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National Rotor Testbed Requirements

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Abstract

This document serves both as a guide and a record for requirements management associated with design of retrofit rotors for the Sandia SWiFT turbines. The rotors will support a long-term experimental campaign. Data gathered during the campaign will support formal verification and validation of complex flow numerical models for prediction of metrics deemed important for wind energy plant efficiency.

These integrated projects involve multiple years of effort, dozens of engineers and collaborators, and dozens of stakeholders in the form of the research community, National Lab staff, and DOE staff. Creationg of formal, written requirements will ensure flowdown of activities from high-level goals, aid communication, and enable clear verification of activities.

A custom requirements schema is created and described. Commercial requirements management software —IBM Rational DOORS—is used to organize the information and ensure traceability. This document serves as a record of the process as well as a record of the exported, detailed contents of the DOORS database.

Document Revisions

Date	Version	Description
15-Oct-2015	1.10	Release SAND2015-9142 for rotor design review.
24-Oct-2014	1.00	Initial release.
21-Oct-2014	0.12	Draft update.

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Nomenclature

β blade pitch angle

CDR Critical Design Review

CFD Computational Fluid Dynamics

C_l section lift coefficient

C_d section drag coefficient

C_m section pitching moment coefficient

C_P Rotor power performance coefficient

C_T Rotor thrust coefficient

CLT Classical Laminate Theory

C_{m_b} airfoil pitching moment computed about h_b

DB Double-Bias (plus/minus 45 degree) composite material

DOE Department of Energy

DOF Degree-of-freedom

DOORS Dynamic Object-Oriented Requirements System

E_1 longitudinal elastic modulus of a single layer of UD material

E_x longitudinal elastic modulus of a combination of layers

ES&H Environmental Health and Safety

GB gearbox ratio

h_{ac} chordwise location of actual airfoil aerodynamic center

h_b chordwise location of assumed aerodynamic center; typically $h_b = 0.25$

h_{ref} chordwise location of blade reference axis

L blade length

LE Leading Edge

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λ tip-speed-ratio; TSR

NACA National Advisory Committee for Aeronautics

ν Poisson ratio

OEM Original Equipment Manufacturer

PIRT Phenomenon Identification and Ranking Table

PDR Preliminary Design Review

r rotor radius coordinate

R rotor Radius

rpm revolutions per minute

ρ_f density of fiber material

ρ_m density of matrix material

SME Subject Matter Expert

SDR System Design Review

SNL Sandia National Laboratories

SRR System Requirements Review

SWiFT Scaled Wind Farm Test facility

SWiFTX SWiFT eXperiment

TE Trailing Edge

TRX Triax composite material

TRR Test Readiness Review

TSR Tip-Speed-Ratio

UD Uni-directional composite material

UQ Uncertainty Quantificaiton

VCRM Verification Cross Reference Matrix

VSVP Variable Speed Variable Pitch

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Chapter 1

Summary

This document serves both as a guide and a record for requirements management associated with design of retrofit rotors for the Sandia SWiFT turbines. The rotors will support a long-term experimental campaign. Data gathered during the campaign will support formal verification and validation of complex flow numerical models for prediction of metrics deemed important for wind energy plant efficiency.

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A custom requirements schema is created and described. Commercial requirements management software —IBM Rational DOORS—is used to organize the information and ensure traceability. This document serves as a record of the process as well as a record of the exported, detailed contents of the DOORS database.

Chapter 2 provides high level background on the topic of Requirements Engineering as applicable to the current project. Readers who are unfamiliar with formal requirements engineering can get background from this chapter.

Chapter 3 builds on background provided in Chapter 2 to describe a custom framework for requirements relationships specific to SWiFT-X1 test planning and execution.

Chapter 4 discusses proposed reviews to will cover the entire requirements and design space—including scope of influence and participating expertise—occurring throughout the life of the SWiFT-X1 projects.

Chapter 5 and Chapter 6 contain the actual requirements text. These chapters serve as a detailed record of the exported objects contained within the IBM Rational DOORS database for this project. The chapters contain the full, raw listing of requirements and their traceability.

Chapter 7 describes the verification requirements which, when met, ensure that the hardware will acheive the stated goals.

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1.1 Problem Statement

The DOE Wind Power Program's 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.

1.2 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.

1. Design, build, and test a scaled wind turbine rotor capable of reproducing the wake characteristics observed in utility-scale turbines; verify scaling capability.

2. Utilize data in conjunction with high-fidelity models through formal and systematic Verification and Validation (V&V) process developed within the A2e initiative.

3. Complement other A2e experimental campaigns in the wind tunnel and utility-scale wind farms to understand the impact of scaling on rotor aerodynamics.

1.3 References

The following information was used to create this requirements document:

Several high-level requirements originate from the Sandia/DOE Wind Power Program FY15 AOP [1] as well as from discussion with DOE stakeholders. The primary meeting driving most of the requirements was August 14, 2014 at Sandia Labs, attended by DOE Tech Lead Shreyas Ananthan.

Rotor and SWiFT site requirements were largely driven by discussions during the August 28, 2014 National Rotor Testbed review at the Sandia Blade workshop [2].

The 2015 PIRT process, led by Richard Hills (SNL), was the primary driver of test goals. These goals are driven by gaps in knowledge or experimental data which were identified by the PIRT process. This process engaged several dozens of wind energy researchers meeting on December 4–5, 2014 at the NWTC as well as on February 25–26, 2015 in Washington, DC for the High Fidelity Modeling (HFM) workshop hosted by NREL and Sandia.

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Technical characteristics of the rotor are driven by functionality of a GE 1.5-77 with 37c blades. More information on that system can be found in the Official Use Only report at Sandia [3]. The OUO report, and its contents, are not for public distribution.

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Chapter 2

Requirements Background

2.1 Purpose

In product development and process optimization, a requirement is a documented physical and functional need that a particular design, product or process must be able to perform. It is most commonly used in a formal sense in systems engineering, software engineering, or enterprise engineering. It is a statement that identifies a necessary attribute, capability, characteristic, or quality of a system for it to have value and utility to a customer, organization, internal user, or other stakeholder. A specification (often abbreviated as spec) may refer to an explicit set of requirements to be satisfied by a material, design, product, or service.

In the classical engineering approach, sets of requirements are used as inputs into the design stages of product development. Requirements are also an important input into the verification process, since tests should trace back to specific requirements. Requirements show what elements and functions are necessary for the particular project.

Requirements achieve the following:

Validate. Ensure you are building the right product; "Are we doing the right thing?"

Verify. Ensure you are building the product right; "Are we doing the thing right?"

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2.2 Definition

Figure 2.1 illustrates a requirements schema for a simple product. It contains three levels of requirements:

User requirements. User requirements capture what the system will do from the user's perspective; highest level requirements with least amount of detail.

System/functional requirements. System/functional requirements capture what the system will do from the designer/builder's perspective.

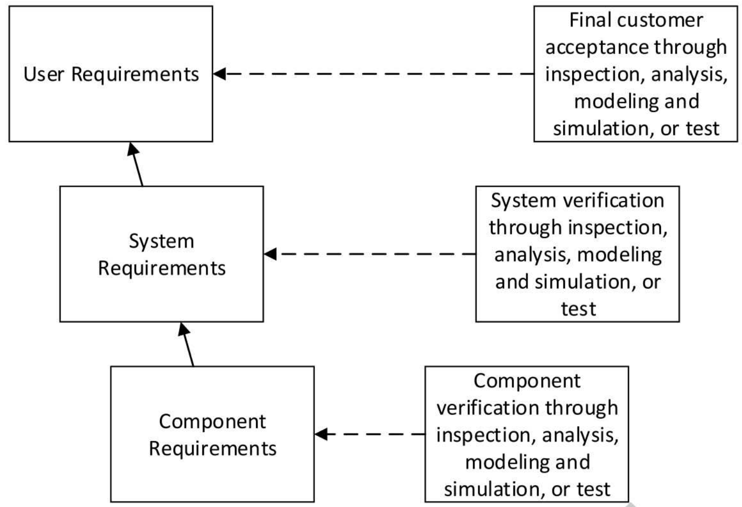

Figure 2.1. A simple requirements and verification schema.

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Component requirements. Design level list of all things that each component must do; contains enough detail and information that any engineer can design and build the component from the description.

The schema illustrates relationships between requirements and verification of requirements. Vertical arrows indicate how low-level requirements *satisfy* higher-level requirements—e.g. Component Requirements satisfy System Requirements and System Requirements satisfy User Requirements. Horizontal arrows indicate how verification requirements *verify* requirements—e.g. specific modeling and simulation or specific testing may serve to verify the component design intent which is captured by Component Requirements.

2.3 Chronology

Boxes in Figure 2.1 are staggered horizontally. The boxes are crudely arranged in chronological order as if the horizontal axis of the figure is *time*. User requirements are set at the start by the customer. Increasing levels of technical detail are included in subsequent system requirements to satisfy user requirements. A system requirements review or a system design review may be held to verify that the project plan is on track.

Deeper technical details are included component requirements to satisfy system requirements. A preliminary design review is held. The design is implemented and then verified.

Requirements verification often begins at the detailed component level, followed by verifications at the system level and then the user level. The final verification basically poses the following question in the form of a demonstration, "After all that work, does the final integrated product meet the customer's expectations?"

2.4 Structure

Good requirements follow strict guidelines. A requirement must be objectively verifiable (by test, analysis, inspection, or demonstration) to prove compliance. The requirement shall be written in a fashion such that the means of verification is clearly understood.

Requirements must be a complete sentence. Good performance requirements benefit from consistent application of three elements—function, operating condition, and performance.

"The system shall..." +function +operating condition +performance

An example, "The system shall control is position within 6 inches at speeds up to 80 mph." Or, "The system shall display a heading with accuracy of 0.1 degrees within 0.5 seconds of any change."

A desired capability that cannot be objectively verified should be written as a design goal ("should"), not a requirement ("shall"). "Shall", "will", "must" indicate mandatory; "should" or "may" indicate optional requirements.

2.5 Formality

Sometimes, requirements are verbal between stakeholder and developer—common in agile environments. This form of requirement is the easiest to create, but the hardest to verify. Verbal requirements may lead to misunderstandings and development problems. They are appropriate for short development cycles.

"User stories" are a narrative of the user-oriented view of the system. Such stories may be written down or recorded and act as a consistent guide for development. User stories have the drawback of not being translated into technical language, leaving translation to the design engineer. With multiple design engineers working on a system, each one may interpret the user story into different technical constraints, creating system integration problems. An example of a large collection of user stories may been seen as the notes from expert discussions held in August 2014 [2]. These user stories help to guide the development of requirements.

The need for formal SWiFT-X1 requirements. SWiFT-X1 involves more than two years of effort, dozens of engineers and collaborators, and dozens of stakeholders in the form of the research community, National Lab staff, and DOE staff. The authors are aiming to reduce misunderstandings, lack of verification, and system integration problems by creating the formal, written requirements document.

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2.6 Elicitation

Requirements elicitation can occur in various ways including interviews, brainstorming, requirements workshop, prototyping, or document review. SWiFT-X1 requirements began through a combination of all of these methods—without the rigorous framework of this document. Specifically, the August meeting served as one source [2].

2.7 Verification

Requirements verification is defined by MIL-STD-961E as follows—*Confirmation, through the provision of acceptable objective evidence, that specified requirements have been fulfilled. Objective evidence may be obtained through observation, measurement, test, or other means.*

A Verification Requirements purpose is to establish the requirement's intent and to establish completion criteria for the requirement. Following are keys to writing a good verification requirement:

- Verify by (insert method here) that .....
- The (use above method) will show that ......

An example follows—"Verify by Demonstration that when power is supplied to the unit in accordance with the established interface defined in BCD XXX the operator is provided visual status. Demonstration will show that when proper power is provided a continuous visual indication is provided to the operator."

Verification Requirements come in several forms:

- Inspection
- Analysis
- Modeling and Simulation
- Demonstration
- Test

The best verification requirements must answer five questions:

- Objective. What is the purpose of this verification?

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- Method. What method do you need performed? What are the verification circumstances (e.g., laboratory, desk-top analysis, flight test)?
- Environment. What are the environmental conditions under which the item will be verified?
- Special Conditions (if necessary) Are there any unique conditions (e.g., item configurations) necessary for the execution of the verification?
- Success Criteria. What results are to expected?

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Chapter 3

SWiFT-X1 Requirements Schema

SWiFT-X1 refers to a 1^{st} eXperimental campaign at the SWiFT facility. The campaign will include high level goals, specific test and measurement objectives, sensing plans, and supporting hardware. Figure 3.1 shows the schema for SWiFT-X1 requirements. The overall aim of the entire effort is stated at the top of the Figure.

Solid-line arrows indicate satisfaction of requirements—e.g. the Experiment Campaign Plan *satisfies* requirements in the Model Assessment Objectives.

Dotted-line arrows indicate verification of requirements–e.g. the Component Modeling and Simulation Specification *verifies* Component Requirements for turbine, rotor, and flow measurements. An example is when aeroelastic simulations are used to verify rotor design requirements. In many cases, Design Reviews serve as the method to verify requirements—e.g. Programmatic Review and Prioritization of PIRT Objectives, Review of Model Assessment Objectives, and Test Readiness Review.

Unlike the schema represented in Figure 2.1, the SWiFT-X1 requirements framework is complex because of a unique distinction. Typically, tests appear in a framework as one of several methods to verify requirements—other methods being inspection or modeling and simulation. The SWiFT-X1 framework is unique in that a test campaign appears as a means to satisfy the overarching goals of the project. That is, the test campaign is one of the components required to meet the high level goal. Thus, at the deepest level of SWiFT-X1 requirements there are three types of "components" working together to satisfy the goal: 1) test articles (turbine and rotor), 2) instrumentation suites (farm flow measurements, rotor measurements, and turbine measurements), and 3) the test campaign plan.

There are two types of testing present in the framework. The test campaign is itself one type of test. The campaign is driven at the highest level by gaps which were identified in the PIRT process [4]. These tests satisfy the need to execute a formal V&V campaign for complex flow models, a top-level requirement. Experiments will gather adequately accurate data from specific test configurations which have been driven by needs of numerical model assessments.

Another type of testing is used to verify component design. These tests are all collected in the box titled *Component Test Plan* within the *Component Verification* frame of the schema, Figure 3.1. Examples of these tests include ground-based static pull tests to verify the overall flapwise strength of a prototype blade, or rotor commissioning tests in which baseline rotor C_P is determined. More

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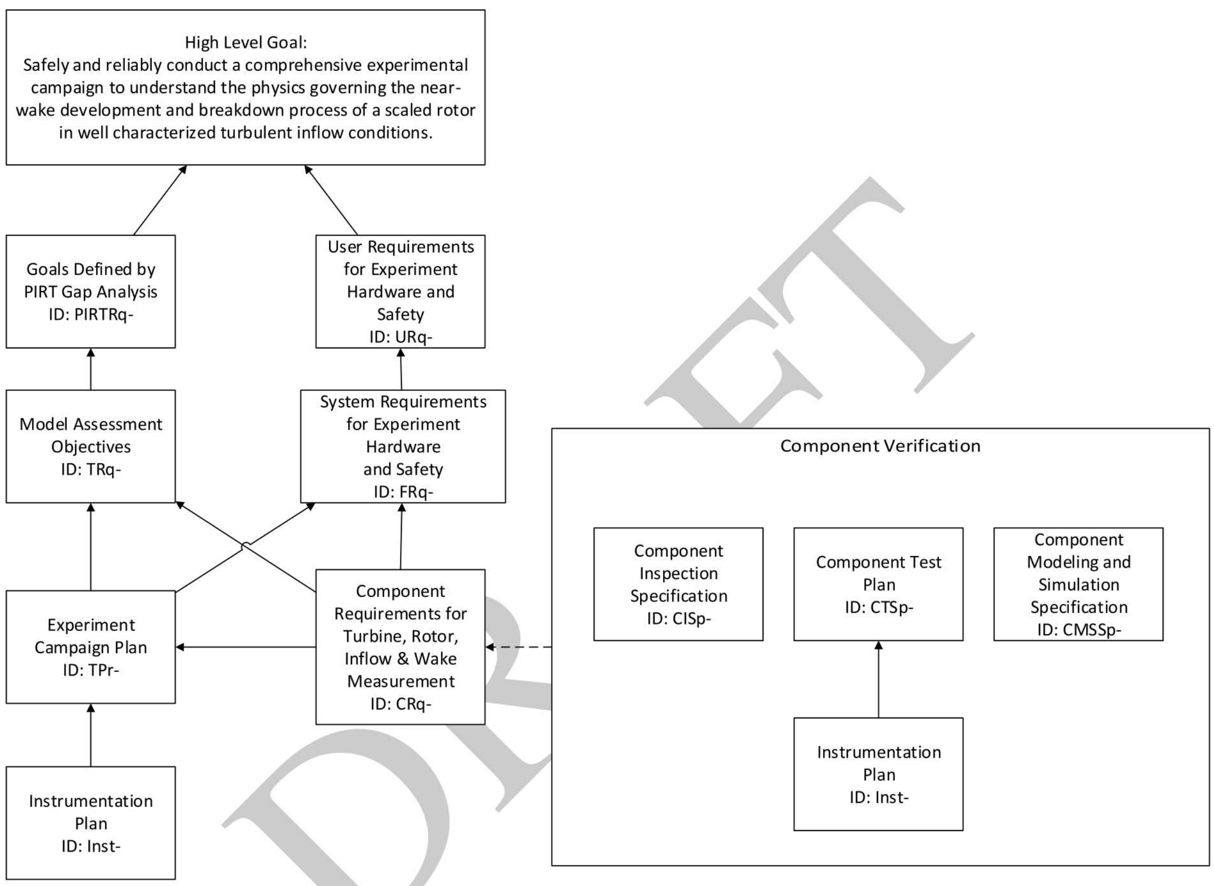

Figure 3.1. Requirements and verification schema for SWiFT-X1.

information regarding Verification Requirements is found in Chapter 7 of this report.

