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Defining a Testbed for the U.S. Turbine Industry: The National Experimental Turbine (NExT)

Karen A. Thole[1], Michael D. Barringer[2], Reid A. Berdanier[3], Scott Fishbone[4], and Joel H. Wagner[5]
Penn State University, University Park, PA 16802, USA

Richard Dennis[6], James Black[7], Patcharin Burke[8], and Doug Straub[9]
U.S. Department of Energy, National Energy Technology Laboratory, Pittsburgh, PA 16236, USA

Frank O'Neill[10]
Agilis Engineering Inc., Palm Beach Gardens, FL 33410, USA

Curtis K. Stimpson[11] and Ardeshir Riahi[12]
Honeywell Aerospace, Phoenix, AZ 85034, USA

Andrew Aggarwala[13], Sean Bradshaw[14], Atul Kohli[15], Dominic Mongillo[16], and Thomas Praisner[17]
Pratt & Whitney, East Hartford, CT 06118, USA

Jose Rodriguez[18]
Siemens Energy, Orlando, FL 32826, USA

Michael Fox[19] and Yong W. Kim[20]
Solar Turbines, San Diego, CA 92101, USA

The importance of continued advancements in gas turbine technology for power generation, aviation, and oil and gas applications is critical to reducing the carbon footprint and to the U.S. economy. To reduce the time, costs, and risks involved in making substantial advancements, a collaborative approach with strong support from a federal agency is essential. This paper presents such a collaborative approach among U.S. gas turbine engine manufacturers representing each of the application areas, a turbine design firm, and academia all through strong support by the U.S. Department of Energy's National Energy Technology Lab. The collaborative effort involves the design, development, manufacturing, and testing of

[1] Distinguished Professor and Department Head, Department of Mechanical Engineering, Associate Fellow AIAA.
[2] Associate Research Professor, Department of Mechanical Engineering.
[3] Assistant Research Professor, Department of Mechanical Engineering, Senior Member AIAA.
[4] Engineering Project Manager, Department of Mechanical Engineering.
[5] Principal Research Engineer, Department of Mechanical Engineering.
[6] Turbines Technology Manager, Advanced Energy Systems.
[7] Researcher, Research and Innovation Center.
[8] Program Manager, Advanced Energy Systems.
[9] Researcher, Research and Innovation Center.
[10] President, CEO.
[11] Advanced Mechanical Design Engineer, Turbines.
[12] Senior Technical Manager, Military and Advanced Technology Engines.
[13] Aerodynamics Engineer, Hot Section Engineering.
[14] Technical Fellow of Sustainable Propulsion, Advanced Concepts & Technology.
[15] Senior Technical Fellow, Hot Section Engineering.
[16] Turbine Durability Discipline Chief, Hot Section Engineering.
[17] Turbine Aerodynamics Discipline Chief, Hot Section Engineering.
[18] Senior Turbine Engineer, Power and Gas.
[19] Manager, Heat Transfer and Secondary Flow.
[20] Turbine Engineer.

a single stage research turbine referred to as the National Experimental Turbine (NExT). The primary goal for the effort is to develop a modern research turbine for U.S. manufacturers and institutions that provides a platform for acquiring detailed data to be used for new design method development and new design concept validation. Multiple institutions will also be engaged in the project through the DOE University Turbine Systems Research (UTSR) program. Beyond the initial test campaigns that are planned to acquire detailed data for the baseline geometry, collaborating partners will be given opportunities to develop proprietary concepts that can be incorporated into the existing NExT framework thereby reducing time, costs, and risks associated with research programs. This paper provides the background and goals for the NExT project; it describes relevant design practices, identifies collaborating members, introduces the research facility where the NExT will be operated, and provides an overview for measurements defining the initial test programs.

