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National Rotor Testbed Test Campaign Review — Status, Direction, and Accomplishments

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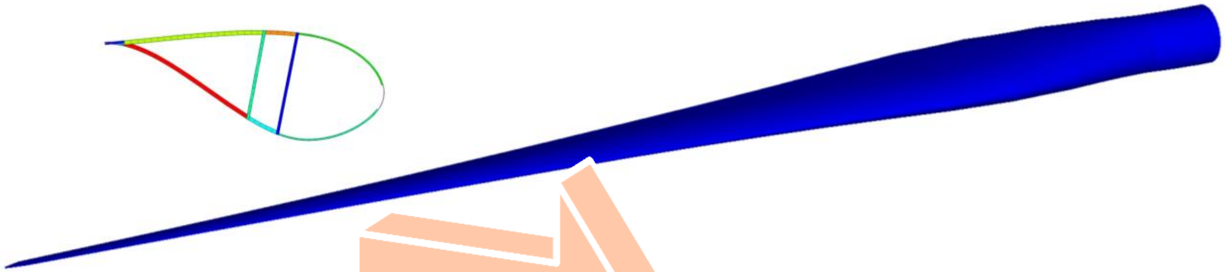
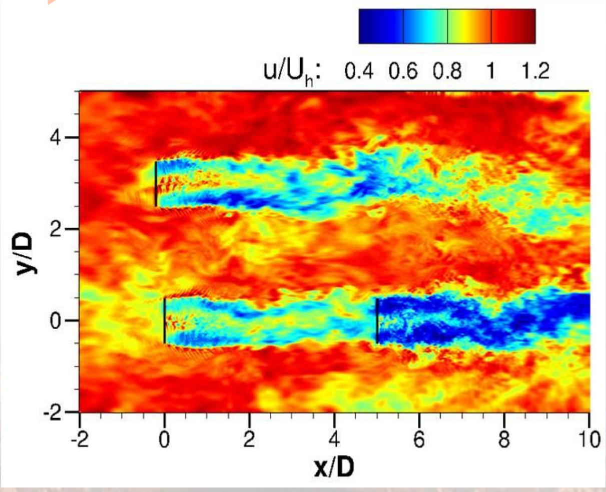
Vision



Aero-structural rotor design

Building connections between rotor designs and rotor wake research

Wakes and turbine-turbine interaction



Vision—SWiFT Experiment I: Inflow & Near-Wake Characterization

- **Problem Statement**
  - The Atmosphere to electrons (A2e) initiative has identified the evolution of wakes in turbulent inflow as the key physical process affecting the power production and turbine loads in multi-array wind plants. High-quality experimental data is necessary to understand the physical processes governing the generation and evolution of wakes and to validate high-fidelity computational models using a formal and systematic Verification and Validation (V&V) approach.
- **Goal**
  - Conduct a comprehensive experimental campaign to understand the physics governing the *near-wake* development and breakdown process of a scaled rotor in well characterized turbulent inflow conditions.

Vision—SWiFT Experiment I: Inflow & Near-Wake Characterization

- **Objectives**
  - Detailed characterization of the turbulent inflow conditions and atmospheric boundary layer profiles at the SWiFT Facility.
  - Design, build, and test a scaled wind turbine rotor capable of reproducing the wake characteristics observed in utility-scale turbines; verify scaling capability.
  - Detailed characterization of the near-wake coherent structures (primarily tip vortices), the turbulent wake breakdown process in the intermediate range, and the preliminary stages of fully turbulent Gaussian far-wake profile.
  - Utilize data in conjunction with high-fidelity models through formal and systematic Verification and Validation (V&V) process developed within the A2e initiative.
  - Complement other A2e experimental campaigns in the wind tunnel and utility-scale wind farms to understand the impact of scaling on rotor aerodynamics.
- **Success Criteria**
  - Able to quantify model bias and uncertainties in turbulent inflow and near-wake region.
  - High-quality experimental data for use in V&V exercises to develop and improve high-fidelity inflow and wake models.