In the schema, there are two vertical columns of *Component–(satisfies)–System–(satisfies)–User* requirements. The first column, labeled **PIRT Gap Analysis** at the top, satisfies the high level requirements which are the PIRT findings. Requirements in this track are designed to satisfy formal model assessment needs through definition of appropriate experiment configurations and data accuracy. These requirements are documented in Chapter 5.

The second column, labeled **Experiment Hardware and Safety Requirements**, satisfies the high level objective to produce high quality, safe, and reliable hardware. Requirements associated with safety and reliability are satisfied generally by industry standards which define design and design verification guidelines. Requirements associated with safety and reliability are also satisfied by ES&H practices and procedures. These requirements are documented in Chapter 6.

Recognition of two types of testing among the SWiFT-X1 requirements helps to keep relationships traceable and delineates planning activities between two teams of researchers: 1) model assessment and experiment campaign team and 2) SWiFT operational and hardware design team. The two tracks represent different stakeholder involvement. On the PIRT side are modeling and simulation experts working with experimentalists. On the hardware side, hardware designers, test engineers, and operations engineers work together to ensure availability of capable test hardware and instrumentation.

Finally, tracks are not completely separate. Tracks are connected because of a need for component capabilities—rotor, turbine, and flow measurement capabilities—to satisfy experiment objectives. In some cases, the test plan must also satisfy system level operational requirements of the hardware.

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Chapter 4

Reviews

This chapter describes proposed reviews associated with planning and execuation of a test campaign at SWiFT.

4.1 Definitions

Typically, there are several reviews types formally implemented in the course of a complex project. Following are five types of reviews [5]. Each are utilized in this plan:

System Requirements Review (SRR). The SRR examines the functional requirements and performance requirements defined for the system and the preliminary program or project plan and ensures that the requirements and the selected concept will satisfy the mission. The purpose of the SRR is to review the system requirements specification document, to ensure the documented requirements reflect the current knowledge of the customer requirements, to identify requirements that may not be consistent with product development constraints, and to put the requirements document under version control to serve as a stable baseline for continued new product development.

System Design Review (SDR). The SDR examines the proposed system architecture and design and the flow down to all functional elements of the system.

Preliminary Design Review (PDR). The purpose of the PDR is to review the conceptual design to ensure that the planned technical approach will meet the requirements within the cost and schedule constraints and establishes the basis for proceeding with detailed design. It will show that the correct design options have been selected, interfaces have been identified, and verification methods have been described.

The following are typical objectives of a PDR:

- Ensure that all system requirements have been allocated, the requirements are complete, and the flowdown is adequate to verify system performance.
- Show that the proposed design is expected to meet the functional and performance requirements.
- Show sufficient maturity in the proposed design approach to proceed to final design.

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- Show that the design is verifiable and that the risks have been identified, characterized, and mitigated where appropriate.

Critical Design Review (CDR). The purpose of the CDR is to review the detailed design to ensure that the design implementation has met the requirements. The CDR verifies that the final design fulfills the specifications established at the PDR.

Test Readiness Review (TRR). The purpose of the TRR is to review preparations and readiness for testing. A TRR ensures that the test articles, test facility, support personnel, and test procedures are ready for testing and data acquisition and reduction.

4.2 Reviews Summary Table

Reviews in Table 4.1 are listed in approximate chronological order for a scenario in which high level objectives are created first, followed by definition of increasing levels of detail as requirements flow down to the individual hardware components, test procedures, and instrumentation.

Where possible, it's optimal to involve only 5–6 people as reviewers for each review.

4.3 Proposed Committees

Specific names are shown only as examples of researchers who's roles, skills and experience may serve well in the position. Roles, skills and experience change with time. It is expected that committee memberships are dynamic. Specific committee roles, however, should remain consistent for most effectiveness.

4.3.1 Programmatic Review

Stakeholders within A2e leadership and the DOE WWPTO.

Derby (DOE), The A2e EMC (Various).

4.3.2 Project Coordination/Integration

Experts with high-level knowledge in V&V, SWiFT testing, Wind Tunnel Testing, and Numerical Simulation.

Hills (SNL), Resor (SNL), Schreck (NREL), Maniaci (SNL).

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Table 4.1. Description of reviews through the life of a campaign at SWiFT.

Review	Purpose	Prepared by	Reviewed by	When
Programmatic Review and Prioritization of PIRT Objectives	A PIRT ranking of challenges typically identifies topics which are beyond scope of available funding. PIRT objectives must be down-selected and to focus on near-term Program objectives. This review provides focus for all subsequent work.	• V&V • PIRT Participants	• Programmatic Review	After the PIRT process is complete. Before definition of the final experiment objectives.
SWiFT-X1 Model Assessment Objectives Review	Verify model assessment objectives, including quantities of interest (QoI), are relevant and well-written. Verify objectives properly flow down from high-level goals. Objectives should be written clearly and completely such that there can be no misunderstanding of outcomes. This review provides focus for all subsequent work.	• Modeling • SWiFT Experimentalists	• V&V • Modeling	After the experiment objectives have been defined. After basic hardware requirements have been defined to satisfy the experiment objectives. Before detailed component design.
SWiFT-X1 Sensors and Instrumentation Review	Verify flow down of sensors and instrumentation from stated test objectives. This review includes a conceptual test plan, but not the final test plan. (The final test plan is reviewed during the TRR.)	• SWiFT Experimentalists	• V&V • Modeling	After the experiment objectives have been defined.
SWiFT-X1 Hardware PDR	Verify hardware requirements have been fully captured, including the flow down from high-level requirements. Completion of the PDR enables detailed hardware design to move forward. The PDR also verifies completeness and adequacy of proposed requirements verification, i.e. the VCRM.	• SWiFT Experimentalists	• Rotor Aero-Structural • SWiFT Operations • Sandia Management	After experiment objectives have been defined. After component requirements and associated verification requirements have been defined. Before detailed component design.
SWiFT Hardware CDR	Judge whether verifications defined during the PDR have been completed. Judge the overall technical quality and accuracy of the work performed to meet verification goals. Completion of the CDR enables hardware selection, manufacture, or acquisition to move forward.	• SWiFT Experimentalists	• Rotor Aero-Structural • SWiFT Operations • Sandia Management	After the PDR and after detailed component designs.
SWiFT-X1 TRR	Internal organizational review of operational aspects of the test campaign plan. Verify that the test procedure is written clearly and completely such that there can be no misunderstanding of objectives and such that the test will execute safely.	• SWiFT Experimentalists	• Sandia Management • SWiFT Operations • SWiFT Researchers • Sandia ES&H	Prior to initiation of active work associated with the test procedure.

PDR=Preliminary Design Review, CDR=Critical Design Review, TRR=Test Readiness Review

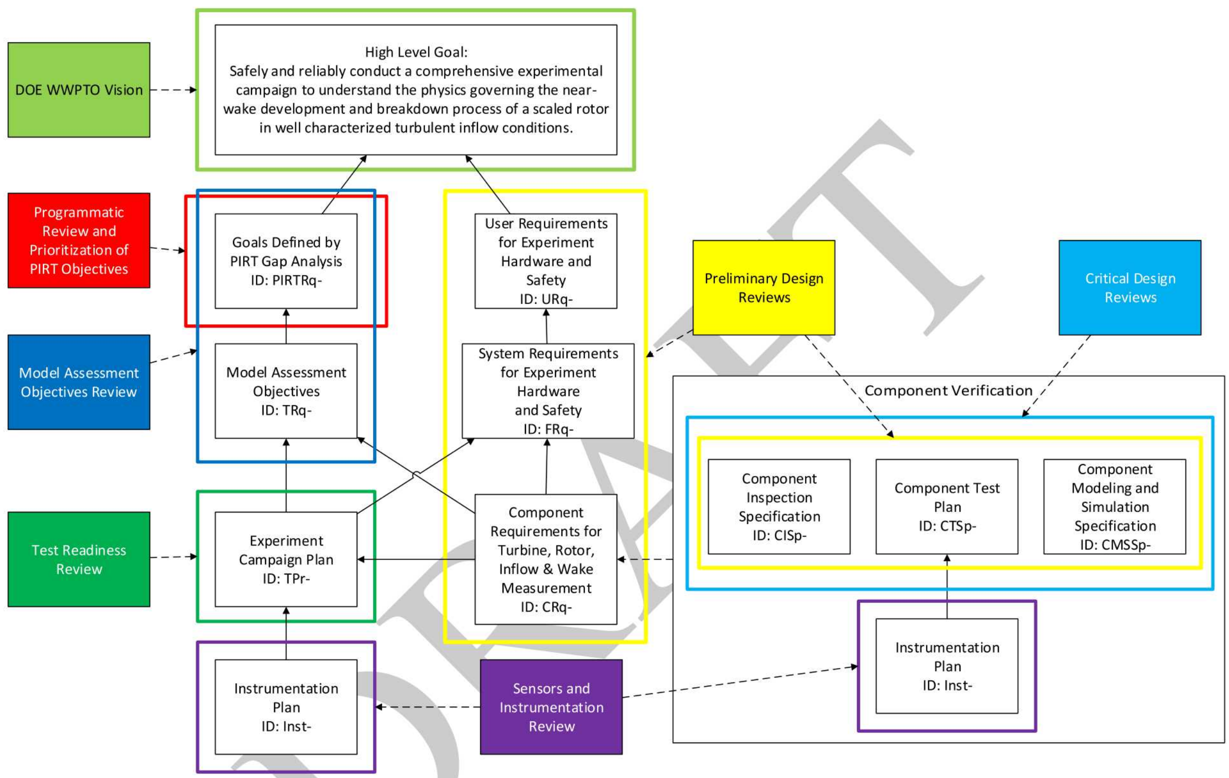

Figure 4.1. Schema with colored boxes indicating scope of reviews.

4.3.3 SWiFT Operations

Experts in SWiFT operational requirements and capabilities.

White (SNL), LeBlance (SNL), Johnson (SNL), Mitchell (SNL).

4.3.4 Rotor Aero-Structural

Experts in rotor design and measurements associated with rotor experimentation.

Griffin (DNV) , Bottasso (TU-Munich), Standish (Siemens), Gupta (Vestas), Veers (NREL), Schreck (NREL).

4.3.5 SWiFT Experimentalists

Planning and execution of the experimental research campaign at SWiFT.

Naughton (SNL), Maniaci (SNL), Kelley (SNL), Ennis (SNL), Berg (SNL), Paquette (SNL), LeBlanc (SNL), Herges (SNL).

4.3.6 Sandia Management

Ultimate responsibility for quality and safety of work performed by Sandia.

Minster (SNL); Senior managers, as dictated by Minster.

4.3.7 Modeling

Participants in the PIRT process who also have expert experience in numerical modeling of mesoscale atmospheric flow, wind farm aerodynamics, and wind turbine rotor aerodynamics.

Maniaci (SNL), Churchfield (NREL), Sotiropoulos (U.Minn), Barone (SNL) , Linn (LANL), Sprague (NREL).

4.3.8 V&V

Experts in planning and execution of the V&V and UQ processes. These people ensure predictions and tests are done in a manner conducive to stated model assessment goals.

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Hills (SNL), Maniaci (SNL), Naughton (U.Wy).

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Chapter 5

SWiFT-X1 Test Campaign Requirements

5.1 High-Level Requirements: Overarching Goals

Test objectives stated in DOE inputs along with gaps identified during the Phenomena Identification and Ranking Table (PIRT) process are the source of requirements at this level. A detailed description of the PIRT process is contained in Reference [4]. The PIRT process identified topics which are most likely to yield large improvements in prediction of a specific high-level metric. In this case, the specific metric was *wind plant power prediction in the presence of complex atmospheric and intra-array flow*.

Important notes regarding high-level goals: 1) The goal of representing a 1.5MW GE turbine at subscale has been clearly stated by the DOE Program. 2) The detailed test campaign which achieves desired goals has not been created as of the release of this report. The topic areas from the PIRT gap analysis are shown here only to familiarize the reader with the types of campaigns which are anticipated.

5.1.1 DOE Objectives and PIRT Objectives

DOE Objectives

PIRTRq-32 Design, build, and test a scaled wind turbine rotor capable of reproducing the wake characteristics observed in utility-scale turbines. The SWiFT-scale rotor will represent the aerodynamic functionality of a utility-scale GE1.5-77sle with 37c blades. Recreation of rotor wake characteristics is the primary scaling objective.

PIRTRq-83 Verify a rotor scaling methodology.

Other Objectives

PIRTRq-82 The rotor shall be rigid. Subsequent rotors may include aeroelastic effects, but are beyond the scope of the current rotor project.

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Output of PIRT Gap Analysis

PIRTRq-53 Blade aero/wake generation with atmospheric inflow–Blade generated turbulence (energetic scales)

Comments: This is a desirable secondary focus for initial experiments.

PIRTRq-54 Blade aero/wake generation with atmospheric inflow–Boundary layer state (roughness, soiling, ...)

Comments: This is a desirable secondary focus for initial experiments.

PIRTRq-55 Blade aero/wake generation with atmospheric inflow–Rotational augmentation

Comments: This is a desirable secondary focus for initial experiments.

PIRTRq-56 Blade aero/wake generation with atmospheric inflow–Dynamic stall

Comments: This is a desirable secondary focus for initial experiments.

PIRTRq-76 Blade aero/wake generation with controlled inflow–Blade generated turbulence (energetic scales)

Comments: This is a goal of wind tunnel experiments.

PIRTRq-77 Blade aero/wake generation with controlled inflow–Boundary layer state (roughness, soiling, ...)

Comments: This is a goal of wind tunnel experiments.

PIRTRq-78 Blade aero/wake generation with controlled inflow–Rotational augmentation

Comments: This is a goal of wind tunnel experiments.

PIRTRq-79 Blade aero/wake generation with controlled inflow–Dynamic stall

Comments: This is a goal of wind tunnel experiments.

PIRTRq-59 Wake development (growth/recovery)–Skew and meander of aggregate wake

Comments: This is a desirable primary focus for initial experiments.

PIRTRq-60 Wake development (growth/recovery)–Wake vorticity diffusion and dissipation

Comments: This is a desirable primary focus for initial experiments

PIRTRq-61 Wake development (growth/recovery)–ABL Wind tunnel turbulence

Comments: This objective is not applicable for SWiFT.

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PIRTRq-62 Wake development (growth/recovery)–ABL unsteady inflow

Comments: This is a desirable primary focus for initial experiments.

PIRTRq-63 Multi-turbine wake effects–Wake interaction, merging, motion

Comments: This is a desirable primary focus for future experiments.

PIRTRq-64 Multi-turbine wake effects–Wake steering (yaw tilt effects)

Comments: This is a desirable primary focus for future experiments.

PIRTRq-65 Multi-turbine wake effects–Wake evolution and dissipation

Comments: This is a desirable primary focus for future experiments.

PIRTRq-66 Multi-turbine wake effects–Wake Impingement (full, half, etc.)

Comments: This is a desirable primary focus for future experiments.

PIRTRq-67 Inflow Turbulence/wake interaction–Wind direction (shear/veer/asymmetry)

Comments: This is a desirable primary focus for future experiments.

PIRTRq-68 Inflow Turbulence/wake interaction–Surface Conditions (roughness, canopy, waves, surface heat flux, topography)

Comments: These data should be acquired as needed for validation. They are not a validation objective.

PIRTRq-69 Inflow Turbulence/wake interaction–Turbulence Statistics (mean, variance, correlation, stratification)

Comments: This is a desirable primary focus for future experiments.

PIRTRq-70 Inflow Turbulence/wake interaction–Momentum transport (horizontal and vertical fluxes)

Comments: These data should be acquired as needed for validation. They are not a validation objective. Future campaigns could address momentum transport across the wind farm control volume as a parameter.

5.1.2 DOE Objectives and PIRT Objectives Traceability

Every requirement is listed. For each requirement, the lower-level requirements which satisfy the requirement are also listed. They appear as *In-link*s. There should be at least one *In-link* listed to satisfy the requirement. In cases where no *In-links* are listed, there is an open gap in the

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requirements which must be filled.

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Requirement PIRTRq-32: Design, build, and test a scaled wind turbine rotor capable of reproducing the wake characteristics observed in utility-scale turbines. The SWiFT-scale rotor will represent the aerodynamic functionality of a utility-scale GE1.5-77sle with 37c blades. Recreation of rotor wake characteristics is the primary scaling objective.

In-links (Experiment Objectives):

STRq-9

Kinematic Similarity. The rotor shall exhibit the same operational Region 2 TSR as the full-scale rotor in order to enable validation of numerical models in a regime which is relevant to utility scale turbines. Lower tip speed ratios—6 or lower—have been shown to be less challenging for high fidelity numerical simulation and they are not as relevant to modern turbines.

STRq-10

Partial Dynamic Similarity. The subscale rotor design shall exhibit the same spanwise distribution of non-dimensional circulation as the full-scale rotor for Region II operation such that blade-tip shed-vorticity is relevant to utility-scale turbines.

STRq-94

The rotor C_P of the subscale design will represent the C_P of the full-scale design within $\pm 5\%$ at the design operating point for Region 2 operation.

STRq-97

Dynamic Similarity in Gust Response. Dynamic loads of the subscale rotor shall be on par with dynamic loads expected for the full-scale rotor.

