AIAA SciTech 2025
Orlando, FL
January 8, 2025

Design of a Preliminary Family of Airfoils for High Reynolds Number Wind Turbine Applications

Cody Karcher*

California State University, Long Beach

David Maniaci, Chris Kelley, Alan Hsieh, and Nate deVelder

Sandia National Laboratories

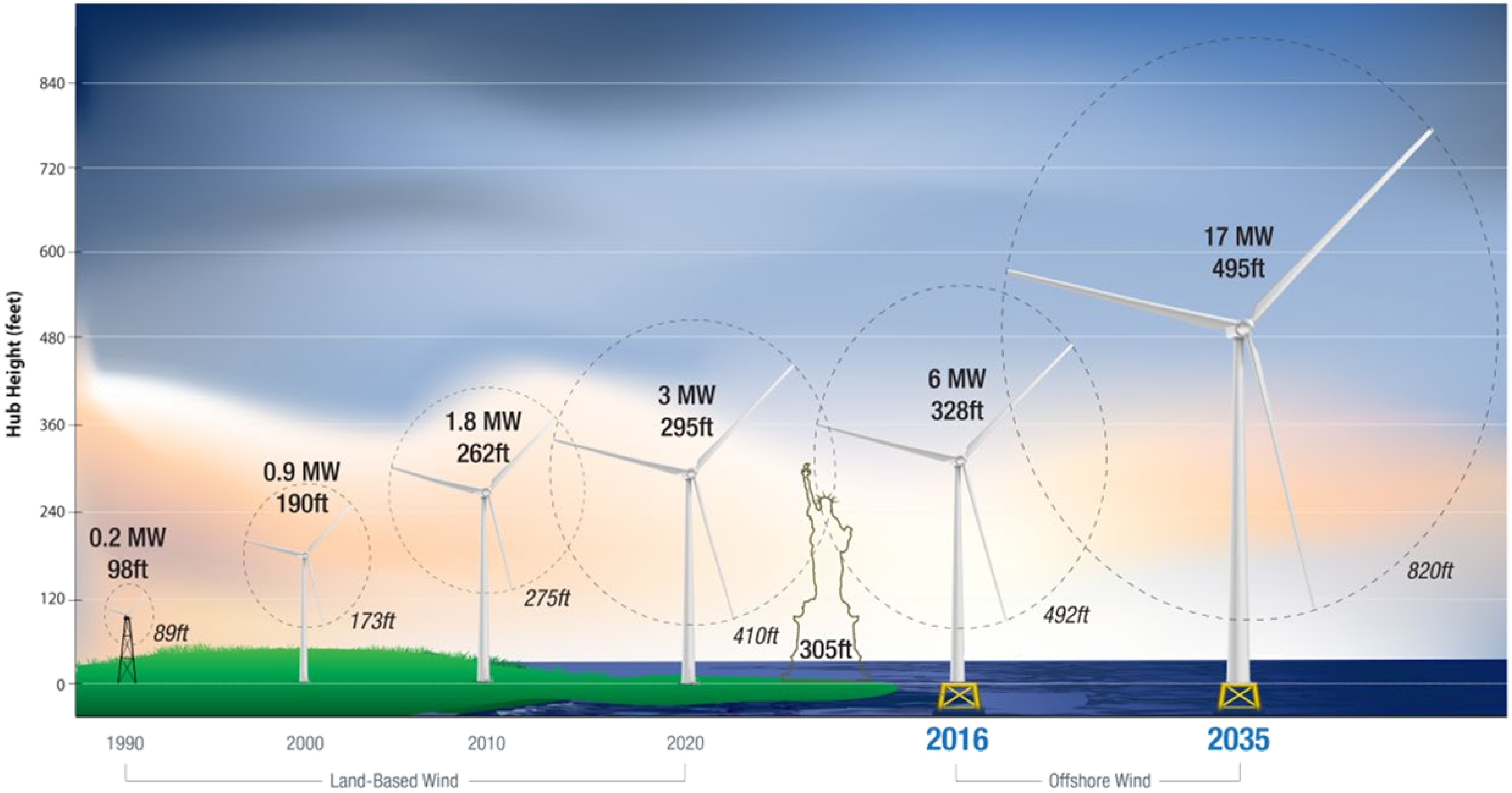
Anurag Gupta

National Renewable Energy Laboratory

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

SAND2025-00716C

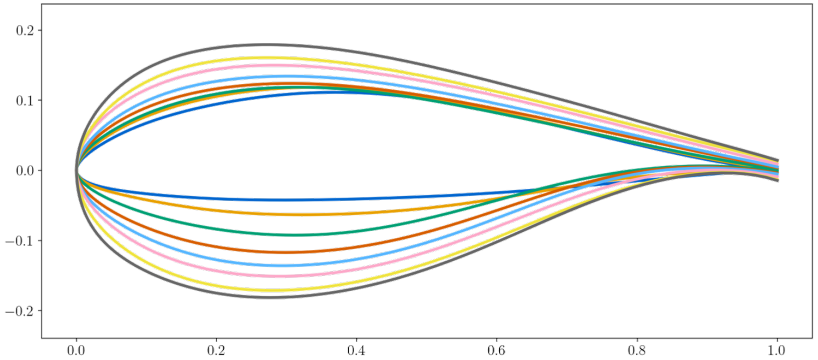
Wind turbines have significantly increased in size over time



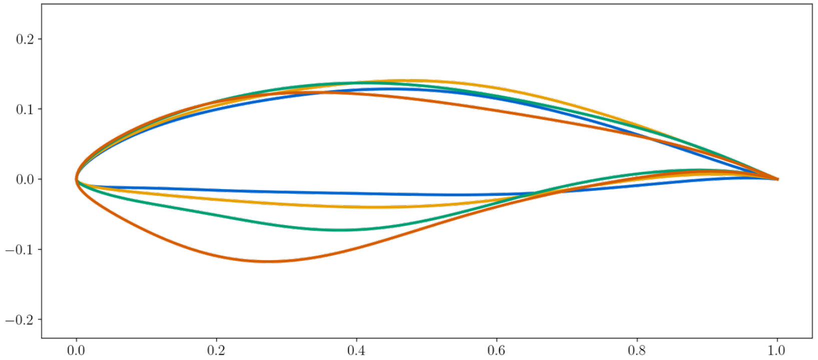
https://www.energy.gov/eere/articles/wind-turbines-bigger-better

Some airfoils exist, but do not match the current need

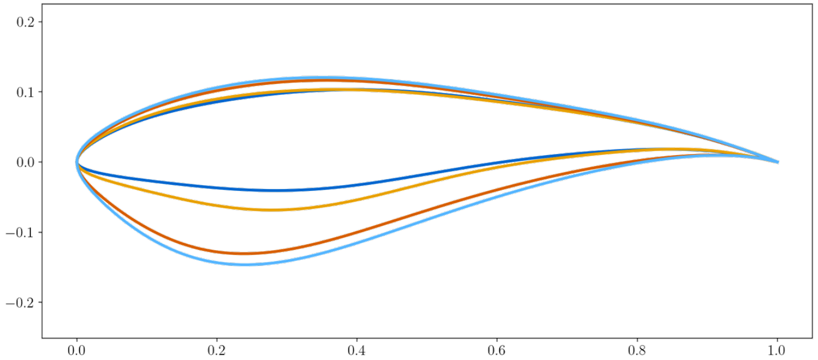
FFA



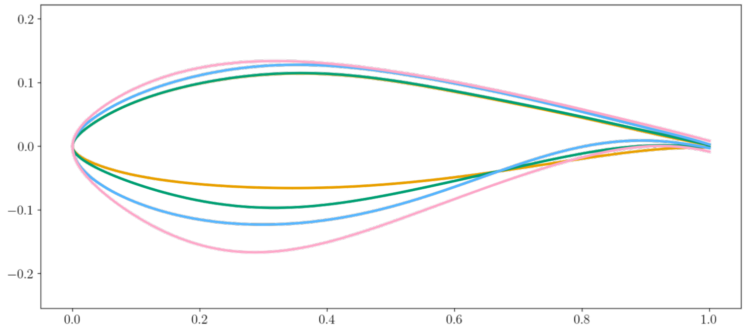
S-25



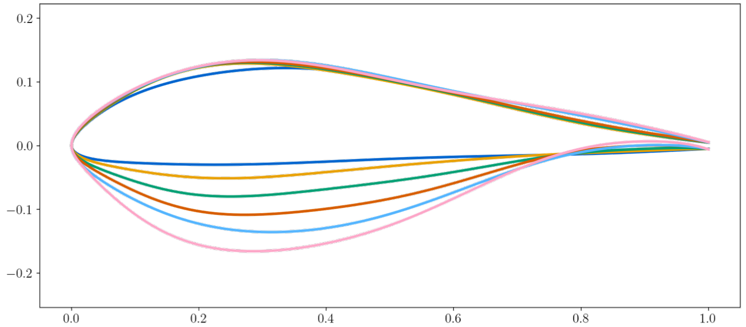
S-40



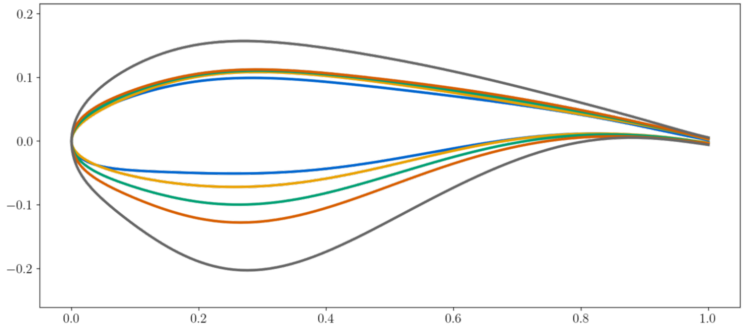
DU



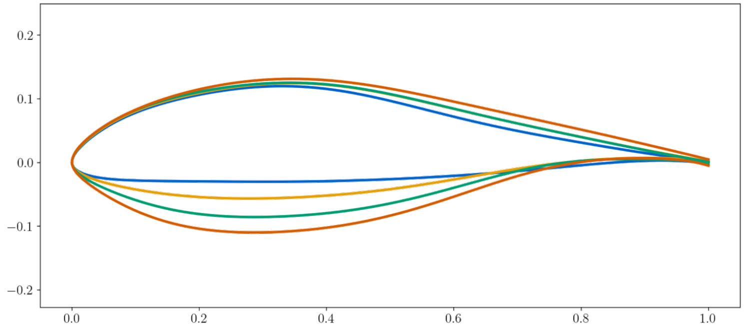
RISO-A



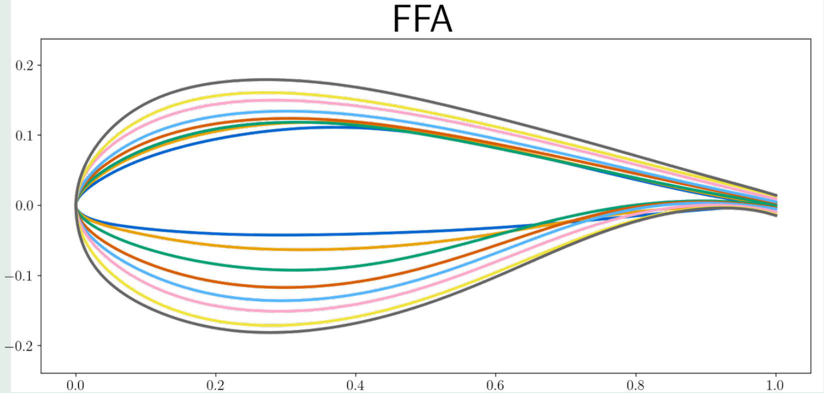
RISO-B

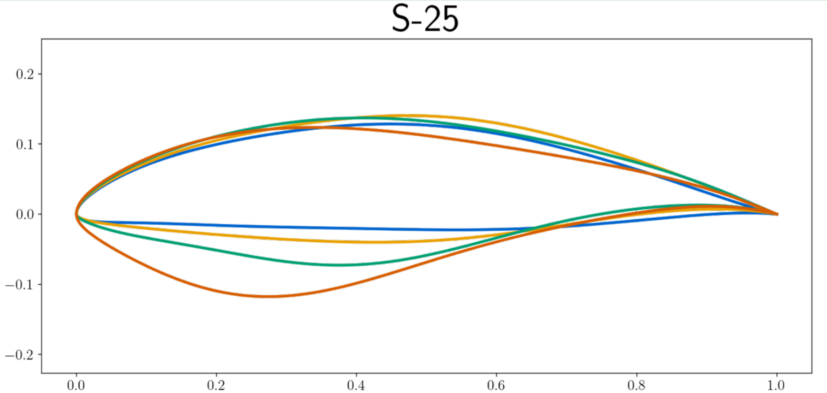


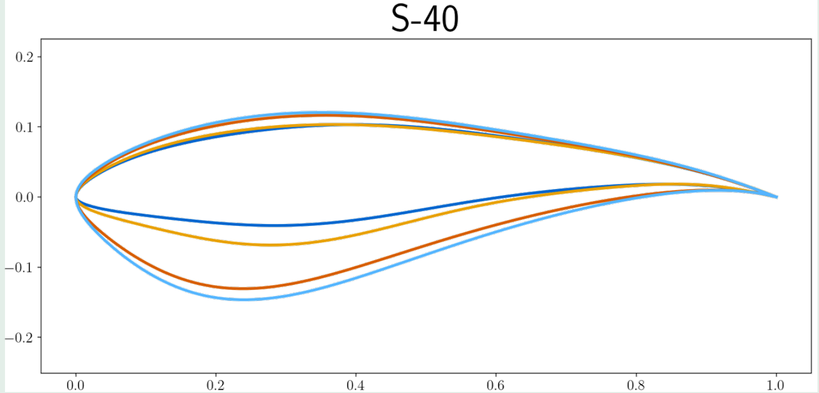
RISO-P



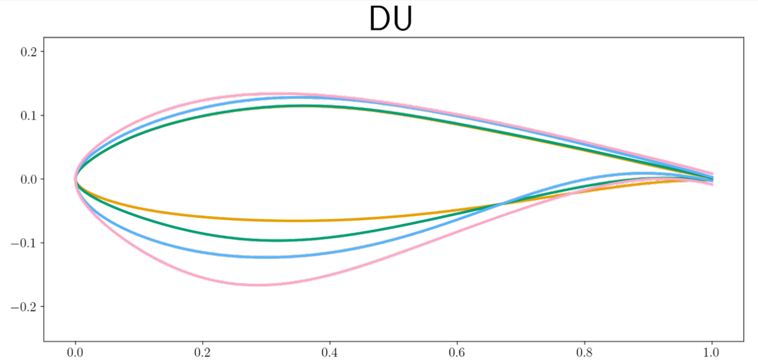
There are also access issues for many of the best airfoils





