

Laboratory Studies of Wind Turbines

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Challenges:

Educate decision makers (research) that we still have a lot to learn.

Cannot Predict Wind Turbine Performance

Scale of Modern Wind Turbines



Source: Enercon Wind



Source: Siemens AG



Source: REpower



Source: Siemens AG



Cannot Predict Wind Turbine Performance



Size of wake (domain): kilometers

Smallest length scale in boundary layer on blade: less than a millimeter

Cannot simulate **numerically** or test in a conventional **wind tunnel**

Testing and Studying Large Wind Turbines

~~Reynolds number~~ $\text{Re} = \frac{\rho R U}{\mu}$ ~~Tip Speed Ratio~~ $\lambda = \frac{\omega R}{U}$

Velocity

$$\frac{R_{\text{model}}}{R_{\text{full}}} \approx \frac{1}{100} \rightarrow \begin{aligned} U_{\text{model}} &\approx 1000 \text{ (m/s)} \\ \omega_{\text{model}} &\approx 100,000 \text{ (RPM)} \end{aligned}$$

Standard
atmospheric
conditions and

$$U = 10 \text{ m/s}$$



Source: NREL.gov



Source: nhpr.org



Full-Scale Similarity with Wind Turbines

Reynolds number

$$Re = \frac{\rho 2RU}{\mu}$$

Fluid Density

Velocity

Tip Speed Ratio

$$\lambda = \frac{\omega R}{U}$$



High Reynolds number Test Facility (HRTF)

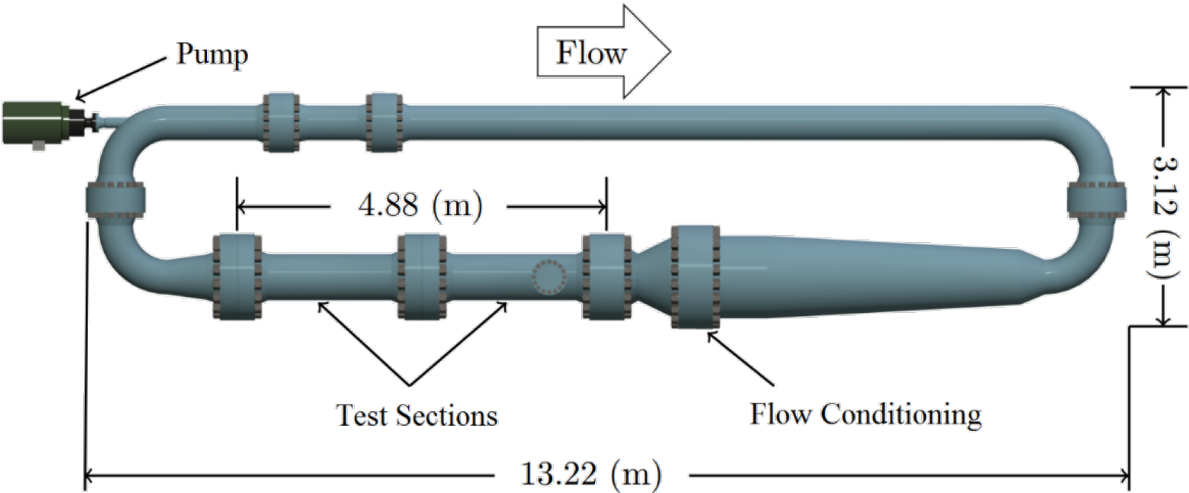
Working Pressure	1 – 238 Atm.
Velocity	1 – 10 m/s
Sound Speed	291 m/s – 330 m/s