STRq-99

Tip design shall be done in a manner which encourages matching of the target circulation distribution as well as possible.

STRq-102

Full Dynamic Similarity. The spanwise distribution of full-scale and subscale chord Reynolds numbers shall match.

STRq-103

Rotor Shear. Non-dimensional rotor shear, i.e. $\frac{dU/dU_\infty}{dz/D}$, shall be similar for full-scale and subscale rotors.

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STRq-104

Strouhal Number. Wake meandering characteristics will be recreated at subscale through replication of the rotor Strouhal Number, $St = \frac{fD_{rotor}}{U_{infty,hub}}$ where f is the frequency of vortex shedding.

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Requirement PIRTRq-83: Verify a rotor scaling methodology.

In-links (Experiment Objectives):

STRq-84

Type I scaling verification–Verify scaled design. Prediction by numerical simulation and measurements during experiments shall be used to achieve Type I scaling verification. Predictions and measurements will show that "Rotor Performance—Scaling Requirements" (withinin this Test Campaign Specification) have been met.

STRq-90

Type II scaling verification–Verify scaling methodology. Use model predictions to verifyto the best of their abilitythat the chosen scaling approach is successful. Numerical predictions will show that the subscale rotor has the same character as the full-scale rotor.

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Requirement PIRTRq-82: The rotor shall be rigid. Subsequent rotors may include aeroelastic effects, but are beyond the scope of the current rotor project.

In-links (Experiment Objectives):

STRq-91

Blades shall be sufficiently rigid—in torsional and flapwise directions—for numerical models of the SWiFT-X1 experiment to neglect blade elastic behavior.

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Requirement PIRTRq-53: Blade aero/wake generation with atmospheric inflow–Blade generated turbulence (energetic scales)

In-links (Experiment Objectives):

STRq-77

This is a secondary focus for SWiFT experiments.

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Requirement PIRTRq-54: Blade aero/wake generation with atmospheric inflow–Boundary layer state (roughness, soiling, ...)

In-links (Experiment Objectives):

STRq-77

This is a secondary focus for SWiFT experiments.

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Requirement PIRTRq-55: Blade aero/wake generation with atmospheric inflow–Rotational augmentation

In-links (Experiment Objectives):

STRq-77

This is a secondary focus for SWiFT experiments.

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Requirement PIRTRq-56: Blade aero/wake generation with atmospheric inflow–Dynamic stall

In-links (Experiment Objectives):

STRq-77

This is a secondary focus for SWiFT experiments.

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Requirement PIRTRq-76: Blade aero/wake generation with controlled inflow–Blade generated turbulence (energetic scales)

In-links (Experiment Objectives):

STRq-79

This is a primary or secondary objective for wind tunnel experiments.

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Requirement PIRTRq-77: Blade aero/wake generation with controlled inflow–Boundary layer state (roughness, soiling, ...)

In-links (Experiment Objectives):

STRq-79

This is a primary or secondary objective for wind tunnel experiments.

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Requirement PIRTRq-78: Blade aero/wake generation with controlled inflow–Rotational augmentation

In-links (Experiment Objectives):

STRq-79

This is a primary or secondary objective for wind tunnel experiments.

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Requirement PIRTRq-79: Blade aero/wake generation with controlled inflow–Dynamic stall

In-links (Experiment Objectives):

STRq-79

This is a primary or secondary objective for wind tunnel experiments.

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Requirement PIRTRq-59: Wake development (growth/recovery)–Skew and meander of aggregate wake

In-links (Experiment Objectives):

STRq-59

SWiFT Model Assessment: Measured and predicted wake initiation angle and wake offset distance at several locations downstream of the rotor will be compared for several high-yaw error configurations (wake steering) as well as zero yaw error configuration (no wake steering) in a variety of ABL conditions.

Objectives: Assess accuracy of existing wake steering models for use in guiding R&D for wind farm flow control. These data will enable validation of wake trajectory as extracted from HFM predictions, and validation/calibration of low order wake models.

STRq-60

SWiFT Model Assessment: Measured and predicted frequency spectrum of wake offset (i.e. frequency character of wake meandering) will be compared for data gathered in a variety of ABL conditions.

Objectives: Assess accuracy of existing wake steering models for use in guiding R&D for wind farm flow control to minimize wind farm LCOE. These data will enable validation of wake trajectory as extracted from HFM predictions, and validation/calibration of low order wake models.

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Requirement PIRTRq-60: Wake development (growth/recovery)–Wake vorticity diffusion and dissipation

In-links (Experiment Objectives):

STRq-64

SWiFT Model Assessment: Measured and predicted correlated three-components of inflow (rotor inflow and rotor aerodynamic loads) and near wake structure (circulation strength and tip vortex diameter) will be compared in a variety of ABL conditions. These measurements are made possible by SWIS and by a highly-instrumented aero-sensors blade.

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Requirement PIRTRq-61: Wake development (growth/recovery)–ABL Wind tunnel turbulence

In-links (Experiment Objectives):

STRq-78

This is not applicable to SWiFT experiments.

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Requirement PIRTRq-62: Wake development (growth/recovery)–ABL unsteady inflow

In-links (Experiment Objectives):

STRq-61

SWiFT Model Assessment: The Sandia Wake Imaging System (SWIS) will make high-resolution time and spatial measurements of rotor inflow in the ABL with yaw error representative of normal operation. Measured inflow to the rotor will be prescribed as input to an aeroelastic model of the rotor. Resulting measured and predicted time domain blade root loads will be correlated to inflow and compared.

STRq-64

SWiFT Model Assessment: Measured and predicted correlated three-components of inflow (rotor inflow and rotor aerodynamic loads) and near wake structure (circulation strength and tip vortex diameter) will be compared in a variety of ABL conditions. These measurements are made possible by SWIS and by a highly-instrumented aero-sensors blade.

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Requirement PIRTRq-63: Multi-turbine wake effects–Wake interaction, merging, motion

In-links (Experiment Objectives):

STRq-66

Wake interaction and merging. Turbines two side by side. Wake interaction and merging using SNL-1 and Vestas turbines. This would be a long term goal.

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Requirement PIRTRq-64: Multi-turbine wake effects–Wake steering (yaw tilt effects)

In-links (Experiment Objectives):

STRq-60

SWiFT Model Assessment: Measured and predicted frequency spectrum of wake offset (i.e. frequency character of wake meandering) will be compared for data gathered in a variety of ABL conditions.

Objectives: Assess accuracy of existing wake steering models for use in guiding R&D for wind farm flow control to minimize wind farm LCOE. These data will enable validation of wake trajectory as extracted from HFM predictions, and validation/calibration of low order wake models.

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Requirement PIRTRq-65: Multi-turbine wake effects–Wake evolution and dissipation

In-links (Experiment Objectives):

STRq-62

SWiFT Model Assessment: Measured and predicted wake deficit and turbulence intensity downstream of the rotor will be compared at several locations downstream of the rotor for several collective pitch settings and tip speed ratios for data gathered in a variety of ABL conditions.

Objective: Assess the accuracy of existing near and far wake models in predicting the inflow to a downstream rotor.

STRq-63

SWiFT Model Assessment: Measured and predicted downstream rotor inflow and performance will be compared for several collective pitch settings and tip speed ratios (as well as possible rotor design innovations) while the downstream turbine is partially/fully waked for data gathered in a variety of ABL conditions.

Objective: Assess the accuracy of low order and high fidelity model (HFM) predictions of rotor energy capture and structural loads for partially and fully waked turbines. The differences between measured and predicted downstream turbine inflow and performance will be used to assess credibility of existing wake models for guiding rotor induction control algorithm development to minimize wind farm COE.

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Requirement PIRTRq-66: Multi-turbine wake effects–Wake Impingement (full, half, etc.)

In-links (Experiment Objectives):

STRq-63

SWiFT Model Assessment: Measured and predicted downstream rotor inflow and performance will be compared for several collective pitch settings and tip speed ratios (as well as possible rotor design innovations) while the downstream turbine is partially/fully waked for data gathered in a variety of ABL conditions.

Objective: Assess the accuracy of low order and high fidelity model (HFM) predictions of rotor energy capture and structural loads for partially and fully waked turbines. The differences between measured and predicted downstream turbine inflow and performance will be used to assess credibility of existing wake models for guiding rotor induction control algorithm development to minimize wind farm COE.

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Requirement PIRTRq-67: Inflow Turbulence/wake interaction–Wind direction (shear/veer/asymmetry)

In-links (Experiment Objectives):

STRq-65

The eventual challenge is to provide forecasts of wind farm power. Measured and predicted wind turbine power output will be compared for different ABL conditions (consistent stable, consistent neutral, and consistent unstable). Data would be used to assess credibility of existing coupled meso-, micro-, and turbine/rotor-scale models for predicting inflow to turbine scale and predicting turbine and farm power output. These models will be used for long-range forecasting of wind plant performance. This prediction represents a grand challenge and is beyond the scope of this proposal, but is the logical follow-on project which would be enabled by this project.

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Requirement PIRTRq-68: Inflow Turbulence/wake interaction–Surface Conditions (roughness, canopy, waves, surface heat flux, topography)

In-links (Experiment Objectives):

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Requirement PIRTRq-69: Inflow Turbulence/wake interaction–Turbulence Statistics (mean, variance, correlation, stratification)

In-links (Experiment Objectives):

STRq-81

This is a inherent aspect of all SWiFT test objectives.

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Requirement PIRTRq-70: Inflow Turbulence/wake interaction–Momentum transport (horizontal and vertical fluxes)

In-links (Experiment Objectives):

STRq-82

This is beyond the scope of the current work. It may be the focus of future work.

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5.2 Mid-Level Requirements: Experiment Objectives

At the system requirements level, the SWiFT-X1 test campaign specification satisfies the PIRT requirements.

5.2.1 Experiment Objectives

Rotor Scaling Verification

A rotor scaling methodology enables performance of new, undemonstrated rotor innovations to be tested on subscale rotors in a manner in which afterwards it can be rapidly deployed at full scale with sufficiently low risk to catalyze private investment; i.e. with confidence that the full scale innovation will perform as intended. The successful approach will enable rapid progress of radical designs from low to high TRL.

Typically, scaling of all physics cannot be accomplished in full for a single subscale rotor. The scaling approach is dependent on the desired application. The scaling approach defines the specific functional characteristics which are the subscale design requirements. These functional characteristics are specific to the technology or physics which are being demonstrated.

Regarding verification, it follows that there are two Types of scaling verification—I) verification that subscale design requirements have been satisfied and II) verification that the subscale design requirements, when implemented, produce a subscale rotor which represents intended physics of the full scale rotor.

Type I scaling verification—Verify scaled design. Prediction by numerical simulation or measurements during experiments shall be used to achieve Type I scaling verification.

Type II scaling verification—Verify scaling methodology. Type II scaling verification is achieved in either of two ways. First, measured quantities of interest representing the functional characteristics are compared for full scale and subscale experiments. Second, predicted quantities of interest representing the functional characteristics are compared for full scale and subscale numerical simulation. It is preferable that models with high credibility are used to perform the numerical predictions. (suggest breaking this into 3 types of verification rather than two with one that has two sub points)

The current A2e effort includes no plans for full scale testing. Therefore, experimental measurements will not be used for verification of scaling.

The current A2e effort includes plans to establish credibility of numerical models. Predictions by these models can be used to verify—to the best of their ability—that the chosen scaling approach is successful.

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Rotor Performance—Scaling Requirements

STRq-9 Kinematic Similarity. The rotor shall exhibit the same operational Region 2 TSR as the full-scale rotor in order to enable validation of numerical models in a regime which is relevant to utility scale turbines. Lower tip speed ratios—6 or lower—have been shown to be less challenging for high fidelity numerical simulation and they are not as relevant to modern turbines.

STRq-102 Full Dynamic Similarity. The spanwise distribution of full-scale and subscale chord Reynolds numbers shall match.

Comments: It is not possible to meet this requirement. It is included here only to show that it was a desirable requirement to achieve.

STRq-10 Partial Dynamic Similarity. The subscale rotor design shall exhibit the same spanwise distribution of non-dimensional circulation as the full-scale rotor for Region II operation such that blade-tip shed-vorticity is relevant to utility-scale turbines.

STRq-97 Dynamic Similarity in Gust Response. Dynamic loads of the subscale rotor shall be on par with dynamic loads expected for the full-scale rotor.

STRq-103 Rotor Shear. Non-dimensional rotor shear, i.e. $\frac{dU/dU_\infty}{dz/D}$, shall be similar for full-scale and subscale rotors.

STRq-104 Strouhal Number. Wake meandering characteristics will be recreated at subscale through replication of the rotor Strouhal Number, $St = \frac{fD_{rotor}}{U_{infty,hub}}$ where f is the frequency of vortex shedding.

STRq-94 The rotor C_P of the subscale design will represent the C_P of the full-scale design within $\pm 5\%$ at the design operating point for Region 2 operation.

STRq-99 Tip design shall be done in a manner which encourages matching of the target circulation distribution as well as possible.

STRq-91 Blades shall be sufficiently rigid—in torsional and flapwise directions—for numerical models of the SWiFT-X1 experiment to neglect blade elastic behavior.

Verify Scaling Capability

STRq-84 Type I scaling verification–Verify scaled design. Prediction by numerical simulation and measurements during experiments shall be used to achieve Type I scaling verification. Predictions and measurements will show that "Rotor Performance—Scaling Requirements" (withinin this Test Campaign Specification) have been met.

STRq-90 Type II scaling verification–Verify scaling methodology. Use model predictions to verifyto the best of their abilitythat the chosen scaling approach is successful. Numerical predictions will show that the subscale rotor has the same character as the full-scale rotor.

Characterize and predict effects of inflow stability on turbine-turbine interactions

STRq-101 SWiFT Model Assessment: Measured and predicted 10 minute average power for SNL-1 and SNL-2 turbines will be compared for a variety of ABL inflow directions (centered on the primary SNL-1-to-SNL-2 wind direction) and inflow stability states (stable and unstable).

Correlate Rotor Loads to Unique Inflow Structures

STRq-61 SWiFT Model Assessment: The Sandia Wake Imaging System (SWIS) will make high-resolution time and spatial measurements of rotor inflow in the ABL with yaw error representative of normal operation. Measured inflow to the rotor will be prescribed as input to an aeroelastic model of the rotor. Resulting measured and predicted time domain blade root loads will be correlated to inflow and compared.

Comments: Background: Inflow states can include uniform/steady inflow, turbulence intensity, shear, and transient occurrences commonly referred to as “extreme events”. Inflow will be simultaneously measured along with rotor flow field to relate inflow structures to ensuing blade loads and to validate model predictions.

Objectives: Measure inflow to the wind turbine model domain for model assessment. Assess accuracy of existing rotor aerodynamics models in predicting rotor loads due to uniform, stationary random, and unique, non-stationary inflow structures. Comparison of these measurements with reduced order model predictions and with HFM aerodynamic load predictions will facilitate the assessment of these two classes of models.

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Initiation of Wake By Rotor

STRq-64 SWiFT Model Assessment: Measured and predicted correlated three-components of inflow (rotor inflow and rotor aerodynamic loads) and near wake structure (circulation strength and tip vortex diameter) will be compared in a variety of ABL conditions. These measurements are made possible by SWIS and by a highly-instrumented aero-sensors blade.

Comments: Background: Interaction of inflow with the blades elicits responses in blade boundary layer state, flow field structure, and structural loads. Because boundary layer state and flow field drive vorticity production and shedding, these are directly responsible for wake production and thus key to this project for physics comprehension and model validation. Structural loads also are useful adjuncts, to complement detailed flow field information.

Objectives: Assess accuracy of existing rotor models for use in predicting the time rate of change of the near wake structures.

Wake Skew

STRq-59 SWiFT Model Assessment: Measured and predicted wake initiation angle and wake offset distance at several locations downstream of the rotor will be compared for several high-yaw error configurations (wake steering) as well as zero yaw error configuration (no wake steering) in a variety of ABL conditions.

Objectives: Assess accuracy of existing wake steering models for use in guiding R&D for wind farm flow control. These data will enable validation of wake trajectory as extracted from HFM predictions, and validation/calibration of low order wake models.

Comments: Background: Vorticity shed from the rotating blades forms a helicoidal wake, which trails downstream. Wake trajectory can deviate from center in steady (skewed) or dynamic (meander) fashion depending on rotor geometry, operating state, and wind inflow. Wake skew and meander simultaneously affect induction on the associated upstream rotor and defines where the wake impinges downstream. They also govern the authority of proposed wind farm control approaches to affect the flow through a turbine array.

Wake Meander

STRq-60 SWiFT Model Assessment: Measured and predicted frequency spectrum of wake offset (i.e. frequency character of wake meandering) will be compared for data gathered in a variety of ABL conditions.

Objectives: Assess accuracy of existing wake steering models for use in guiding R&D for wind farm flow control to minimize wind farm LCOE. These data will enable validation of wake trajectory as extracted from HFM predictions, and validation/calibration of low order wake models.

Comments: Background: Vorticity shed from the rotating blades forms a helicoidal wake, which trails downstream. Wake trajectory can deviate from center in steady (skewed) or dynamic (meander) fashion depending on rotor geometry, operating state, and wind inflow. Wake skew and meander simultaneously affect induction on the associated upstream rotor and defines where the wake impinges downstream. They also govern the authority of proposed wind farm control approaches to affect the flow through a turbine array.

Wake Advection, Instability, and Dissipation

STRq-62 SWiFT Model Assessment: Measured and predicted wake deficit and turbulence intensity downstream of the rotor will be compared at several locations downstream of the rotor for several collective pitch settings and tip speed ratios for data gathered in a variety of ABL conditions.