I. Nomenclature

C = Chord
M = Mass
R = Radius
P = Pressure, Instrumentation Plane
S = Seconds
X = Axial Direction
θ = Circumferential Direction

II. Introduction

The importance of continued advancements in gas turbine technology for power generation, aviation, and oil and gas applications is critical to reducing the carbon footprint and to the U.S. economy. The time, costs, and risks in developing these advancements, however, impede progress that results in climate impacts as well as economic implications. For example, developing a turbine stage with cast blades requires significant resources in terms of personnel and with a financial investment. To address such a need, this program forges a team uniting industry, academia, and the U.S. Department of Energy to define the future of gas turbine research.

Other factors that need to be considered when building a test program are the ability and costs required to achieve temporally- and spatially-resolved data in a turbine engine at full-scale operating pressures and temperatures. By comparison a research-scale test turbine provides the opportunity to achieve relevant, detailed data sets at reduced temperatures and pressures by matching operational Reynolds and Mach numbers. In such a test turbine, important flow physics can be learned, but attention to detail is required to ensure the data can be related to an operational turbine, which most often drives a particular testing protocol. One commonly used testing protocol for turbine test rigs is back-to-back testing between a baseline geometry and an advanced turbine geometry, such that a change in aerodynamic and/or thermal performance can be assessed.

Turbine-relevant geometries and flow conditions for today's engine designs are highly proprietary and, as will be discussed in the next section of this paper, public versions are few – especially when considering jet engines have been operational since the 1940's. And yet, to advance technology beyond existing designs, relevant geometries are necessary to evaluate new technologies. This need is acutely important for academic institutions with a mission to educate the future workforce and a desire to enable students to be knowledgeable in modern design concepts and turbine architectures. Consider the example of a film-cooling hole whereby prior to 2015, many researchers in the field compared the performance of new cooling hole shapes to those of a simple round hole. However, the majority of turbine designers use shaped diffusing cooling holes on the body of the airfoil if costs permit. In 2015, Schroeder and Thole [1] introduced a public 7-7-7 diffusing film-cooling hole that is now being used by over 50 institutions and frequently appears in turbine cooling publications.

With these challenges in mind, there was strong support from the U.S. Department of Energy and from U.S. gas turbine manufacturers to develop a new turbine testbed, referred to as the National Experimental Turbine (NExT). The NExT project was initiated in mid-2019 and, thus far, one design review and significant design iterations have been completed with collaborative and constructive feedback. The focus of this paper is to provide the background on existing, multiple-user turbine geometries, provide goals for the NExT project as well as the team members and decision process, describe the first facility in which NExT will be placed, and finally discuss the design process and resulting geometry.

III. Studies Using Public Turbine Geometries

This particular review discusses turbine airfoil geometries that have been reported in the open literature that are not industry proprietary. It is important to note, however, that although these geometries have been shown or partially shown, not all of the airfoil coordinates and operating conditions are fully accessible. Also important is that there are numerous geometries that have been used in turbine cascades, some of which have been adapted from a stage geometry. The focus of this review is public geometries that have been used in turbine stage studies rather than linear cascades.

The Energy Efficient Engine (E3) was a program funded by NASA in the 1970s with the aim of developing technologies suitable for energy efficient turbofans [2]. This particular program led to decades of researchers using the geometry from the two-stage design. The goal of the program was to improve the thrust-specific fuel consumption by 12% relative to a state-of-the-art turbine design at the time. The program itself was very successful with new technology developments that impacted existing and future turbine designs. Although the E3 program concluded in 1987, the geometry lived on with many researchers using it for both experiments and computations, demonstrating the need of relevant geometries for study. Continuing in this tradition, NASA also supported the development of the C3X vane, which contained several cooling features [3]. This particular vane was used by many researchers early on in developing predictive methods given the experimental measurements of the conjugate heat transfer [4-6]. The C3X vane geometry is still in common use today [7]. More recently NASA has published its 2030 vision study on a path to revolutionary computational aero-sciences for aerospace applications, which motivated a current 2021 AIAA publication [8] that focuses on the challenges of transient full engine simulations related to gas turbine propulsion and emphasizes the need for real, public databases from experimental campaigns for CFD validation.

