD/Experiment Benchmark



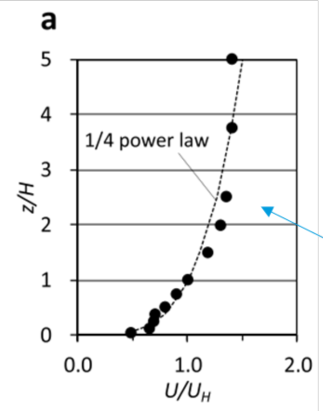

Works to be compared to Gaussian ATD models: Woodward et al. [71] (a); Keshavarzian et al. (2021) [70] (b); Keshavarzian et al. (2022) [66] (c); Chavez et al. [72] (d); and Tominaga and Stathopoulos (2018) [74] (e).




Top and side views of particle concentration found using RLZ k-e by Nimmatoori et al. for high (right) and low (left) wind speeds [78].

# Simulation Setup to Reproduce Tominaga 2018

$$\frac{U(z)}{U_{ref}} = \left(\frac{z}{z_{ref}}\right)^{1/4}$$



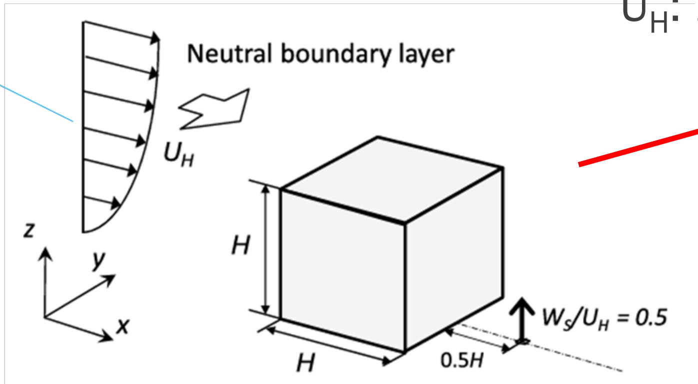
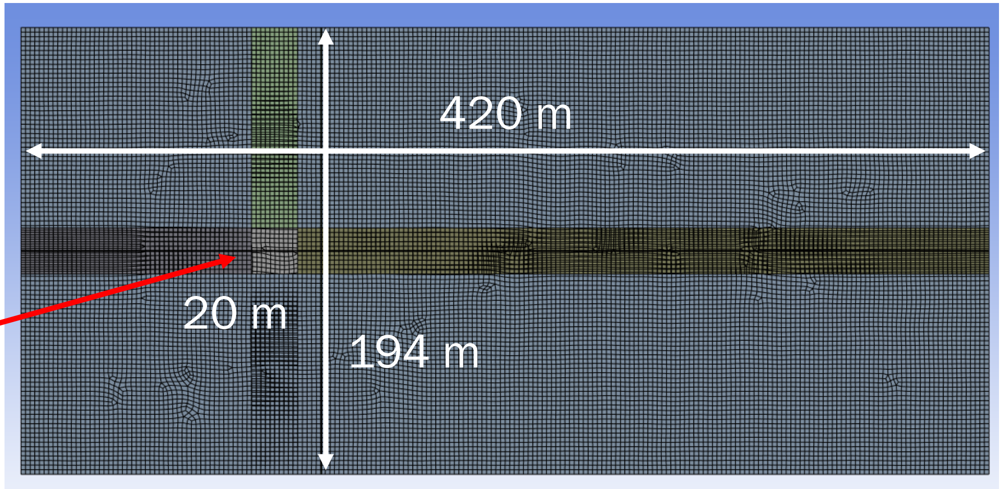
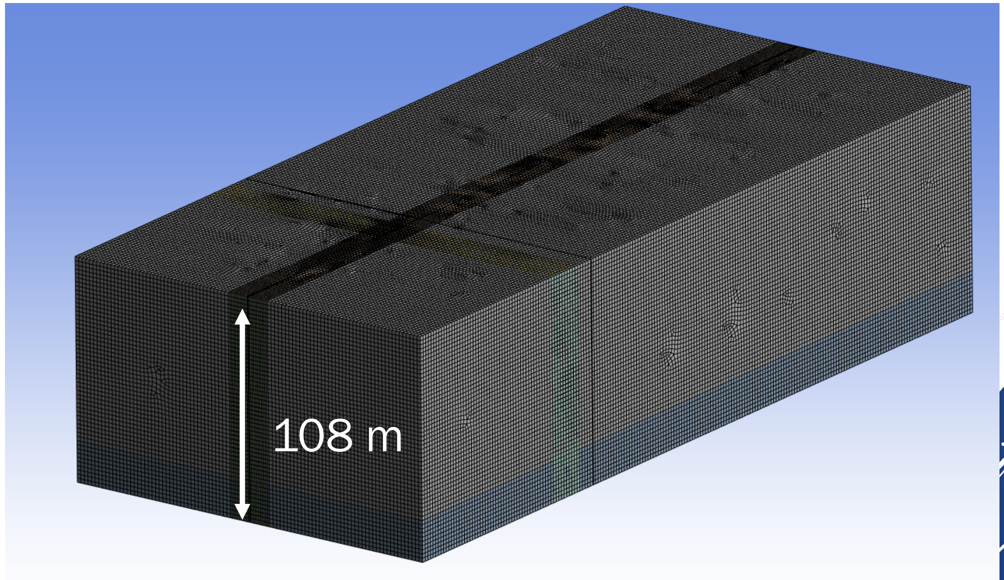