Objective: Assess the accuracy of existing near and far wake models in predicting the inflow

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to a downstream rotor.

Comments: Background: As the aggregate wake travels downwind in a skewed/meandering trajectory, instabilities can arise within the wake as vorticity concentrations interact, and dissipation occurs as turbulent and molecular processes diffuse wake vorticity. These physics are important because they determine wake size and energy as it proceeds downstream and what impact it will have when it impinges downstream rotors.

Wake Impingement on Downwind Turbine

STRq-63 SWiFT Model Assessment: Measured and predicted downstream rotor inflow and performance will be compared for several collective pitch settings and tip speed ratios (as well as possible rotor design innovations) while the downstream turbine is partially/fully waked for data gathered in a variety of ABL conditions.

Objective: Assess the accuracy of low order and high fidelity model (HFM) predictions of rotor energy capture and structural loads for partially and fully waked turbines. The differences between measured and predicted downstream turbine inflow and performance will be used to assess credibility of existing wake models for guiding rotor induction control algorithm development to minimize wind farm COE.

Comments: Background: In the multi-row wind plant environment, the wake produced by the upstream rotor may impinge on a downstream rotor, after undergoing the combined influences of skew, meander, instability, and dissipation. Coupled with impingement, the collective action of these four processes determines reductions in energy capture and amplification in fatigue loading.

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Outside the Scope of the Project

STRq-65 The eventual challenge is to provide forecasts of wind farm power. Measured and predicted wind turbine power output will be compared for different ABL conditions (consistent stable, consistent neutral, and consistent unstable). Data would be used to assess credibility of existing coupled meso-, micro-, and turbine/rotor-scale models for predicting inflow to turbine scale and predicting turbine and farm power output. These models will be used for long-range forecasting of wind plant performance. This prediction represents a grand challenge and is beyond the scope of this proposal, but is the logical follow-on project which would be enabled by this project.

STRq-82 This is beyond the scope of the current work. It may be the focus of future work.

STRq-77 This is a secondary focus for SWiFT experiments.

STRq-78 This is not applicable to SWiFT experiments.

STRq-79 This is a primary or secondary objective for wind tunnel experiments.

STRq-66 Wake interaction and merging. Turbines two side by side. Wake interaction and merging using SNL-1 and Vestas turbines. This would be a long term goal.

General Notes

STRq-81 This is a inherent aspect of all SWiFT test objectives.

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Chapter 6

SWiFT-X1 Rotor Hardware Requirements

6.1 User Requirements

These requirements are primarily related to safe and reliable operation of the turbines at the SWiFT site.

6.1.1 User Requirements for Rotor Hardware

Test Hardware Objectives

URq-2 Sandia will create a rotor to enable model validation activities at SWiFT which support assessment of model credibility for applications involving complex flow and turbine-turbine interactions. The rotor will be of *validation quality*—i.e. highly characterized and easily modeled.

URq-10 The rotor will feature a research-quality suite of mechanical and aerodynamic sensors to support high-fidelity measurements of rotor aerodynamic loads and structural loads for model validation.

Comments: Acknowledgement that aerodynamic sensors are a highly desireable feature of the new rotor instrumentation suite per DOE Sponsors.

URq-7 All test data and model files will be released publicly to the international research community.

Safety

URq-5 The new rotor will operate safely and reliably on existing SWiFT turbines.

URq-114 The test campaign will be planned and executed such that SWiFT site requirements are fulfilled. Turbines will operate within their capabilities such that there is no harm to personnel at the site or the public.

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6.1.2 Traceability of User Requirements for Rotor Hardware

Every requirement is listed. For each requirement, the lower-level requirements which satisfy the requirement are also listed. They appear as *In-link*s. There should be at least one *In-link* listed to satisfy the requirement. In cases where no *In-links* are listed, there is an open gap in the requirements which must be filled.

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Requirement URq-2: Sandia will create a rotor to enable model validation activities at SWiFT which support assessment of model credibility for applications involving complex flow and turbine-turbine interactions. The rotor will be of *validation quality*—i.e. highly characterized and easily modeled.

In-links (System Requirements):

SFRq-99

The rotor shall have repeatable, predictable aerodynamics performance and integrated rotor loads for the relevant range of Re numbers.

SFRq-174

Blade design shall be done in a manner which promotes the design-for-analysis philosophy—i.e. blade tips should be created primarily such that they are represented readily in numerical simulation, such as the CFD mesh.

SFRq-177

The rotor shape shall be well quantified.

SFRq-178

The rotor sensors and sensor locations shall be well quantified.

SFRq-179

The rotor structure shall be well quantified.

SFRq-180

The rotor external surface roughness shall be well quantified.

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Requirement URq-10: The rotor will feature a research-quality suite of mechanical and aerodynamic sensors to support high-fidelity measurements of rotor aerodynamic loads and structural loads for model validation.

In-links (System Requirements):

SFRq-175

Blade tips design shall be done in a manner which maximizes the available interior blade volume near the blade tip. Interior blade volume is needed in order to maximize the instrumentation options available at the blade tip.

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Requirement URq-7: All test data and model files will be released publicly to the international research community.

In-links (System Requirements):

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Requirement URq-5: The new rotor will operate safely and reliably on existing SWiFT turbines.

In-links (System Requirements):

SFRq-29

The blade shall have lightning protection adequate for use in Lubbock, Texas.

SFRq-118

Blades will exhibit nominal pitching moment such that the rotor will passively pitch-to-feather in a scenario where loss of pitch control is experienced.

SFRq-119

Blade structural dynamics shall not be excited by turbine operation.

SFRq-141

The rotor design shall withstand load cases as described in wind turbine standards.

SFRq-144

The blades shall be designed using verified design tools.

SFRq-157

Turbine stresses at the interface of blade to hub resulting from design loads shall not exceed design strength as described in Ref [6].

SFRq-161

Blade mass and rotor moment of inertia shall be compared to OEM values. If the new blades are heavier or the new rotor inertia is higher, then special scrutiny on rotor dynamics calculations may be warranted.

SFRq-173

The turbine mechanical braking systems shall be capable of bringing the rotor to a full stop in case of collective pitch failure in a worst-case operating scenario.

SFRq-181

Blades shall not experience aeroelastic instability during normal operation or during emergency

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operating scenarios.

SFRq-183

Tower structural dynamics shall not be excited by turbine operation

SFRq-187

The rotor and turbine shall not fail while operating in non-standard configurations which are the result of specific SWiFT test configurations.

SFRq-189

Physical connection of blades to the OEM turbine hub shall be achieved with no alteration of existing hub hardware.

SFRq-190

Ultimate limits on generator torque, speed and power shall be observed.

SFRq-193

The SWiFT hardware-in-the-loop (HIL) capability shall be used to test the turbine controller associated with the new rotor prior to deployment on the full turbine.

SFRq-195

Turbine stresses at the interface of hub to low speed shaft resulting from design loads shall not exceed design strength as described in Ref [6].

SFRq-197

Foundation forces and moment resulting from design loads shall not exceed design strength as described in Ref [7, 8].

SFRq-198

It shall not be possible for the turbine to experience a tower strike by any blade.

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Requirement URq-114: The test campaign will be planned and executed such that SWiFT site requirements are fulfilled. Turbines will operate within their capabilities such that there is no harm to personnel at the site or the public.

In-links (System Requirements):

SFRq-184

The proposed rotor design shall not violate SWiFT facility debris throw requirements in the event of an overspeed and subsequent rotor failure.

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6.2 System Requirements for Rotor Hardware

These requirements satisfy the higher level user requirements. They primarily satisfy safe and reliable operation of the turbines at the SWiFT site. They also address rotor goals in terms of hardware quality and aerodynamic and structural performance.

6.2.1 System Requirements for Rotor Hardware

Turbine and Rotor Operation, Reliability, and Safety

SFRq-184 The proposed rotor design shall not violate SWiFT facility debris throw requirements in the event of an overspeed and subsequent rotor failure.

SFRq-161 Blade mass and rotor moment of inertia shall be compared to OEM values. If the new blades are heavier or the new rotor inertia is higher, then special scrutiny on rotor dynamics calculations may be warranted.

SFRq-173 The turbine mechanical braking systems shall be capable of bringing the rotor to a full stop in case of collective pitch failure in a worst-case operating scenario.

SFRq-190 Ultimate limits on generator torque, speed and power shall be observed.

SFRq-29 The blade shall have lightning protection adequate for use in Lubbock, Texas.

SFRq-141 The rotor design shall withstand load cases as described in wind turbine standards.

SFRq-187 The rotor and turbine shall not fail while operating in non-standard configurations which are the result of specific SWiFT test configurations.

SFRq-157 Turbine stresses at the interface of blade to hub resulting from design loads shall not exceed design strength as described in Ref [6].

SFRq-195 Turbine stresses at the interface of hub to low speed shaft resulting from design loads shall not exceed design strength as described in Ref [6].

SFRq-197 Foundation forces and moment resulting from design loads shall not exceed design strength as described in Ref [7, 8].

SFRq-119 Blade structural dynamics shall not be excited by turbine operation.

SFRq-183 Tower structural dynamics shall not be excited by turbine operation

SFRq-118 Blades will exhibit nominal pitching moment such that the rotor will passively pitch-to-feather in a scenario where loss of pitch control is experienced.

SFRq-181 Blades shall not experience aeroelastic instability during normal operation or during

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emergency operating scenarios.

SFRq-189 Physical connection of blades to the OEM turbine hub shall be achieved with no alteration of existing hub hardware.

SFRq-193 The SWiFT hardware-in-the-loop (HIL) capability shall be used to test the turbine controller associated with the new rotor prior to deployment on the full turbine.

SFRq-198 It shall not be possible for the turbine to experience a tower strike by any blade.

SFRq-144 The blades shall be designed using verified design tools.

Rotor Performance—V&V-Quality Test Requirements

SFRq-177 The rotor shape shall be well quantified.

SFRq-180 The rotor external surface roughness shall be well quantified.

SFRq-179 The rotor structure shall be well quantified.

SFRq-178 The rotor sensors and sensor locations shall be well quantified.

SFRq-99 The rotor shall have repeatable, predictable aerodynamics performance and integrated rotor loads for the relevant range of Re numbers.

SFRq-174 Blade design shall be done in a manner which promotes the design-for-analysis philosophy—i.e. blade tips should be created primarily such that they are represented readily in numerical simulation, such as the CFD mesh.

Rotor Performance—General Requirements

SFRq-175 Blade tips design shall be done in a manner which maximizes the available interior blade volume near the blade tip. Interior blade volume is needed in order to maximize the instrumentation options available at the blade tip.

6.2.2 Traceability of System Requirements for Rotor Hardware

Every requirement is listed. For each requirement, the lower-level requirements which satisfy the requirement are also listed. They appear as *In-link*s. There should be at least one *In-link* listed to satisfy the requirement. In cases where no *In-links* are listed, there is an open gap in the requirements which must be filled. For each requirement, the higher-level requirements which are satisfied by the requirement are also listed. They appear as *Out-link*s. There should be at least one

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Out-link listed for each requirement. In cases where no *Out-links* are listed, scope-creep may be present because the requirement is not traceable to a higher-level requirement.

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Requirement SFRq-184: The proposed rotor design shall not violate SWiFT facility debris throw requirements in the event of an overspeed and subsequent rotor failure.

Out-links (User Requirements Hardware):

URq-114

The test campaign will be planned and executed such that SWiFT site requirements are fulfilled. Turbines will operate within their capabilities such that there is no harm to personnel at the site or the public.

In-links (Component Requirements):

CRq-235

Debris throw analysis shall show that fewer than 5% of potential rotor debris will reach outside the boundary of the Reese facility property in the event of a rotor overspeed and subsequent rotor failure.

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Requirement SFRq-161: Blade mass and rotor moment of inertia shall be compared to OEM values. If the new blades are heavier or the new rotor inertia is higher, then special scrutiny on rotor dynamics calculations may be warranted.

Out-links (User Requirements Hardware):

URq-5

The new rotor will operate safely and reliably on existing SWiFT turbines.

In-links (Component Requirements):

CRq-113

Predicted and manufactured blade mass shall be compared to the average weight of current OEM blades, 660 kg [9]. Blade mass shall be equal to or less than OEM blade mass so that the overall rotor weight of the retrofit rotor does not cause additional stress on the SWiFT turbines, in terms of downward force on the nacelle and drivetrain.

CRq-114

The predicted and manufactured blade static balance shall be compared to the measured average static balance of current OEM blades, $659.2\ kg * 4.195\ m = 27,653 kg - m$ [9].

CRq-264

The predicted rotor moment of inertia, $I = \int_m r^2\,\mathrm{d}m$, shall be compared to the estimated rotor moment of inertia for the OEM rotor. The FAST aeroelastic model of the OEM SWiFT turbines [10] can be used to estimate the rotor moment of inertia for the OEM rotor. Rotor moment of inertia shall be equal to or less than the estimated OEM moment of inertia so that rotor angular momentum, $L_{max} = I\omega_{max}$, at maximum rotor speed, ω_{max} is not higher for the retrofit rotor than the OEM rotor.

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Requirement SFRq-173: The turbine mechanical braking systems shall be capable of bringing the rotor to a full stop in case of collective pitch failure in a worst-case operating scenario.

Out-links (User Requirements Hardware):

URq-5

The new rotor will operate safely and reliably on existing SWiFT turbines.

In-links (Component Requirements):

CRq-248

The turbine mechanical braking systems shall bring the pitched-to-run, operational rotor to a full stop in case of collective pitch failure during an extreme wind speed ramp with zero yaw error. The wind loading scenario which tests this requirement is described as follows: It begins with normal steady turbine operation at the lowest steady wind speed which commands rotor maximum operating speed for full pitched-to-run configuration—typically this is the top wind speed for Region II.5. Then, wind speed increases to 18 m/s over a 3 second duration. Finally, wind speed remains steady at 18 m/s. This input load case was taken from recommendations by NREL based on experience at the CART site. When successful, the simulation will verify that the rotor can be stopped during simultaneous collective pitch failure and extreme wind speed ramp.

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Requirement SFRq-190: Ultimate limits on generator torque, speed and power shall be observed.

Out-links (User Requirements Hardware):

URq-5

The new rotor will operate safely and reliably on existing SWiFT turbines.

In-links (Component Requirements):

CRq-118

Rated generator power shall never exceed 195 kW—the current production controller setting. Full rated generator power is 225 kW.

CRq-119

Rated HSS speed shall be set to 1,210 rpm because current production rated HSS speed is 1,210 rpm. This corresponds to 43.9 rpm at the gearbox ratio of 27.5647. Maximum generator speed is around 1,700 rpm.

CRq-120

HSS torque shall never exceed 1,600 kNm. Maximum rated HSS torque is 1,600 kNm (1183 lb-ft full load torque from generator spec sheet).

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Requirement SFRq-29: The blade shall have lightning protection adequate for use in Lubbock, Texas.

Out-links (User Requirements Hardware):

URq-5

The new rotor will operate safely and reliably on existing SWiFT turbines.

In-links (Component Requirements):

CRq-259

The blade shall have lightning protection adequate for use in Lubbock, Texas.

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Requirement SFRq-141: The rotor design shall withstand load cases as described in wind turbine standards.

Out-links (User Requirements Hardware):

URq-5

The new rotor will operate safely and reliably on existing SWiFT turbines.

In-links (Component Requirements):

CRq-243

Standard load cases. The rotor design shall be able to withstand all design load cases (DLC's) as described in the IEC standard [11]. Wind Turbine Class is characterized as IEC III-C at SWiFT turbine hub-height. The average wind speed at the site at SWiFT hub-height is 6.6 m/s. The reference turbulence intensity at SWiFT hub-height, I_{ref}, is 0.11.

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Requirement SFRq-187: The rotor and turbine shall not fail while operating in non-standard configurations which are the result of specific SWiFT test configurations.

Out-links (User Requirements Hardware):

URq-5

The new rotor will operate safely and reliably on existing SWiFT turbines.

In-links (Component Requirements):

CRq-164

Turbine yaw-lock Requirement CRq-162 can lead to operation of the turbine in configurations with high amounts of yaw error. Additionally, experimental configurations for wake steering will lead to operation of the turbine with high yaw error. Simulations shall verify that rotor and turbine loads in these high-yaw configurations do not exceed allowable strength in the turbine or rotor.

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Requirement SFRq-157: Turbine stresses at the interface of blade to hub resulting from design loads shall not exceed design strength as described in Ref [6].

Out-links (User Requirements Hardware):

URq-5

The new rotor will operate safely and reliably on existing SWiFT turbines.

In-links (Component Requirements):

CRq-112

The blade root bending moment, $M_{x_{b,i}}$ and $M_{y_{b,i}}$, (design load) shall not exceed 210 kNm under any normal operating or emergency operating conditions. Design load is the characteristic load multiplied by the partial safety factor for loads as described in IEC Section 7.6 Ultimate Limit State Analysis [11].

CRq-194

The blade root shear force, $F_{x_{b,i}}$ and $F_{y_{b,i}}$, (design load) shall not exceed 700 kN under any normal operating or emergency operating conditions. Design load is the characteristic load multiplied by the partial safety factor for loads as described in IEC Section 7.6 Ultimate Limit State Analysis [11].

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Requirement SFRq-195: Turbine stresses at the interface of hub to low speed shaft resulting from design loads shall not exceed design strength as described in Ref [6].

Out-links (User Requirements Hardware):

URq-5

The new rotor will operate safely and reliably on existing SWiFT turbines.