The objectives of ongoing testing at the Air Force Research Lab (AFRL) Aerospace Systems Directorate are to assess aerodynamic and thermal performance of turbines in serving the needs of the U.S. Department of Defense [9]. A non-proprietary turbine geometry called the High-Impact Technologies (HIT) turbine was designed and manufactured as a 1.5-stage high-work turbine. The goals, much like the effort reported in this paper, were to advance the state-of-the art for high-efficiency turbine engines. The HIT rotor geometry is consistent with transonic turbine stage designs operating at high pressure ratio (approximately four) and is reflective of government-owned propulsion turbines. Numerous publications have been produced as a result of work associated with the HIT geometry, which has led to important insights in turbine physics. Most recently, they have evaluated the effects of fluid-structure interactions [10] and the effects of manufacturing variations consistent with design for variability (DFV) [11].

There is a strong effort to work collaboratively as part of the Global Power and Propulsion Society (GPPS) [12], through which several researchers have begun to offer complete data sets including geometries for axial turbines. These data sets come from ETH Zurich, TU-Darmstadt, and Seoul National University with the first encompassing rotating turbine studies. As there is a strong push towards accelerated turbine development, these data sets become increasingly valuable for improving tool development. Although the GPPS efforts are noteworthy, an open, U.S.-based configuration is needed to support technology development with U.S. companies.

IV. Goals and Teaming Arrangement for NExT

As already described, there is a critical need to have a testbed for U.S. turbine manufacturers. In developing that testbed, however, a set of principles and goals were developed through discussions with the Department of Energy – National Energy Technology Lab and with the industry partners consistent with discussions involving other U.S. government agencies. The teaming arrangements, which will be described in this section were formed based on interest from U.S. companies as well as willingness to support the effort based on a contributing cost-share. In addition, the companies bring valuable expertise that is critical for designing a relevant turbine testbed.

The agreed-upon goals for the NExT testbed development are the following:

- Develop a relevant research turbine testbed for US companies and university/research institutions that provides a platform for comparing detailed data;
- Provide the ability for more rapid and less expensive collaborations with turbine manufacturers to further increase turbine efficiencies, aerodynamic and thermal performance, as well as increased life and operating temperature capability;
- Provide detailed data for a NExT baseline turbine geometry and operating conditions to enable improvements in modeling capabilities for designing turbines; and
- Increase collaboration between institutions to gather in-depth data sets while providing the opportunity for developing new measurement devices and leveraging innovative manufacturing methods to achieve turbine performance, cost, and durability requirements.

The first goal sets the primary direction for the NExT project. Specifically, during the design phases with input from the manufacturers, a number of trade-offs were discussed that resulted in a configuration with general applications to a wide range of turbine operating conditions from propulsion to power generation. These discussions were balanced with increased cost and scope of the project relative to what is already available in terms of hardware in the existing Steady Thermal Aero Research Turbine (START) Lab facility at Penn State, which will be described later in this paper.

With the testbed and detailed data provided to the turbine manufacturers for the baseline operating conditions, those partners will have access to the geometries and the facility to conduct proprietary testing quickly and in a cost-effective manner beyond the initial NExT development effort funded by the Department of Energy. Given a baseline performance will have already been documented, only the advanced designs will need to be tested, thereby conforming to important testing protocols discussed in the introduction of this paper.

The last goal was also important in defining the scope of the program. Since the early 1990's, the Department of Energy has coordinated a dedicated university research program focused on turbine topics that is known today as the University Turbine Systems Research program (UTSR). The UTSR program is led by the DOE co-authors on this paper. This community of researchers at a number of universities is interested in relevant geometries and, as such, one of the NExT goals was to provide access to the geometry and other pertinent data through an appropriate data management plan.