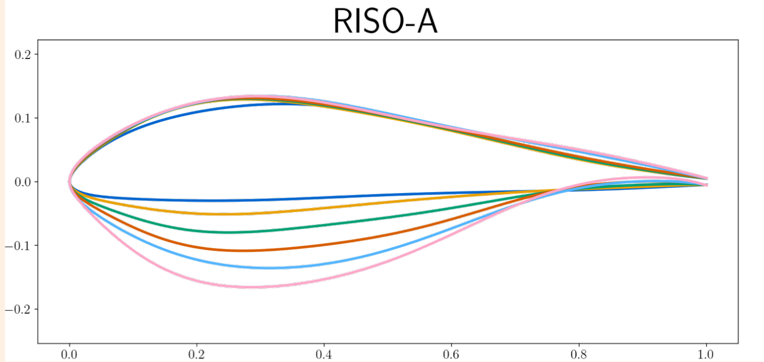


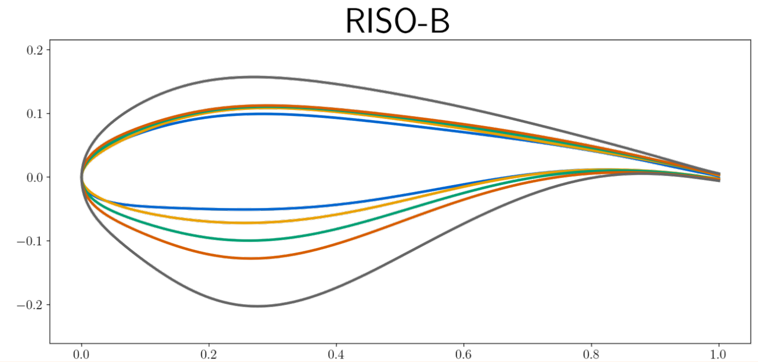
Fully Open Source

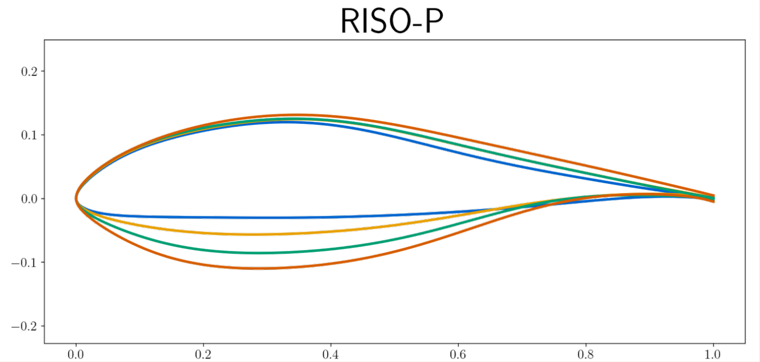


Not Open Source

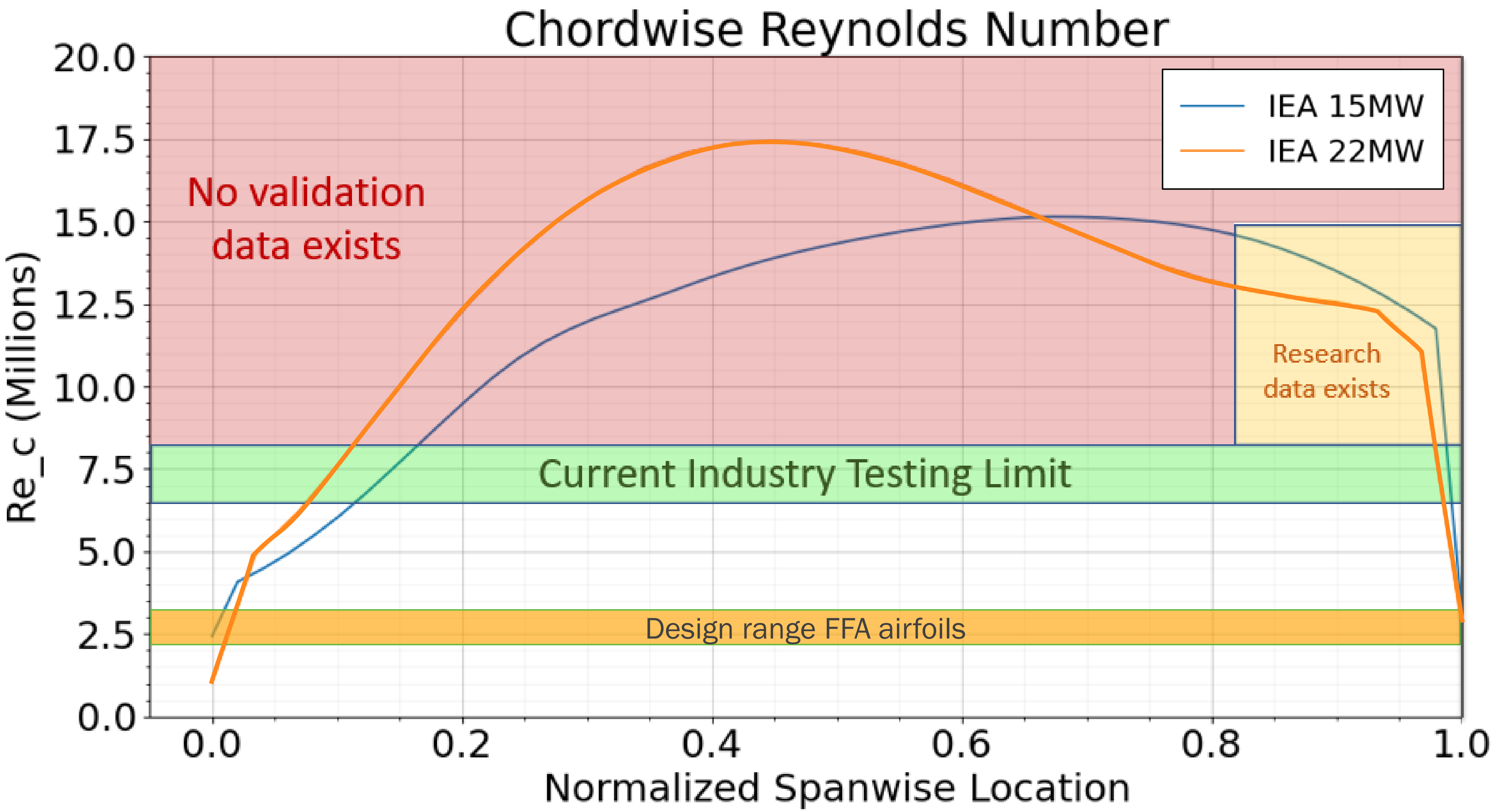
(approximated from images in the literature)



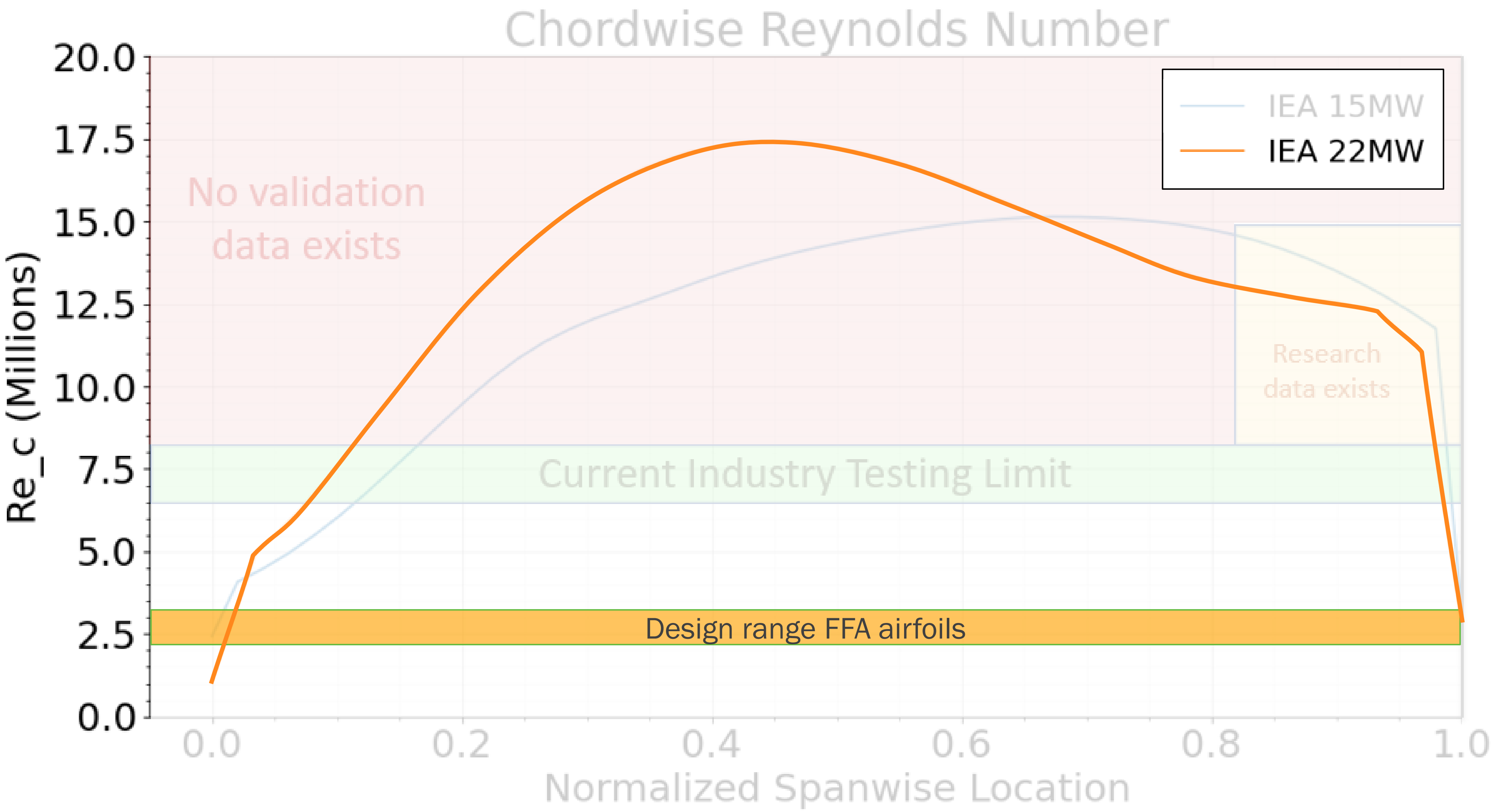




This increase in size has pushed us into new physics regimes

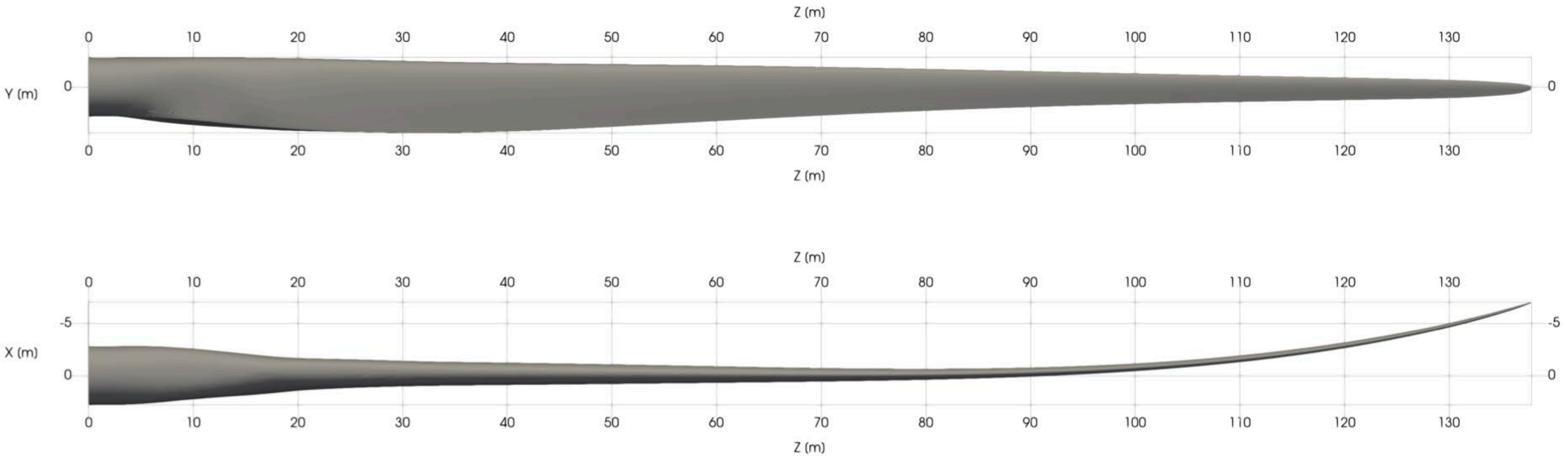


But these airfoils are not designed for this task…

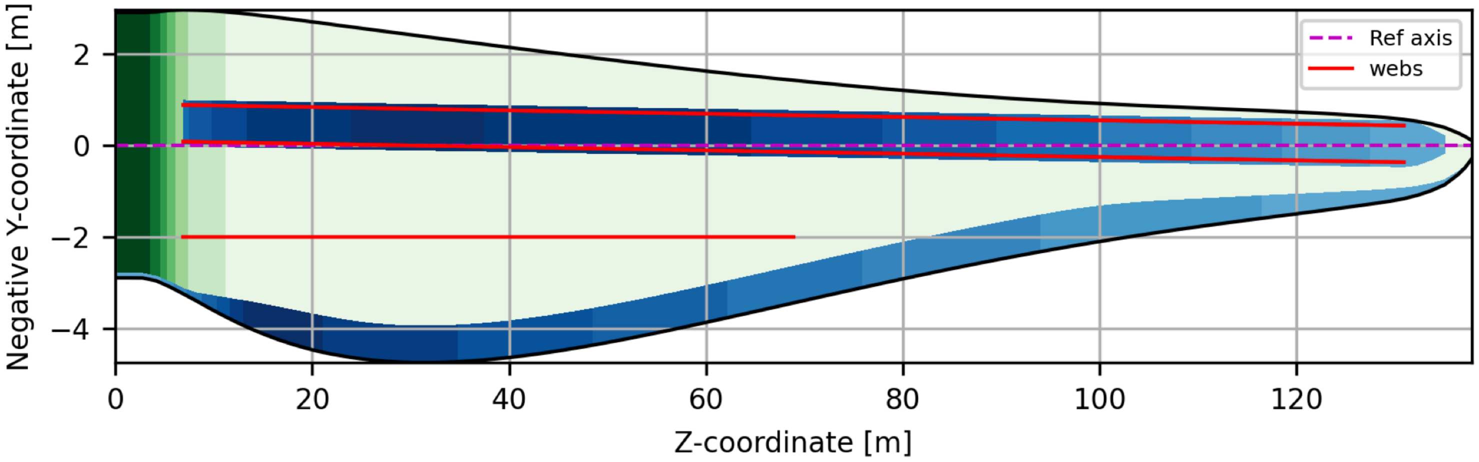


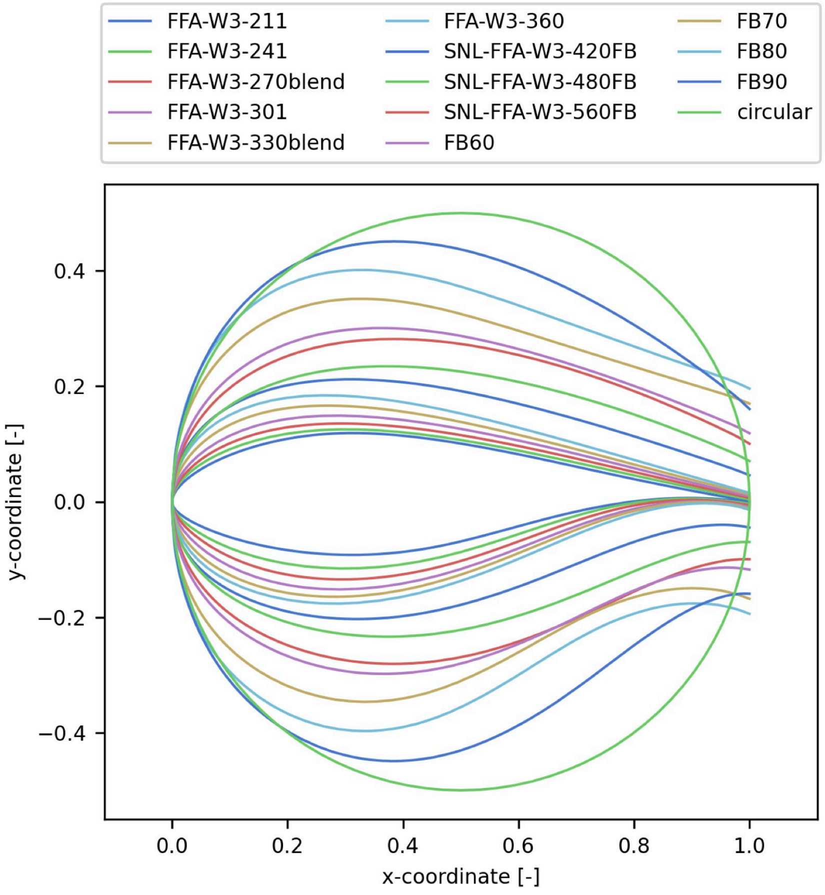
IEA 22MW Reference Turbine uses the FFA Airfoils

Outer Mold Line



Internal Structure





Zahle et. al., Definition of the IEA Wind 22-Megawatt Offshore Reference Wind Turbine, 2024

We need new airfoil options that are:

1. Open Source
2. Designed for modern applications
3. A reflection the state of airfoil design post 1990

Today we are presenting preliminary results

We want input from the community!

Design Approach

Meetings with advisory committee yielded design requirements

Normalized Thickness	21%	24%	27%	30%
Design Lift Coefficient	1.5	1.4	1.3	1.2
Angle of Attack	N/A	N/A	N/A	N/A
Reynolds Number	12e6	13e6	16e6	18e6
Clean L/D	200	190	185	180
Rough L/D	110	110	105	100
Stall Margin	4 deg	4 deg	4 deg	4 deg
Pre-Stall Lift Coefficient Margin	0.2	0.2	0.2	0.2
Change in C_L due to Roughness	0.15	0.14	0.13	0.12
C_M Clean	N/A	N/A	N/A	N/A
C_M Rough	N/A	N/A	N/A	N/A
LE Radius	0.01	0.025	0.03	0.04
Flap Stiffness (I_{xx})	0.00028	0.00041	0.00058	0.00080
Edge Stiffness (I_{yy})	0.00494	0.00561	0.00633	0.00706
Torsion Stiffness (I_{zz})	0.00522	0.00602	0.00691	0.00786
Area	0.11478	0.13051	0.14661	0.16290

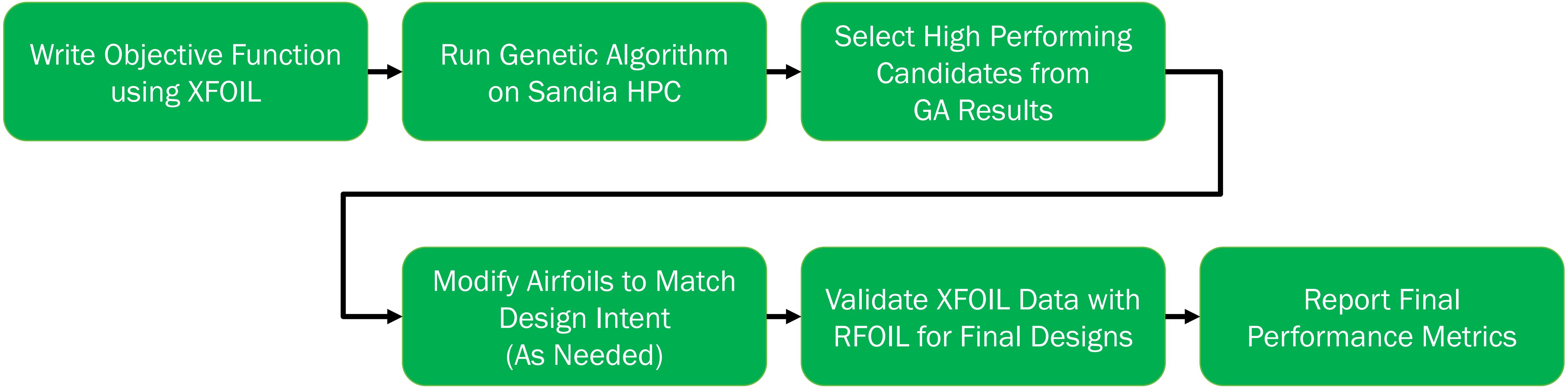
Specifically seeking guidance on Lift Coefficient…

Normalized Thickness	21%	24%	27%	30%
Design Lift Coefficient	1.5	1.4	1.3	1.2
Angle of Attack	N/A	N/A	N/A	N/A
Reynolds Number	12e6	13e6	16e6	18e6
Clean L/D	200	190	185	180
Rough L/D	110	110	105	100
Stall Margin	4 deg	4 deg	4 deg	4 deg
Pre-Stall Lift Coefficient Margin	0.2	0.2	0.2	0.2
Change in C_L due to Roughness	0.15	0.14	0.13	0.12
C_M Clean	N/A	N/A	N/A	N/A
C_M Rough	N/A	N/A	N/A	N/A
LE Radius	0.01	0.025	0.03	0.04
Flap Stiffness (I_{xx})	0.00028	0.00041	0.00058	0.00080
Edge Stiffness (I_{yy})	0.00494	0.00561	0.00633	0.00706
Torsion Stiffness (I_{zz})	0.00522	0.00602	0.00691	0.00786
Area	0.11478	0.13051	0.14661	0.16290