Using compressed air as working fluid

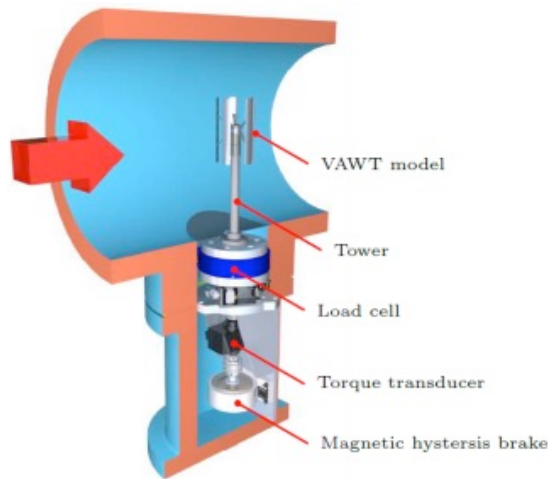
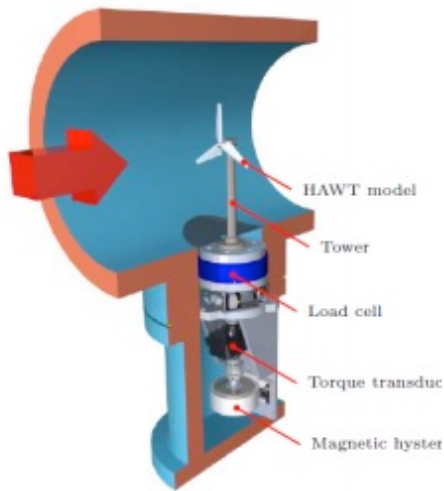
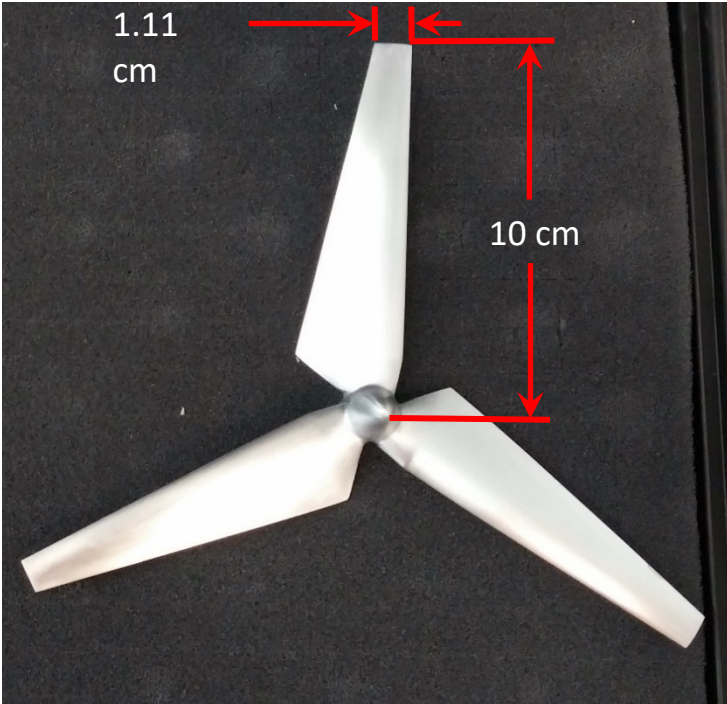
$$\frac{R_{model}}{R_{full}} = \frac{1}{100} + \frac{\rho_{model}}{\rho_{full}} = 100$$

$$\frac{\omega_{model}}{\omega_{full}} \approx 100 \text{ (4,000 RPM)}$$

$$\frac{U_{model}}{U_{full}} = 1$$



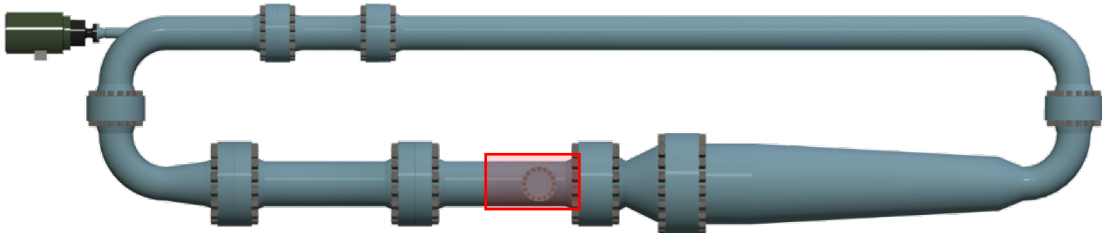
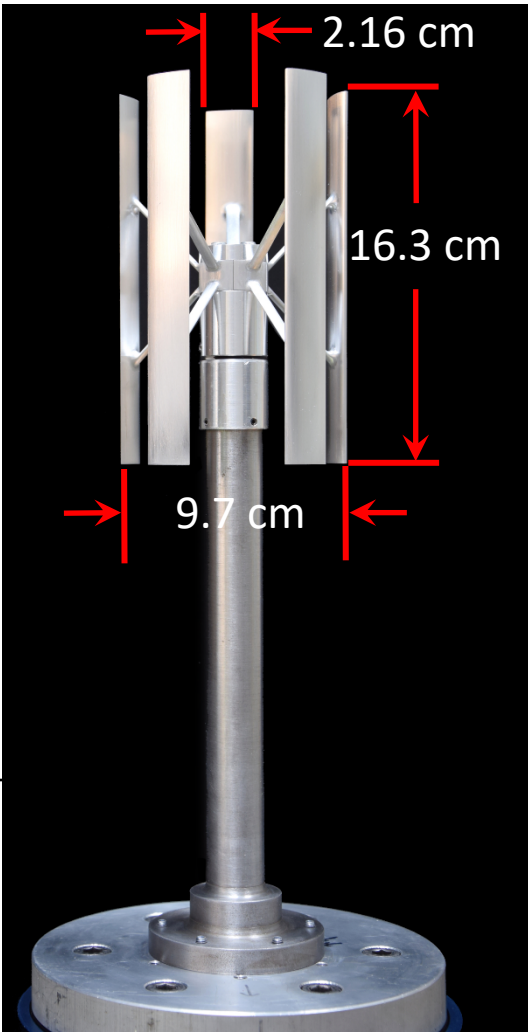
Test Setups and Models