A. Teaming Partners

The teaming partners were critical to the success of this project. Their expertise and engagement in the effort was needed to make the development of this new test turbine program a success. It was also important to involve engine manufacturers that represented all relevant applications. Those partners who joined this collaboration and who are also co-authors on this paper include: Honeywell, Pratt & Whitney, Siemens, and Solar Turbines. Also important to the team was a turbine design firm, Agilis, to complete the Conceptual, Preliminary, Detailed, and Final design reviews. Finally, Penn State University (PSU) is the university chosen to lead the NExT research effort and coordinate the overall project with the teaming partners. Throughout the project, periodic briefings are conducted with the team partners along with requested input which is given annually to other U.S. federal agencies including NASA, the Air Force, and the Navy.

B. Input from Team Members

This section of the paper provides summary statements from the team members that describe their interest and motivation in the project and paper:

The U.S. Department of Energy's National Energy Technology Lab (DOE-NETL) is dedicated to ensuring the U.S. energy security and developing and improving novel energy technologies. Improving turbine performance is a core component of NETL's Advanced Turbines Program. With industry support, the DOE-NETL has spearheaded the development of a National Experimental Turbine (NExT) rig to help modernize the nation's gas turbine energy infrastructure. The NExT rig will provide a testing platform for all the companies in the partnership to innovate the nation's next generation of gas turbines. In addition to NETL's project management expertise, researchers from NETL are working closely with Penn State, Pratt & Whitney, and Ames Laboratory to develop baseline and advanced airfoil cooling designs, which will be evaluated using the START and NExT turbine rig. Several of the advanced cooling designs planned for testing at START using the NExT turbine rig were developed as part of the University Turbine Systems Research (UTSR) program funded and managed by NETL. Availability of these new test rigs provides capability for promising cooling configurations to be tested in a rotating environment to more accurately predict their performance prior to use in real turbines.

Turbine rigs are necessary to mature cooling technologies for implementation into turbine engines as expressed by Honeywell. However, such tests can be expensive, even prohibitively in some cases. Participation in the NExT research program provides an opportunity to mature proprietary technologies to a point where they are prepared to be used in modern turbines. Collaborating and sharing cost with other partners enables each partner to perform research that would not likely be realized without NExT. Furthermore, high fidelity and comprehensive data, such as that being collected in the NExT program, is often not available to turbine analysts for calibration and validation of their thermal and aerodynamic design tools. The data provided by the NExT program will be used to improve design tools. Improved design tools will result in engine designs that perform closer to the original design intent.

As mentioned earlier, Pratt and Whitney is a member of the NExT development team formed between U.S. academia, industry, and government. The NExT turbine is being designed to represent the first stage of a product relevant high pressure turbine (HPT); one of the most highly thermally and mechanically loaded components in the aero-engine industry. At take-off conditions, the gases flowing around the HPT first blade can exceed the melting temperature of the blade material, while the centripetal forces acting on the blades can be tens of thousands time greater than the force of gravity. Despite these harsh operating conditions, HPT components must provide world-class durability and performance levels along with safe engine operation. So, the NExT turbine, testing within the framework of the PSU START facility, will provide key learning for improving aerodynamic and heat-load-management features, design tools and instrumentation to help meet the significant challenges faced in modern turbine design.

Siemens Energy sees this NExT program and the START rig as a great opportunity to advance turbine technology development mainly because the rig offers the capability to test the interactions between aerodynamics, heat transfer and secondary air systems, i.e. this system approach is seen as critical to developing a better overall turbine design. This rig matches Siemens design philosophy of using 0D, 1D and 2D design systems for the concept design and a strong 3D approach that uses full conjugate heat transfer CFD [13] and Multi-Disciplinary Optimization (MDO) for the final product as a system.

Solar Turbines has indicated that advances in manufacturing technology and increasing demand for highly efficient turbomachinery call for improved design tools for the main gas path and cooling circuits. Solar is confident that the NExT rig will not only serve as a proof-of-concept testbed but provide much-needed high quality calibration data for advancing turbine aero and heat transfer tools to meet future gas turbine system requirements.