Accomplishments

- Project began FY13 with "modern rotors for the SWIFT machines"
- Creation of a subscale GE1.5-77 with 37c blades focused the design
- A candidate design was created by early FY14 by Wetzel Engineering and SNL
- Turbine load constraint assumptions were identified as a critical project element—led to careful characterization of SWiFT turbine strength
- Test objectives were even more focused with formation of A2e—ie, model validation
- A related project—the FY14 Tip Speed Study ($75k)—provided numerous lessons learned regarding rotor and system design methods to affect this rotor
- SNL and U.Minn performed numerous rotor wake simulations to learn about effects of rotor design on wake character—found strong motivation for current path forward
- CFD used to preview effects of desired airfoils at lower-than-intended Reynolds numbers

A list of scaling drivers

- Blade architecture and geometry
- Airfoil thickness distribution and blade thickness distribution
- Rotor solidity
- Tip speed ratio

- Thrust force distribution
- Thrust and power coefficient distributions
- Circulation Distribution
- Distribution of axial and tangential induction factors
- Reynolds number
- Lift coefficient distribution
- Maximum lift and stall characteristics

- Wake meandering behavior
- Downstream flow character
- Characteristic size of inflow and downstream turbulence
- Wind shear relative to rotor

- Aero-acoustic noise
- Mach number

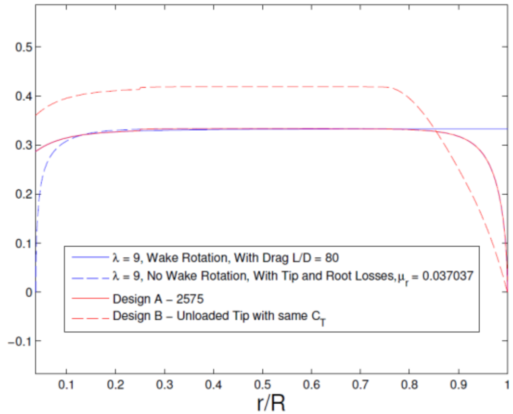
- Lock number
- Non-dimensional natural frequencies
- Blade mode shapes
- Tip deflection
- Bend-twist coupled dynamics of blades
- Non-dimensional time

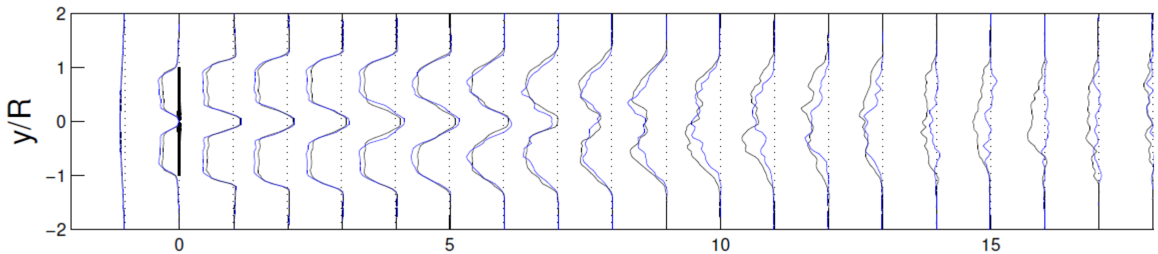
Scaling criteria

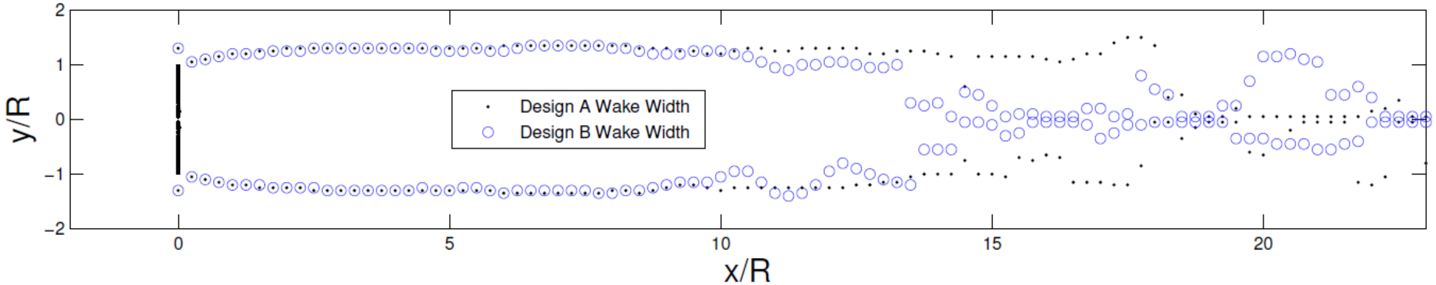
- **Primary**
  - Design tip speed ratio, lambda
  - Blade loading distribution, Gamma—either axial inflow or non-dimensional circulation
  - Rotor thrust coefficient, C_T
  - Rotor power coefficient, C_P
- **Secondary**
  - Shape of C_p—lambda curve
  - Local lift coefficient deltas; difference between operational and maximum C_l
  - Raw tip velocity
- **Above all: design within the strength of the SWIFT turbines**
- **Out of our control—not ignored, but carefully monitored**
  - Reynolds numbers—Effects $C_{l,max}$ and, therefore, inboard flow attachment and dynamic loads
  - Characteristic turbulence length scales at rotor heights