Challenge: Forces and Power vary proportionally to density

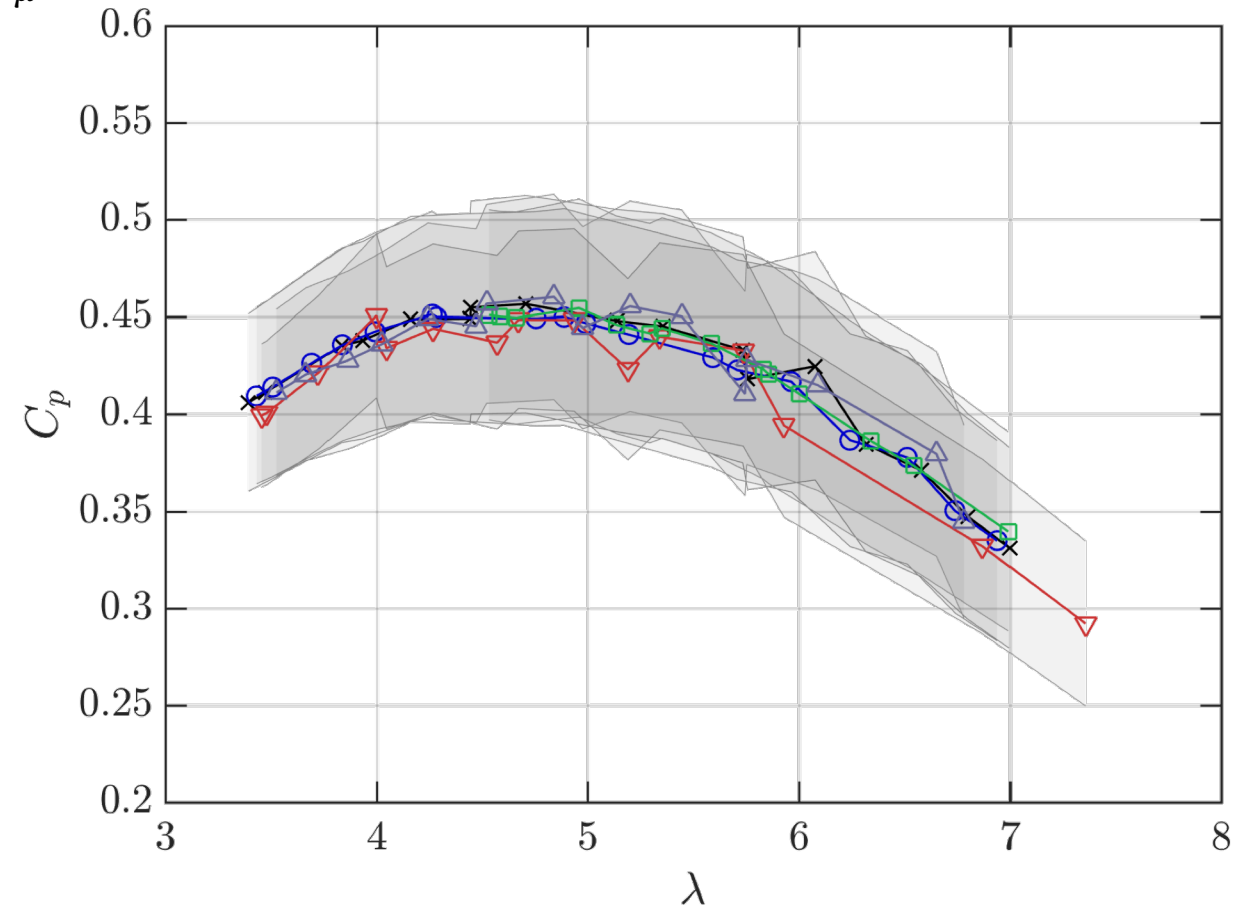