...along with Moment Coefficient

Normalized Thickness	21%	24%	27%	30%
Design Lift Coefficient	1.5	1.4	1.3	1.2
Angle of Attack	N/A	N/A	N/A	N/A
Reynolds Number	12e6	13e6	16e6	18e6
Clean L/D	200	190	185	180
Rough L/D	110	110	105	100
Stall Margin	4 deg	4 deg	4 deg	4 deg
Pre-Stall Lift Coefficient Margin	0.2	0.2	0.2	0.2
Change in C_L due to Roughness	0.15	0.14	0.13	0.12
C_M Clean	N/A	N/A	N/A	N/A
C_M Rough	N/A	N/A	N/A	N/A
LE Radius	0.01	0.025	0.03	0.04
Flap Stiffness (I_{xx})	0.00028	0.00041	0.00058	0.00080
Edge Stiffness (I_{yy})	0.00494	0.00561	0.00633	0.00706
Torsion Stiffness (I_{zz})	0.00522	0.00602	0.00691	0.00786
Area	0.11478	0.13051	0.14661	0.16290

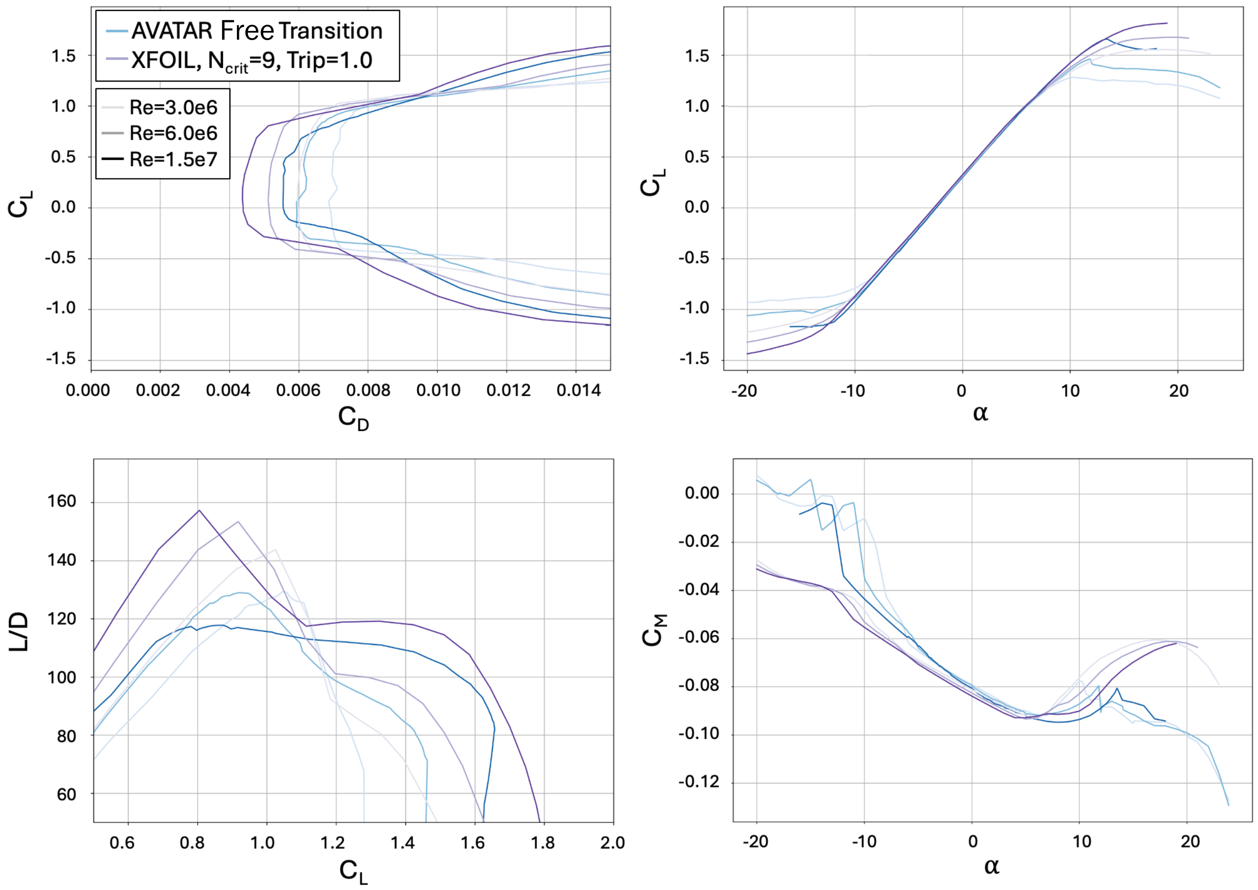
Design process uses XFOIL with RFOIL for validation

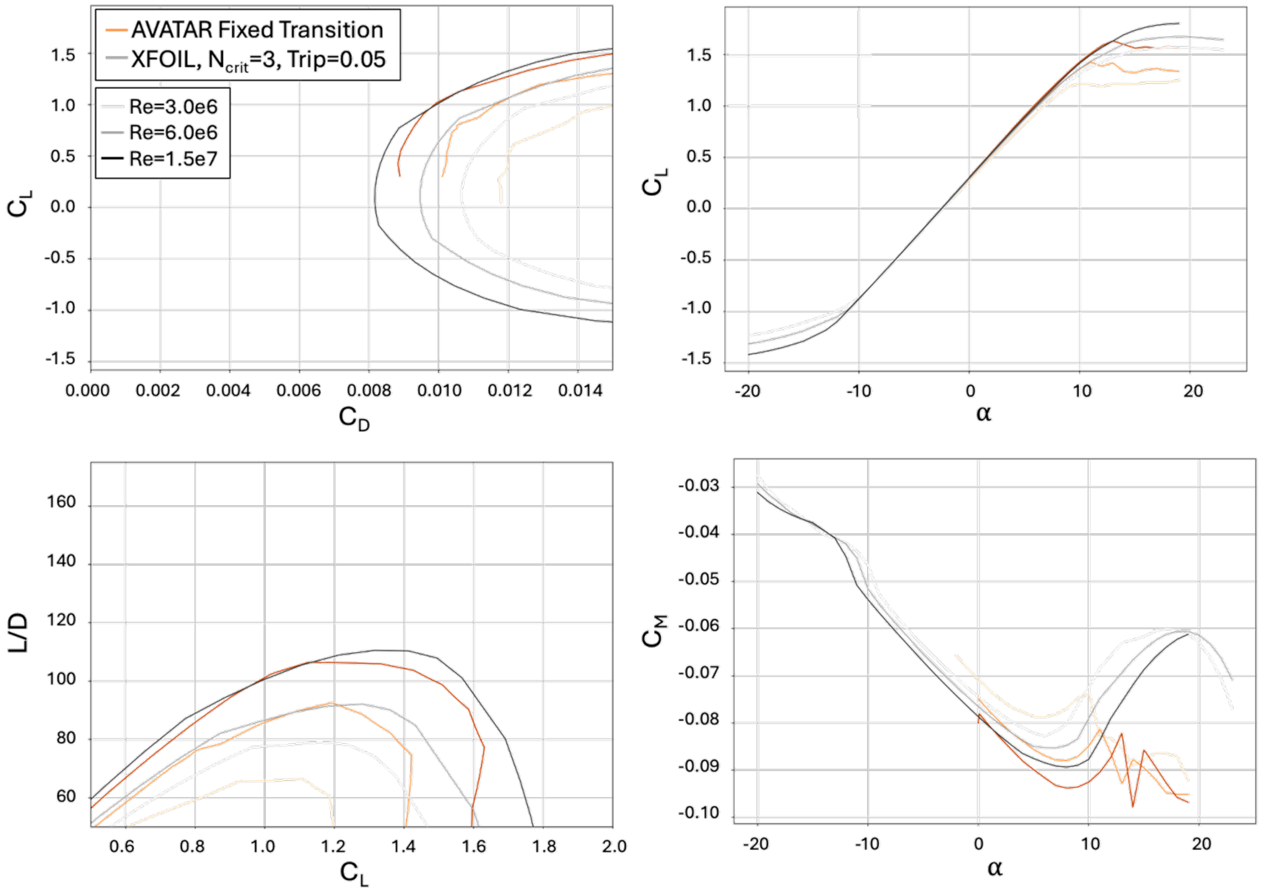


Does XFOIL capture the design space to the extent we need?

1. Write Objective Function using XFOIL
2. Run Genetic Algorithm on Sandia HPC
3. Select High Performing Candidates from GA Results
4. Modify Airfoils to Match Design Intent (As Needed)
5. Validate XFOIL Data with RFOIL for Final Designs
6. Report Final Performance Metrics

XFOIL untrustworthy in an absolute sense, but is OK for design



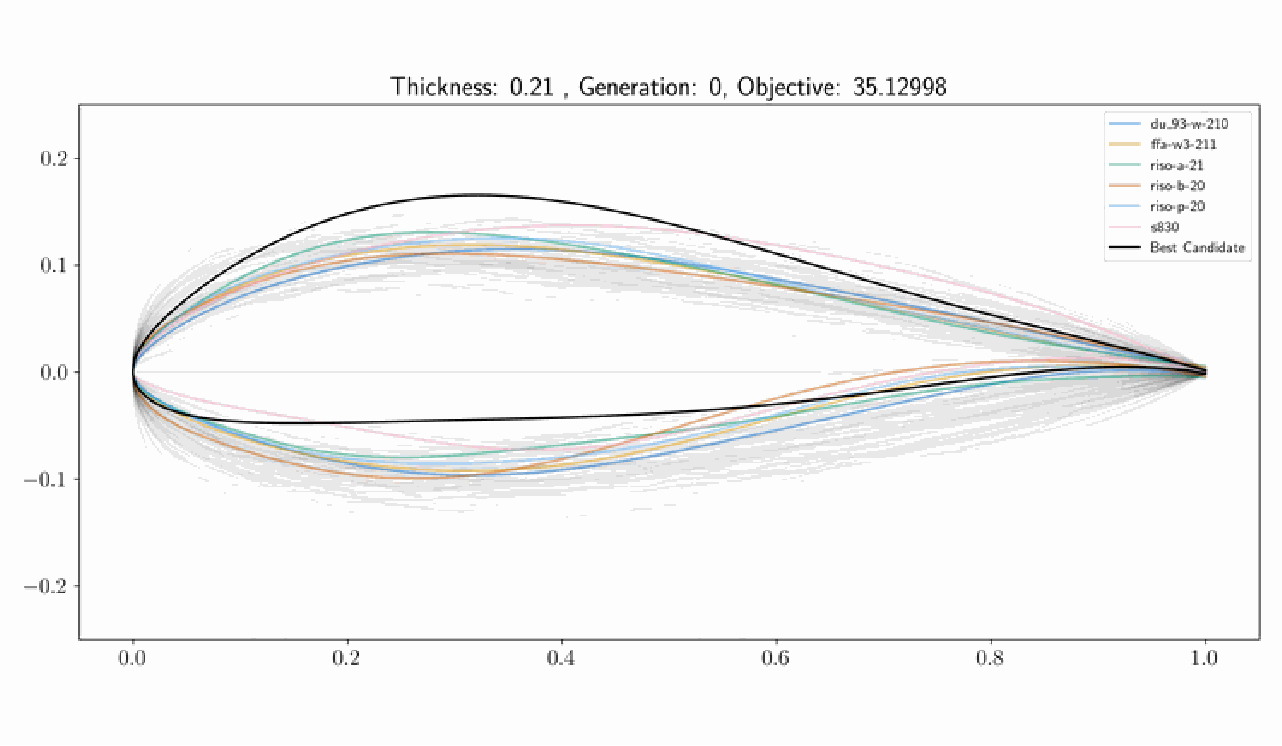


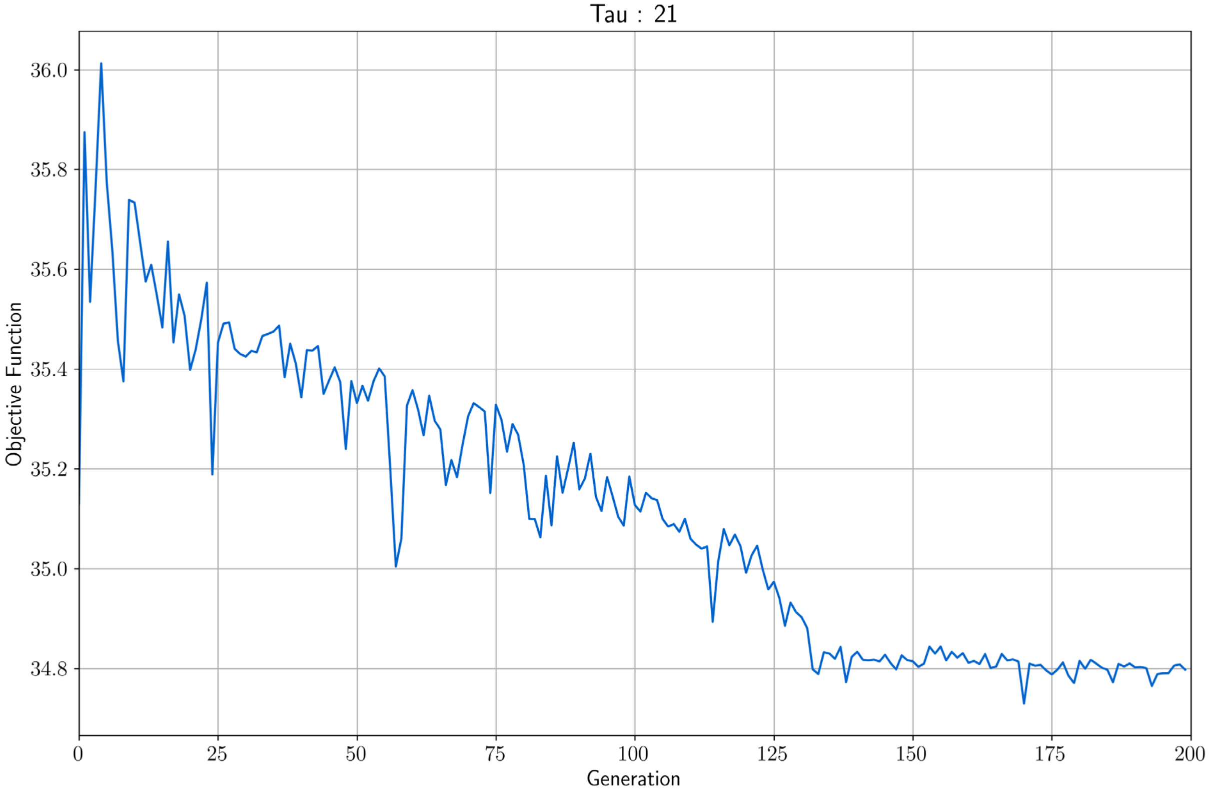
Pires et. al., Analysis of High Reynolds Numbers Effects on a Wind Turbine Airfoil Using 2D Wind Tunnel Test Data, 2016

How does the Genetic Algorithm Perform?

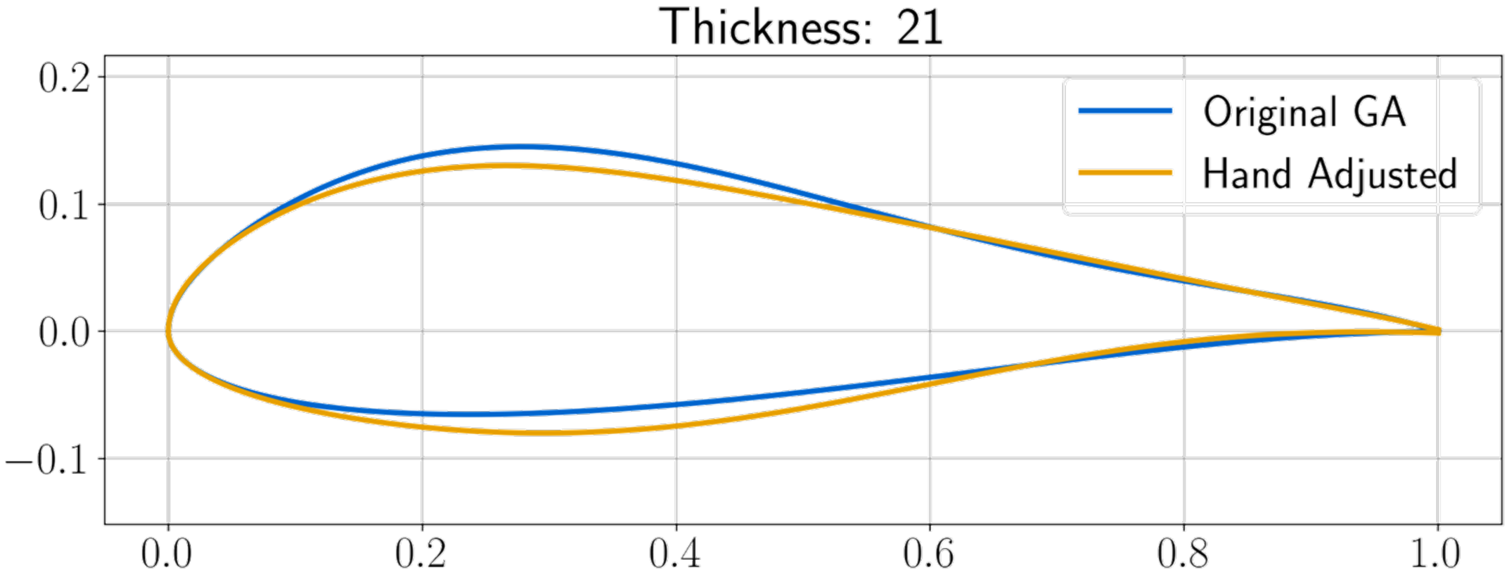
1. Write Objective Function using XFOIL
2. **Run Genetic Algorithm on Sandia HPC**
3. Select High Performing Candidates from GA Results
4. Modify Airfoils to Match Design Intent (As Needed)
5. Validate XFOIL Data with RFOIL for Final Designs
6. Report Final Performance Metrics