**Fig. 1.** Model flow field.

$U_H$: 1.26 m/s

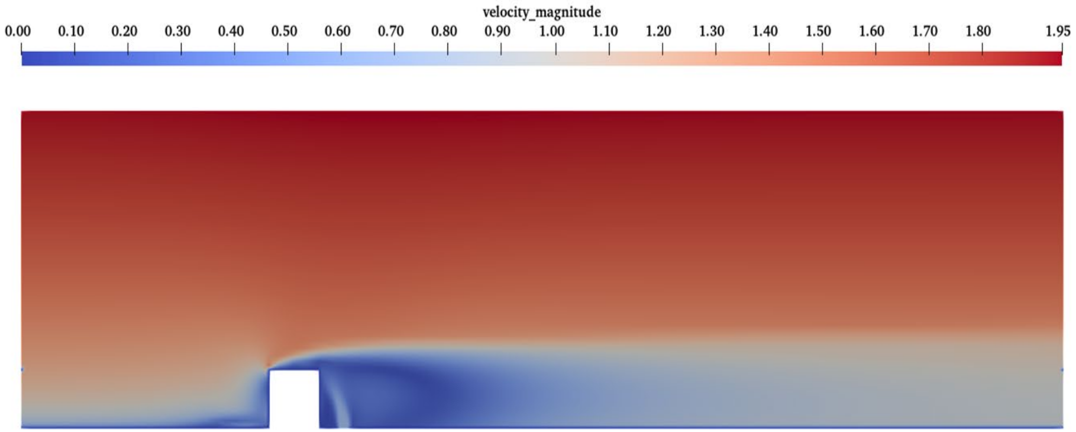


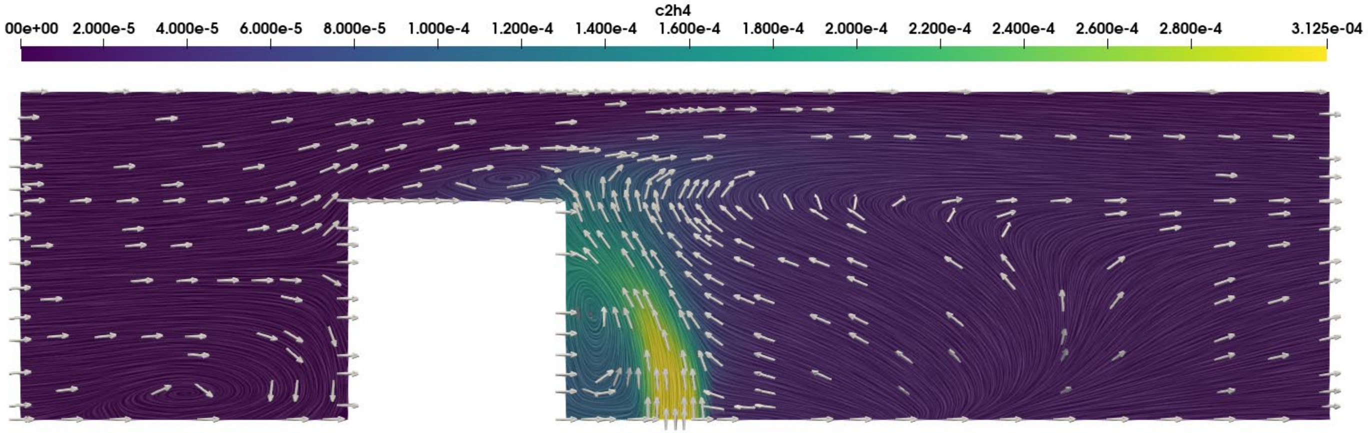

- Geometric parameters are linearly scaled
- Non-geometric parameters are scaled based on ¼ power law
- $C_0$ is maintained (312.5 ppm)

| Parameter | Experiment | 1:100 |
|---|---|---|
| $H$ [m] | 0.2 | 20 |
| $U_H$ [m/s] | 0.4 | 1.26 |
| $W_s$ [m/s] | 0.2 | 0.63 |
| $C_0$ [ppm] | 312.5 | 312.5 |