In-links (Component Requirements):

CRq-111

The rotor thrust, F_{x_s}, (design load) shall not exceed 57.6 kN under any normal operating or emergency operating conditions. Design load is the characteristic load multiplied by the partial safety factor for loads as described in IEC Section 7.6 Ultimate Limit State Analysis [11].

CRq-196

The rotor vertical shear, F_{z_s}, (design load) shall not exceed 126.4 kN under any normal operating or emergency operating conditions. Design load is the characteristic load multiplied by the partial safety factor for loads as described in IEC Section 7.6 Ultimate Limit State Analysis [11].

CRq-198

The rotor torque, M_{x_s}, (design load) shall not exceed 55 kNm under any normal operating or emergency operating conditions. Design load is the characteristic load multiplied by the partial safety factor for loads as described in IEC Section 7.6 Ultimate Limit State Analysis [11].

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Requirement SFRq-197: Foundation forces and moment resulting from design loads shall not exceed design strength as described in Ref [7, 8].

Out-links (User Requirements Hardware):

URq-5

The new rotor will operate safely and reliably on existing SWiFT turbines.

In-links (Component Requirements):

CRq-257

The foundation design overturning moment, M, shall never exceed 3,326,407 ft-lbs.

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Requirement SFRq-119: Blade structural dynamics shall not be excited by turbine operation.

Out-links (User Requirements Hardware):

URq-5

The new rotor will operate safely and reliably on existing SWiFT turbines.

In-links (Component Requirements):

CRq-225

Rotor structural dynamic frequencies shall not be in the ranges of 2.9P–3.1P or 5.95P–6.05P.

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Requirement SFRq-183: Tower structural dynamics shall not be excited by turbine operation

Out-links (User Requirements Hardware):

URq-5

The new rotor will operate safely and reliably on existing SWiFT turbines.

In-links (Component Requirements):

CRq-226

The maximum rotor speed control setpoint shall never exceed 47 rpm over all regions of operation. This is based on a 10% margin away from the first tower frequency at 1 Hz, or 60 rpm, 10% margin on the overspeed safety setting, and a 3% tolerance on control of maximum rotor speed by the turbine controller. Max speed in rpm, $60 * 0.9 * 0.9 * 0.97 = 43.9$.

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Requirement SFRq-118: Blades will exhibit nominal pitching moment such that the rotor will passively pitch-to-feather in a scenario where loss of pitch control is experienced.

Out-links (User Requirements Hardware):

URq-5

The new rotor will operate safely and reliably on existing SWiFT turbines.

In-links (Component Requirements):

CRq-251

The blade design shall exhibit an overall blade root pitching moment of -1000 Nm ($\pm$10%) at the top of Region II. The blade pitching moment shall always decrease (increasingly negative) with increasing wind speed.

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Requirement SFRq-181: Blades shall not experience aeroelastic instability during normal operation or during emergency operating scenarios.

Out-links (User Requirements Hardware):

URq-5

The new rotor will operate safely and reliably on existing SWiFT turbines.

In-links (Component Requirements):

CRq-237

Aeroelastic instability, i.e. flutter, shall not occur within the normal operational range of rotor speeds up to rotor terminal velocity.

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Requirement SFRq-189: Physical connection of blades to the OEM turbine hub shall be achieved with no alteration of existing hub hardware.

Out-links (User Requirements Hardware):

URq-5

The new rotor will operate safely and reliably on existing SWiFT turbines.

In-links (Component Requirements):

CRq-76

The new rotor shall utilize the same carrots for root hardware as the OEM rotor.

CRq-104

The blade root outer shell diameter shall be no greater than the OEM outer root shell diameter, which is 592.6 mm per B.LeBlanc measurements on 4/3/14.

CRq-105

The bolt circle diameter (BCD) of the blade shall be 508 mm, $\pm$ 1 mm (per OEM documents)

CRq-106

There shall be 30 evenly spaced bolts at the root attachment. (per OEM documents)

CRq-107

The blade root bolts shall be of type M20, 180 mm studs. The OEM torque spec on these bolts is 500 Nm greased. (per OEM documents)

CRq-160

Bolted connections at the blades root shall meet requirements of GL2010—6.5 bolted connections, using VDI2230.

CRq-253

Blade root geometry shall be cylindrical—i.e.chord and absolute thickness distributions shall be constant—at the blade root outboard to a point beyond the root hardware and associated inserts—i.e. outboard to at least 350 mm span.

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Requirement SFRq-193: The SWiFT hardware-in-the-loop (HIL) capability shall be used to test the turbine controller associated with the new rotor prior to deployment on the full turbine.

Out-links (User Requirements Hardware):

URq-5

The new rotor will operate safely and reliably on existing SWiFT turbines.

In-links (Component Requirements):

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Requirement SFRq-198: It shall not be possible for the turbine to experience a tower strike by any blade.

Out-links (User Requirements Hardware):

URq-5

The new rotor will operate safely and reliably on existing SWiFT turbines.

In-links (Component Requirements):

CRq-125

Tower Clearance. The blade maximum tip out-of-plane deflection shall not be more than 1.328 m under any simulated design load cases (DLC's). Allowable tip deflection of 1.328 meters includes the total safety factor of 1.485 on the actual tower clearance of $1.328\ m * 1.485 = 1.973\ m$

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Requirement SFRq-144: The blades shall be designed using verified design tools.

Out-links (User Requirements Hardware):

URq-5

The new rotor will operate safely and reliably on existing SWiFT turbines.

In-links (Component Requirements):

CRq-159

Sandia rotor design tools are not formally verified. Therefore, the Sandia rotor design concept shall be verified by Wetzel Engineering calculations during the detailed design phase of the rotor.

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Requirement SFRq-177: The rotor shape shall be well quantified.

Out-links (User Requirements Hardware):

URq-2

Sandia will create a rotor to enable model validation activities at SWiFT which support assessment of model credibility for applications involving complex flow and turbine-turbine interactions. The rotor will be of *validation quality*—i.e. highly characterized and easily modeled.

In-links (Component Requirements):

CRq-59

Tolerance on manufactured airfoil shapes shall recreate desired airfoil shapes within 0.3 mm on the portion of the blade which is outboard of maximum chord.

CRq-60

Manufactured airfoil trailing edge thickness shall be $1/100^{th}$ blade chord except that it will be no greater than 10 mm and no less than 2 mm.

CRq-208

Aerodynamic shape of the new blades shall be characterized to adequate quality for CFD meshing of a model of the blades. We need to measure with enough accuracy to build a good model of what we have. (need a little more detail)

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Requirement SFRq-180: The rotor external surface roughness shall be well quantified.

Out-links (User Requirements Hardware):

URq-2

Sandia will create a rotor to enable model validation activities at SWiFT which support assessment of model credibility for applications involving complex flow and turbine-turbine interactions. The rotor will be of *validation quality*—i.e. highly characterized and easily modeled.

In-links (Component Requirements):

CRq-210

Surface roughness of tested airfoils on new blades shall be quantified before and after execution of validation quality data gathering.

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Requirement SFRq-179: The rotor structure shall be well quantified.

Out-links (User Requirements Hardware):

URq-2

Sandia will create a rotor to enable model validation activities at SWiFT which support assessment of model credibility for applications involving complex flow and turbine-turbine interactions. The rotor will be of *validation quality*—i.e. highly characterized and easily modeled.

In-links (Component Requirements):

CRq-177

Ground-based static and modal tests on blades shall characterize spanwise stiffness distribution.

CRq-185

One blade shall be dissected to characterize spanwise mass distribution.

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Requirement SFRq-178: The rotor sensors and sensor locations shall be well quantified.

Out-links (User Requirements Hardware):

URq-2

Sandia will create a rotor to enable model validation activities at SWiFT which support assessment of model credibility for applications involving complex flow and turbine-turbine interactions. The rotor will be of *validation quality*—i.e. highly characterized and easily modeled.

In-links (Component Requirements):

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Requirement SFRq-99: The rotor shall have repeatable, predictable aerodynamics performance and integrated rotor loads for the relevant range of Re numbers.

Out-links (User Requirements Hardware):

URq-2

Sandia will create a rotor to enable model validation activities at SWiFT which support assessment of model credibility for applications involving complex flow and turbine-turbine interactions. The rotor will be of *validation quality*—i.e. highly characterized and easily modeled.

In-links (Component Requirements):

CRq-59

Tolerance on manufactured airfoil shapes shall recreate desired airfoil shapes within 0.3 mm on the portion of the blade which is outboard of maximum chord.

CRq-130

Region II Similarity. The airfoil family shall enable replication of the mean and variability in circulation distribution of the full-scale rotor during operation in turbulent inflow.

CRq-131

Region II.5 Performance. Airfoils shall have a high stall-angle-of-attack. Such airfoils allow a rotor in which the operating angle of attack is sufficiently below stall over most of Region II.5—therefore enabling the rotor is able to reach rated power after reaching maximum allowable rotor speed.

CRq-132

Roughness Sensitivity. Anticipated changes in surface roughness shall have minimal effect on the intended blade circulation distribution of the rotor.

CRq-133

Stall Characteristics. Airfoils shall have docile stall characteristics to promote predictable gust response and to minimize the amplitude of unrepresentative blade elastic bending oscillations.

CRq-136

Quality Experimental Data. Airfoils shall have thoroughly documented, publicly available airfoil polars taken in a high-quality wind tunnel.

CRq-137

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Field Experience. Airfoils shall have extensive experience in the field at Reynolds numbers which are relevant to the design of this rotor.

CRq-138

Root Airfoils Transition Region. Airfoils shall have available polar data for thick airfoils which are anticipated in the root-to-maximum-chord transition region of the blade.

CRq-260

The aerodynamic blade shape shall not contain excessive and problematic spanwise flowfields.

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Requirement SFRq-174: Blade design shall be done in a manner which promotes the design-for-analysis philosophy—i.e. blade tips should be created primarily such that they are represented readily in numerical simulation, such as the CFD mesh.

Out-links (User Requirements Hardware):

URq-2

Sandia will create a rotor to enable model validation activities at SWiFT which support assessment of model credibility for applications involving complex flow and turbine-turbine interactions. The rotor will be of *validation quality*—i.e. highly characterized and easily modeled.

In-links (Component Requirements):

CRq-250

The tip shape shall be prescribed in a manner which is most conducive to creation of blade-resolved CFD meshes.

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Requirement SFRq-175: Blade tips design shall be done in a manner which maximizes the available interior blade volume near the blade tip. Interior blade volume is needed in order to maximize the instrumentation options available at the blade tip.

Out-links (User Requirements Hardware):

URq-10

The rotor will feature a research-quality suite of mechanical and aerodynamic sensors to support high-fidelity measurements of rotor aerodynamic loads and structural loads for model validation.

In-links (Component Requirements):

CRq-236

A high-solidity rotor shall be used to enable a high stiffness blade as well as a blade with greater interior volume. The high-solidity rotor will be made possible by intentionally low design-C_l.

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6.3 Rotor Component Requirements

These component requirements—i.e. design requirements—satisfy 1) the higher level hardware system requirements as well as 2) general test campaign requirements.

6.3.1 Rotor Component Requirements

Turbine

CRq-226 The maximum rotor speed control setpoint shall never exceed 47 rpm over all regions of operation. This is based on a 10% margin away from the first tower frequency at 1 Hz, or 60 rpm, 10% margin on the overspeed safety setting, and a 3% tolerance on control of maximum rotor speed by the turbine controller. Max speed in rpm, $60*0.9*0.9*0.97 = 43.9$.

CRq-251 The blade design shall exhibit an overall blade root pitching moment of -1000 Nm ($\pm 10\%$) at the top of Region II. The blade pitching moment shall always decrease (increasingly negative) with increasing wind speed.

Comments: This is the currently proposed approach to tailoring of pitching moment. The topic of desired pitching moment for the new blades is a topic of debate at the present time—resolution is tbd.

CRq-259 The blade shall have lightning protection adequate for use in Lubbock, Texas.

Design Load Cases

CRq-243 Standard load cases. The rotor design shall be able to withstand all design load cases (DLC's) as described in the IEC standard [11]. Wind Turbine Class is characterized as IEC III-C at SWiFT turbine hub-height. The average wind speed at the site at SWiFT hub-height is 6.6 m/s. The reference turbulence intensity at SWiFT hub-height, I_{ref}, is 0.11.

CRq-248 The turbine mechanical braking systems shall bring the pitched-to-run, operational rotor to a full stop in case of collective pitch failure during an extreme wind speed ramp with zero yaw error. The wind loading scenario which tests this requirement is described as follows: It begins with normal steady turbine operation at the lowest steady wind speed which commands rotor maximum operating speed for full pitched-to-run configuration—typically this is the top wind speed for Region II.5. Then, wind speed increases to 18 m/s over a 3 second duration. Finally, wind speed remains steady at 18 m/s. This input load case was taken from recommendations by NREL based on experience at the CART site. When successful, the simulation will verify that the rotor can be stopped during simultaneous collective pitch failure and extreme wind speed ramp.

CRq-235 Debris throw analysis shall show that fewer than 5% of potential rotor debris will

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reach outside the boundary of the Reese facility property in the event of a rotor overspeed and subsequent rotor failure.

CRq-164 Turbine yaw-lock Requirement CRq-162 can lead to operation of the turbine in configurations with high amounts of yaw error. Additionally, experimental configurations for wake steering will lead to operation of the turbine with high yaw error. Simulations shall verify that rotor and turbine loads in these high-yaw configurations do not exceed allowable strength in the turbine or rotor.

Rotor Airfoils

CRq-208 Aerodynamic shape of the new blades shall be characterized to adequate quality for CFD meshing of a model of the blades. We need to measure with enough accuracy to build a good model of what we have. (need a little more detail)

CRq-60 Manufactured airfoil trailing edge thickness shall be $1/100^{th}$ blade chord except that it will be no greater than 10 mm and no less than 2 mm.

Comments: The V27 OEM blade trailing edges are 14.6 mm near the root and 4.5 mm just past the location of maximum chord.

CRq-59 Tolerance on manufactured airfoil shapes shall recreate desired airfoil shapes within 0.3 mm on the portion of the blade which is outboard of maximum chord.

Comments: We've had a blade manufacturer claim that they can use a zone approach for tolerances where the outer $^1/_2$ or $^1/_3$ of blade is ± 0.500 mm on the profile and some fraction of radians on the twist. Tolerance is relaxed on the inboard stations to ± 1 mm. Typical wind-tunnel airfoil models are accurate to within 0.005 inches, 0.127 mm.

CRq-210 Surface roughness of tested airfoils on new blades shall be quantified before and after execution of validation quality data gathering.

CRq-135 Thickness Requirement. Airfoils thickness-to-chord ratios shall be as large as reasonable. The goal of this requirement is to promote use of airfoils which are thicker, but not excessively thick. Thin airfoils achieve aerodynamic goals much easier than thick airfoils, but this requirement aims to encourage the use of thicker airfoils in order to enable goals of a stiff blade and a blade with large internal volume for onboard instrumentation packages.

CRq-130 Region II Similarity. The airfoil family shall enable replication of the mean and variability in circulation distribution of the full-scale rotor during operation in turbulent inflow.

CRq-131 Region II.5 Performance. Airfoils shall have a high stall-angle-of-attack. Such airfoils allow a rotor in which the operating angle of attack is sufficiently below stall over most of Region II.5—therefore enabling the rotor is able to reach rated power after reaching maximum allowable rotor speed.

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CRq-132 Roughness Sensitivity. Anticipated changes in surface roughness shall have minimal effect on the intended blade circulation distribution of the rotor.

CRq-133 Stall Characteristics. Airfoils shall have docile stall characteristics to promote predictable gust response and to minimize the amplitude of unrepresentative blade elastic bending oscillations.

CRq-136 Quality Experimental Data. Airfoils shall have thoroughly documented, publicly available airfoil polars taken in a high-quality wind tunnel.

CRq-137 Field Experience. Airfoils shall have extensive experience in the field at Reynolds numbers which are relevant to the design of this rotor.

CRq-138 Root Airfoils Transition Region. Airfoils shall have available polar data for thick airfoils which are anticipated in the root-to-maximum-chord transition region of the blade.

Rotor Aerodynamics

CRq-152 The rotor shall exhibit an operational tip speed ratio of 9 in Region II with a fine pitch setting of zero degrees. Note that Region II operational TSR is different from design TSR for max C_P.

CRq-153 The rotor shall exhibit a spanwise distribution of nondimensional circulation matching the GE1.5-77sle rotor model, as documented in Reference [3] (the distribution is also shown in Reference [12], Figure 7.2. Nondimensional circulation distributions of full-scale and subscale designs shall be forced to match only outboard of 25% rotor span. Uncertainty of inboard aerodynamics dictate that inboard blade shape design be driven by practical aspects of blending the circular root to outboard airfoils. Also, inboard transition region design should be driven by the need, as well as possible, to prevent inboard blade stall.

CRq-242 The rotor maximum C_P of the subscale design will represent the maximum C_P of the full-scale design within $\pm 5\%$.

CRq-204 Circulation distribution shall be smooth for all relevant operating conditions. There shall be no weird stall interactions—e.g. spanwise pressure gradients which influence separation. Specifically, airfoil transition regions should be checked: a) root, b) middle, c) tip.

Comments: Avoiding repeat of Mexico and UAE Phase 6.

CRq-207 Tip design shall enable an exact match of the full-scale non-dimensional circulation distribution, $\Gamma'(r/R)$ and the non-dimensional circulation distribution of the design shall be smooth. Chord distribution, $c/R(r/R)$, of the tip may not necessarily match the chord distribution of the full-scale rotor, but it shall be smooth.

Comments: Tip design is a topic of advanced research and is likely the target of future test campaigns.