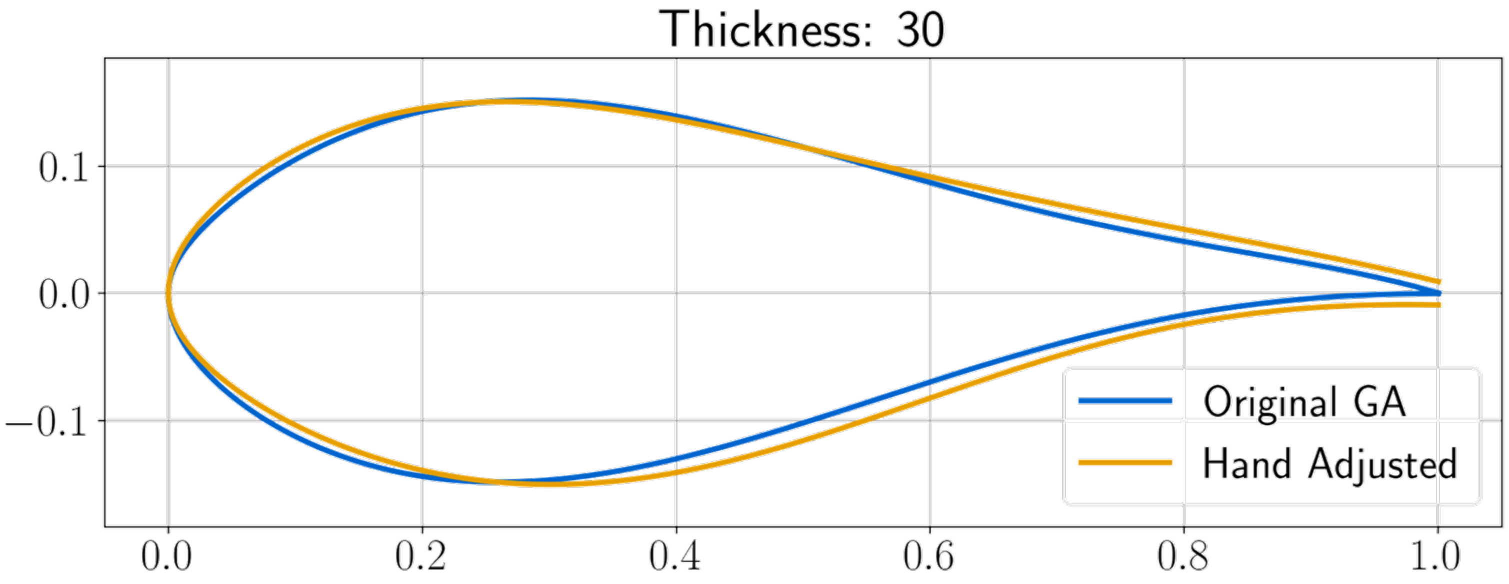
Genetic Algorithm successfully identifies promising designs





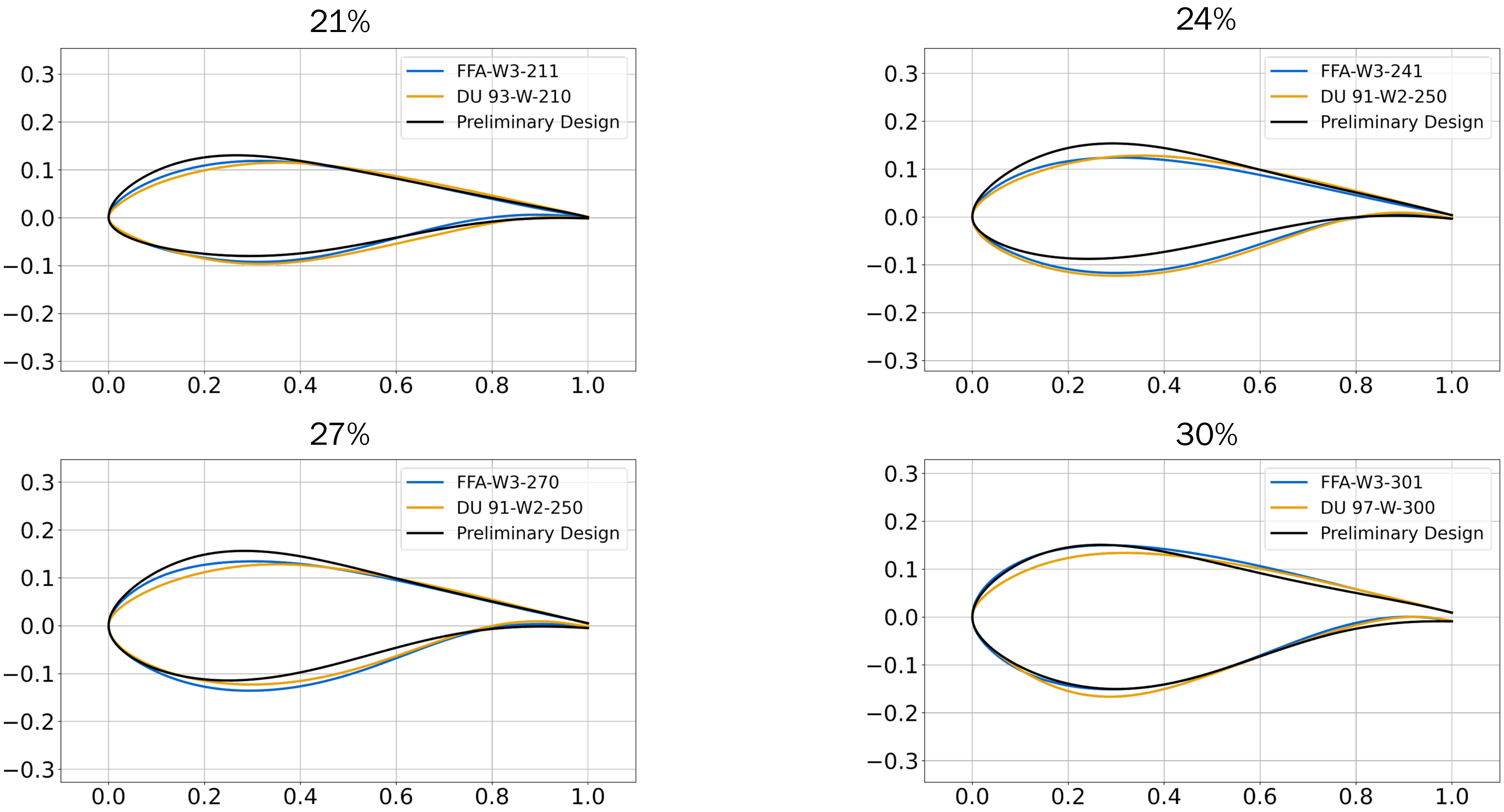
Hand adjustments are made as needed to improve designs



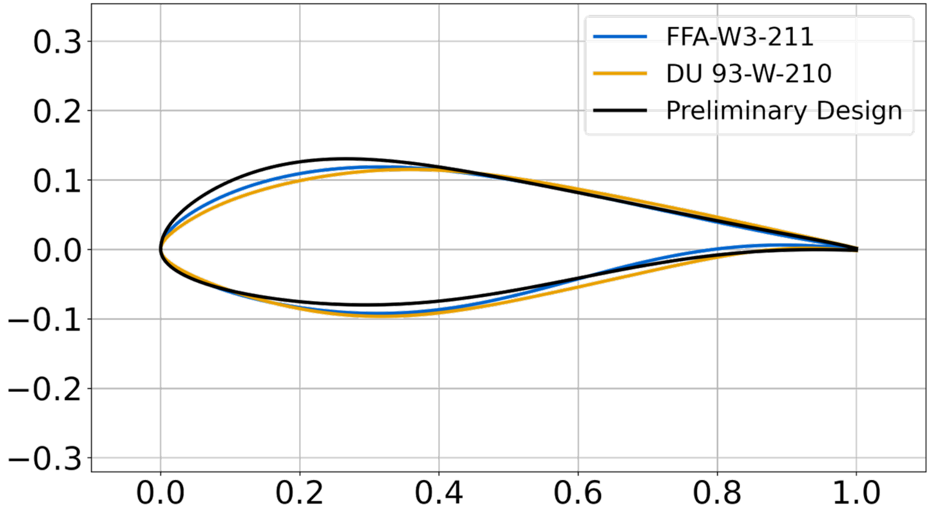


Airfoils and Performance Results

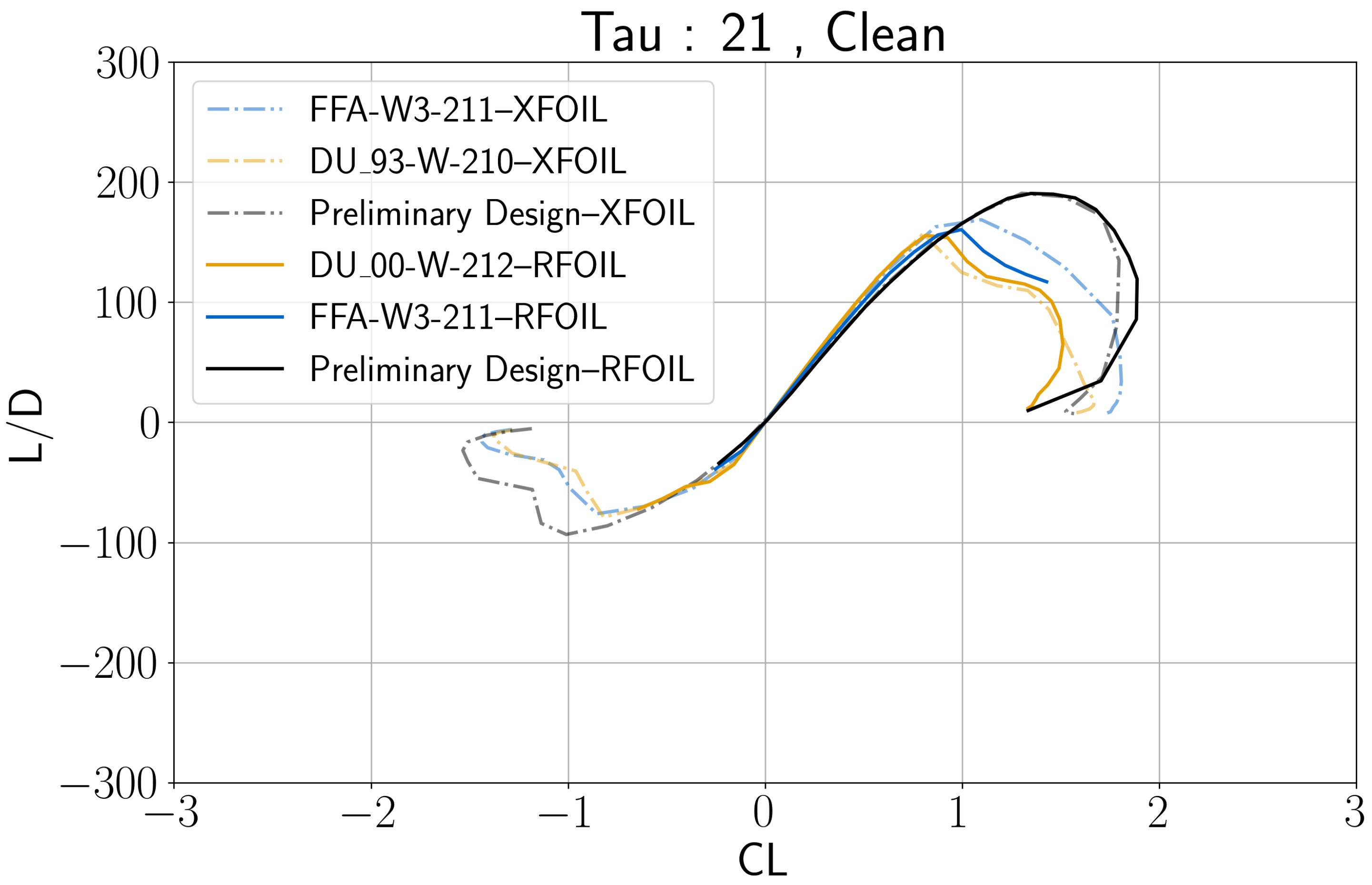
The Preliminary Airfoil Family



21% Airfoil

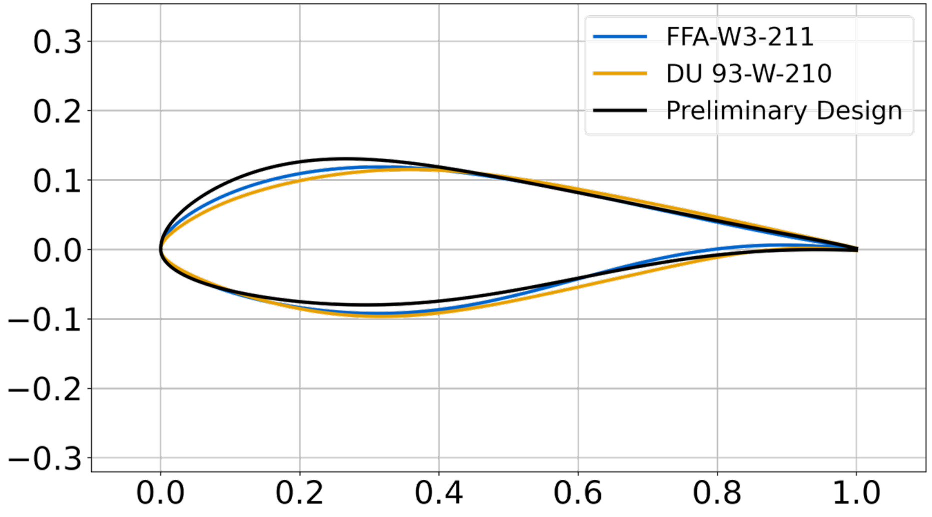


FFA-W3-211
DU 93-W-210
Preliminary Design
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
0.0
0.2
0.4
0.6
0.8
1.0

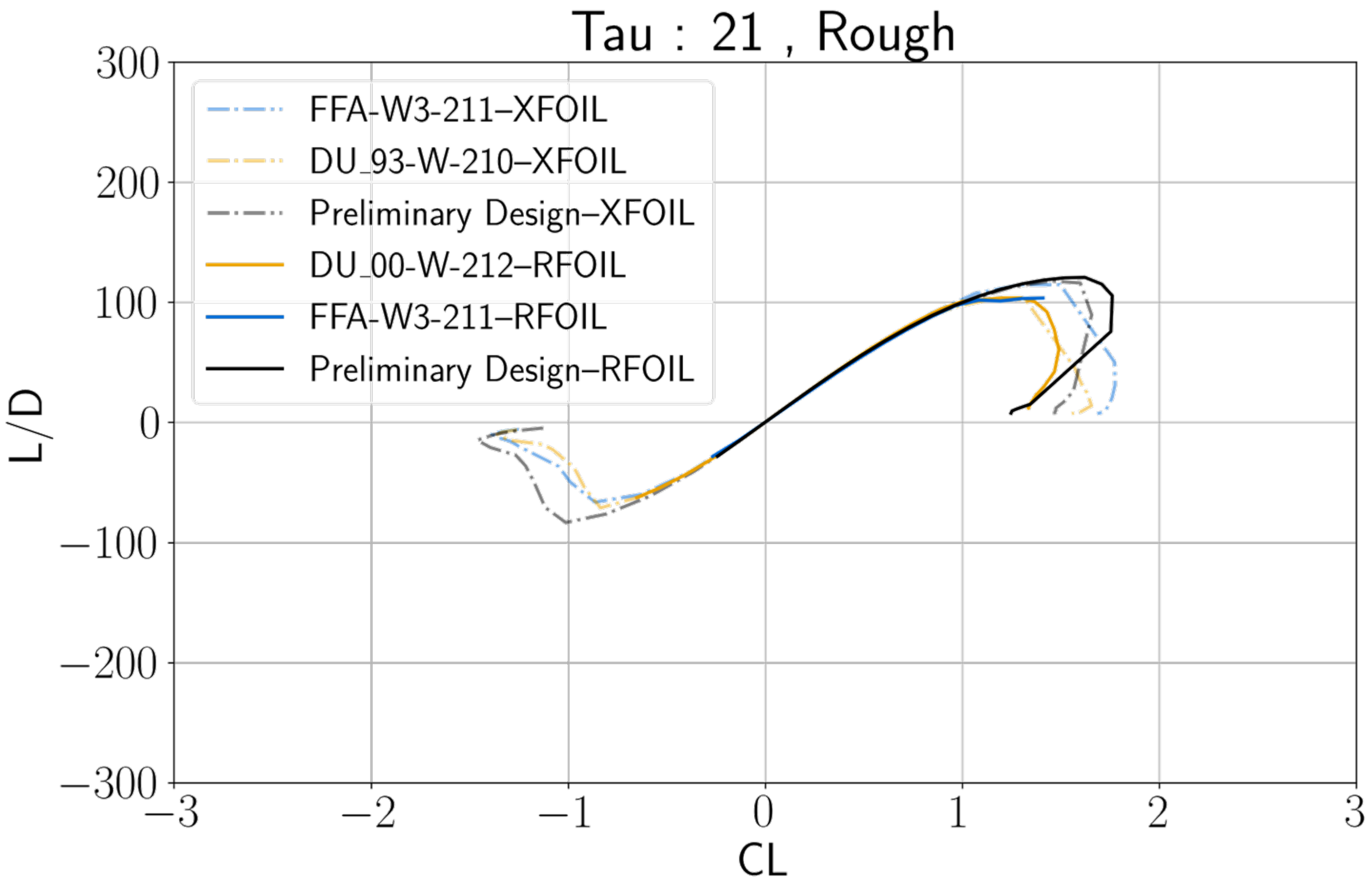


Tau : 21 , Clean
FFA-W3-211–XFOIL
DU_93-W-210–XFOIL
Preliminary Design–XFOIL
DU_00-W-212–RFOIL
FFA-W3-211–RFOIL
Preliminary Design–RFOIL
L/D
CL
300
200
100
0
−100
−200
−300
−3
−2
−1
0
1
2
3