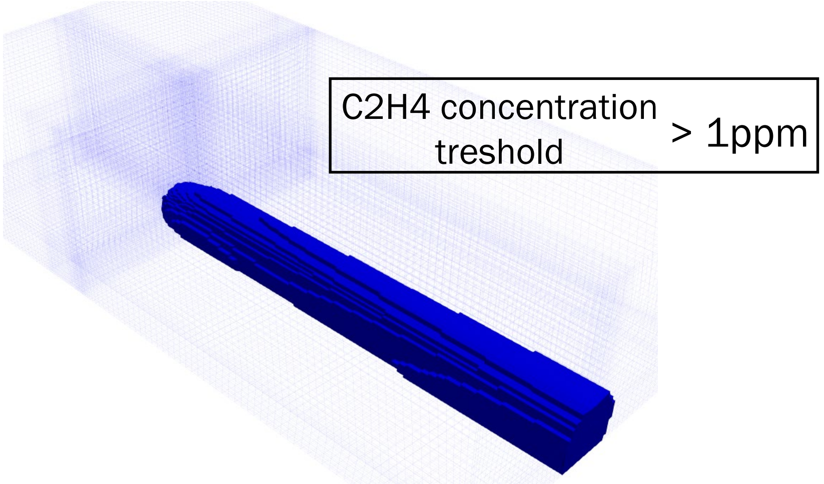
# Updated CFD Simulation



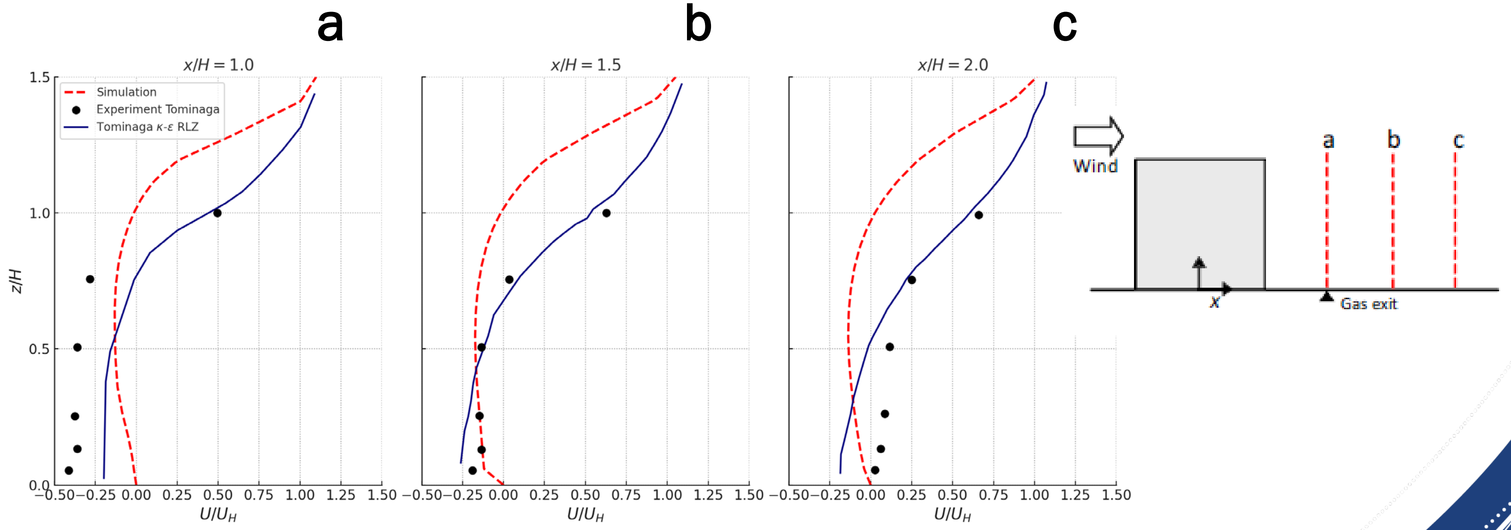

Velocity magnitude




Velocity streamlines and C2H4 concentration

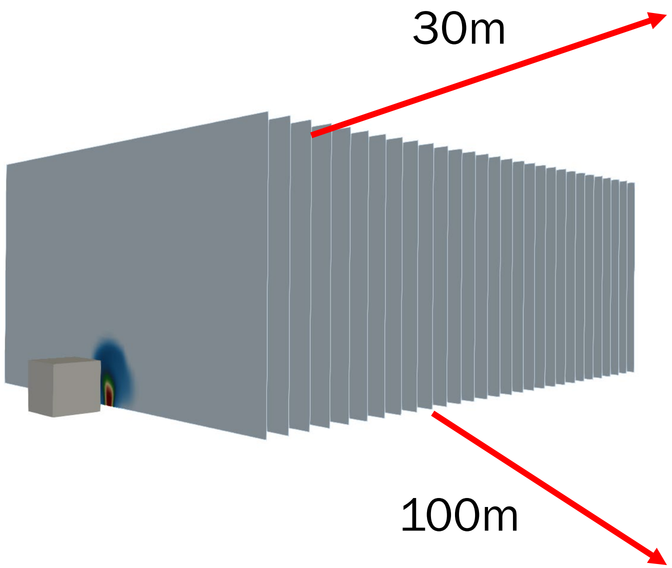


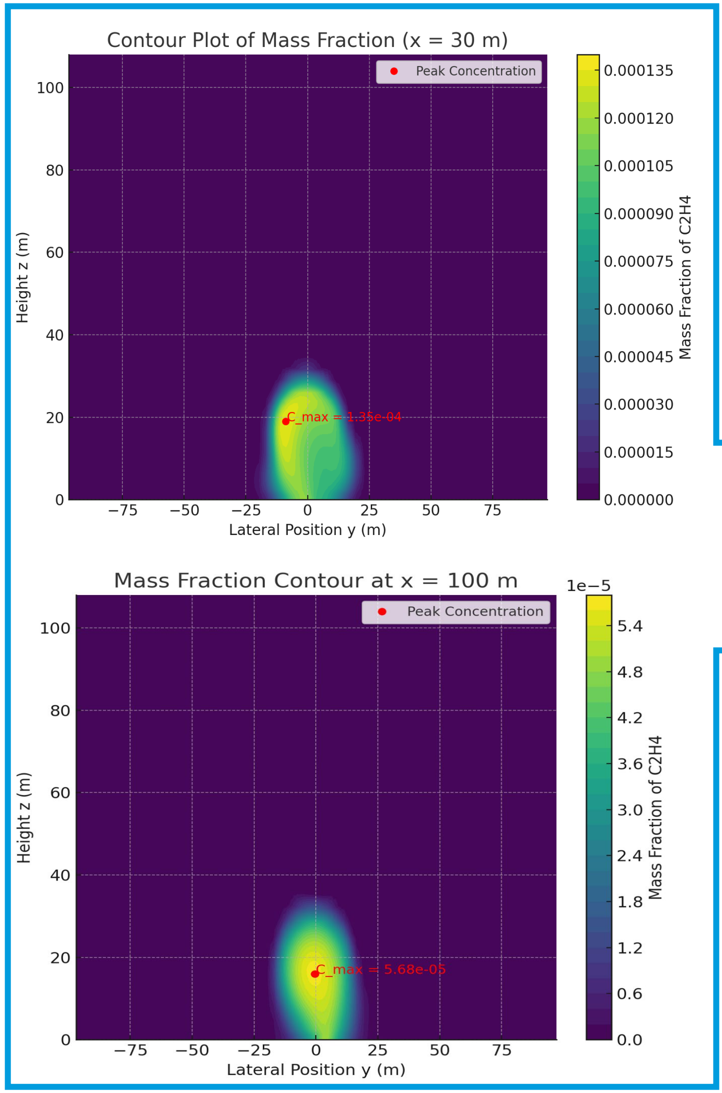

C2H4 threshold contour




Normalized velocity by normalized vertical distance comparison

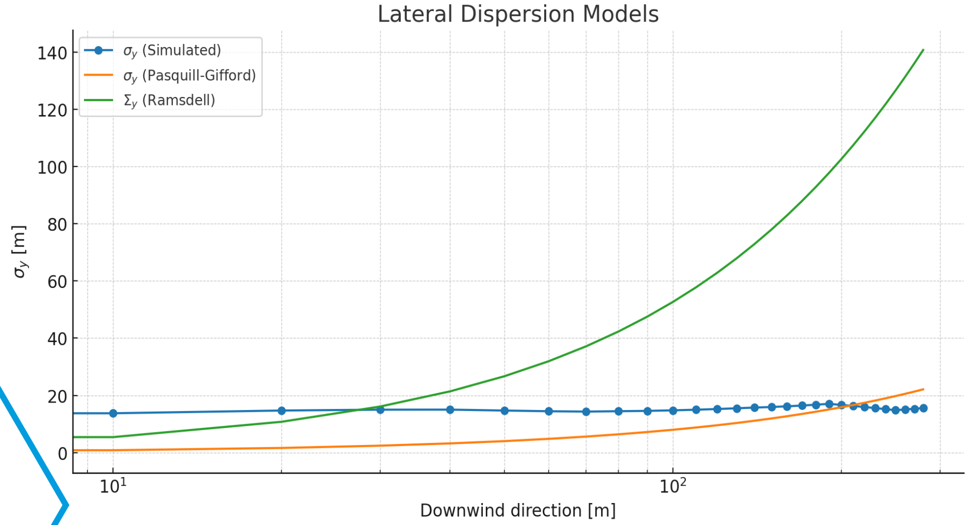
# Near-Field Pollutant Dispersion

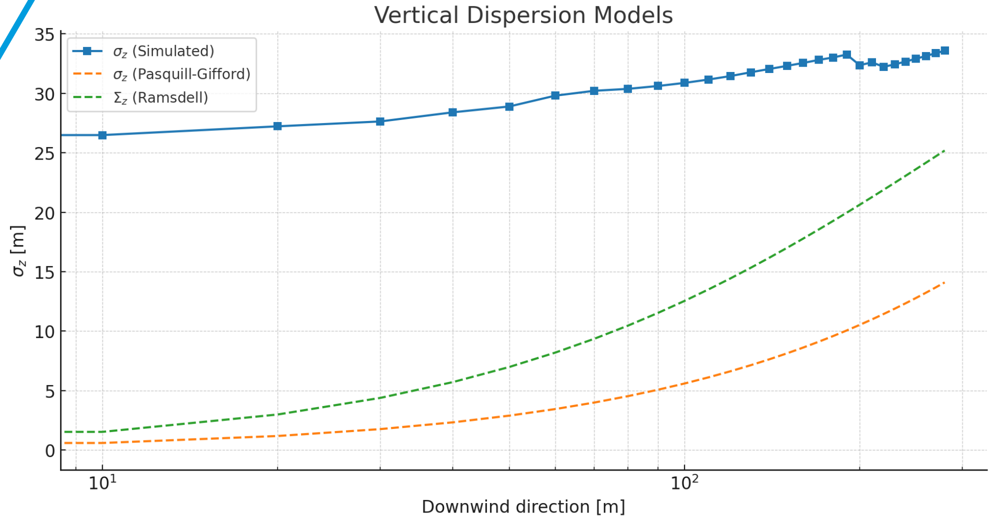


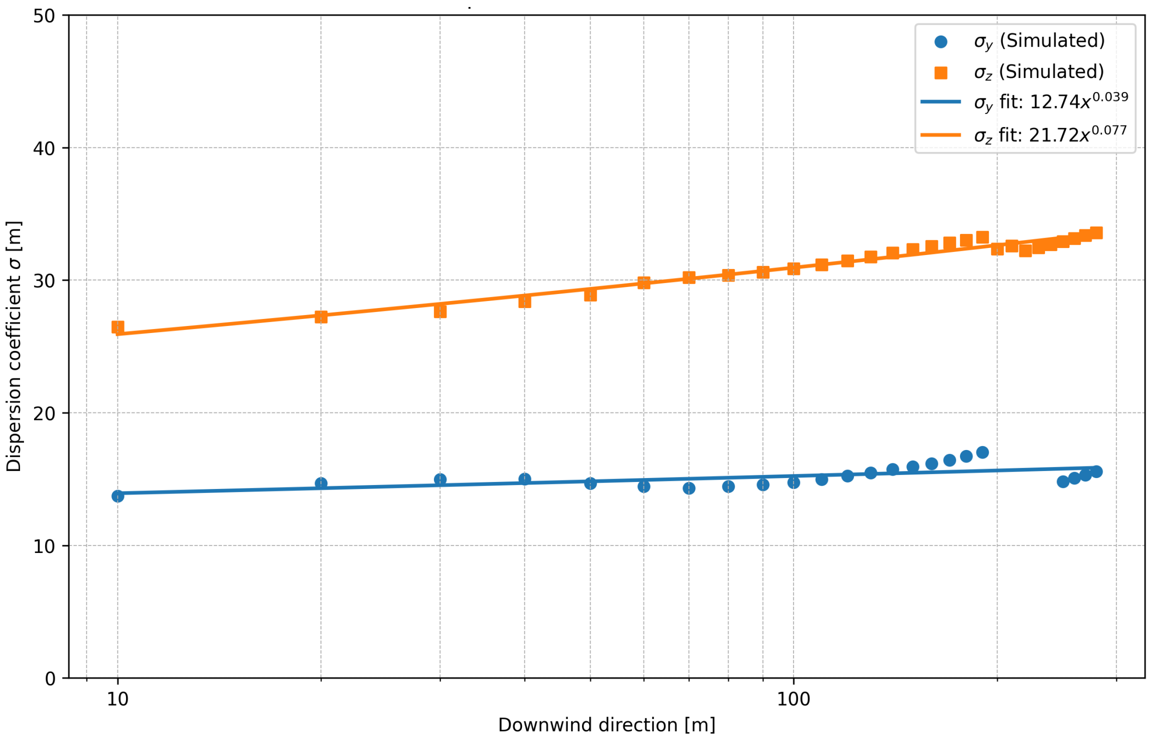

**Larger $\sigma$ implies:**

- Wider plume spread
- Lower peak concentration