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CRq-250 The tip shape shall be prescribed in a manner which is most conducive to creation of blade-resolved CFD meshes.

CRq-236 A high-solidity rotor shall be used to enable a high stiffness blade as well as a blade with greater interior volume. The high-solidity rotor will be made possible by intentionally low design-C_l.

CRq-261 Non-dimensional rotor shear, i.e. $\frac{dU/dU_\infty}{dz/D}$, shall be similar for full-scale and subscale rotors.

CRq-262 Strouhal Number. Wake meandering characteristics will be recreated at subscale through replication of the rotor Strouhal Number, $St = \frac{fD_{rotor}}{U_{infty,hub}}$ where f is the frequency of vortex shedding.

CRq-260 The aerodynamic blade shape shall not contain excessive and problematic spanwise flowfields.

CRq-240 Perform simulations to verify scaling methodology. Numerical predictions will show that the subscale rotor has the same character as the full-scale rotor. Specific traits will be shown similar: 1) radial profile of near-wake velocity deficit at 1-D downstream of the rotor; 2) wake energy recovery as a function of distance downstream of the rotor.

CRq-263 The spanwise distribution of full-scale and subscale Reynolds numbers are not expected to match. In lieu of a Reynolds number match, airfoils for the sub-scale design shall be chosen for specific operation at the anticipated subscale Reynolds numbers.

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Rotor Inertia

CRq-113 Predicted and manufactured blade mass shall be compared to the average weight of current OEM blades, 660 kg [9]. Blade mass shall be equal to or less than OEM blade mass so that the overall rotor weight of the retrofit rotor does not cause additional stress on the SWiFT turbines, in terms of downward force on the nacelle and drivetrain.

CRq-114 The predicted and manufactured blade static balance shall be compared to the measured average static balance of current OEM blades, $659.2\ kg * 4.195\ m = 27,653 kg - m$ [9].

CRq-264 The predicted rotor moment of inertia, $I = \int_m r^2 \, \mathrm{d}m$, shall be compared to the estimated rotor moment of inertia for the OEM rotor. The FAST aeroelastic model of the OEM SWiFT turbines [10] can be used to estimate the rotor moment of inertia for the OEM rotor. Rotor moment of inertia shall be equal to or less than the estimated OEM moment of inertia so that rotor angular momentum, $L_{max} = I\omega_{max}$, at maximum rotor speed, ω_{max} is not higher for the retrofit rotor than the OEM rotor.

Blade Structural Dynamics

CRq-225 Rotor structural dynamic frequencies shall not be in the ranges of 2.9P–3.1P or 5.95P–6.05P.

Rotor Aeroelastic

CRq-73 Flap Stiffness. The blade shall have sufficient flap stiffness that section body velocities under normal aerodynamic operation do not add to dynamic C_l or α and cause exceedance of section stall values for Region II operation. Effects on pitch moment due to section C_m and blade sweep shall both be considered.

Comments: There are two sources of dynamic changes to blade section angles of attack from nominal, steady design values: (1) inflow changes due to turbulence and/or gusts and (2) flapwise (and/or edgewise) blade section body velocities due to blade elasticity.

Changes in alpha due to natural causes (1) are allowable.

Changes in alpha due to blade elasticity (2) shall be eliminated as much as possible.

CRq-227 Torsional Stiffness. The blade shall have sufficient torsional stiffness such that the blade sections do not experience dynamic changes in section angles of attack of more than 1 degree from nominal, steady design values for Region II operation. Effects on pitch moment due to section C_m and blade sweep shall both be considered.

Comments: There are two sources of dynamic changes to blade section angles of attack from nominal, steady design values: (1) inflow changes due to turbulence and/or gusts and (2) flapwise (and/or edgewise) blade section body velocities due to blade elasticity.

Changes in alpha due to natural causes (1) are allowable.

Changes in alpha due to blade elasticity (2) shall be eliminated as much as possible.

CRq-125 Tower Clearance. The blade maximum tip out-of-plane deflection shall not be more than 1.328 m under any simulated design load cases (DLC's). Allowable tip deflection of 1.328 meters includes the total safety factor of 1.485 on the actual tower clearance of $1.328\ m * 1.485 = 1.973\ m$

CRq-228 Design for loaded operation. Static blade twist distribution shall be designed to match a target distribution at a single operating point of $U_\infty = 6\ m/s$ (a middle wind speed in Region II). Deviation from nominal twist design at other operating points in Region II shall not exceed 0.5 degrees. This requirement is meant to ensure that the blade performs as intended under steady aeroelastic loading at the stated operating wind inflow speed.

CRq-237 Aeroelastic instability, i.e. flutter, shall not occur within the normal operational range of rotor speeds up to rotor terminal velocity.

DRAFT

CRq-254 Structural Linearity. The blade tip shall not deflect more than 5% of blade length under any normal operating loads. A blade structure which does not deflect more than 5% of its length is assumed to have linear elastic behavior.

Blade Root Geometry

CRq-104 The blade root outer shell diameter shall be no greater than the OEM outer root shell diameter, which is 592.6 mm per B.LeBlanc measurements on 4/3/14.

CRq-253 Blade root geometry shall be cylindrical—i.e.chord and absolute thickness distributions shall be constant—at the blade root outboard to a point beyond the root hardware and associated inserts—i.e. outboard to at least 350 mm span.

Blade/Hub Fastener Strategy

CRq-106 There shall be 30 evenly spaced bolts at the root attachment. (per OEM documents)

CRq-107 The blade root bolts shall be of type M20, 180 mm studs. The OEM torque spec on these bolts is 500 Nm greased. (per OEM documents)

CRq-105 The bolt circle diameter (BCD) of the blade shall be 508 mm, $\pm$ 1 mm (per OEM documents)

CRq-160 Bolted connections at the blades root shall meet requirements of GL2010—6.5 bolted connections, using VDI2230.

CRq-76 The new rotor shall utilize the same carrots for root hardware as the OEM rotor.

Blade Loads—Blade/Hub

CRq-112 The blade root bending moment, $M_{x_{b,i}}$ and $M_{y_{b,i}}$, (design load) shall not exceed 210 kNm under any normal operating or emergency operating conditions. Design load is the characteristic load multiplied by the partial safety factor for loads as described in IEC Section 7.6 Ultimate Limit State Analysis [11].

CRq-194 The blade root shear force, $F_{x_{b,i}}$ and $F_{y_{b,i}}$, (design load) shall not exceed 700 kN under any normal operating or emergency operating conditions. Design load is the characteristic load multiplied by the partial safety factor for loads as described in IEC Section 7.6 Ultimate Limit State Analysis [11].

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Rotor Loads—Hub/LSS

CRq-111 The rotor thrust, F_{x_s}, (design load) shall not exceed 57.6 kN under any normal operating or emergency operating conditions. Design load is the characteristic load multiplied by the partial safety factor for loads as described in IEC Section 7.6 Ultimate Limit State Analysis [11].

CRq-198 The rotor torque, M_{x_s}, (design load) shall not exceed 55 kNm under any normal operating or emergency operating conditions. Design load is the characteristic load multiplied by the partial safety factor for loads as described in IEC Section 7.6 Ultimate Limit State Analysis [11].

CRq-196 The rotor vertical shear, F_{z_s}, (design load) shall not exceed 126.4 kN under any normal operating or emergency operating conditions. Design load is the characteristic load multiplied by the partial safety factor for loads as described in IEC Section 7.6 Ultimate Limit State Analysis [11].

Foundation Loads–Tower Base/Foundation

CRq-257 The foundation design overturning moment, M, shall never exceed 3,326,407 ft-lbs.

Rotor Design Tools Verification

CRq-159 Sandia rotor design tools are not formally verified. Therefore, the Sandia rotor design concept shall be verified by Wetzel Engineering calculations during the detailed design phase of the rotor.

Rotor Characterization

CRq-177 Ground-based static and modal tests on blades shall characterize spanwise stiffness distribution.

CRq-185 One blade shall be dissected to characterize spanwise mass distribution.

Generator

CRq-118 Rated generator power shall never exceed 195 kW—the current production controller setting. Full rated generator power is 225 kW.

CRq-119 Rated HSS speed shall be set to 1,210 rpm because current production rated HSS speed is 1,210 rpm. This corresponds to 43.9 rpm at the gearbox ratio of 27.5647. Maximum generator speed is around 1,700 rpm.

DRAFT

CRq-120 HSS torque shall never exceed 1,600 kNm. Maximum rated HSS torque is 1,600 kNm (1183 lb-ft full load torque from generator spec sheet).

6.3.2 Traceability of Rotor Component Requirements

Every requirement is listed. For each requirement, the higher-level requirements which are satisfied by the requirement are listed. They appear as *Out-link*s. There should be at least one *Out-link* listed for each requirement. In cases where no *Out-links* are listed, scope-creep may be present because the requirement is not traceable to a higher-level requirement.

DRAFT

Requirement CRq-226: The maximum rotor speed control setpoint shall never exceed 47 rpm over all regions of operation. This is based on a 10% margin away from the first tower frequency at 1 Hz, or 60 rpm, 10% margin on the overspeed safety setting, and a 3% tolerance on control of maximum rotor speed by the turbine controller. Max speed in rpm, $60 * 0.9 * 0.9 * 0.97 = 43.9$.

Out-links (System Requirements for Hardware):

SFRq-183

Tower structural dynamics shall not be excited by turbine operation

Out-links (Experiment Objectives):

DRAFT

Requirement CRq-251: The blade design shall exhibit an overall blade root pitching moment of -1000 Nm (±10%) at the top of Region II. The blade pitching moment shall always decrease (increasingly negative) with increasing wind speed.

Out-links (System Requirements for Hardware):

SFRq-118

Blades will exhibit nominal pitching moment such that the rotor will passively pitch-to-feather in a scenario where loss of pitch control is experienced.

Out-links (Experiment Objectives):

DRAFT

Requirement CRq-259: The blade shall have lightning protection adequate for use in Lubbock, Texas.

Out-links (System Requirements for Hardware):

SFRq-29

The blade shall have lightning protection adequate for use in Lubbock, Texas.

Out-links (Experiment Objectives):

DRAFT

Requirement CRq-243: Standard load cases. The rotor design shall be able to withstand all design load cases (DLC's) as described in the IEC standard [11]. Wind Turbine Class is characterized as IEC III-C at SWiFT turbine hub-height. The average wind speed at the site at SWiFT hub-height is 6.6 m/s. The reference turbulence intensity at SWiFT hub-height, I_{ref}, is 0.11.

Out-links (System Requirements for Hardware):

SFRq-141

The rotor design shall withstand load cases as described in wind turbine standards.

Out-links (Experiment Objectives):

DRAFT

Requirement CRq-248: The turbine mechanical braking systems shall bring the pitched-to-run, operational rotor to a full stop in case of collective pitch failure during an extreme wind speed ramp with zero yaw error. The wind loading scenario which tests this requirement is described as follows: It begins with normal steady turbine operation at the lowest steady wind speed which commands rotor maximum operating speed for full pitched-to-run configuration—typically this is the top wind speed for Region II.5. Then, wind speed increases to 18 m/s over a 3 second duration. Finally, wind speed remains steady at 18 m/s. This input load case was taken from recommendations by NREL based on experience at the CART site. When successful, the simulation will verify that the rotor can be stopped during simultaneous collective pitch failure and extreme wind speed ramp.

Out-links (System Requirements for Hardware):

SFRq-173

The turbine mechanical braking systems shall be capable of bringing the rotor to a full stop in case of collective pitch failure in a worst-case operating scenario.

Out-links (Experiment Objectives):

DRAFT

Requirement CRq-235: Debris throw analysis shall show that fewer than 5% of potential rotor debris will reach outside the boundary of the Reese facility property in the event of a rotor overspeed and subsequent rotor failure.

Out-links (System Requirements for Hardware):

SFRq-184

The proposed rotor design shall not violate SWiFT facility debris throw requirements in the event of an overspeed and subsequent rotor failure.

Out-links (Experiment Objectives):

DRAFT

Requirement CRq-164: Turbine yaw-lock Requirement CRq-162 can lead to operation of the turbine in configurations with high amounts of yaw error. Additionally, experimental configurations for wake steering will lead to operation of the turbine with high yaw error. Simulations shall verify that rotor and turbine loads in these high-yaw configurations do not exceed allowable strength in the turbine or rotor.

Out-links (System Requirements for Hardware):

SFRq-187

The rotor and turbine shall not fail while operating in non-standard configurations which are the result of specific SWiFT test configurations.

Out-links (Experiment Objectives):

DRAFT

Requirement CRq-208: Aerodynamic shape of the new blades shall be characterized to adequate quality for CFD meshing of a model of the blades. We need to measure with enough accuracy to build a good model of what we have. (need a little more detail)

Out-links (System Requirements for Hardware):

SFRq-177

The rotor shape shall be well quantified.

Out-links (Experiment Objectives):

DRAFT

Requirement CRq-60: Manufactured airfoil trailing edge thickness shall be 1/100th blade chord except that it will be no greater than 10 mm and no less than 2 mm.

Out-links (System Requirements for Hardware):

SFRq-177

The rotor shape shall be well quantified.

Out-links (Experiment Objectives):

DRAFT

Requirement CRq-59: Tolerance on manufactured airfoil shapes shall recreate desired airfoil shapes within 0.3 mm on the portion of the blade which is outboard of maximum chord.

Out-links (System Requirements for Hardware):

SFRq-99

The rotor shall have repeatable, predictable aerodynamics performance and integrated rotor loads for the relevant range of Re numbers.

SFRq-177

The rotor shape shall be well quantified.

Out-links (Experiment Objectives):

DRAFT

Requirement CRq-210: Surface roughness of tested airfoils on new blades shall be quantified before and after execution of validation quality data gathering.

Out-links (System Requirements for Hardware):

SFRq-180

The rotor external surface roughness shall be well quantified.

Out-links (Experiment Objectives):

DRAFT

Requirement CRq-135: Thickness Requirement. Airfoils thickness-to-chord ratios shall be as large as reasonable. The goal of this requirement is to promote use of airfoils which are thicker, but not excessively thick. Thin airfoils achieve aerodynamic goals much easier than thick airfoils, but this requirement aims to encourage the use of thicker airfoils in order to enable goals of a stiff blade and a blade with large internal volume for onboard instrumentation packages.

Out-links (System Requirements for Hardware):

Out-links (Experiment Objectives):

STRq-91

Blades shall be sufficiently rigid—in torsional and flapwise directions—for numerical models of the SWiFT-X1 experiment to neglect blade elastic behavior.

DRAFT

Requirement CRq-130: Region II Similarity. The airfoil family shall enable replication of the mean and variability in circulation distribution of the full-scale rotor during operation in turbulent inflow.

Out-links (System Requirements for Hardware):

SFRq-99

The rotor shall have repeatable, predictable aerodynamics performance and integrated rotor loads for the relevant range of Re numbers.

Out-links (Experiment Objectives):

STRq-97

Dynamic Similarity in Gust Response. Dynamic loads of the subscale rotor shall be on par with dynamic loads expected for the full-scale rotor.

DRAFT

Requirement CRq-131: Region II.5 Performance. Airfoils shall have a high stall-angle-of-attack. Such airfoils allow a rotor in which the operating angle of attack is sufficiently below stall over most of Region II.5—therefore enabling the rotor is able to reach rated power after reaching maximum allowable rotor speed.

Out-links (System Requirements for Hardware):

SFRq-99

The rotor shall have repeatable, predictable aerodynamics performance and integrated rotor loads for the relevant range of Re numbers.

Out-links (Experiment Objectives):

DRAFT

Requirement CRq-132: Roughness Sensitivity. Anticipated changes in surface roughness shall have minimal effect on the intended blade circulation distribution of the rotor.

Out-links (System Requirements for Hardware):

SFRq-99

The rotor shall have repeatable, predictable aerodynamics performance and integrated rotor loads for the relevant range of Re numbers.

Out-links (Experiment Objectives):

DRAFT

Requirement CRq-133: Stall Characteristics. Airfoils shall have docile stall characteristics to promote predictable gust response and to minimize the amplitude of unrepresentative blade elastic bending oscillations.

Out-links (System Requirements for Hardware):

SFRq-99

The rotor shall have repeatable, predictable aerodynamics performance and integrated rotor loads for the relevant range of Re numbers.

Out-links (Experiment Objectives):

DRAFT

Requirement CRq-136: Quality Experimental Data. Airfoils shall have thoroughly documented, publicly available airfoil polars taken in a high-quality wind tunnel.

Out-links (System Requirements for Hardware):

SFRq-99

The rotor shall have repeatable, predictable aerodynamics performance and integrated rotor loads for the relevant range of Re numbers.

Out-links (Experiment Objectives):

DRAFT

Requirement CRq-137: Field Experience. Airfoils shall have extensive experience in the field at Reynolds numbers which are relevant to the design of this rotor.

Out-links (System Requirements for Hardware):

SFRq-99

The rotor shall have repeatable, predictable aerodynamics performance and integrated rotor loads for the relevant range of Re numbers.

Out-links (Experiment Objectives):

DRAFT

Requirement CRq-138: Root Airfoils Transition Region. Airfoils shall have available polar data for thick airfoils which are anticipated in the root-to-maximum-chord transition region of the blade.

Out-links (System Requirements for Hardware):

SFRq-99

The rotor shall have repeatable, predictable aerodynamics performance and integrated rotor loads for the relevant range of Re numbers.

Out-links (Experiment Objectives):

DRAFT

Requirement CRq-152: The rotor shall exhibit an operational tip speed ratio of 9 in Region II with a fine pitch setting of zero degrees. Note that Region II operational TSR is different from design TSR for max C_P.