21% Airfoil

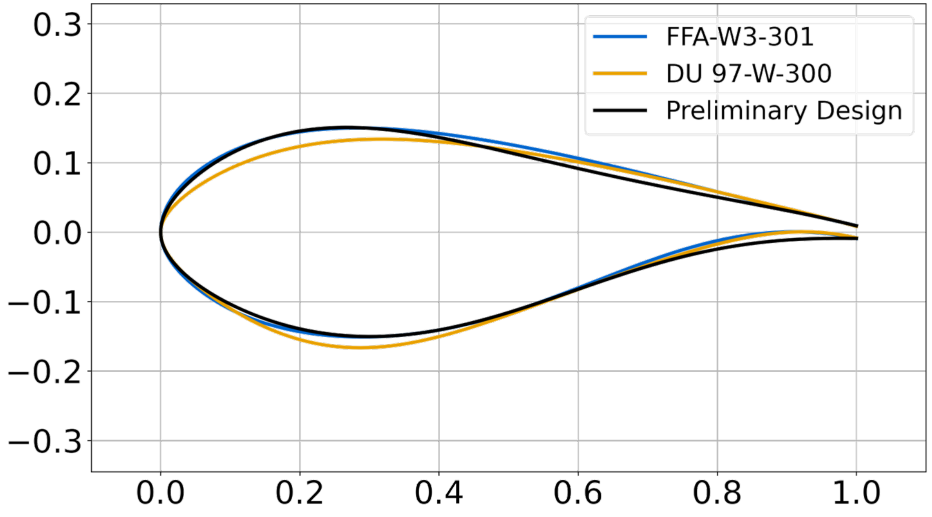


FFA-W3-211
DU 93-W-210
Preliminary Design
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
0.0
0.2
0.4
0.6
0.8
1.0

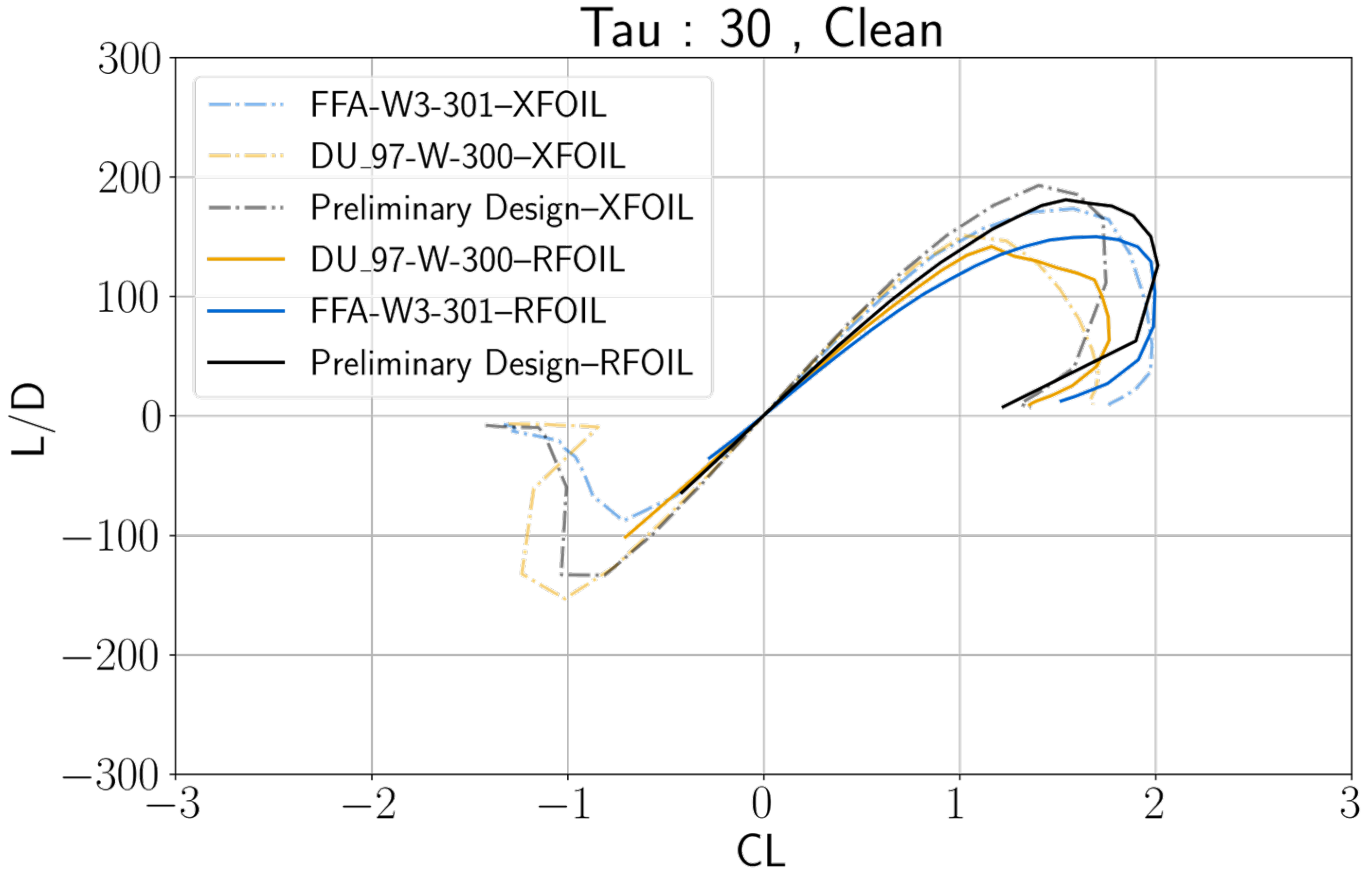


Tau : 21 , Rough
FFA-W3-211–XFOIL
DU_93-W-210–XFOIL
Preliminary Design–XFOIL
DU_00-W-212–RFOIL
FFA-W3-211–RFOIL
Preliminary Design–RFOIL
L/D
CL
300
200
100
0
−100
−200
−300
−3
−2
−1
0
1
2
3

30% Airfoil

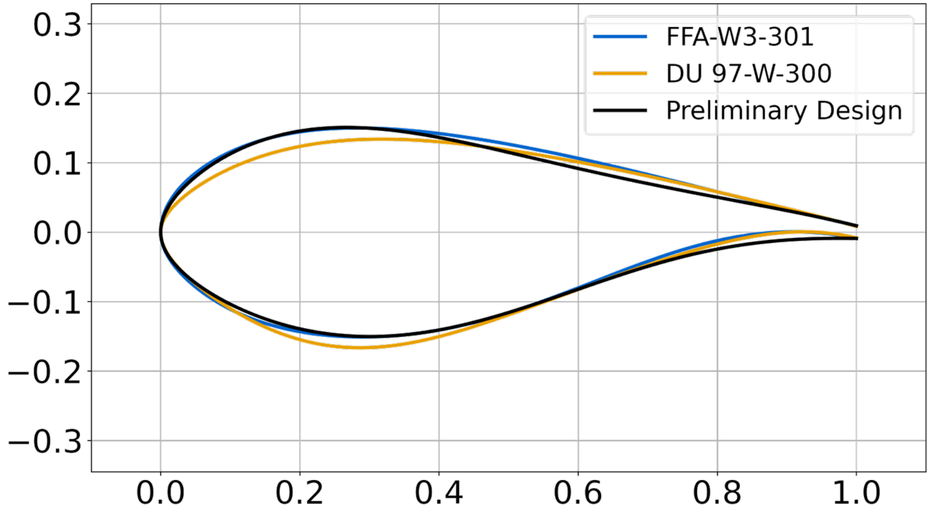


FFA-W3-301
DU 97-W-300
Preliminary Design
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
0.0
0.2
0.4
0.6
0.8
1.0

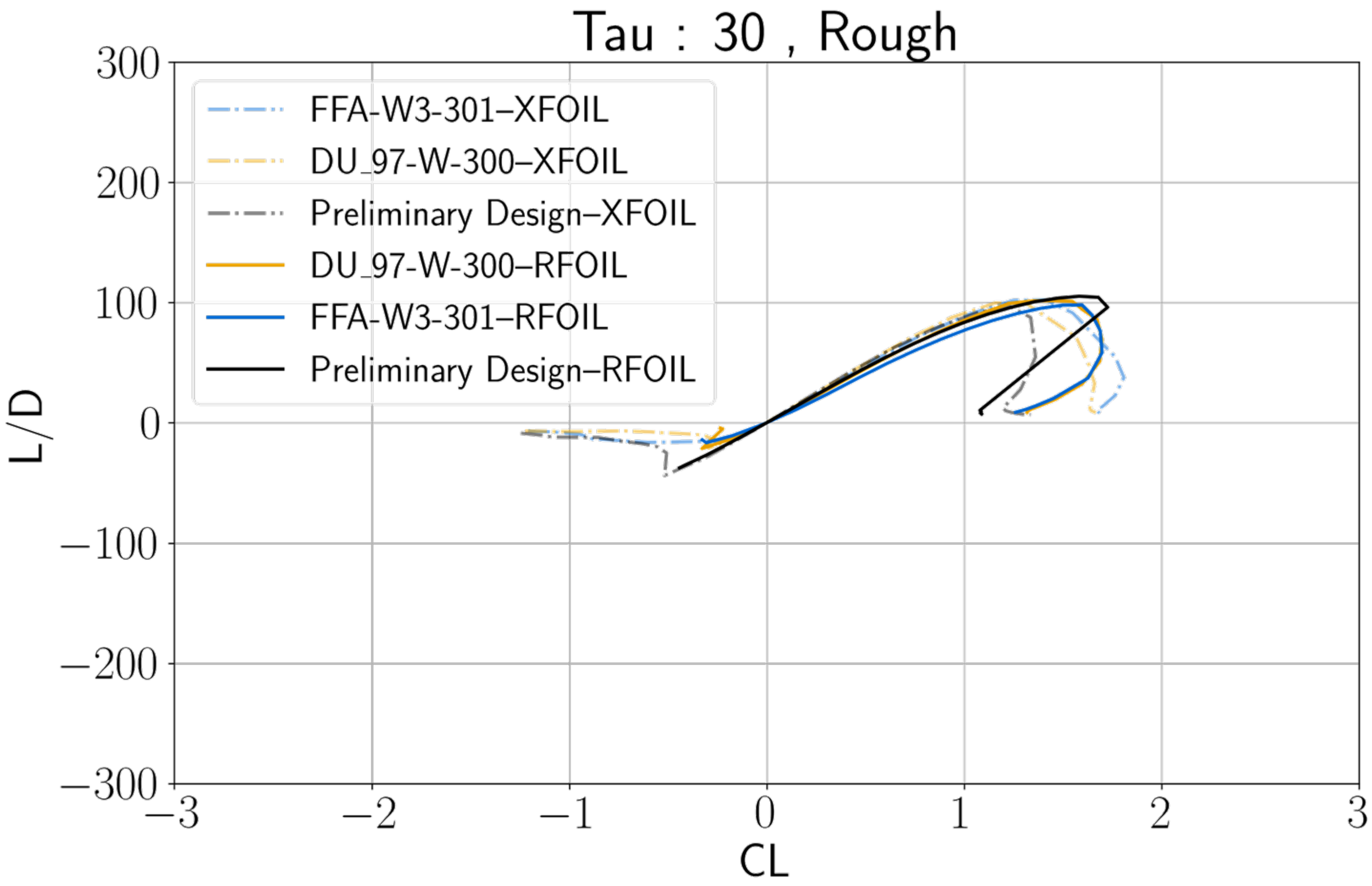


Tau : 30 , Clean
FFA-W3-301–XFOIL
DU_97-W-300–XFOIL
Preliminary Design–XFOIL
DU_97-W-300–RFOIL
FFA-W3-301–RFOIL
Preliminary Design–RFOIL
L/D
CL
300
200
100
0
−100
−200
−300
−3
−2
−1
0
1
2
3

30% Airfoil



FFA-W3-301
DU 97-W-300
Preliminary Design
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
0.0
0.2
0.4
0.6
0.8
1.0

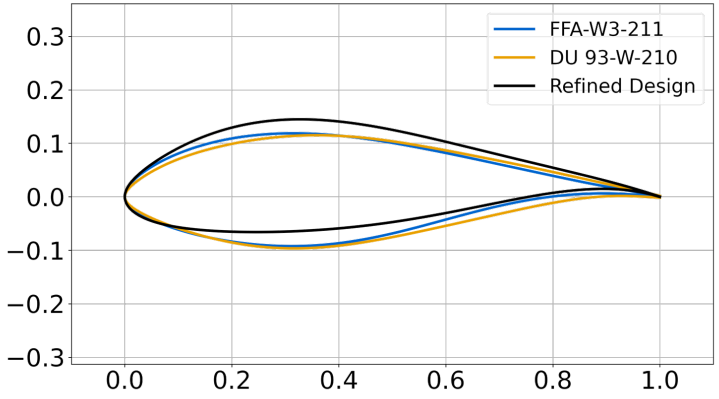


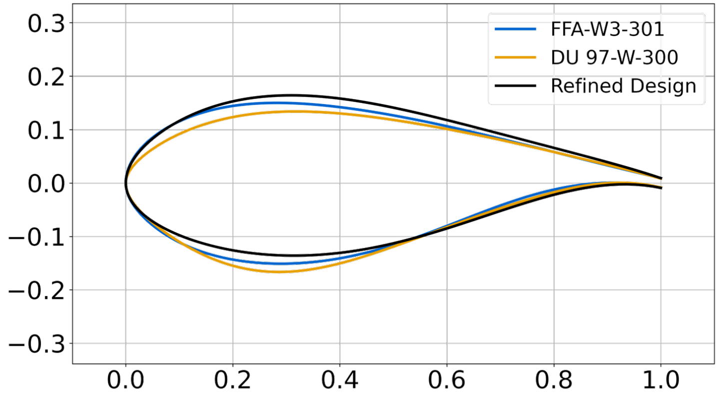
Tau : 30 , Rough
FFA-W3-301–XFOIL
DU_97-W-300–XFOIL
Preliminary Design–XFOIL
DU_97-W-300–RFOIL
FFA-W3-301–RFOIL
Preliminary Design–RFOIL
L/D
CL
300
200
100
0
−100
−200
−300
−3
−2
−1
0
1
2
3

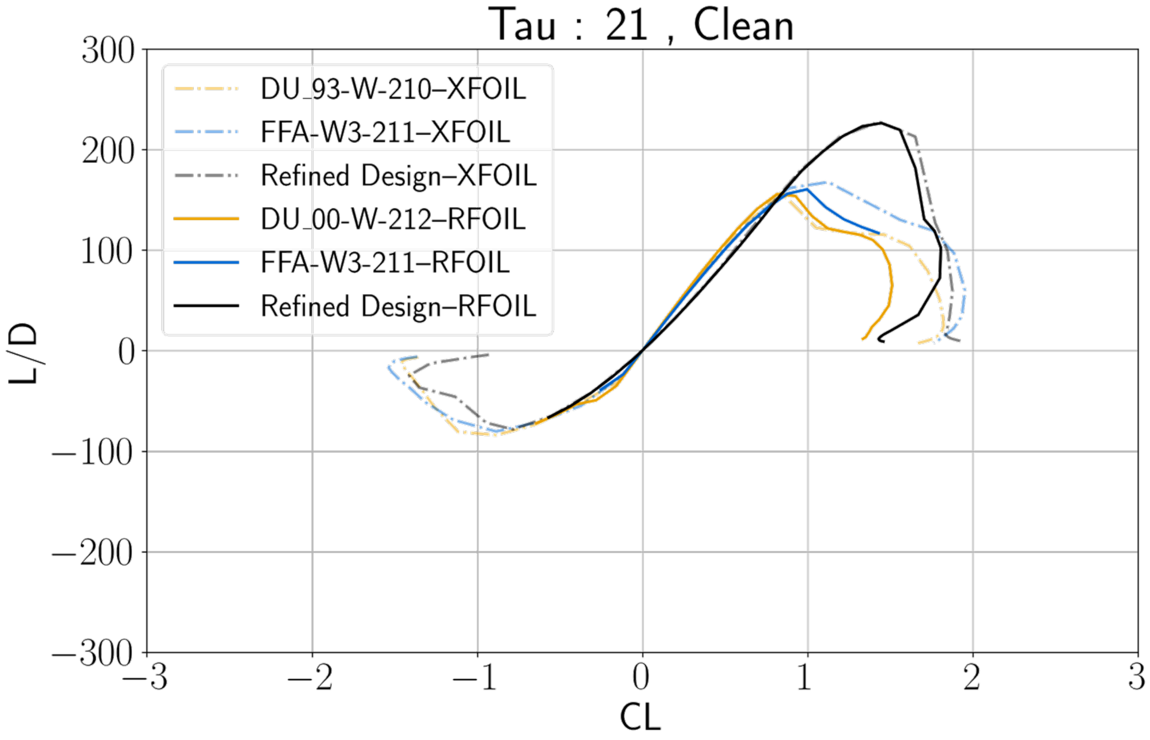
Hand Modified airfoils perform well in design metrics (RFOIL)