# Near-Field Pollutant Dispersion




Lateral ($\sigma_y$) and Vertical ($\sigma_z$) fitted dispersion coefficients

Table: Neutral (Class D) weather stability dispersion coefficients

| | Formula |
|---|---|
| Pasquill | $\sigma_y = \frac{0.11x}{\sqrt{1+0.0001x}}$ <br> $\sigma_z = \frac{0.06x}{\sqrt{1+0.0015x}}$ |
| Ramsdell | $\Sigma_y = \left(\sigma_y^2 + \Delta\sigma_{y1}^2 + \Delta\sigma_{y2}^2\right)^{1/2}$ <br> $\Sigma_z = (\sigma_z^2 + \Delta\sigma_{z1}^2 + \Delta\sigma_{z2}^2)^{1/2}$ |
| Site-specific | $\sigma_y = 12.74x^{0.039}$ <br> $\sigma_z = 21.72x^{0.077}$ |

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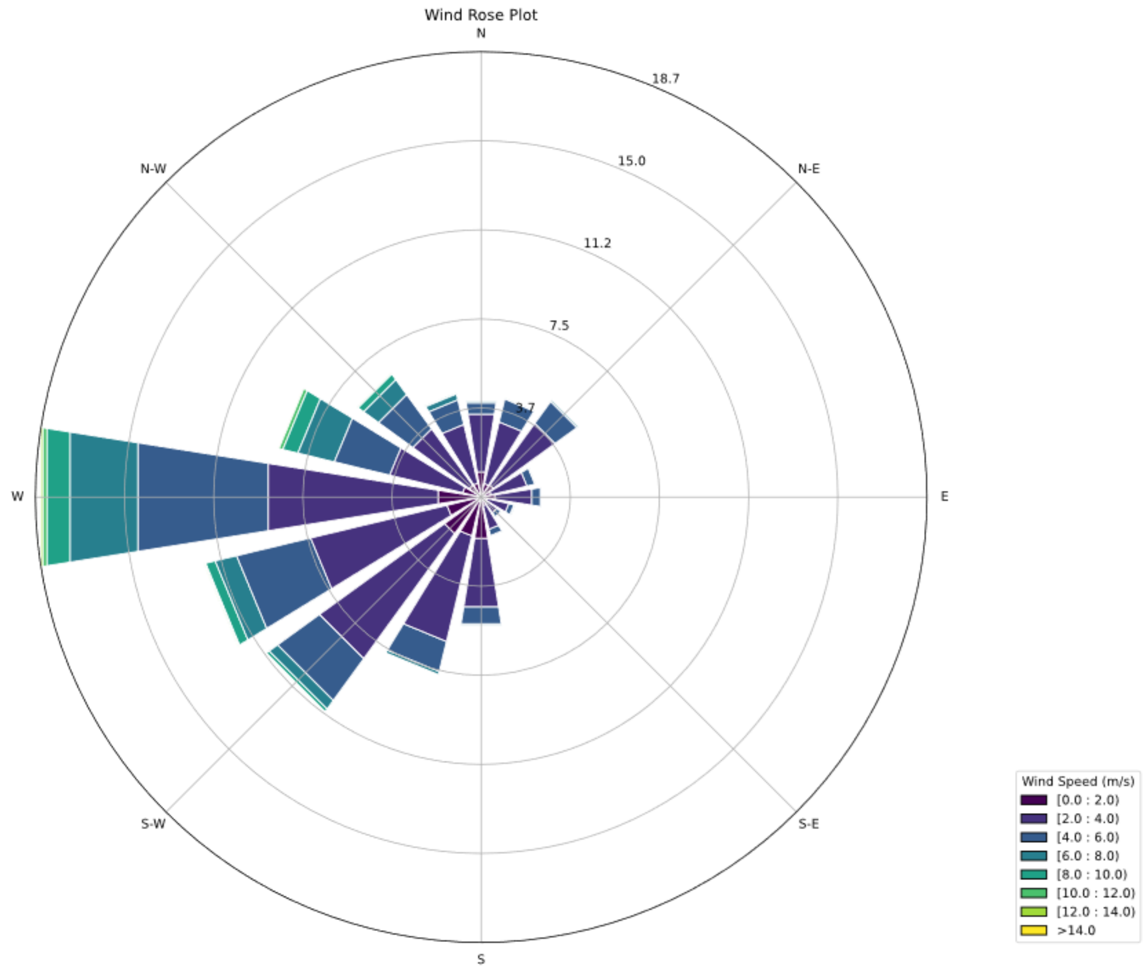
# Meteorological Data – Penn State