Out-links (System Requirements for Hardware):

Out-links (Experiment Objectives):

STRq-9

Kinematic Similarity. The rotor shall exhibit the same operational Region 2 TSR as the full-scale rotor in order to enable validation of numerical models in a regime which is relevant to utility scale turbines. Lower tip speed ratios—6 or lower—have been shown to be less challenging for high fidelity numerical simulation and they are not as relevant to modern turbines.

DRAFT

Requirement CRq-153: The rotor shall exhibit a spanwise distribution of nondimensional circulation matching the GE1.5-77sle rotor model, as documented in Reference [3] (the distribution is also shown in Reference [12], Figure 7.2. Nondimensional circulation distributions of full-scale and subscale designs shall be forced to match only outboard of 25% rotor span. Uncertainty of inboard aerodynamics dictate that inboard blade shape design be driven by practical aspects of blending the circular root to outboard airfoils. Also, inboard transition region design should be driven by the need, as well as possible, to prevent inboard blade stall.

Out-links (System Requirements for Hardware):

Out-links (Experiment Objectives):

STRq-10

Partial Dynamic Similarity. The subscale rotor design shall exhibit the same spanwise distribution of non-dimensional circulation as the full-scale rotor for Region II operation such that blade-tip shed-vorticity is relevant to utility-scale turbines.

DRAFT

Requirement CRq-242: The rotor maximum C_P of the subscale design will represent the maximum C_P of the full-scale design within ±5%.

Out-links (System Requirements for Hardware):

Out-links (Experiment Objectives):

STRq-94

The rotor C_P of the subscale design will represent the C_P of the full-scale design within ±5% at the design operating point for Region 2 operation.

DRAFT

Requirement CRq-204: Circulation distribution shall be smooth for all relevant operating conditions. There shall be no weird stall interactions—e.g. spanwise pressure gradients which influence separation. Specifically, airfoil transition regions should be checked: a) root, b) middle, c) tip.

Out-links (System Requirements for Hardware):

Out-links (Experiment Objectives):

STRq-10

Partial Dynamic Similarity. The subscale rotor design shall exhibit the same spanwise distribution of non-dimensional circulation as the full-scale rotor for Region II operation such that blade-tip shed-vorticity is relevant to utility-scale turbines.

DRAFT

Requirement CRq-207: Tip design shall enable an exact match of the full-scale non-dimensional circulation distribution, $\Gamma'(r/R)$ and the non-dimensional circulation distribution of the design shall be smooth. Chord distribution, $c/R(r/R)$, of the tip may not necessarily match the chord distribution of the full-scale rotor, but it shall be smooth.

Out-links (System Requirements for Hardware):

Out-links (Experiment Objectives):

STRq-99

Tip design shall be done in a manner which encourages matching of the target circulation distribution as well as possible.

DRAFT

Requirement CRq-250: The tip shape shall be prescribed in a manner which is most conducive to creation of blade-resolved CFD meshes.

Out-links (System Requirements for Hardware):

SFRq-174

Blade design shall be done in a manner which promotes the design-for-analysis philosophy—i.e. blade tips should be created primarily such that they are represented readily in numerical simulation, such as the CFD mesh.

Out-links (Experiment Objectives):

DRAFT

Requirement CRq-236: A high-solidity rotor shall be used to enable a high stiffness blade as well as a blade with greater interior volume. The high-solidity rotor will be made possible by intentionally low design-C_l.

Out-links (System Requirements for Hardware):

SFRq-175

Blade tips design shall be done in a manner which maximizes the available interior blade volume near the blade tip. Interior blade volume is needed in order to maximize the instrumentation options available at the blade tip.

Out-links (Experiment Objectives):

STRq-91

Blades shall be sufficiently rigid—in torsional and flapwise directions—for numerical models of the SWiFT-X1 experiment to neglect blade elastic behavior.

DRAFT

Requirement CRq-261: Non-dimensional rotor shear, i.e. $\frac{dU/dU_\infty}{dz/D}$, shall be similar for full-scale and subscale rotors.

Out-links (System Requirements for Hardware):

Out-links (Experiment Objectives):

STRq-103

Rotor Shear. Non-dimensional rotor shear, i.e. $\frac{dU/dU_\infty}{dz/D}$, shall be similar for full-scale and sub-scale rotors.

DRAFT

Requirement CRq-262: Strouhal Number. Wake meandering characteristics will be recreated at subscale through replication of the rotor Strouhal Number, $St = \frac{fD_{rotor}}{U_{infty,hub}}$ where f is the frequency of vortex shedding.

Out-links (System Requirements for Hardware):

Out-links (Experiment Objectives):

STRq-104

Strouhal Number. Wake meandering characteristics will be recreated at subscale through replication of the rotor Strouhal Number, $St = \frac{fD_{rotor}}{U_{infty,hub}}$ where f is the frequency of vortex shedding.

DRAFT

Requirement CRq-260: The aerodynamic blade shape shall not contain excessive and problematic spanwise flowfields.

Out-links (System Requirements for Hardware):

SFRq-99

The rotor shall have repeatable, predictable aerodynamics performance and integrated rotor loads for the relevant range of Re numbers.

Out-links (Experiment Objectives):

DRAFT

Requirement CRq-240: Perform simulations to verify scaling methodology. Numerical predictions will show that the subscale rotor has the same character as the full-scale rotor. Specific traits will be shown similar: 1) radial profile of near-wake velocity deficit at 1-D downstream of the rotor; 2) wake energy recovery as a function of distance downstream of the rotor.

Out-links (System Requirements for Hardware):

Out-links (Experiment Objectives):

STRq-90

Type II scaling verification–Verify scaling methodology. Use model predictions to verifyto the best of their abilitythat the chosen scaling approach is successful. Numerical predictions will show that the subscale rotor has the same character as the full-scale rotor.

DRAFT

Requirement CRq-263: The spanwise distribution of full-scale and subscale Reynolds numbers are not expected to match. In lieu of a Reynolds number match, airfoils for the sub-scale design shall be chosen for specific operation at the anticipated subscale Reynolds numbers.

Out-links (System Requirements for Hardware):

Out-links (Experiment Objectives):

STRq-102

Full Dynamic Similarity. The spanwise distribution of full-scale and subscale chord Reynolds numbers shall match.

DRAFT

Requirement CRq-113: Predicted and manufactured blade mass shall be compared to the average weight of current OEM blades, 660 kg [9]. Blade mass shall be equal to or less than OEM blade mass so that the overall rotor weight of the retrofit rotor does not cause additional stress on the SWiFT turbines, in terms of downward force on the nacelle and drivetrain.

Out-links (System Requirements for Hardware):

SFRq-161

Blade mass and rotor moment of inertia shall be compared to OEM values. If the new blades are heavier or the new rotor inertia is higher, then special scrutiny on rotor dynamics calculations may be warranted.

Out-links (Experiment Objectives):

DRAFT

Requirement CRq-114: The predicted and manufactured blade static balance shall be compared to the measured average static balance of current OEM blades, $659.2\,kg * 4.195\,m = 27,653 kg-m$ [9].

Out-links (System Requirements for Hardware):

SFRq-161

Blade mass and rotor moment of inertia shall be compared to OEM values. If the new blades are heavier or the new rotor inertia is higher, then special scrutiny on rotor dynamics calculations may be warranted.

Out-links (Experiment Objectives):

DRAFT

Requirement CRq-264: The predicted rotor moment of inertia, $I = \int_m r^2 \, \mathrm{d}m$, shall be compared to the estimated rotor moment of inertia for the OEM rotor. The FAST aeroelastic model of the OEM SWiFT turbines [10] can be used to estimate the rotor moment of inertia for the OEM rotor. Rotor moment of inertia shall be equal to or less than the estimated OEM moment of inertia so that rotor angular momentum, $L_{max} = I\omega_{max}$, at maximum rotor speed, ω_{max} is not higher for the retrofit rotor than the OEM rotor.

Out-links (System Requirements for Hardware):

SFRq-161

Blade mass and rotor moment of inertia shall be compared to OEM values. If the new blades are heavier or the new rotor inertia is higher, then special scrutiny on rotor dynamics calculations may be warranted.

Out-links (Experiment Objectives):

DRAFT

Requirement CRq-225: Rotor structural dynamic frequencies shall not be in the ranges of 2.9P–3.1P or 5.95P–6.05P.

Out-links (System Requirements for Hardware):

SFRq-119

Blade structural dynamics shall not be excited by turbine operation.

Out-links (Experiment Objectives):

DRAFT

Requirement CRq-73: Flap Stiffness. The blade shall have sufficient flap stiffness that section body velocities under normal aerodynamic operation do not add to dynamic C_l or α and cause exceedance of section stall values for Region II operation. Effects on pitch moment due to section C_m and blade sweep shall both be considered.

Out-links (System Requirements for Hardware):

Out-links (Experiment Objectives):

STRq-91

Blades shall be sufficiently rigid—in torsional and flapwise directions—for numerical models of the SWiFT-X1 experiment to neglect blade elastic behavior.

DRAFT

Requirement CRq-227: Torsional Stiffness. The blade shall have sufficient torsional stiffness such that the blade sections do not experience dynamic changes in section angles of attack of more than 1 degree from nominal, steady design values for Region II operation. Effects on pitch moment due to section C_m and blade sweep shall both be considered.

Out-links (System Requirements for Hardware):

Out-links (Experiment Objectives):

STRq-91

Blades shall be sufficiently rigid—in torsional and flapwise directions—for numerical models of the SWiFT-X1 experiment to neglect blade elastic behavior.

DRAFT

Requirement CRq-125: Tower Clearance. The blade maximum tip out-of-plane deflection shall not be more than 1.328 m under any simulated design load cases (DLC's). Allowable tip deflection of 1.328 meters includes the total safety factor of 1.485 on the actual tower clearance of $1.328\ m * 1.485 = 1.973\ m$

Out-links (System Requirements for Hardware):

SFRq-198

It shall not be possible for the turbine to experience a tower strike by any blade.

Out-links (Experiment Objectives):

DRAFT

Requirement CRq-228: Design for loaded operation. Static blade twist distribution shall be designed to match a target distribution at a single operating point of $U_\infty = 6\ m/s$ (a middle wind speed in Region II). Deviation from nominal twist design at other operating points in Region II shall not exceed 0.5 degrees. This requirement is meant to ensure that the blade performs as intended under steady aeroelastic loading at the stated operating wind inflow speed.

Out-links (System Requirements for Hardware):

Out-links (Experiment Objectives):

STRq-91

Blades shall be sufficiently rigid—in torsional and flapwise directions—for numerical models of the SWiFT-X1 experiment to neglect blade elastic behavior.

DRAFT

Requirement CRq-237: Aeroelastic instability, i.e. flutter, shall not occur within the normal operational range of rotor speeds up to rotor terminal velocity.

Out-links (System Requirements for Hardware):

SFRq-181

Blades shall not experience aeroelastic instability during normal operation or during emergency operating scenarios.

Out-links (Experiment Objectives):

DRAFT

Requirement CRq-254: Structural Linearity. The blade tip shall not deflect more than 5% of blade length under any normal operating loads. A blade structure which does not deflect more than 5% of its length is assumed to have linear elastic behavior.

Out-links (System Requirements for Hardware):

Out-links (Experiment Objectives):

STRq-91

Blades shall be sufficiently rigid—in torsional and flapwise directions—for numerical models of the SWiFT-X1 experiment to neglect blade elastic behavior.

DRAFT

Requirement CRq-104: The blade root outer shell diameter shall be no greater than the OEM outer root shell diameter, which is 592.6 mm per B.LeBlanc measurements on 4/3/14.

Out-links (System Requirements for Hardware):

SFRq-189

Physical connection of blades to the OEM turbine hub shall be achieved with no alteration of existing hub hardware.

Out-links (Experiment Objectives):

DRAFT

Requirement CRq-253: Blade root geometry shall be cylindrical—i.e.chord and absolute thickness distributions shall be constant—at the blade root outboard to a point beyond the root hardware and associated inserts—i.e. outboard to at least 350 mm span.

Out-links (System Requirements for Hardware):

SFRq-189

Physical connection of blades to the OEM turbine hub shall be achieved with no alteration of existing hub hardware.

Out-links (Experiment Objectives):

DRAFT

Requirement CRq-106: There shall be 30 evenly spaced bolts at the root attachment. (per OEM documents)

Out-links (System Requirements for Hardware):

SFRq-189

Physical connection of blades to the OEM turbine hub shall be achieved with no alteration of existing hub hardware.

Out-links (Experiment Objectives):

DRAFT

Requirement CRq-107: The blade root bolts shall be of type M20, 180 mm studs. The OEM torque spec on these bolts is 500 Nm greased. (per OEM documents)

Out-links (System Requirements for Hardware):

SFRq-189

Physical connection of blades to the OEM turbine hub shall be achieved with no alteration of existing hub hardware.

Out-links (Experiment Objectives):

DRAFT

Requirement CRq-105: The bolt circle diameter (BCD) of the blade shall be 508 mm, ± 1 mm (per OEM documents)

Out-links (System Requirements for Hardware):

SFRq-189

Physical connection of blades to the OEM turbine hub shall be achieved with no alteration of existing hub hardware.

Out-links (Experiment Objectives):

DRAFT

Requirement CRq-160: Bolted connections at the blades root shall meet requirements of GL2010—6.5 bolted connections, using VDI2230.

Out-links (System Requirements for Hardware):

SFRq-189

Physical connection of blades to the OEM turbine hub shall be achieved with no alteration of existing hub hardware.

Out-links (Experiment Objectives):

DRAFT

Requirement CRq-76: The new rotor shall utilize the same carrots for root hardware as the OEM rotor.

Out-links (System Requirements for Hardware):

SFRq-189

Physical connection of blades to the OEM turbine hub shall be achieved with no alteration of existing hub hardware.

Out-links (Experiment Objectives):

DRAFT

Requirement CRq-112: The blade root bending moment, $M_{x_{b,i}}$ and $M_{y_{b,i}}$, (design load) shall not exceed 210 kNm under any normal operating or emergency operating conditions. Design load is the characteristic load multiplied by the partial safety factor for loads as described in IEC Section 7.6 Ultimate Limit State Analysis [11].

Out-links (System Requirements for Hardware):

SFRq-157

Turbine stresses at the interface of blade to hub resulting from design loads shall not exceed design strength as described in Ref [6].

Out-links (Experiment Objectives):

DRAFT

Requirement CRq-194: The blade root shear force, $F_{x_{b,i}}$ and $F_{y_{b,i}}$, (design load) shall not exceed 700 kN under any normal operating or emergency operating conditions. Design load is the characteristic load multiplied by the partial safety factor for loads as described in IEC Section 7.6 Ultimate Limit State Analysis [11].

Out-links (System Requirements for Hardware):

SFRq-157

Turbine stresses at the interface of blade to hub resulting from design loads shall not exceed design strength as described in Ref [6].

Out-links (Experiment Objectives):

DRAFT

Requirement CRq-111: The rotor thrust, F_{x_s}, (design load) shall not exceed 57.6 kN under any normal operating or emergency operating conditions. Design load is the characteristic load multiplied by the partial safety factor for loads as described in IEC Section 7.6 Ultimate Limit State Analysis [11].

Out-links (System Requirements for Hardware):

SFRq-195

Turbine stresses at the interface of hub to low speed shaft resulting from design loads shall not exceed design strength as described in Ref [6].

Out-links (Experiment Objectives):

DRAFT

Requirement CRq-198: The rotor torque, M_{x_s}, (design load) shall not exceed 55 kNm under any normal operating or emergency operating conditions. Design load is the characteristic load multiplied by the partial safety factor for loads as described in IEC Section 7.6 Ultimate Limit State Analysis [11].

Out-links (System Requirements for Hardware):

SFRq-195

Turbine stresses at the interface of hub to low speed shaft resulting from design loads shall not exceed design strength as described in Ref [6].

Out-links (Experiment Objectives):

DRAFT

Requirement CRq-196: The rotor vertical shear, F_{z_s}, (design load) shall not exceed 126.4 kN under any normal operating or emergency operating conditions. Design load is the characteristic load multiplied by the partial safety factor for loads as described in IEC Section 7.6 Ultimate Limit State Analysis [11].

Out-links (System Requirements for Hardware):

SFRq-195

Turbine stresses at the interface of hub to low speed shaft resulting from design loads shall not exceed design strength as described in Ref [6].

Out-links (Experiment Objectives):

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Requirement CRq-257: The foundation design overturning moment, M, shall never exceed 3,326,407 ft-lbs.

Out-links (System Requirements for Hardware):

SFRq-197

Foundation forces and moment resulting from design loads shall not exceed design strength as described in Ref [7, 8].

Out-links (Experiment Objectives):

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Requirement CRq-159: Sandia rotor design tools are not formally verified. Therefore, the Sandia rotor design concept shall be verified by Wetzel Engineering calculations during the detailed design phase of the rotor.

Out-links (System Requirements for Hardware):

SFRq-144

The blades shall be designed using verified design tools.

Out-links (Experiment Objectives):

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Requirement CRq-177: Ground-based static and modal tests on blades shall characterize spanwise stiffness distribution.

Out-links (System Requirements for Hardware):

SFRq-179

The rotor structure shall be well quantified.

Out-links (Experiment Objectives):

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Requirement CRq-185: One blade shall be dissected to characterize spanwise mass distribution.

Out-links (System Requirements for Hardware):

SFRq-179

The rotor structure shall be well quantified.

Out-links (Experiment Objectives):

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Requirement CRq-118: Rated generator power shall never exceed 195 kW—the current production controller setting. Full rated generator power is 225 kW.