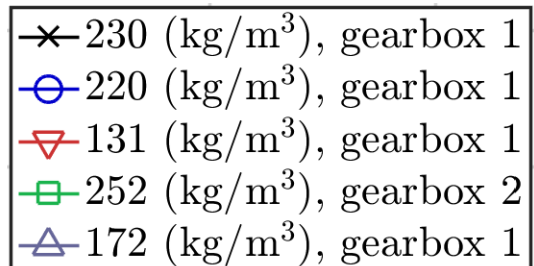
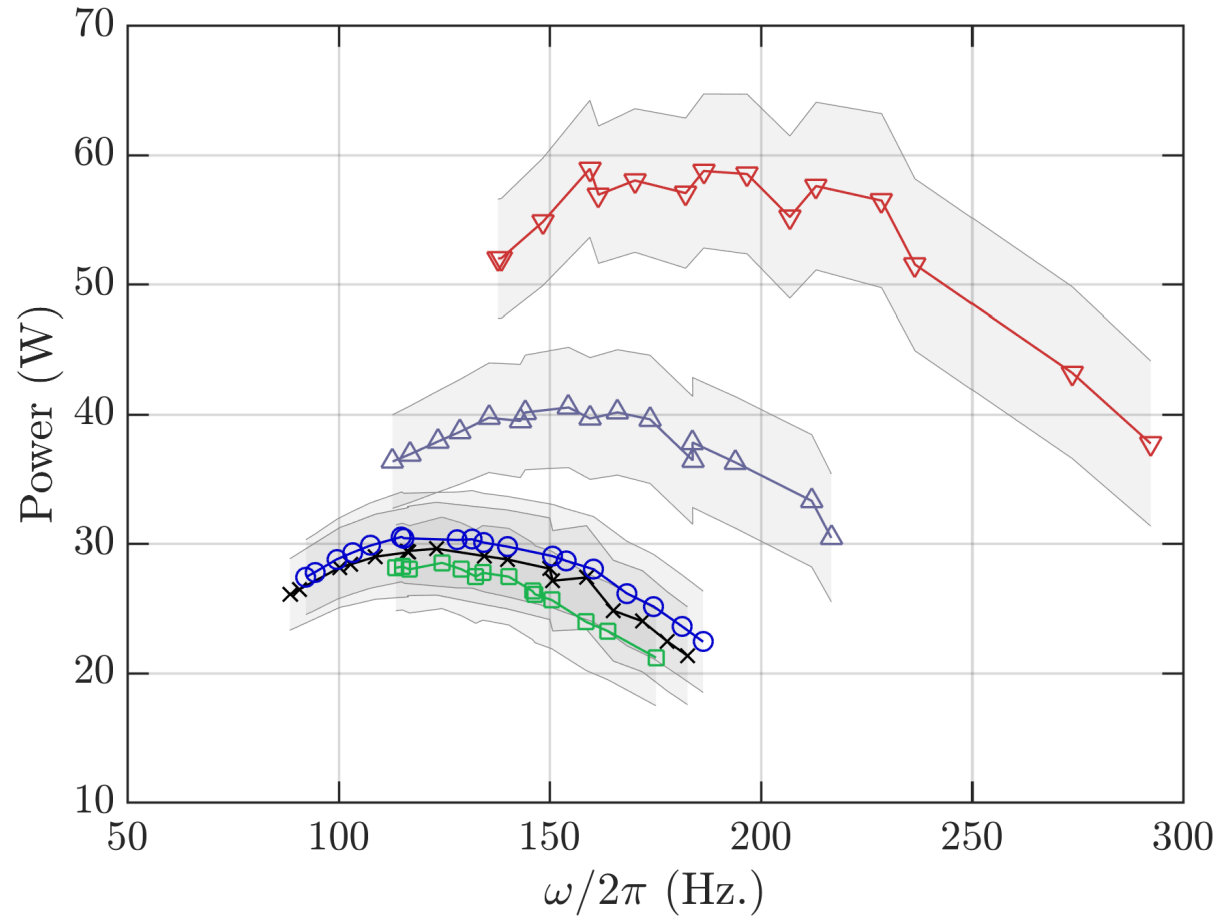
λ	3 – 8
Re_D	1 - 20 million