Agilis is an engineering services provider focused on turbomachinery research and new product development, including engine component and module design, hardware manufacturing, instrumentation, test, and engine health monitoring and blade non-intrusive stress measurement systems (NSMS). The NExT project aligns with Agilis' goals to develop long-term relationships with PSU's START research facility and College of Engineering, to help advance and protect each Teaming Partners' Intellectual Property, and to build and strengthen relationships with DOE-NETL and the Teaming Partners.

C. Data Management and Project Schedule

Because this is a cooled turbine design, technologies developed as part of the NExT project will likely be subject to U.S. government EAR and ITAR export regulations. During the design process, Agilis and the turbine engine Teaming Partners have provided input and guidance for technologies contained within the components which may or may not require licenses for export. In the case of universities, technology control plans (TCP's) will be required. These TCP's will address U.S. export regulations and license requirements. It is also important that those U.S. industries who are contributing to the project be given access to all of the information generated by the program. Table 1 provides a summary of the data management plan for NExT.

Each of the turbine manufacturers contribute to the PSU-led NExT design project through periodic reviews and confidential feedback sessions to maintain anonymity for the partners. Penn State then aggregates the information for discussions with Agilis to maintain proprietary confidentiality. Agilis is responsible for the day-to-day design and analysis effort. In all cases, non-disclosure agreements are in place between Penn State and each of the project partners.

Following a conceptual design review to kick-off the project in late 2019, a Preliminary Design Review (PDR) was completed in April 2020. The PDR generated valuable discussions from the turbine manufacturers which resulted in further design requirements and guidance refinements. A Detailed Design Review (DDR) including the feedback provided after the PDR was also conducted in late 2020. The planned procurement of the NExT hardware will begin in early 2021 with a test program starting in late 2021.

Table 1. Data Management Plan for NExT

Data	Open Publications	U.S. Industry Partners	U.S. Agencies	U.S. Universities
Blade Details	No	Yes	Yes	Yes with TCP
Steady and Unsteady Data	Scaled Data	Yes	Yes	Scaled Data
External / Internal Heat Transfer	Scaled Data	Yes	Yes	Scaled Data

V. Preliminary and Detailed Design Reviews

To reduce NExT baseline testing costs and to facilitate a timely project completion, the NExT testbed will be integrated into the existing PSU START Lab infrastructure, which will be discussed in the following section of this paper. The design envelope for the NExT testbed is shown in Figure 1, and the design process focused on the existing primary turbine components shown in blue that needed to be redesigned. The process by which Agilis is designing the NExT baseline turbine includes several steps:

(i) One and two-dimensional aero design;
(ii) One and two-dimensional heat transfer design;
(iii) Preliminary design review (PDR) with the partners;
(iv) Iteration with Penn State to incorporate partner feedback information from the PDR;
(v) Structures analysis and rotor dynamics;
(vi) Three-dimensional mechanical design;
(vii) Detailed design review (DDR) with the partners; and
(viii) Manufacture the turbine airfoils and new flow path hardware.

Design target ranges for the NExT baseline were initially provided by PSU to Agilis for each of the turbine geometric, aerodynamic, and heat transfer design parameters shown in Table 2. In addition, open literature geometries and data results from experimental studies conducted by the turbine research community were used for specific guidance on geometry, aero, and cooling design, as will be further described in this section.

The overall geometry of the NExT baseline airfoils are modeled after vanes and blades from within first-stage high-pressure gas turbines. In terms of physical size, the aspect ratio of the airfoils, defined as the ratio of airfoil span height to axial chord length, was initially smaller for the vane relative to the blade during the PDR. The corresponding vane-to-blade airfoil count included over double the number of rotating blades compared to the stationary vanes. The relatively low quantity of PDR vane airfoils essentially drove the vane true-chord length to be considerably long, which upon further analysis yielded quite substantial secondary flows to be generated within the vane passages.