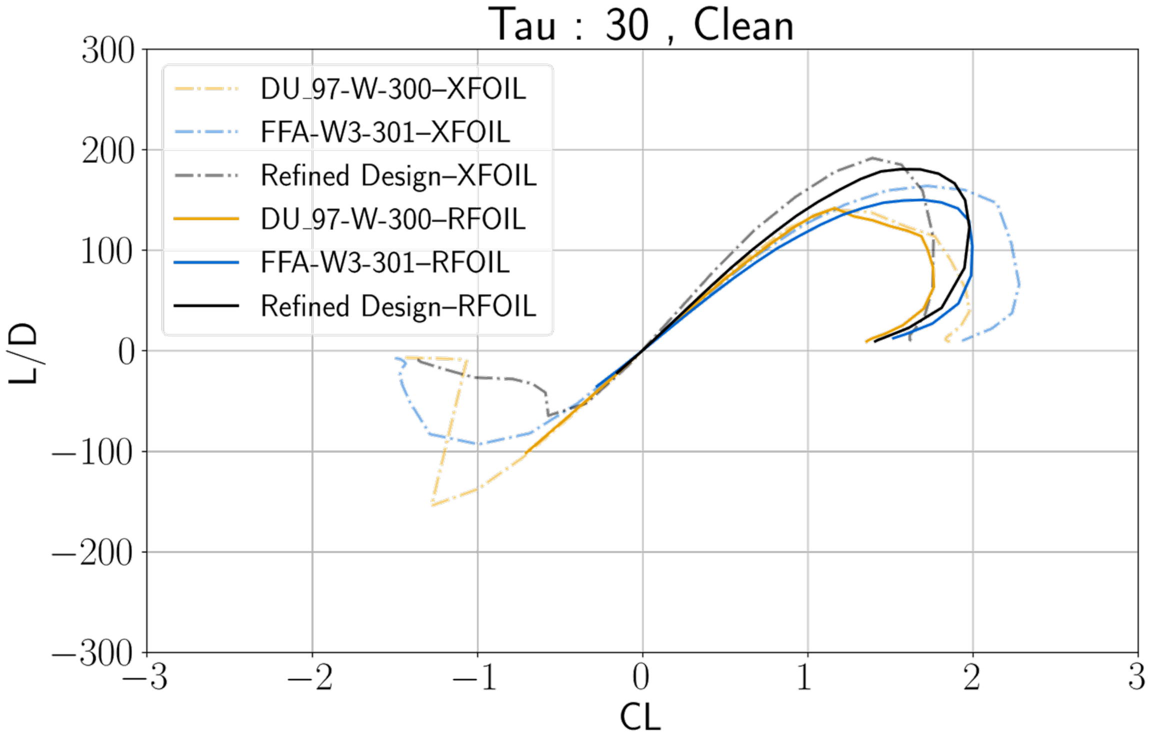
Normalized Thickness	21%	24%	27%	30%
Design Lift Coefficient	1.5	1.4	1.3	1.2
Reynolds Number	12e6	13e6	16e6	18e6
Angle of Attack	9.67	6.39	6.43	7.72
Clean L/D	183.36	202.80	184.58	156.10
Rough L/D	124.14	106.43	109.60	95.42
Stall Margin (degrees)	3.80	4.09	5.98	5.66
Pre-Stall Lift Coefficient Margin	0.39	0.62	0.75	0.81
Change in C_L due to Roughness	0.01	0.08	0.06	0.01
C_M Clean	-0.081	-0.131	-0.118	-0.087
C_M Rough	-0.073	-0.123	-0.110	-0.078
LE Radius	0.02216	0.02881	0.04809	0.05086
Flap Stiffness (I_{xx})	0.00030	0.00043	0.00060	0.00085
Edge Stiffness (I_{yy})	0.00578	0.00637	0.00721	0.00867
Torsion Stiffness (I_{zz})	0.00608	0.00680	0.00782	0.00952
Area	0.12399	0.13782	0.15487	0.17749

Recent Refinements

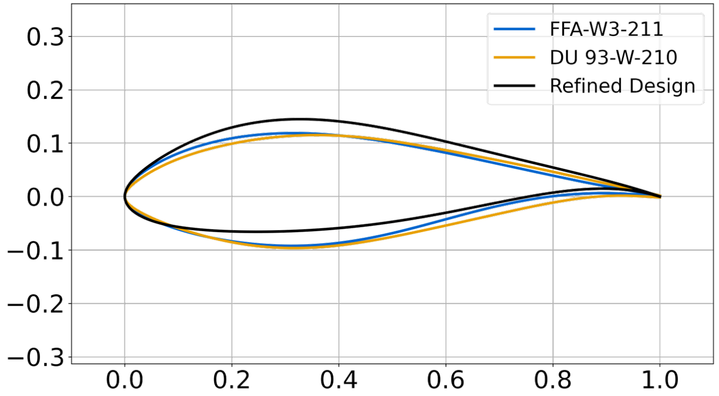


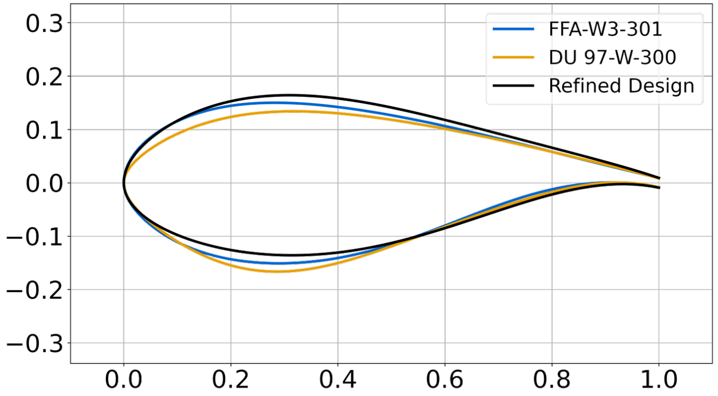


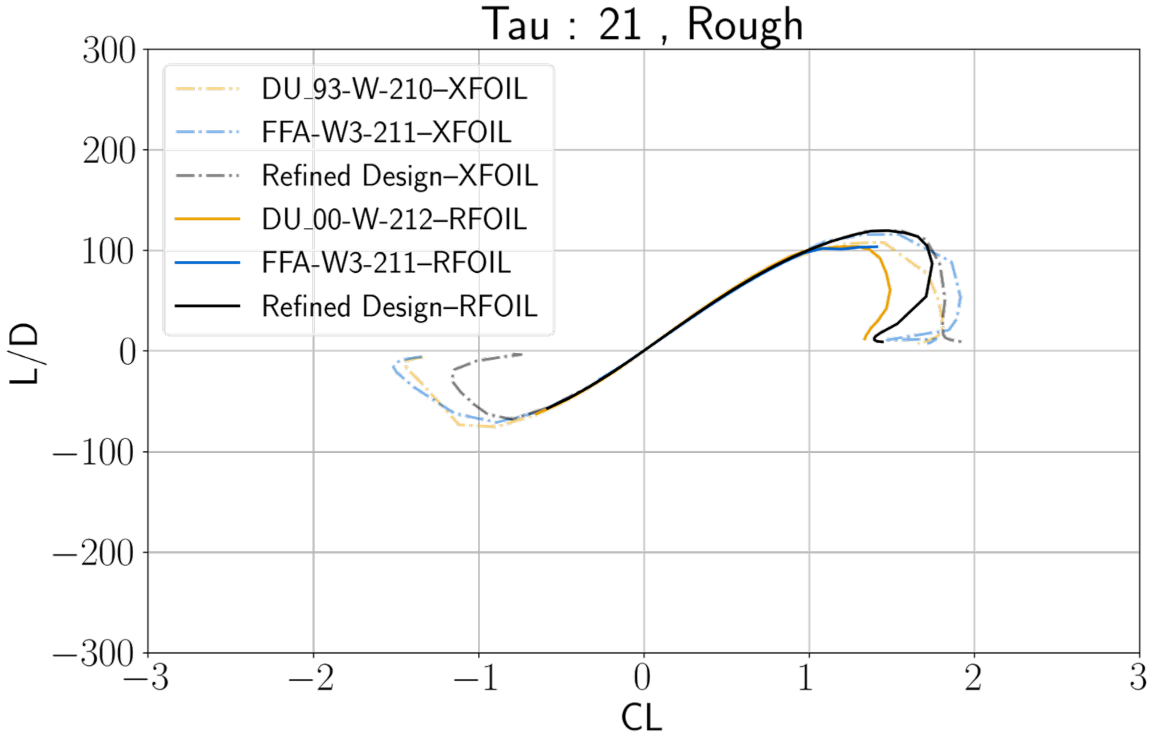


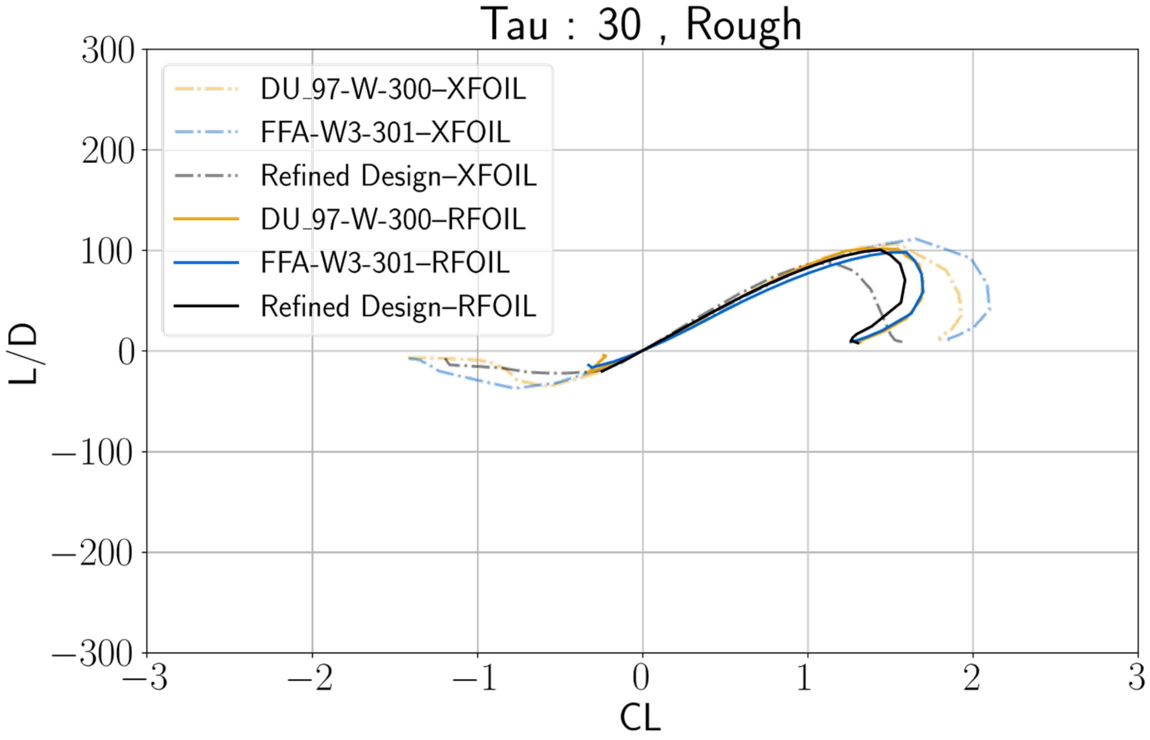


Recent Refinements









Next Steps

Future tasks are refinement and application

1. **Continue to refine the requirements, objective function**
   – Consider family together as a whole and spar layout
   – Consider 3D aero effects
   – Model full rotor performance

2. **Incorporate community feedback**
   – Final versions of these airfoils are being considered as candidates for experimental testing

Questions?

Please send us your comments at:

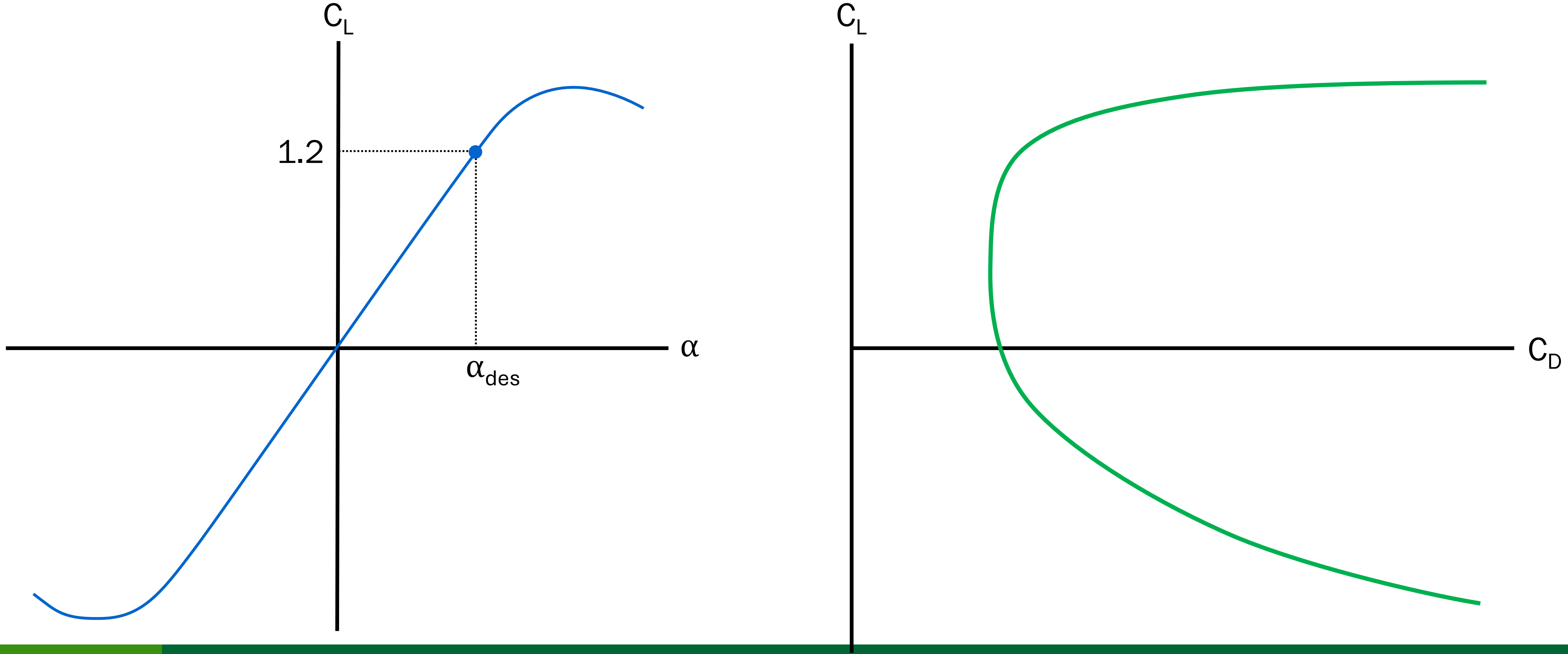
Cody Karcher
cody.karcher@csulb.edu

David Maniaci
dcmania@sandia.gov

Backup

Design Lift Coefficient

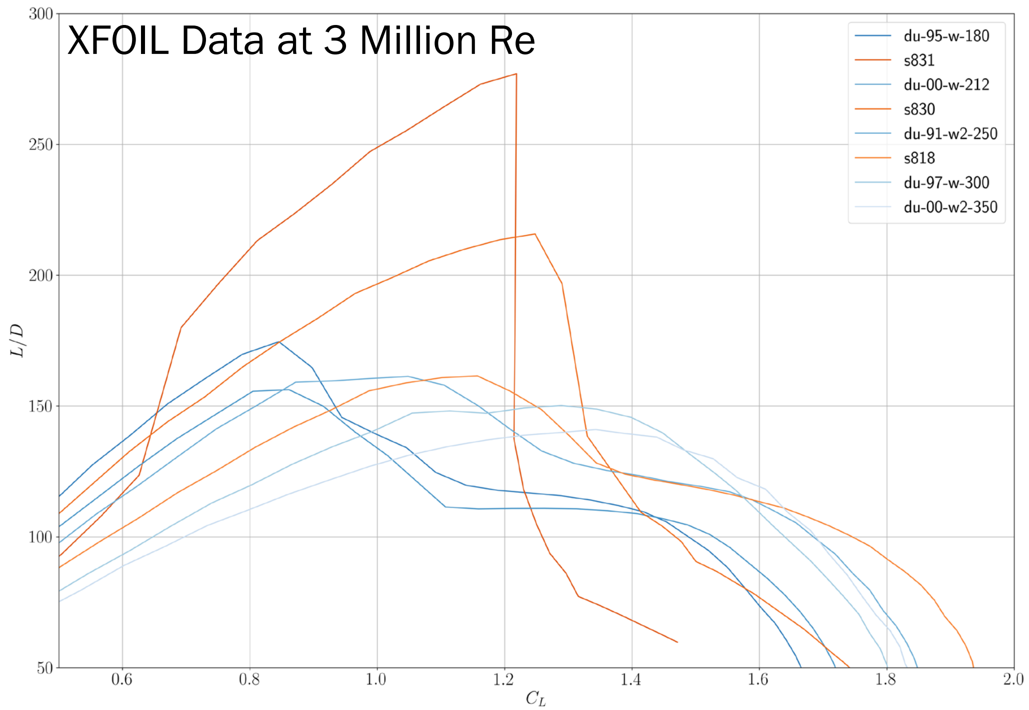
- Initially selected to be C_L=1.2 for the entire family
- Later selected C_L=1.5 at tip reducing to C_L=1.2 at ~40% span to follow IEA 22MW reference turbine design conditions
- Should occur in the linear region of the CL-Alpha curve



Lift to Drag Ratio (L/D)

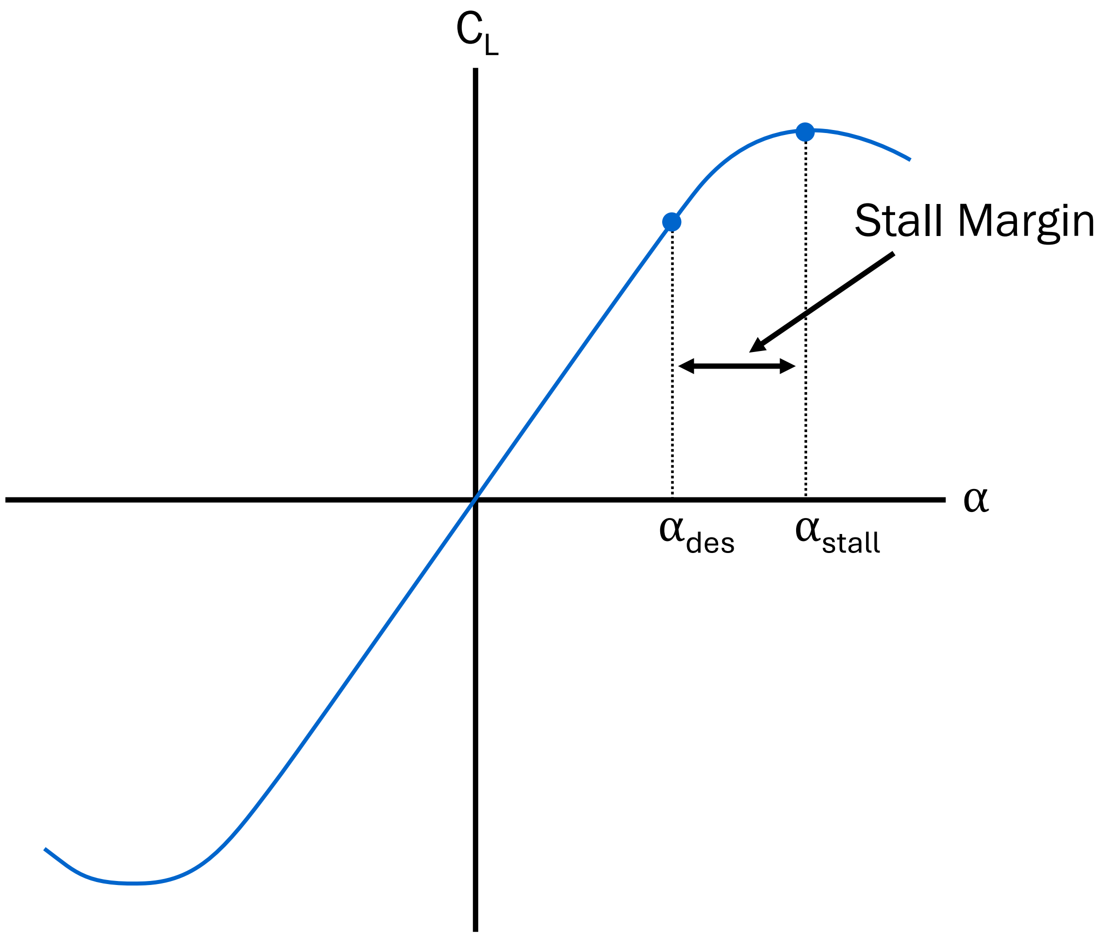
- Should be maximized with a target of between 170 and 200
- Desire a clear increase over DU/FFA/Riso series
- Desire more robust performance than S-series (broader peak, less Re# dependance)