λ	0.7 – 2.2
Re_D	0.5 – 5 million



Horizontal Axis Wind Turbine Results

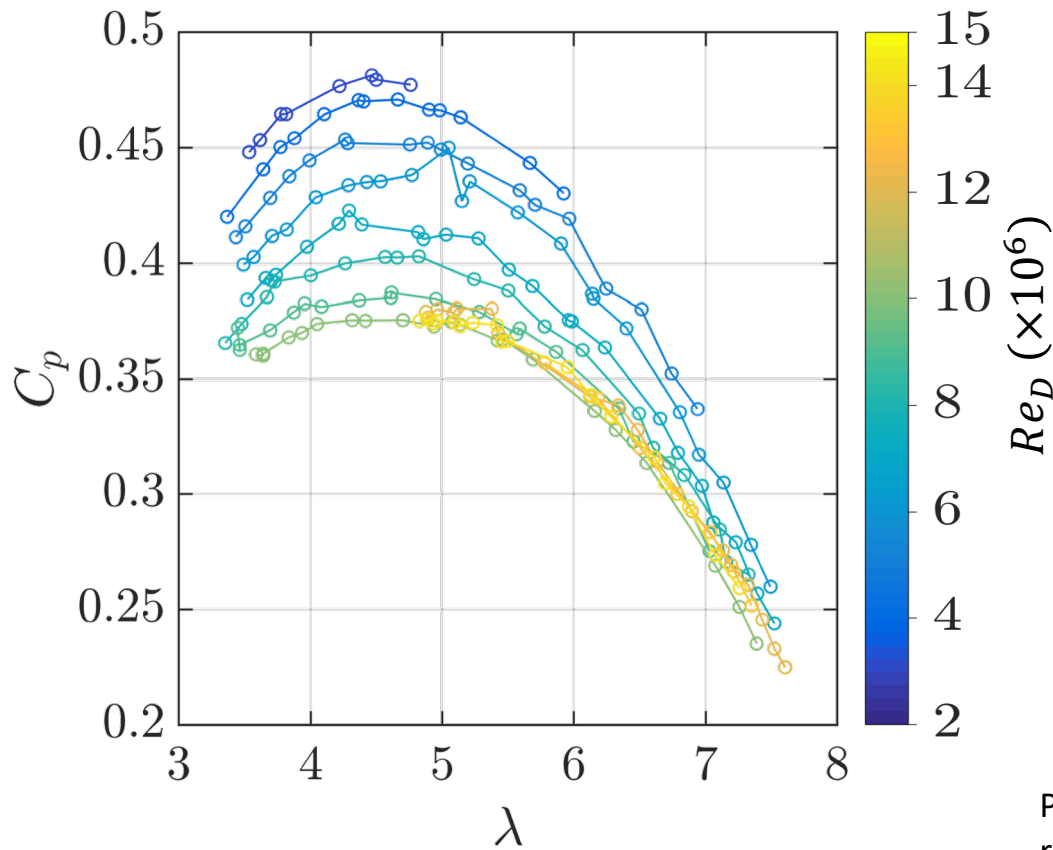
$$\text{Fixed } Re_D = \frac{\rho U D}{\mu} = 5 \times 10^6$$