- Data is treated as the requirements of RG 1.145
- Hourly Weather data (wind speed/direction/stability)
- RG 1.23 requires at least 1 to 3 years of onsite meteorological data





**Data selection for site: UNIVERSITY PARK, PA**
**Database: FAA_RAW**

**Metadata:**

**Id:** KUNV
**Name:** UNIVERSITY PARK
**County:** CENTRE
**State:** PA
**Lat:** 40.850
**Lon:** -77.850
**Elev (ft):** 1240.0
**Start_date:** 1983-09-28
**End_date:** 2024-02-13

Meteorological data for 5 years is ideal, 3 years minimum
15-minute intervals, 64 direction weather data input
http://climate.met.psu.edu/data/ida/index.php?t=3&x=faa_raw&id=KUNV

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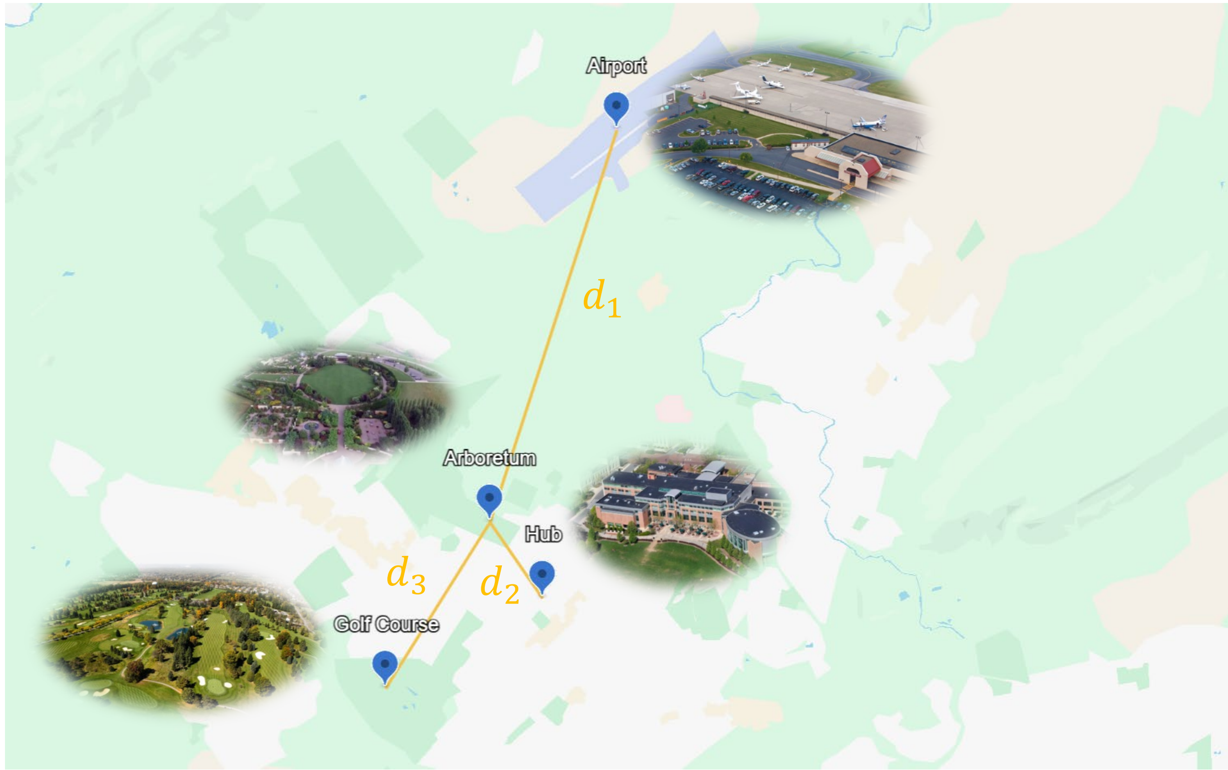
# Weather Data Prediction

Weather data prediction was performed using distance-weighted averaging of nearby measurement towers to mitigate the need for 1–3 years of on-site meteorological measurements in nuclear microreactor licensing.




State College map and weather station locations

**Inverse Distance Weighting (IDW) Interpolation**

$$u(t) = \sum_{i=1}^{N} \omega_i u_i(t)$$

$$v(t) = \sum_{i=1}^{N} \omega_i v_i(t)$$

where, $\omega_i = \frac{1}{d_i^p}$

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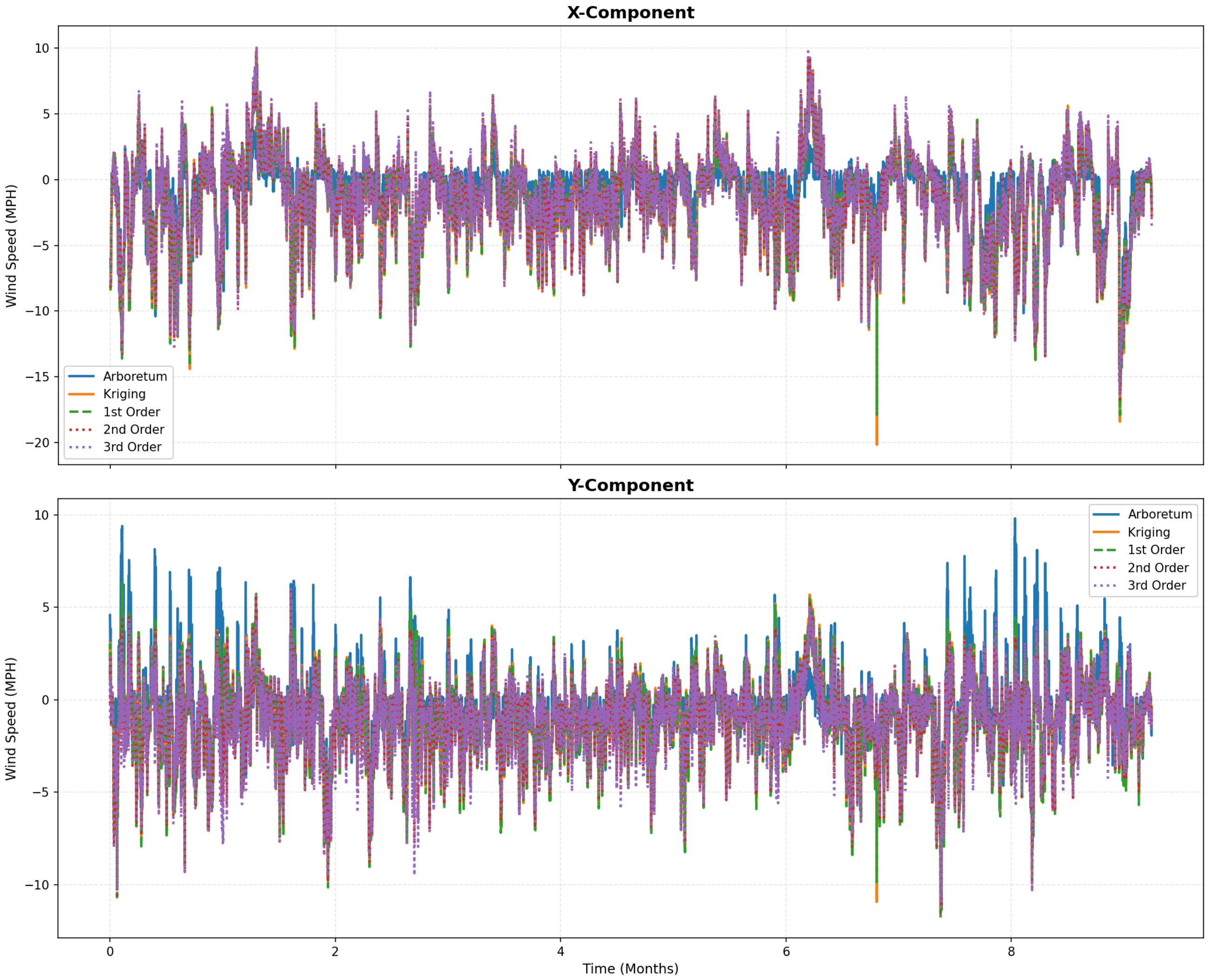
# Weather Data Prediction