Rotor design influence on wake character

- Both designs have same C_T
- Christopher Kelley, Submitted and accepted for AIAA SciTech 2015
- SNL Tech Advance Submitted
- Observations corroborated by U.Minn







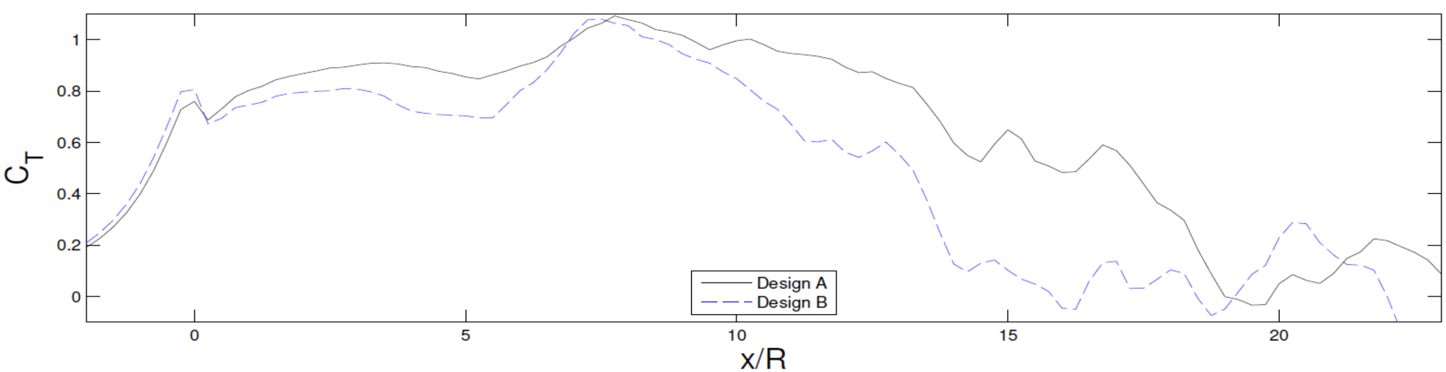
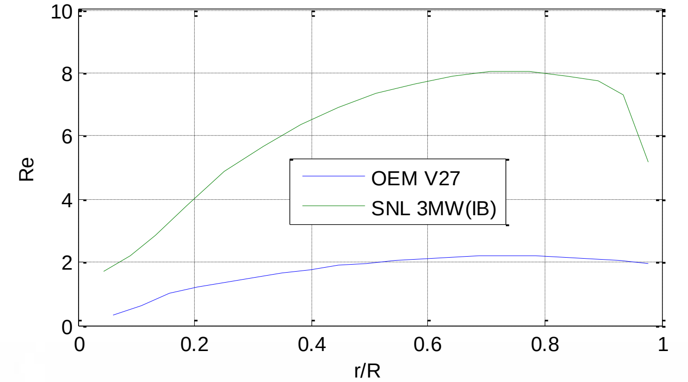
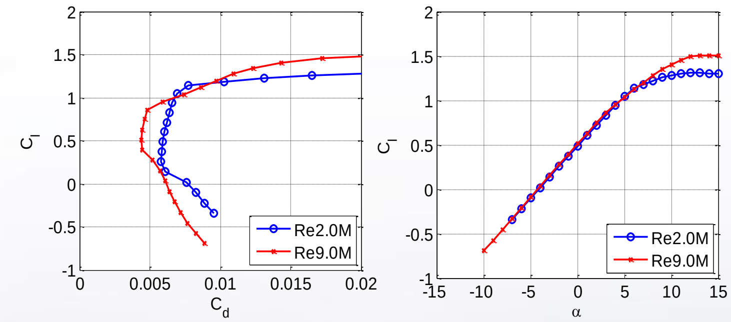