$$C_p = \frac{P}{\frac{1}{2} \rho U^3 \pi R^2} = f(Re_D, \lambda)$$

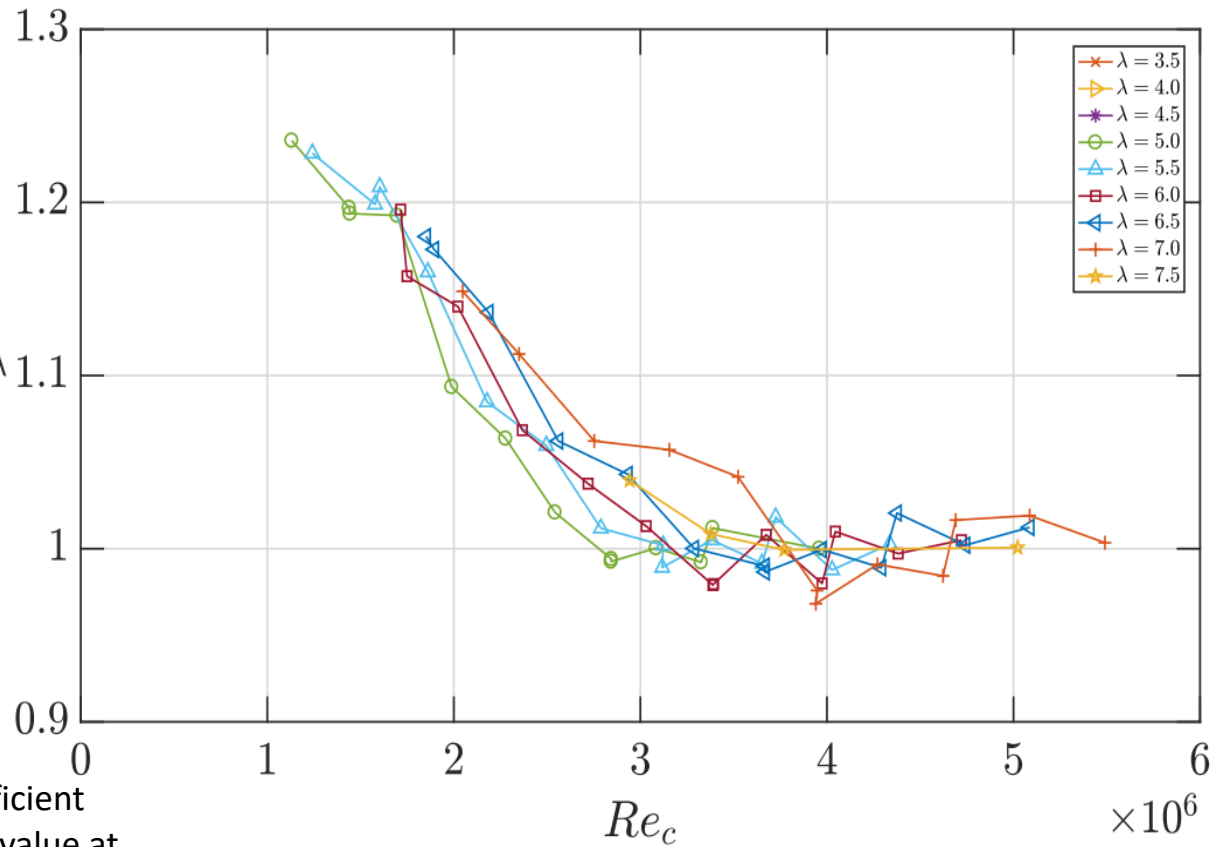


Reynolds Number Trends