| Method | Mean | MAE | RMSE | R^2 |
|---|---|---|---|---|
| Linear | 3.5808 | 1.2280 | 1.6022 | 0.5336 |
| Squared | 3.5630 | 1.1925 | 1.5138 | 0.5839 |
| Cubic | 3.6112 | 1.2376 | 1.5561 | 0.5603 |
| Kriging | 3.6193 | 1.2664 | 1.6506 | 0.5053 |

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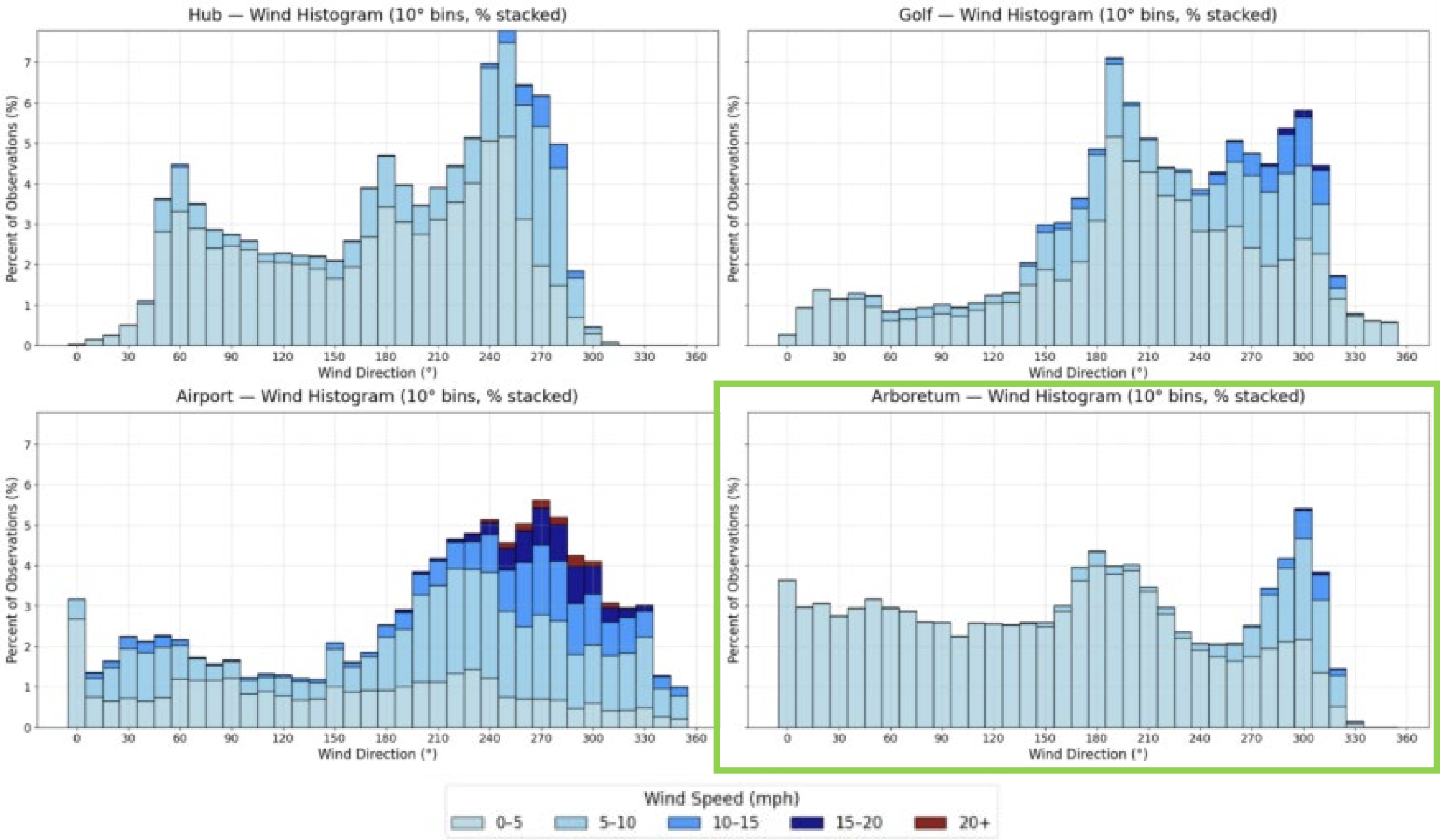
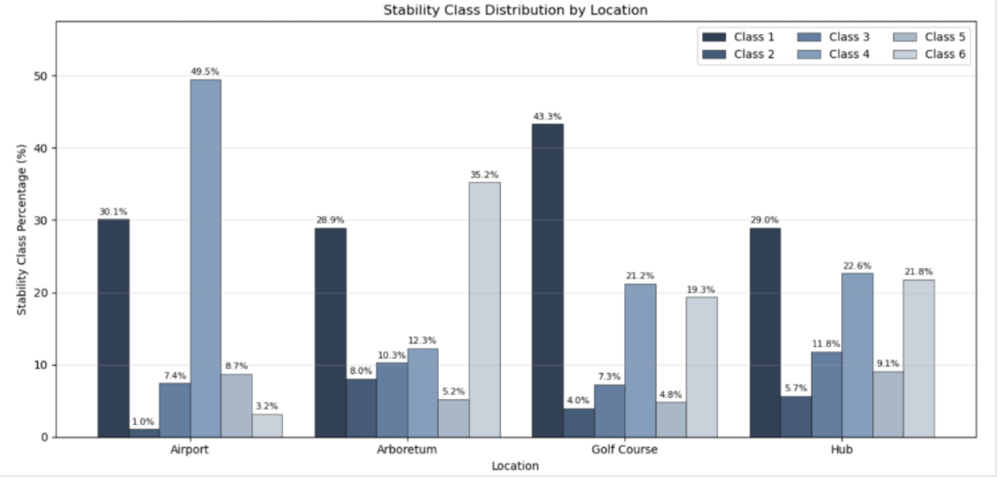
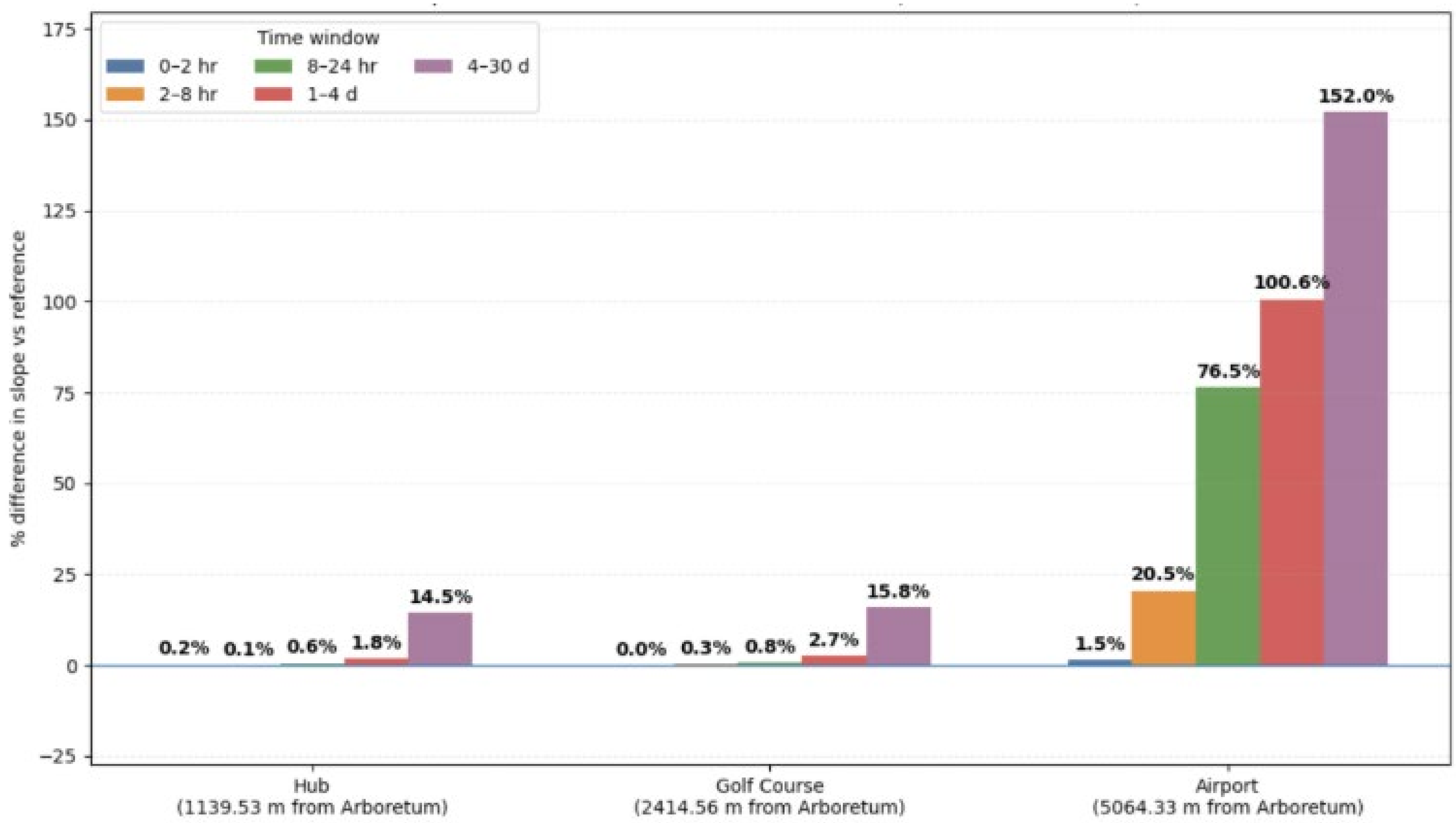
# Weather Data Distribution near the Site Candidate