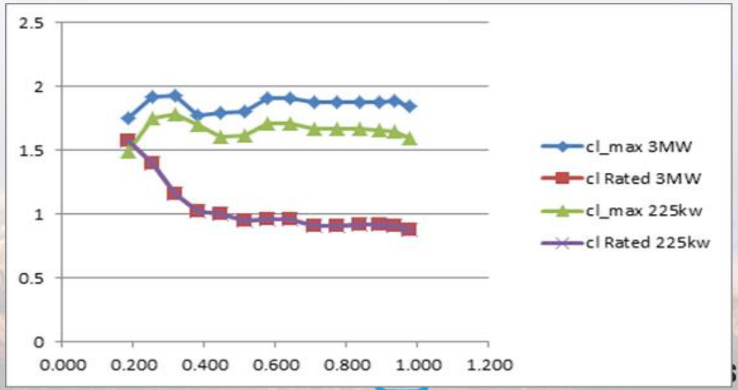
Figure 9. Vertical plane axial momentum deficit for designs A and B.

Reynolds number effects

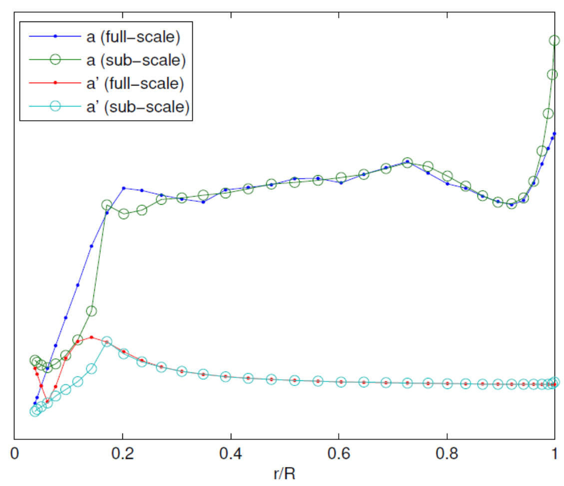
- **Reynolds numbers will not match between scales – we seek merely to understand and account for its effects**
- **A reduction in Reynolds number for a given airfoil (generally) causes**
  - Decrease in max C_l
  - Increase in profile drag
- **It can affect the scaled rotor design if the chord and twist are not modified to account for new polars**
- **New airfoils might be required in extreme cases**