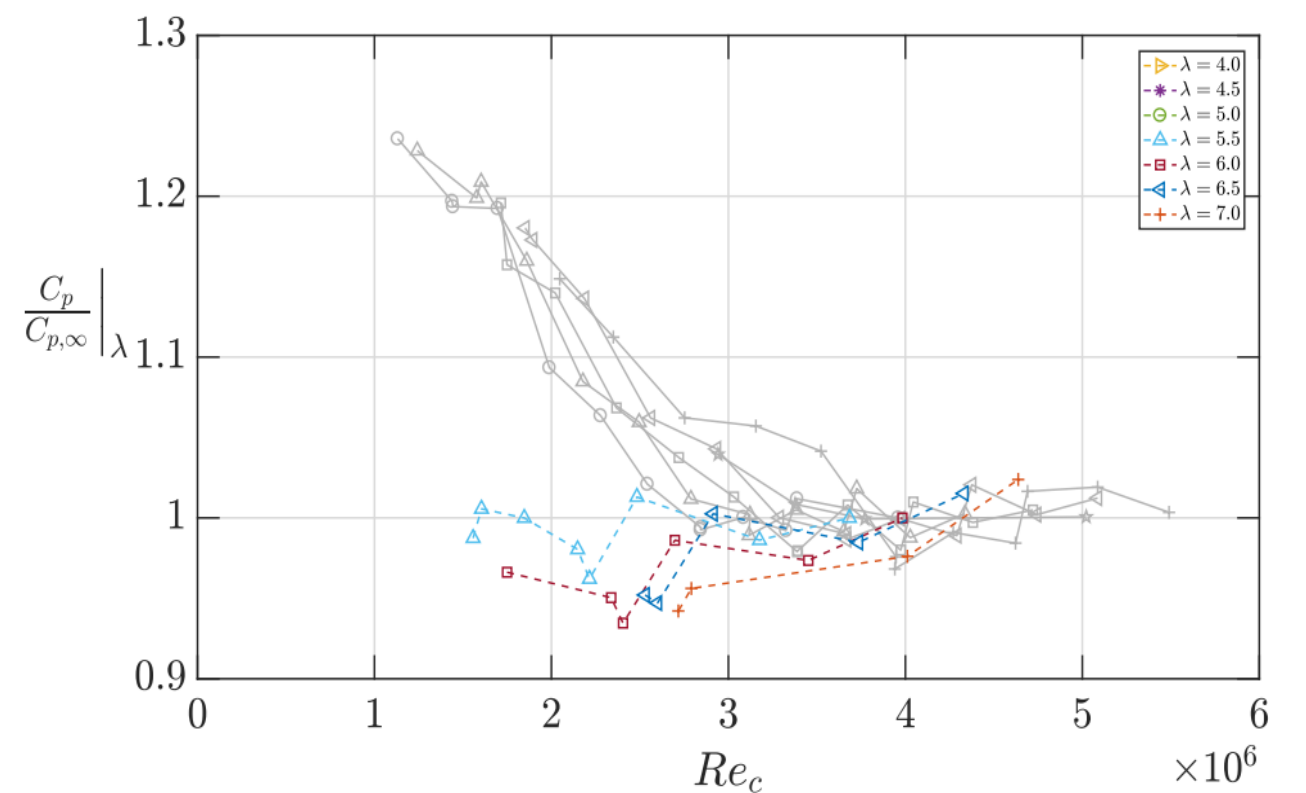
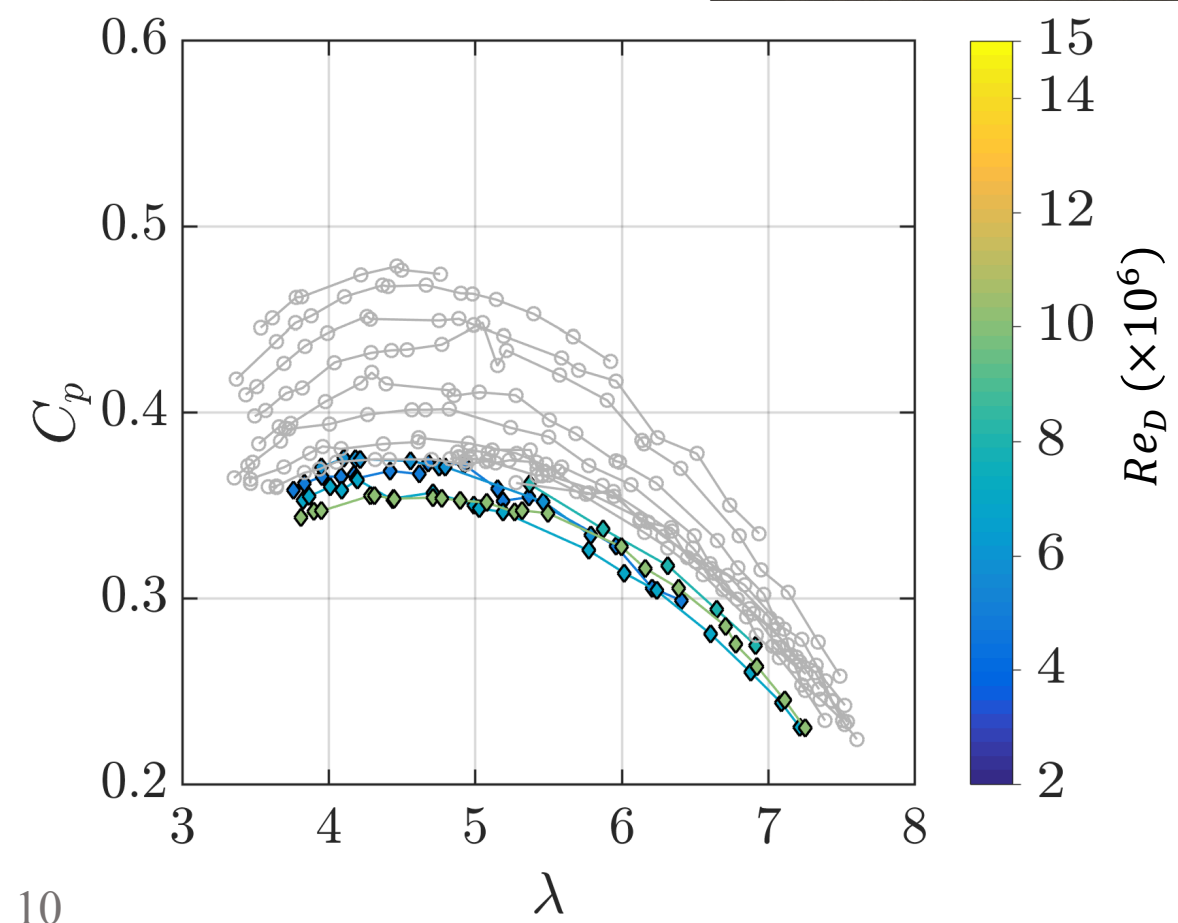
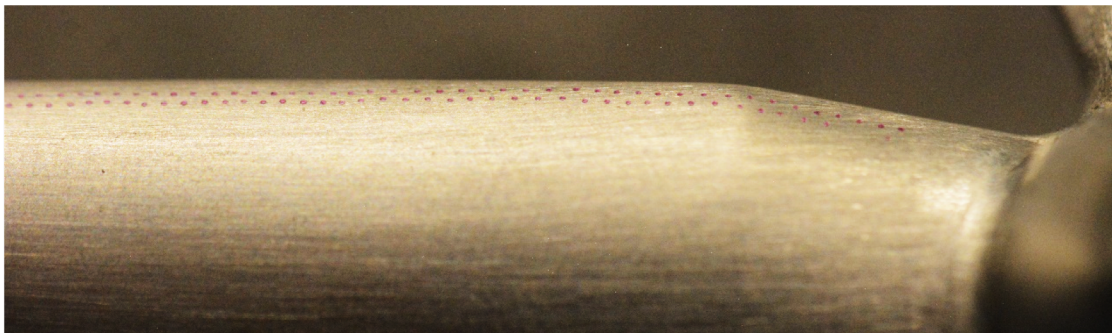