# $\chi/Q$ Comparison Per Location




Percent difference of change in $\chi/Q$

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# Community Engagement Plan

- Community Engagement
  - Nuclear Safety Approach – Being performed by EPZ analysis
  - Benefit to Local Community – Economy and Jobs

- 2024-2025: Sociotechnical Readiness Level (SRL) and Market Analysis

- 2025-2026: Education and Workforce Development Framework

- Immersive Experience (XR) Tool Development

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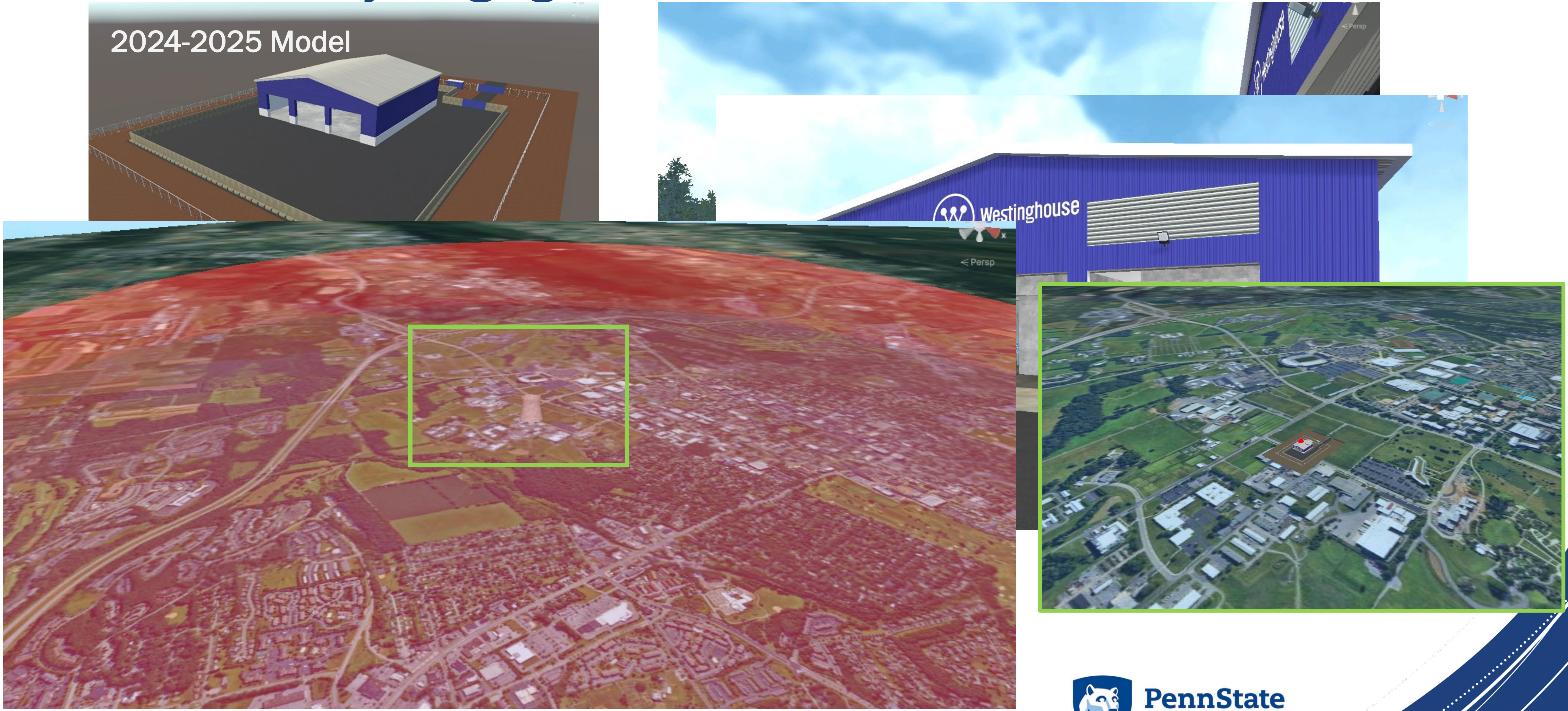
# Immersive Experience (XR) Development for Community Engagement