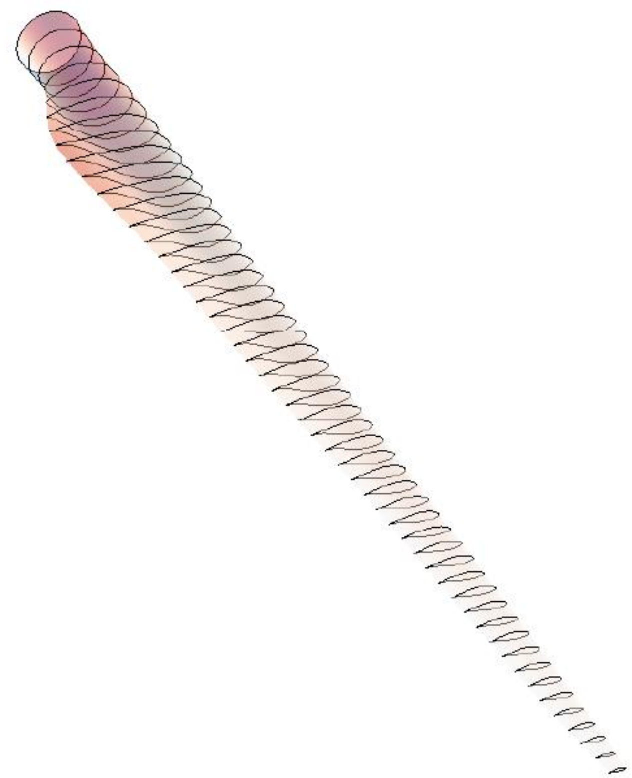


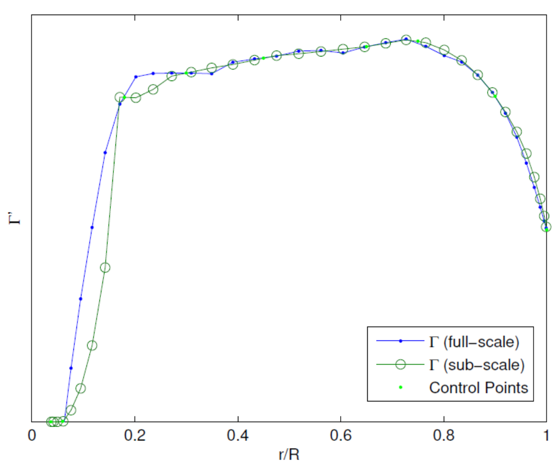
Subscale rotor design

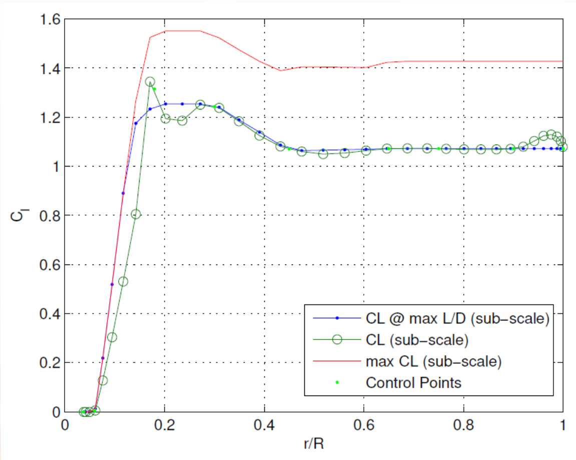


Sandia Selected Airfoils

Section	Shape	$\frac{r}{R}$
1	Circle	0.06
2	DU 97-W-300	0.18
3	DU 91-W2-250	0.45
4	DU 93-W-210	0.65
5	DU 95-W-180	0.75







Open research questions that drive rotor design

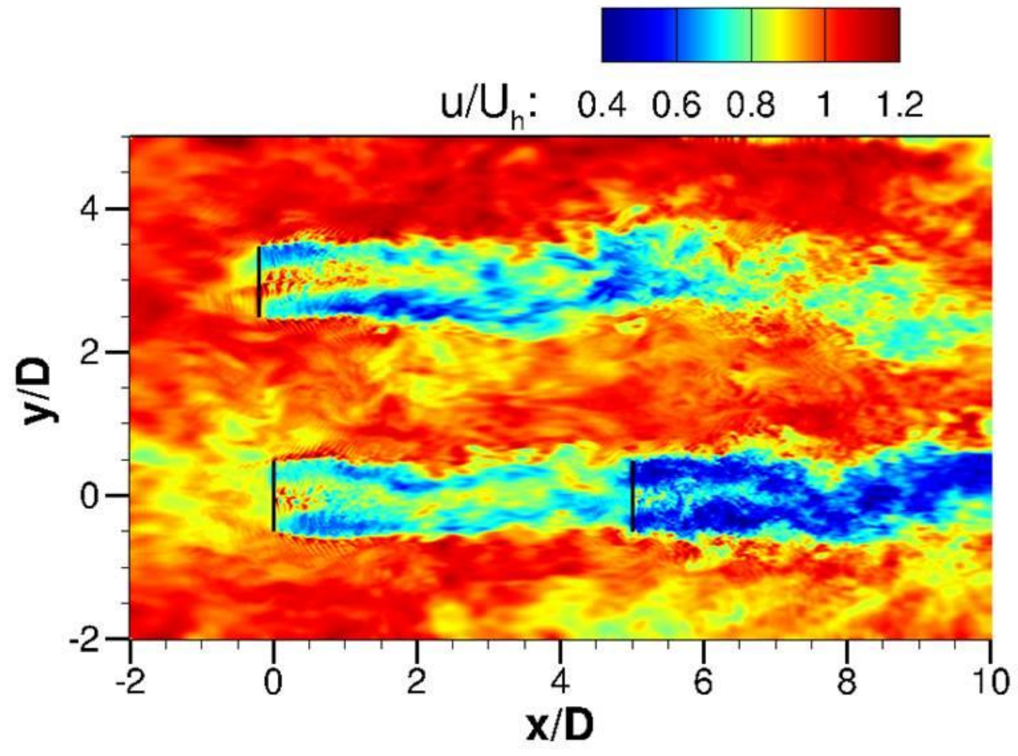
Integrated wake interaction and rotor designs

- wake recovery
- wake stability
- near/far wake behavior
- Representation of utility scale features
- Functional scaling
- High fidelity
- Medium fidelity
- Low fidelity
- Validation of simulation tools
- Sensor suites for rotors
- Subscale wind tunnel test
- Reynolds number effects
- Subscale field test
- Atmospheric boundary layer
- Dynamic rotor loads
- Scaled rotor size and height
- Characteristic turbulence length scales

Subscale rotor design objectives drive cost effective test and validation of A2e research goals

Wake character from LES

- **High fidelity LES methods will be used to guide rotor design**
- **Key questions:**
  - Are the wakes of a MW-scale turbine rotor and the SWIFT rotor similar ?
  - If different, how to translate scaled knowledge to full scale ?
  - How do changes in blade loading distribution resulting from NRT scaled design studies affect the development of the SWIFT wake?