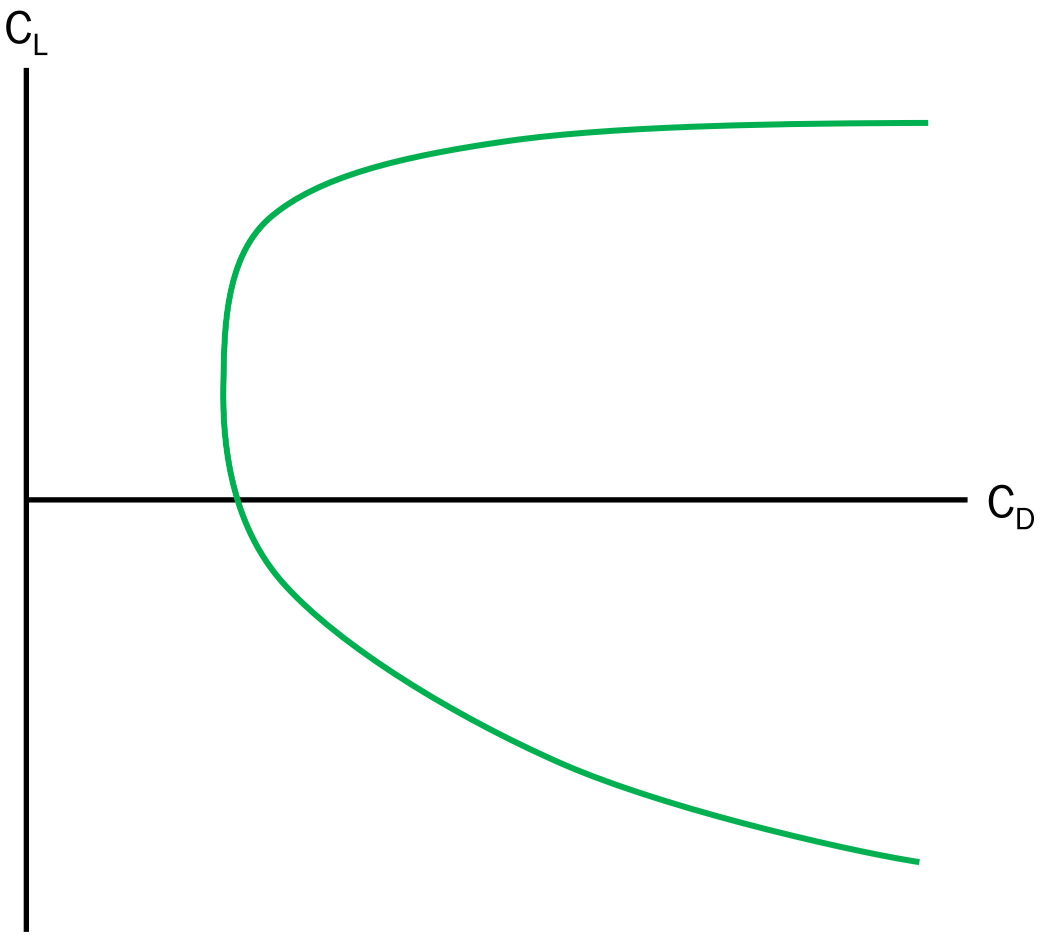
Normalized Thickness	15%	18%	21%	24%	27%	30%	33%	36%
L/D Target	200	200	200	190	185	180	175	170



Stall Margin–Clean

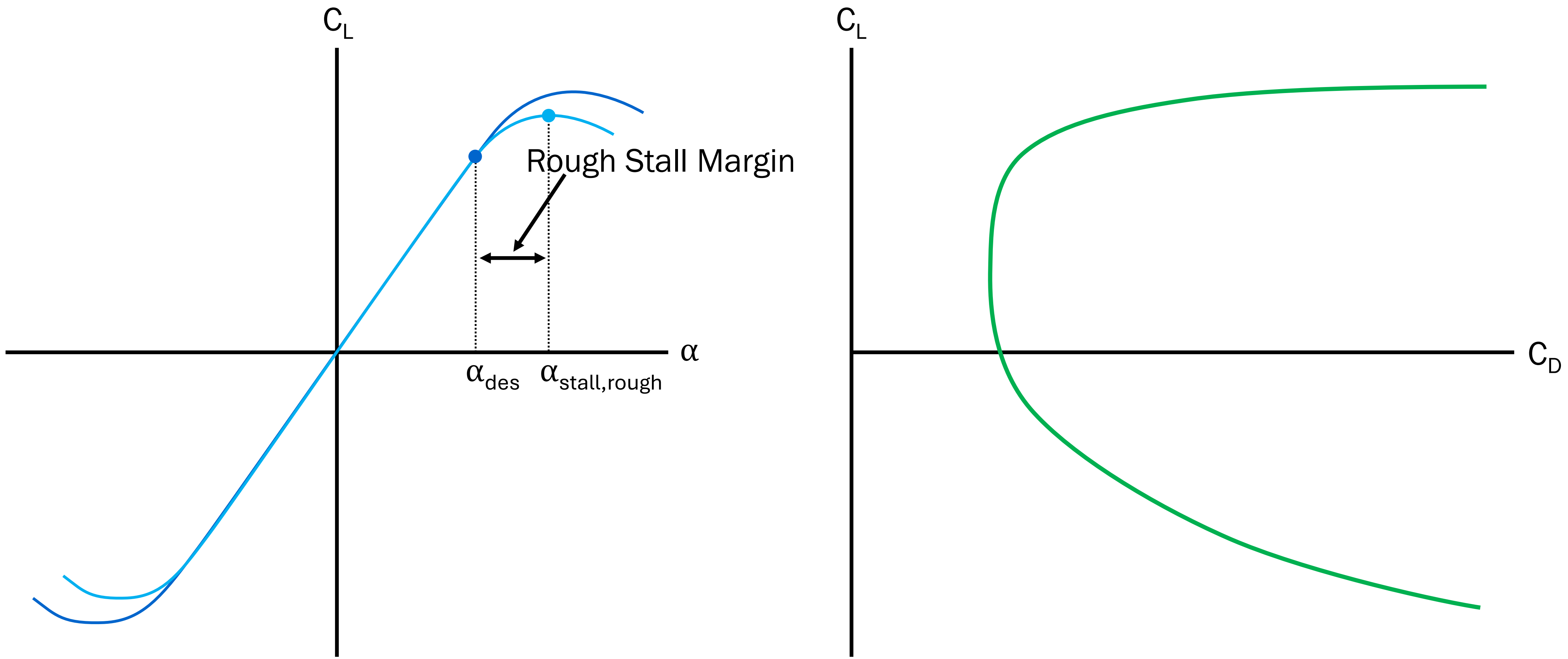
- Angle of attack difference between design C_L and $C_{L,max}$
- *Must* exceed 3 degrees for robustness to real-world conditions





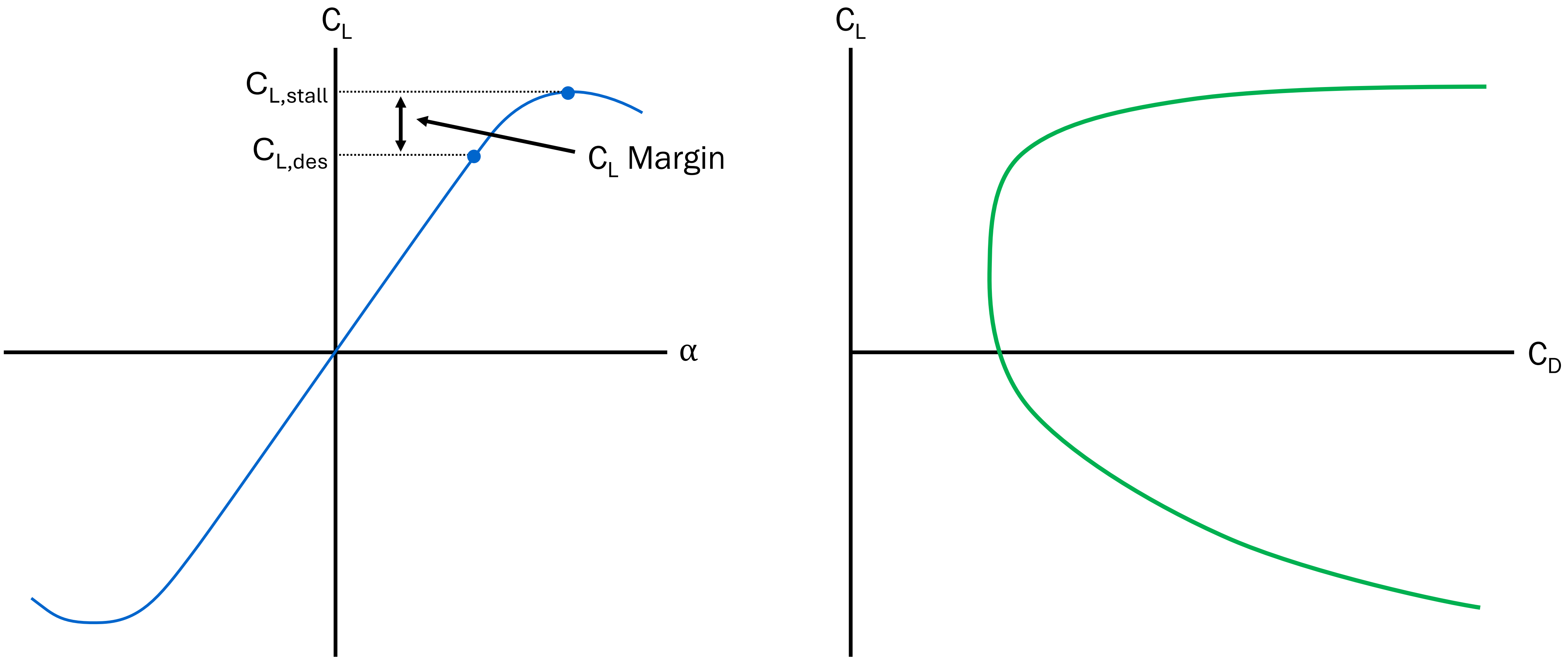
Stall Margin–Rough

- Same as clean, but modeled using N_{crit} and transition location
- *Must* exceed 3 degrees for robustness to real-world conditions



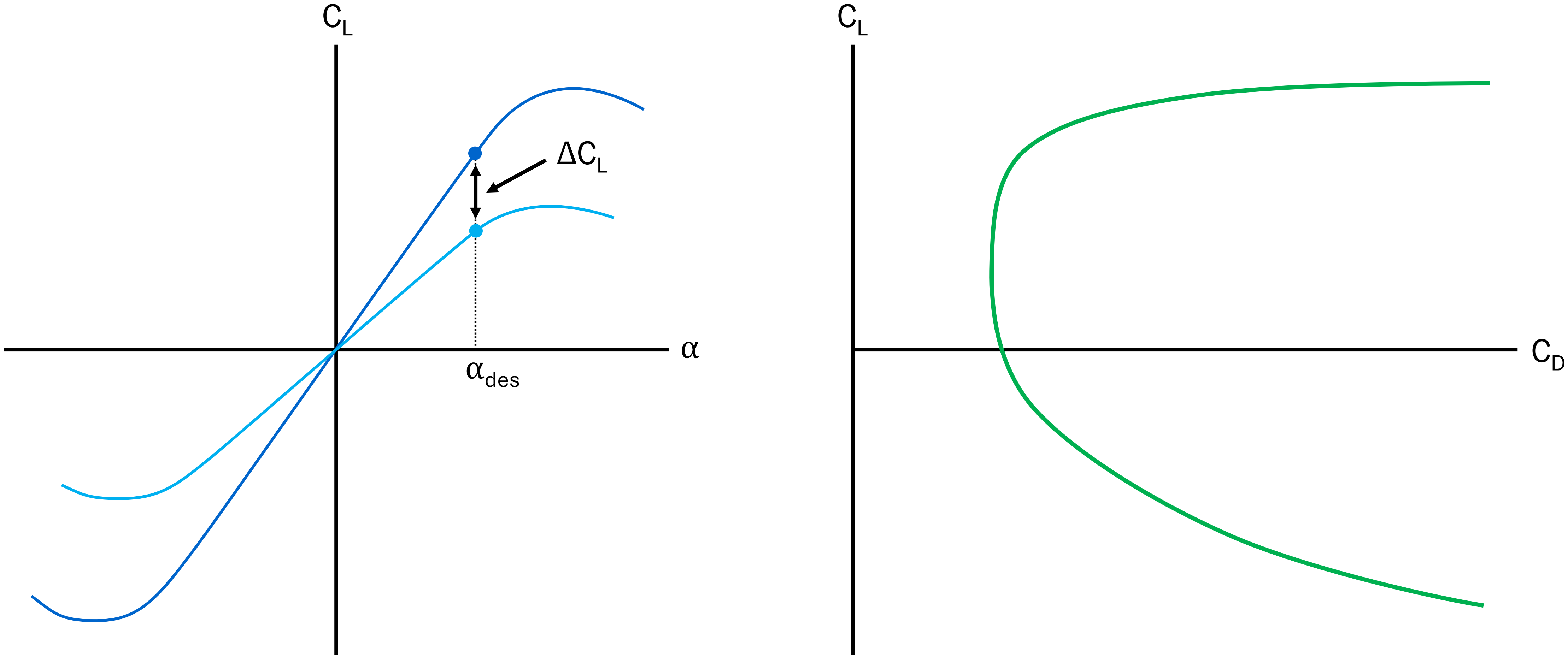
Lift Coefficient Margin to Stall

- Should be minimized to limit gust loading
- Target a nominally small value of 0.2



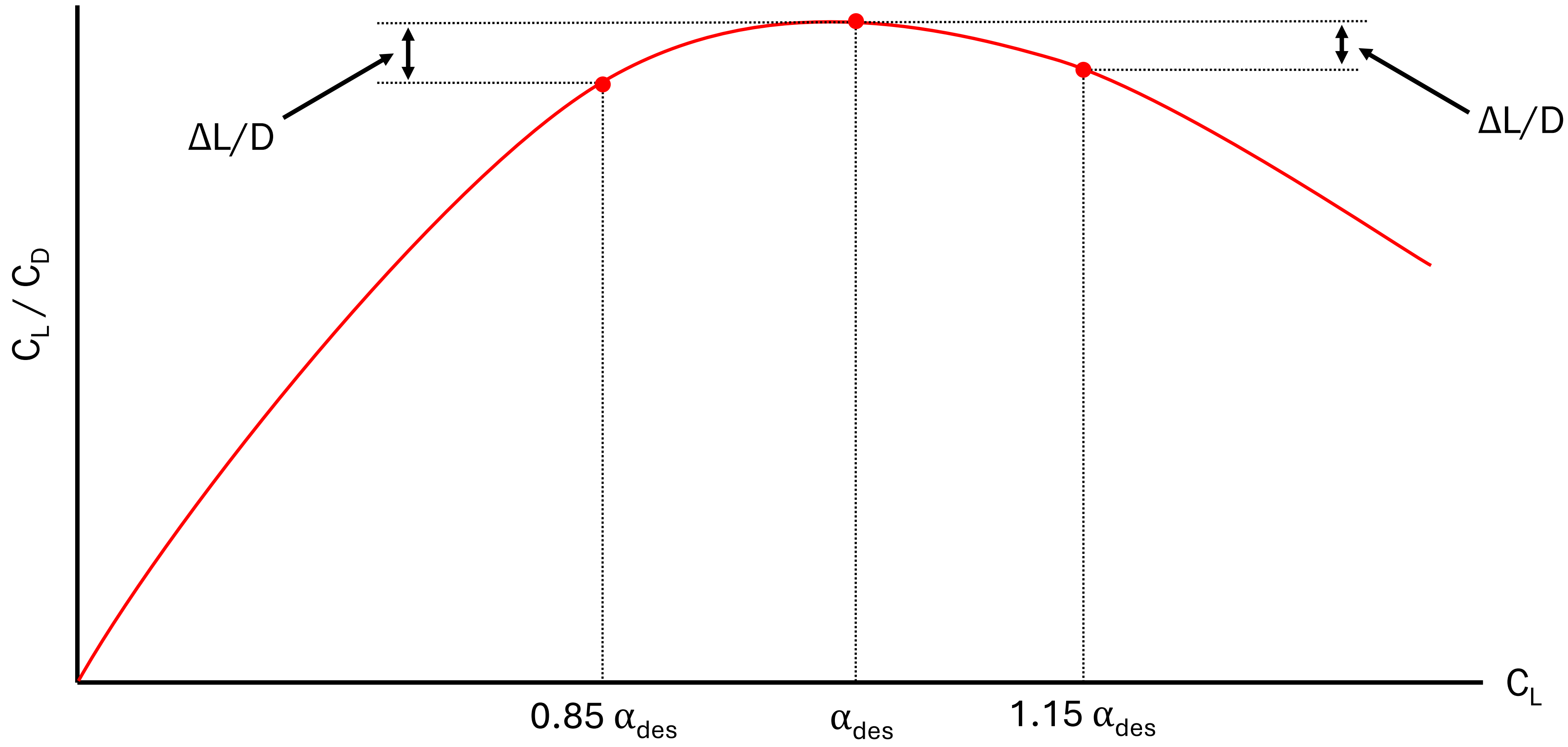
Change in Lift Coefficient Due to Roughness