Out-links (System Requirements for Hardware):

SFRq-190

Ultimate limits on generator torque, speed and power shall be observed.

Out-links (Experiment Objectives):

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Requirement CRq-119: Rated HSS speed shall be set to 1,210 rpm because current production rated HSS speed is 1,210 rpm. This corresponds to 43.9 rpm at the gearbox ratio of 27.5647. Maximum generator speed is around 1,700 rpm.

Out-links (System Requirements for Hardware):

SFRq-190

Ultimate limits on generator torque, speed and power shall be observed.

Out-links (Experiment Objectives):

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Requirement CRq-120: HSS torque shall never exceed 1,600 kNm. Maximum rated HSS torque is 1,600 kNm (1183 lb-ft full load torque from generator spec sheet).

Out-links (System Requirements for Hardware):

SFRq-190

Ultimate limits on generator torque, speed and power shall be observed.

Out-links (Experiment Objectives):

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Chapter 7

Rotor Component Verification Requirements

7.1 Verification Cross Reference Matrix

The Verification Cross Reference Matrix (VCRM) is a tool for tracking requirements compliance. It quickly assesses that at least one verification condition exists for each requirement.

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	Object Short Text	In-links (Component Inspection Specification)	In-links (Component Modeling and Simulation Specifications)	In-links (Component Test Plan)
CRq-226	Maximum rotor speed allowed	CISp-17		
CRq-251	Blade root pitching moment		CMSSp-14	
CRq-259	Ensure protection from lighting	CISp-16		
CRq-243	Standard loading cases		CMSSp-44	
CRq-248	Turbine braking		CMSSp-38	
CRq-235	Debris throw		CMSSp-28	
CRq-164	Operation in high yaw configurations		CMSSp-12	
CRq-208	Blade shape characterization			CTSp-29
CRq-60	Trailing edge thickness	CISp-1		
CRq-59	Tolerance on airfoil manufacturing	CISp-2		
CRq-210	Surface roughness characterization			CTSp-31
CRq-135	Blade thickness	CISp-10		
CRq-130	Region II similarity		CMSSp-29	
CRq-131	Region II.5 performance		CMSSp-16	
CRq-132	Airfoil roughness sensitivity	CISp-8		
CRq-133	Airfoil stall characteristics	CISp-9		
CRq-136	Airfoil quality experimental data	CISp-11		
CRq-137	Airfoils' field experience	CISp-12		
CRq-138	Root airfoils transition region	CISp-13		
CRq-152	Design tip-speed ratio		CMSSp-9	
CRq-153	Spanwise loading distribution		CMSSp-10	CTSp-67
CRq-242	Rotor C_P			CTSp-1
CRq-204	Smoothness of loading distribution		CMSSp-17 CMSSp-18	CTSp-68
CRq-207	Tip design		CMSSp-19 CMSSp-20	
CRq-250	Tip shape for CFD	CISp-19		
CRq-236	High solidity	CISp-15		
CRq-261		CISp-31		
CRq-262		CISp-32		
CRq-260			CMSSp-15	

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CRq-240	Scaling methodology verification		CMSSp-27	
CRq-263		CISp-12		
CRq-113	Maximum allowable blade mass	CISp-20	CMSSp-47	
CRq-114	Blade static balance	CISp-21	CMSSp-49	
CRq-264	Maximum allowable rotor inertia		CMSSp-50	
CRq-225	Rotor frequencies		CMSSp-43	
CRq-73	Blade flapwise stiffness		CMSSp-24	
CRq-227	Blade torsional stiffness		CMSSp-25	
CRq-125	Maximum blade out-of-plane deflection		CMSSp-30	
CRq-228	Design for loaded operation		CMSSp-26	
CRq-237	Flutter		CMSSp-23	
CRq-254	Structural linearity		CMSSp-45	
CRq-104	Blade root outer diameter	CISp-22		
CRq-253	Circular blade root	CISp-23		
CRq-106	Number of bolts	CISp-5		
CRq-107	Type of bolts	CISp-4		
CRq-105	Bolt circle diameter	CISp-6		
CRq-160	Bolted connection design and analysis		CMSSp-6	
CRq-76	Fastener strategy	CISp-24		
CRq-112	Blade root bending moments		CMSSp-8	CTSp-11
CRq-194	Blade root shear force		CMSSp-31	
CRq-111	Rotor thrust		CMSSp-7	
CRq-198	Rotor torque		CMSSp-34	
CRq-196	Rotor vertical force		CMSSp-35	
CRq-257	Foundation moment		CMSSp-40	
CRq-159	Design tools verification	CISp-25		
CRq-177	Blade static and modal tests			CTSp-10 CTSp-12 CTSp-66
CRq-185	Blade mass distribution characterization			CTSp-33
CRq-118	Rated generator power	CISp-26		

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CRq-119	Rated generator speed	CISp-28		
CRq-120	Rated generator torque	CISp-29		

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7.2 Inspection Requirements

Following is a list of inspection requirements which, along with modeling/simulation and test requirements, serve to verify that the component requirements have been met.

Rotor and Turbine

CISp-16 Inspect to verify that the blade has lightning protection adequate for use in Lubbock, Texas.

CISp-1 Inspect to verify that manufactured airfoil trailing edge thickness is $1/100^{th}$ blade chord except that it will be no greater than 10 mm and no less than 2 mm.

CISp-2 Inspect the manufactured blade shape to verify that the shape has been manufactured to within 0.3 mm on the portion of the blade which is outboard of maximum chord.

CISp-4 Inspect manufactured blade root bolts to ensure they are type M20 studs.

CISp-5 Inspect manufactured blade root bolts to ensure they number 30 and are evently spaced around the root diameter.

CISp-6 Inspect the manufactured blade root bolts to ensure they are located on a bolt circle diameter (BCD) of 508 mm, $\pm$ 1 mm.

CISp-20 Measure the as-built weight of each blade and confirm that they are close to the weight of OEM blades, 660 kg [9].

CISp-21 Measure the as-built static balance of one blade and confirm that it is close to the static balance for OEM blades, 27,653 kg [9].

CISp-22 Inspect to verify that the blade root outer shell diameter is not greater than the OEM outer root shell diameter, which is 592.6 mm per B.LeBlanc measurements on 4/3/14.

CISp-23 Inspect to verify that the blade root geometry is cylindrical—i.e.chord and absolute thickness distributions shall be constant—at the blade root outboard to a point beyond the root hardware and associated inserts—i.e. outboard to at least 350 mm span.

CISp-24 Inspect to verify that the rotor utilizes the same carrots for root hardware as the OEM rotor.

CISp-25 Perform design review of Wetzel Engineering detailed blade design work.

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Turbine Controller

CISp-26 Inspect to verify that the controller will never allow the rated generator power to exceed 204 kW—the current production controller setting.

CISp-28 Inspect to verify that the controller is set for rated HSS speed of 1,210 rpm. Current production rated HSS speed is 1,210 rpm. This corresponds to 43.9 rpm at the gearbox ratio of 27.5647.

CISp-29 Inspect to verify that the controller is set such that the HSS torque shall never exceed 1,600 kNm. Maximum rated HSS torque is 1,600 kNm.

CISp-17 Inspect to verify that the rotor speed control setpoint is not higher than 47 rpm over all regions of operation.

Airfoil Polar Data

CISp-8 Inspect airfoil polar data to ensure insensitivity to adverse effects of surface roughness. A weighted decision matrix shall be used to choose the airfoils based on this requirement, and others.

CISp-9 Inspect airfoils polar data to show that they have docile stall characteristics. A weighted decision matrix shall be used to choose the airfoils based on this requirement, and others.

CISp-10 Inspect to ensure chosen airfoils as as thick as possible, in terms of thickness-to-chord ratio. A weighted decision matrix shall be used to choose the airfoils based on this requirement, and others.

CISp-11 Ensure airfoils have thoroughly documented, publicly available airfoil polars taken in a high-quality wind tunnel. A weighted decision matrix shall be used to choose the airfoils based on this requirement, and others.

CISp-12 Airfoils shall have extensive experience in the field at Reynolds numbers which are relevant to the design of this rotor. A weighted decision matrix shall be used to choose the airfoils based on this requirement, and others.

CISp-13 Airfoils shall have available polar data for thick airfoils which are anticipated in the root-to-maximum-chord transition region of the blade. A weighted decision matrix shall be used to choose the airfoils based on this requirement, and others.

Aerodynamic Shape Design

CISp-15 Confirm through expert review that the rotor design is of higher solidity such that internal blade volume is maximized.

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CISp-19 Confirm through expert review that the tip shape is prescribed in a manner which is conducive to creation of blade-resolved CFD meshes.

SWiFT Site Meteorology

CISp-31 Use existing met-tower data to verify that non-dimensional rotor shear, i.e. $\frac{dU/dU_\infty}{dz/D}$, is similar for full-scale and subscale rotors.

CISp-32 Use existing met-tower data to verify that wake meandering characteristics will be recreated at subscale through replication of the rotor Strouhal Number, $St = \frac{fD_{rotor}}{U_{infty,hub}}$ where f is the frequency of vortex shedding.

7.3 Test Requirements

Component level test verification requirements are not listed in detail in this version of the requirements document as they have not been thoroughly defined as of the date of the current release. A sense of anticipated tests to verify component requirements can be found by examining the VCRM in Section 7.1.

7.4 Modeling and Simulation Requirements

Following is a list of modeling and simulation requirements which, along with inspection and test requirements, serve to verify that the component requirements have been met.

Aeroelastic Simulation

CMSSp-44 Perform simulations according to design load cases called out in "Table 2–Design load cases" in IEC [11]. Wind turbine class is IEC III-C (three Cee)

CMSSp-7 Use FAST/AeroDyn to show that the rotor thrust (design load) does not exceed 56.7 kN under any normal operating or emergency operating conditions. Input conditions for the simulation are described by CRq-243 and CRq-248.

CMSSp-8 Use FAST/AeroDyn to show that the blade root bending moment (design load) in any plane does not exceed 210 kNm under any normal operating or emergency operating conditions. Input conditions for the simulation are described by CRq-243 and CRq-248.

CMSSp-31 Use FAST/AeroDyn to show that the blade root shear force (design load) does not exceed 700 kN under any normal operating or emergency operating conditions. Input conditions

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for the simulation are described by CRq-243 and CRq-248.

CMSSp-34 Use FAST/AeroDyn to show that the rotor torque (design load) does not exceed 55 kNm under any normal operating or emergency operating conditions. Input conditions for the simulation are described by CRq-243 and CRq-248.

CMSSp-35 Use FAST/AeroDyn to show that the rotor vertical shear (design load) does not exceed 126.4 kN under any normal operating or emergency operating conditions. Input conditions for the simulation are described by CRq-243 and CRq-248.

CMSSp-40 Use FAST/AeroDyn to show that the tower base overturning moment is never predicted to exceed 3,326,407 ft-lbs during any normal operating or emergency operating conditions. Input conditions for the simulation are described by CRq-243 and CRq-248.

CMSSp-12 Use FAST/AeroDyn to show that rotor and turbine design stresses do not exceed design strengths during design loads due to yaw errors for every 5 degree increment ranging from -45 degrees to 45 degrees for normal operational wind speeds with inflow turbulence included as appropriate.

CMSSp-38 Use FAST/AeroDyn to show that the turbine mechanical braking systems will bring the pitched-to-run, operational rotor to a full stop in case of collective pitch failure during an extreme wind speed ramp with zero yaw error. The wind loading scenario which tests this requirement is described as follows: It begins with normal steady turbine operation at the lowest steady wind speed which commands rotor maximum operating speed for full pitched-to-run configuration—typically this is the top wind speed for Region II.5. Then, wind speed increases to 18 m/s over a 3 second duration. Finally, wind speed remains steady at 18 m/s. This input load case was taken from recommendations by NREL based on experience at the CART site. When successful, the simulation will verify that the rotor can be stopped during simultaneous collective pitch failure and extreme wind speed ramp.

CMSSp-23 Use NuMAD to compute rotor RPM for onset of classical flutter. Show that flutter is not predicted to occur within the normal operational range of rotor speeds.

Comment: Note that the Sandia classical flutter analysis capability is not valid for rotor terminal velocity configurations because it make the assumption that the rotor is operating at the design point for Region II.

CMSSp-24 Use FAST/AeroDyn to verify that the blade has sufficient flap stiffness such that section body velocities do not cause dynamic C_l or α which exceed section stall values for Region II operation. Effects on pitch moment due to section C_m and blade sweep shall both be considered.

CMSSp-25 Use ADAMS/AeroDyn to verify that the blade design has sufficient torsional stiffness such that the blade sections do not experience dynamic changes in section angles of attack of more than 1 degree from nominal, steady design values for Region II operation. Effects on pitch moment due to section C_m and blade sweep shall both be considered.

CMSSp-26 Verify that static blade twist distribution is designed to match a target distribution

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at a single operating point of $U_\infty = X\ m/s$ (somewhere in Region 2). Deviation from nominal twist design at other operating points in Region 2 shall not exceed 0.5 degrees.

CMSSp-28 Use SWiFT rotor debris throw analysis to verify that less than 5% of potential rotor debris will reach outside the boundary of the SWiFT facility grounds in the event of a rotor overspeed and subsequent rotor failure. Maximum rotor velocity used as input for this analysis shall include simple compressible flow effects, which tend to limit rotor terminal velocity.

CMSSp-30 Use FAST/AeroDyn to show that the maximum blade tip deflection will not exceed 1.328 m under any of the specified design load cases, normal and emergency. Simulations shall include the proposed production controller for the actual rotor design. Input conditions for the simulation are described by CRq-243, CRq-164, CRq-248.

CMSSp-45 Use FAST/AeroDyn to show that the maximum blade tip deflection will not exceed 5% of blade length, 0.65 m, under any normal operating design load cases (emergency and high transient loads cases excluded). Simulations shall include the proposed production controller for the actual rotor design.

Structural Simulation

CMSSp-6 Show using engineering calculations that bolted connections at the blades root meet requirements of GL2010—6.5 bolted connections, using VDI2230.

Structural Dynamics Simulation

CMSSp-43 Use BModes to verify that the structural dynamic model of the blade design does not contain any natural resonances in the range 2.9P–3.1P or 5.95P–6.05P.

Inertial Calculations

CMSSp-47 Predict the weight of each blade and confirm that they are close to the weight of OEM blades, 660 kg [9].

CMSSp-49 Predict the static balance for the blade design and confirm that it is close to the measured static balance for OEM blades, 27,653 kg [9].

CMSSp-50 Predict the rotor moment of inertia, $I = \int_m r^2\,\mathrm{d}m$, and compare to the estimated rotor moment of inertia for the OEM rotor. The FAST aeroelastic model of the OEM SWiFT turbines [10] can be used to estimate the rotor moment of inertia for the OEM rotor. Rotor moment of inertia shall be equal to or less than the estimated OEM moment of inertia so that rotor angular momentum, $L_{max} = I\omega_{max}$, at maximum rotor speed, ω_{max} is not higher for the retrofit rotor than the OEM rotor.

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Aerodynamic Simulation

CMSSp-18 Verify by blade boundary layer resolved modeling simulations of the blade to look at 3-D effects of spanwise pressure gradients and rotational augmentation considerations. Success means we identify areas of concern regarding 3-D effects and eliminate or mitigate concerns.

Comment: This defines the span width of transition regions between standard airfoils. This affects how we space our reference airfoils.

CMSSp-17 Verify by blade boundary layer resolved modeling simulations of the stations to look at 2-D data to estimate where 3-D considerations will become important. Success means we identify areas of concern regarding 3-D effects and eliminate or mitigate the concerns.

Comment: This defines the span width of transition regions between standard airfoils. This affects how we space our reference airfoils.

CMSSp-9 Show using numerical simulation that the rotor design exhibits its maximum C_P at an operating tip speed ratio of 9 with a fine pitch setting of zero degrees.

CMSSp-10 Show using numerical simulation that the rotor exhibits a spanwise distribution of nondimensional circulation which emulates that of the GE1.5-77sle rotor model, as documented in Reference [3].

CMSSp-16 Show using numerical simulation that the rotor design is able to produce rated power of 204 kW at the lowest Region III windspeed while at rated rotor speed.

CMSSp-14 Show using FAST/AeroDyn that the blade design exhibits an overall blade root pitching moment of -1000 Nm ($\pm$10%) at the top of Region II. Show using numerical simulations that the blade pitching moment always decreases (increasingly negative) with increasing wind speed.

CMSSp-19 Verify the quality of the proposed tip design. Use blade resolved simulations and vortex methods to check for local circulation distribution and curvature and chordwise pressure gradient changes with outer spans.

CMSSp-20 Verify the quality of the proposed tip design. Use RANS to check how the separation of the tip vortex influences 3-D flow at the blade tip. Verify assumption that shed vorticity comes from trailing edge is not violated.

CMSSp-27 Use the Sandia CACTUS code to verify that the 37c rotor and NRT rotor produce the same wakes.

CMSSp-29 Use FAST/AeroDyn to verify the blade design replicates variability in circulation distribution of the full-scale rotor during operation in turbulent inflow.

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Three-Dimensional Rotor CFD

CMSSp-15 Use 3D rotor CFD analysis to verify that rotor 3-D flow, especially inboard, is not excessive. Excessive 3-D (spanwise) flow can prevent the rotor from performing as intended because most design methods used 2-D flow assumptions or used corrections for 3-D flow on top of 2-D flow approaches. Simulation will show that rotor design is not expected to suffer from massive inboard flow separation due to 3-D effects. If predictions show that the design suffers from massive separation, then design changes to the rotor surface are required.

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