$\frac{C_p}{C_{p,\infty}} \Big|_{\lambda}$

Power coefficient reduced by value at Reynolds number invariance for a given tip speed ratio



Tripped Rotor: Reynolds Number Effects



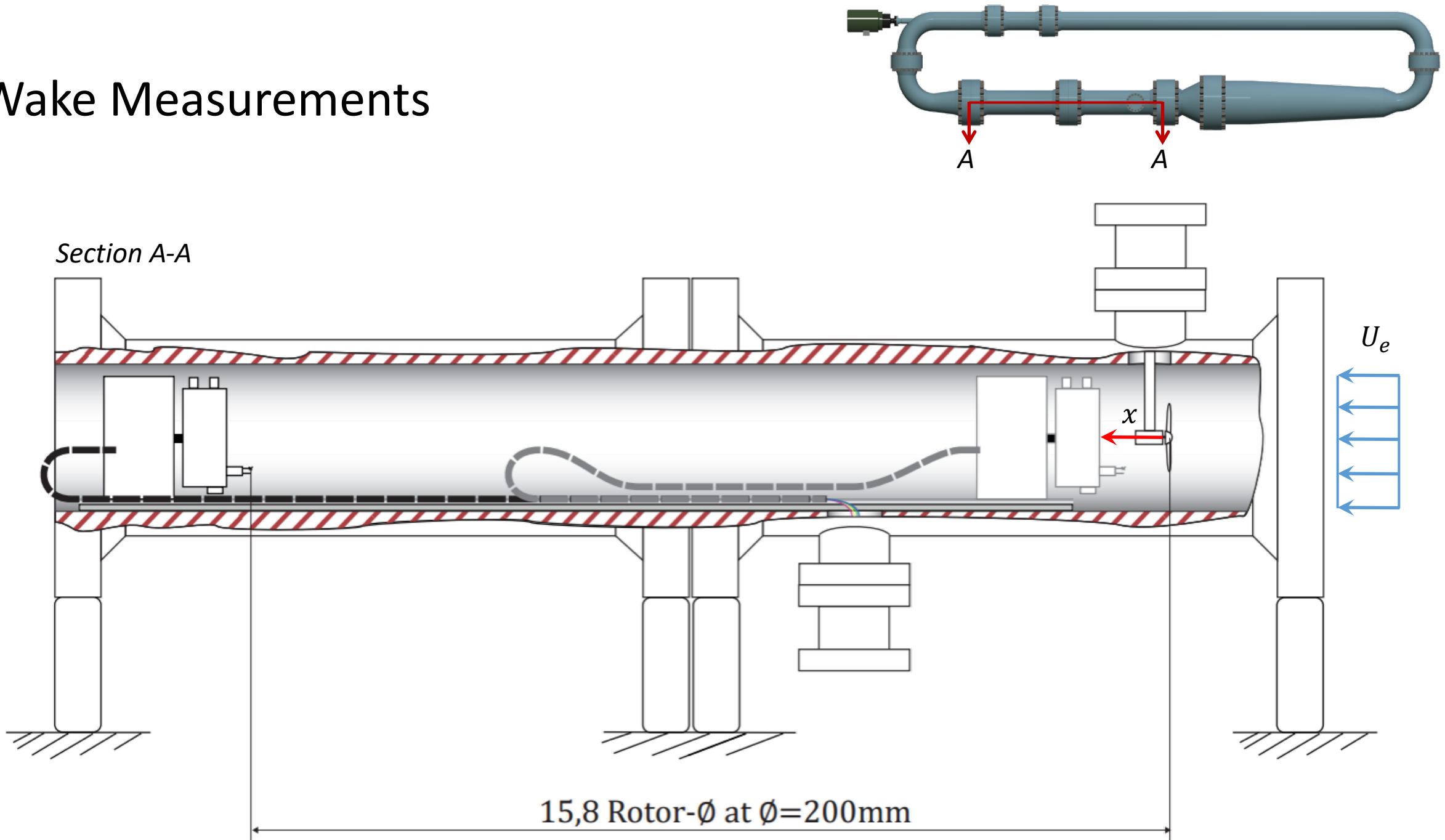
Wind Turbine Wakes and Farms



Source: Vattenfall AB



Wake Measurements

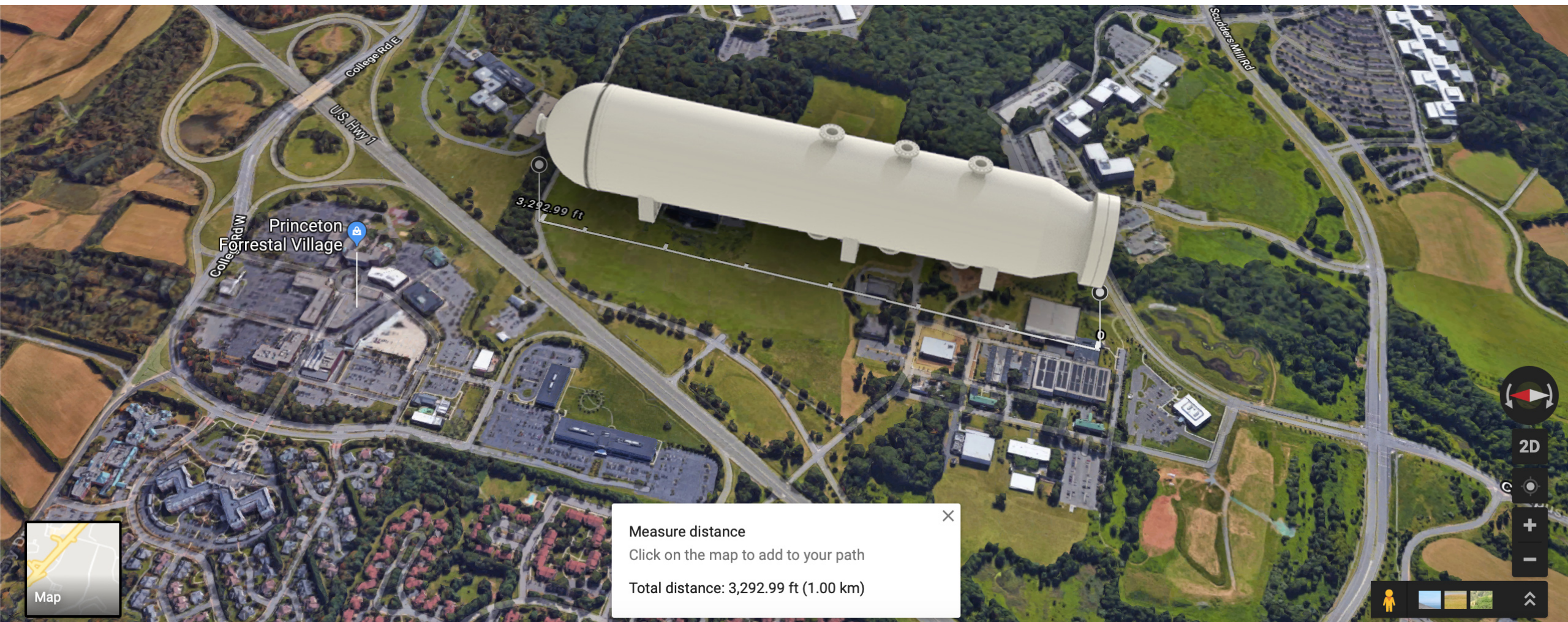


Wind Farm Test Facility



Wind Farm Test Facility

Funded by: Eric and Wendy Schmidt Transformative Technology Fund



Thank you & Questions



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