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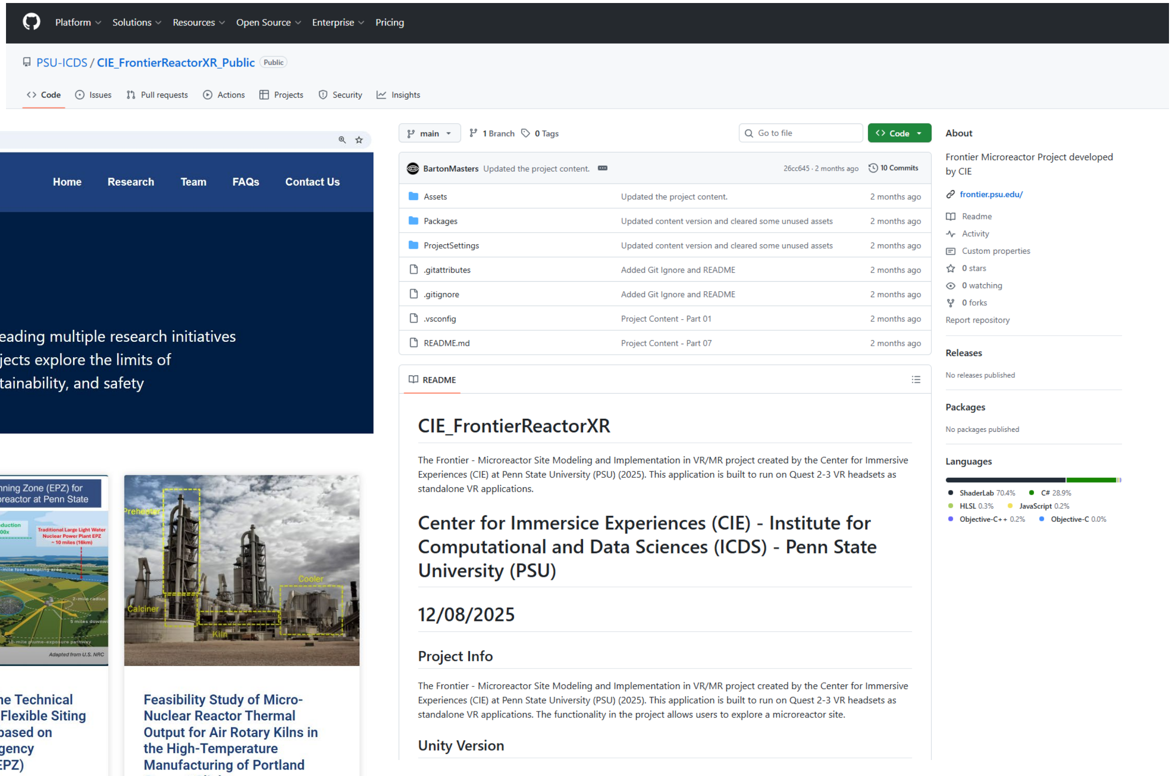
# FRONTIER Webpage and GitHub

https://frontier.psu.edu/research-initiatives/







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# Conclusions

- Recommendations on Atmospheric Dispersion model
  - Penn State Site-Specific Study has been continued.
  - Wind estimation using surrounding weather stations – IDW & Kriging Method
  - Extended CFD simulation is being performed.

- Community and Regulatory Engagement
  - Developing a framework of Nuclear Energy Education and Workforce Development + De-Risking Investment in Nuclear Energy
  - XR Model has been upgraded.
  - Regulatory Engagement: This project will summarize the regulatory engagement effort made during the project period as a guideline for other microreactor developers in the final report.

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# Outcomes

**Journal Papers**

1. Kim, H., Lee, S., Sorokina, N., & Sunoj, D. (2026). Sociotechnical Readiness Level and Natural Language Processing: Tools for Measuring and Managing Societal Acceptance of Nuclear Energy. Nuclear Technology, 1–24. https://doi.org/10.1080/00295450.2025.2588949

**Conference Papers**

1. Misha Goldberg, Erik Hisahara, Christopher Balbier, Saya Lee, "Weather Estimation of a Microreactor Site Candidate using Nearby Weather Stations at PSU" – Accepted for 2026 ANS Student Conference

2. Erik Hisahara, Christopher Balbier, Saya Lee, Rohan Biwalkar, Sola Talabi, "Preliminary Study of Microreactor Emergency Planning Zone." 14th International Topical Meeting on Nuclear Reactor Thermal-Hydraulics, Operation and Safety (NUTHOS-14), August 24 – 29, 2024, Vancouver, Canada.

3. Erik Hisahara, Christopher Balbier, Saya Lee, Rohan Biwalkar, Sola Talabi, "Preliminary Parametric Study of Microreactor EPZ," American Nuclear Society Transactions, Vol. 130, No. 1, 2024, 857-860

4. Kim H, Lee S, Sorokina N, Sunoj D. "Sustainable Energy Marketplace and Societal Readiness." Transactions of the American Nuclear Society. 2025;132(1):130-2.

5. Kim H, Lee S, Sorokina N, Sunoj D. "Social Readiness Level and Natural Language Processing: tools for measurement and management of societal acceptance of nuclear energy." Transactions of the American Nuclear Society. 2025;132(1):137-9.

# Thank You!

Questions?