- Measured as change in C_L at the AoA of the clean design C_L
- Limit to a change of less than 10% from clean baseline



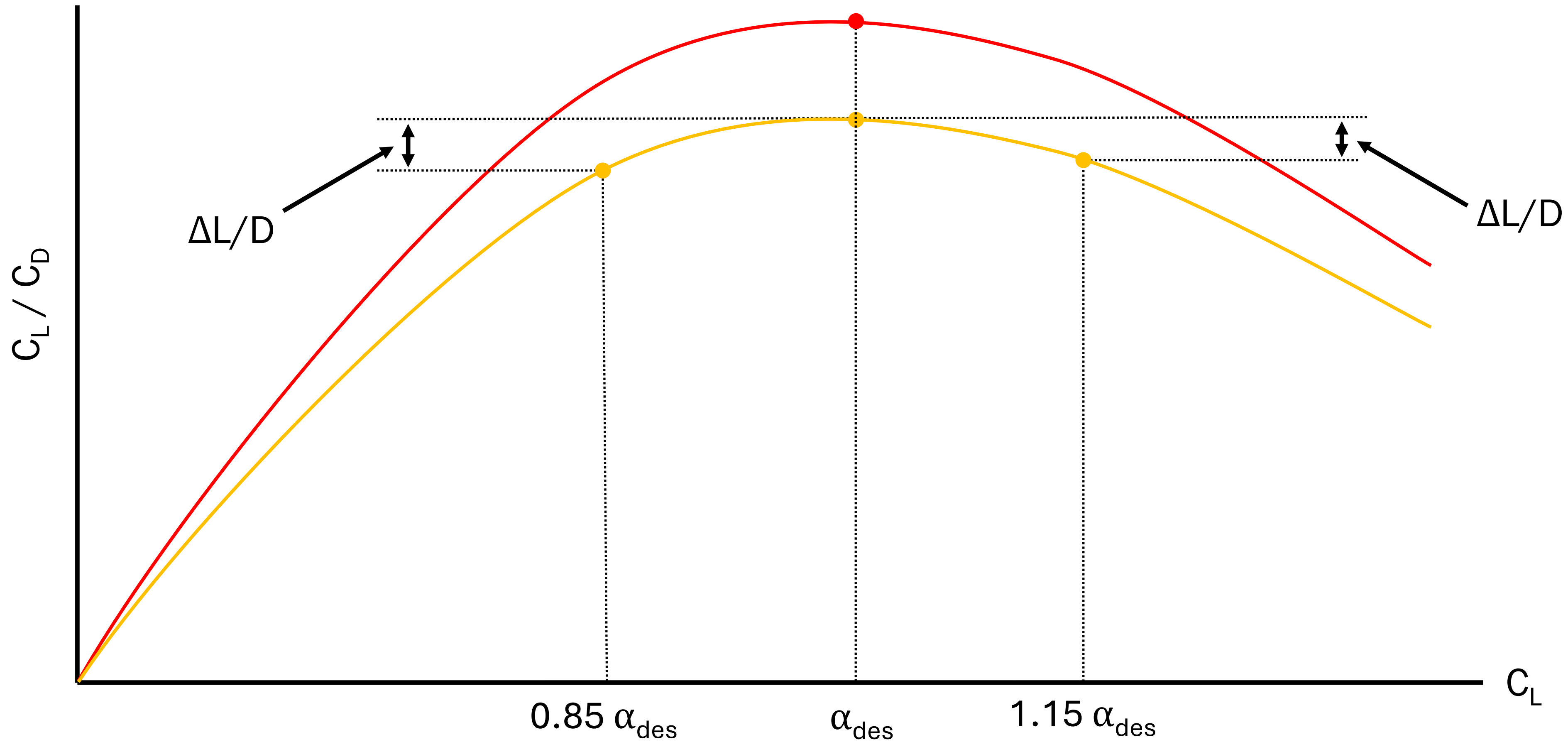
L/D Ratio in the Operating Region–Smooth

- L/D curve should be reasonably flat in the desired operating region
- Target within 15% of $(L/D)_{des}$ within +/-15% of α_{des}



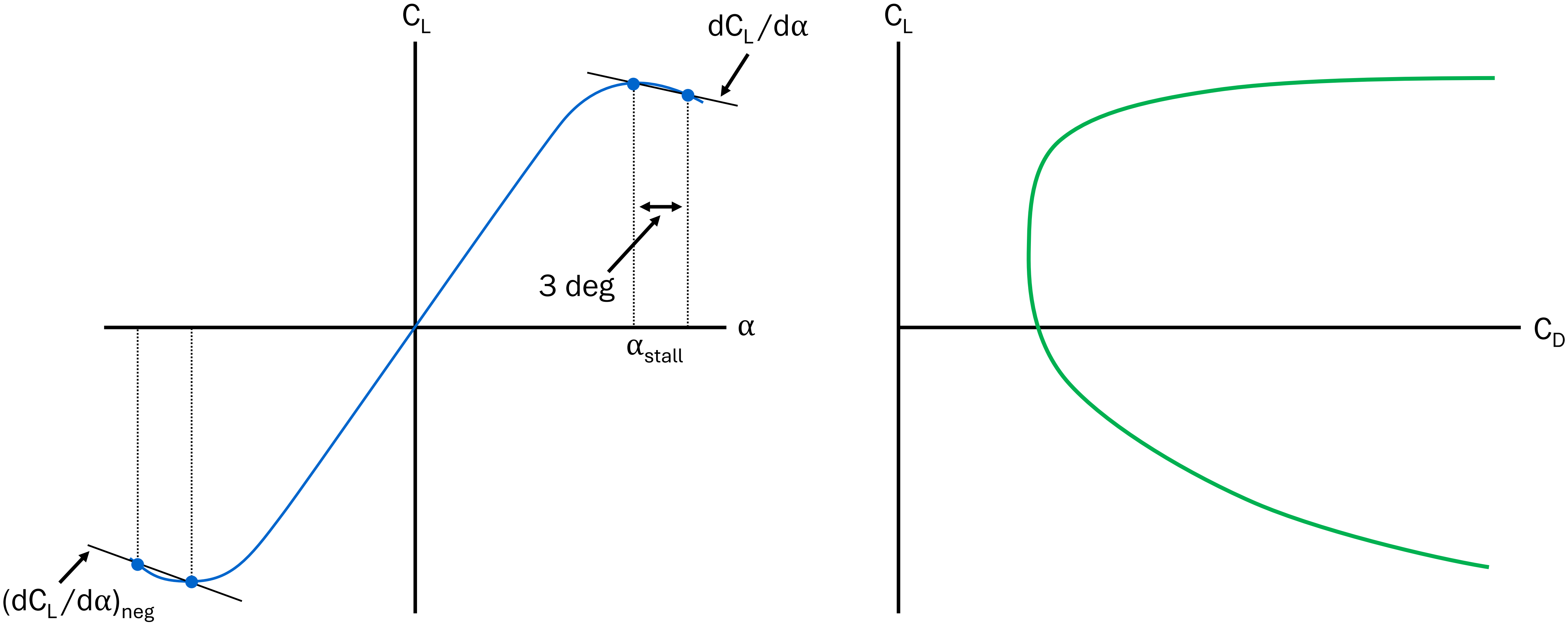
L/D Ratio in the Operating Region–Rough

- Same as before, but for rough airfoil
- Target within 5% of $(L/D)_{des}$ within +/-15% of α_{des}



Post-Stall Behavior

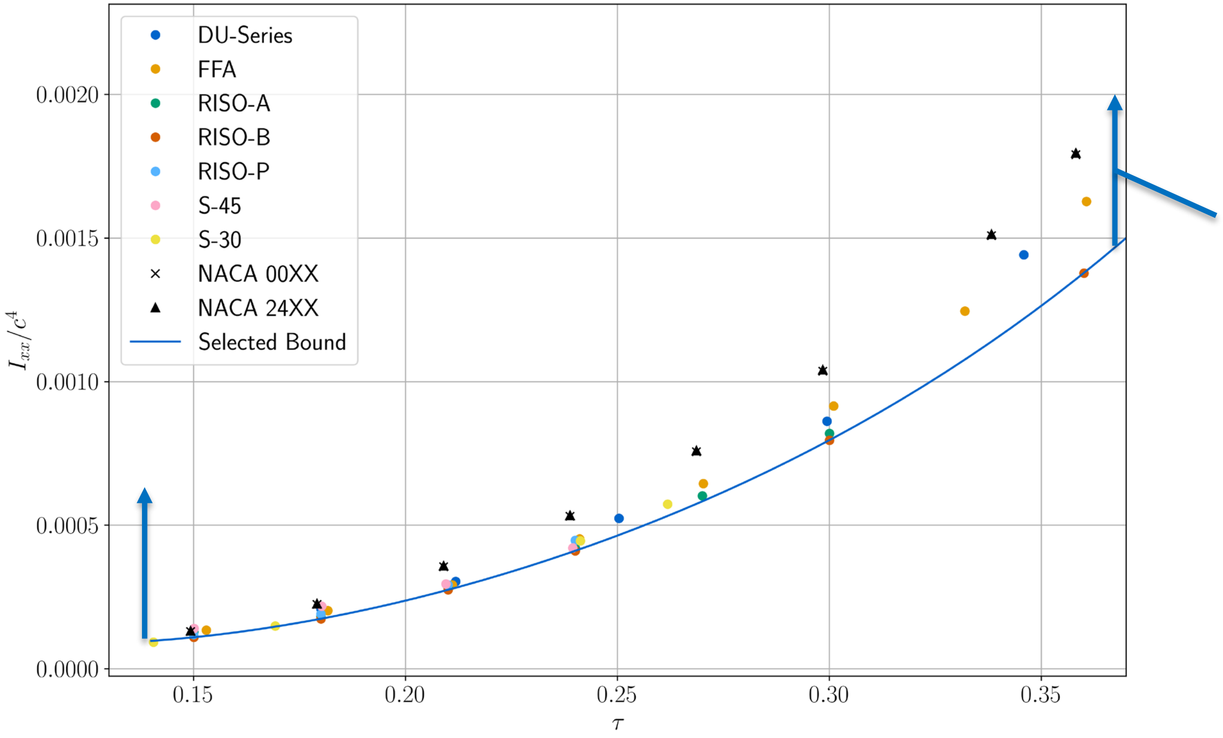
- Post-stall slope is a major factor in blade fatigue
- Should be minimized, but will only be used as a final selection criteria



Structural Performance

Solid Body Geometry Properties

- **Performed a study of solid area geometry properties of existing airfoils**
  - I_{xx} (Bending), I_{yy} (Edgewise), I_{zz} (Torsion), and Area
- **Strong correlation and separation from non-turbine airfoils**
- **Will implement lower bound of existing airfoils as a design constraint**



Require Ixx to be higher than bound

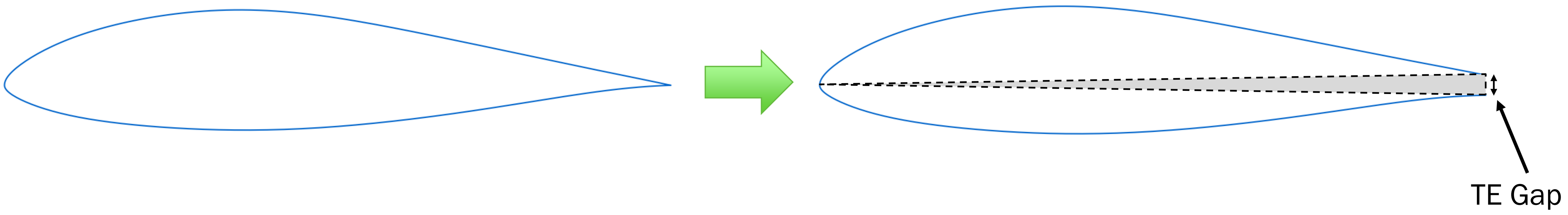
Geometry Considerations

Robustness to Finite Thickness Trailing Edges

- Will be designing sharp since true TE gap cannot be known *a priori*
- Target less than 1% change in all metrics on the following thicknesses:

Normalized Thickness	15%	18%	21%	24%	27%	30%	33%	36%
TE Gap	2mm	2mm	2mm	3mm	3.5mm	4mm	4.5mm	5mm

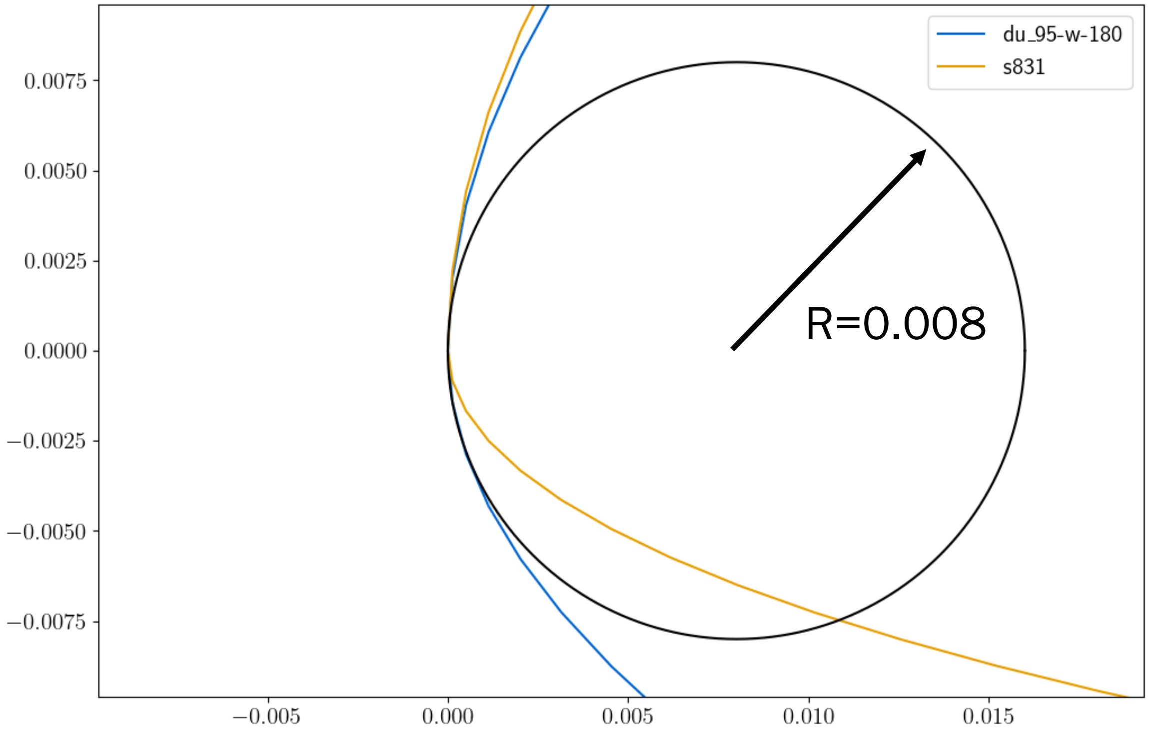
- Thickness targets increase for thicker inboard airfoils



Leading Edge Radius

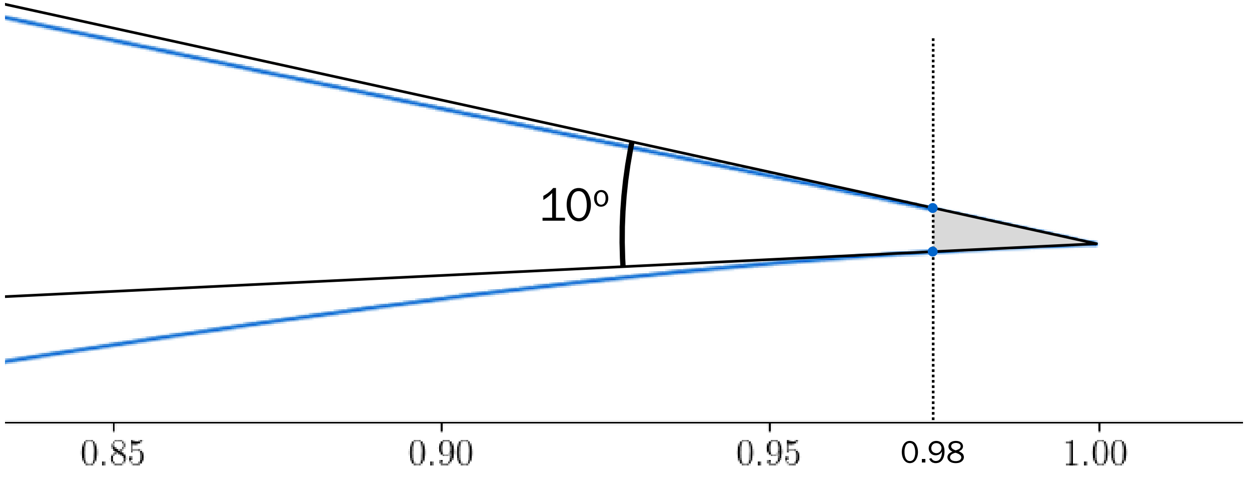
- Small LE radius causes inconsistent and rapid separation
- Limit to somewhere between the DU and S series airfoils

Normalized Thickness	15%	18%	21%	24%	27%	30%	33%	36%
LE Radius	0.007	0.008	0.01	0.025	0.03	0.04	0.06	0.08



Trailing Edge Wedge Angle

- Ensures manufacturability and structural integrity
- Last 2% of chord must have a wedge angle of at least 10 degrees



Maximum Thickness Location

- S-series airfoils had significant spar offsets
- Will constrain max thickness to occur at the same x/c in this work