Instantaneous contours of stream-wise velocity from a Large Eddy Simulation of the SWiFT test site using the University of Minnesota Virtual Wind Simulator.

High fidelity wake models provide realistic previews of upcoming field tests and provides insights to needs of validation

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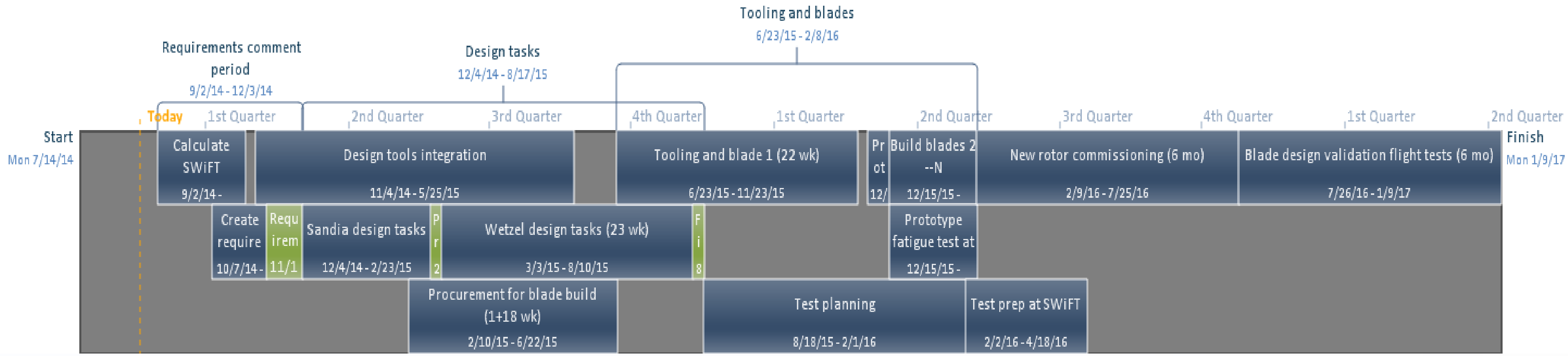
FY15 NRT Timeline



Additionally—publications at conferences and in journals to document work being done in wake simulations

Next Steps and Future Research

FY14/Current research:

- Re-visit and closeout current rotor design specifications
- Rotor design
  - Assembly and verification of aero-structural rotor design tool to enable unconventional design objectives for functionally scaled rotors
- Wake simulations to guide rotor design
  - Vortex wake simulations
  - LES wake simulations (U.Minnesota)
- Airfoils
  - Specification of airfoil families for mid and small scale rotor designs
- SWIFT loads envelope
  - Formal calculation of SWIFT turbine loads envelope to remove conservatism in rotor design
- Sensors
  - Lab and field test of aero sensing strategies to increase confidence of implementation in the field
- Public Review
  - Final rotor design concept(s) for public review at the Sandia Blade Workshop (August 2014)

Next Steps and Future Research

FY15:

- Comprehensive review of entire test campaign by A2e science panel
- Detailed blade design in preparation for manufacture
- Blade and tooling manufacture, manufacture blades, ground test blades, flight test blades

Proposed future research:

These rotors provide the industry with a relevant, open source baseline rotor testbed for public and proprietary research. The initial design represents only the beginning of an exciting future in exploration of wind energy technology innovations.

- Aeroacoustics of blades (quiet blades)
- Aeroelasticity of blades (flexible blades)
- Testing of sensing and measurement technology for blades and wakes
- Blade aerodynamics: tip design, root design, airfoil design and modifications
- Active, passive and hybrid load control
- Wind farm control
- SHM/damage testbed for validation of monitoring capabilities
- Blade subcomponent ground and flight testing
- Baseline and low-radar interference blade
- Material and manufacturing technologies demonstration blade
- High capacity factor rotor