Although the end results of the PDR met several of the desired targets for the NExT turbine stage performance, feedback from the partners triggered a design revision that focused mostly on reducing the vane chord length and increasing the vane airfoil quantity. This design revision was performed prior to the DDR as motivation to reduce the vane passage secondary flows and also to ensure a more favorable ratio of vane-to-blade airfoils that allows computational fluid dynamics (CFD) simulations to be performed using both full wheel and small sector models. The post-PDR work resulted in a vane aspect ratio that more closely matched the blade aspect ratio. The results of the PDR as compared with the DDR are shown in Table 2.

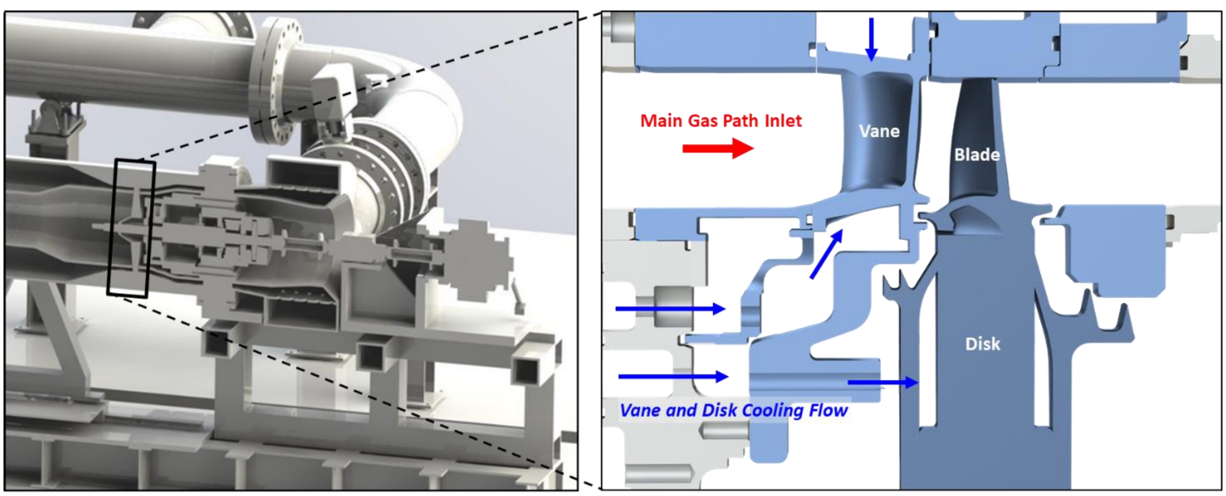


Figure 1. START Lab test infrastructure and highlighted NExT test section design envelope with hardware modifications highlighted in blue.

The aerodynamic shape of the NExT stationary vane is characterized by a leading edge region that is relatively large in size, compared to the mid-chord and trailing edge regions, with a large diameter and stagnation that is line-stacked nearly constant (2D) from root to tip. The vane trailing edge region is characterized by a small streamwise bow from root to tip that is centered about mid-span. These geometric features are similar in concept to those studied by Anthony and Clark [9], Albert and Bogard [14], and Luque et al. [15]. The near 2D nature of the vane leading edge region eases manufacturing, helps integration of different cooling technologies, and allows parallel vane cascade studies to be readily conducted. As a further comparison of the PDR and DDR results, Figure 2 shows the scaled mid-span vane and blade designs.

Table 2. Comparison of the DDR and PDR Designs for NExT

Parameter	Symbol, Units	DDR Design % Change from PDR
Number of Vanes	Quantity	+ 45% PDR
Number of Blades	Quantity	= PDR
Vane Aspect Ratio	Height / Axial Chord	+ 33% PDR
Blade Aspect Ratio	Height / Axial Chord	+ 1% PDR
Stage Efficiency	%	+ 1% PDR
Flow Parameter	$lb_m/s \cdot (Rankine)^{0.5}/psia$	– 8% PDR

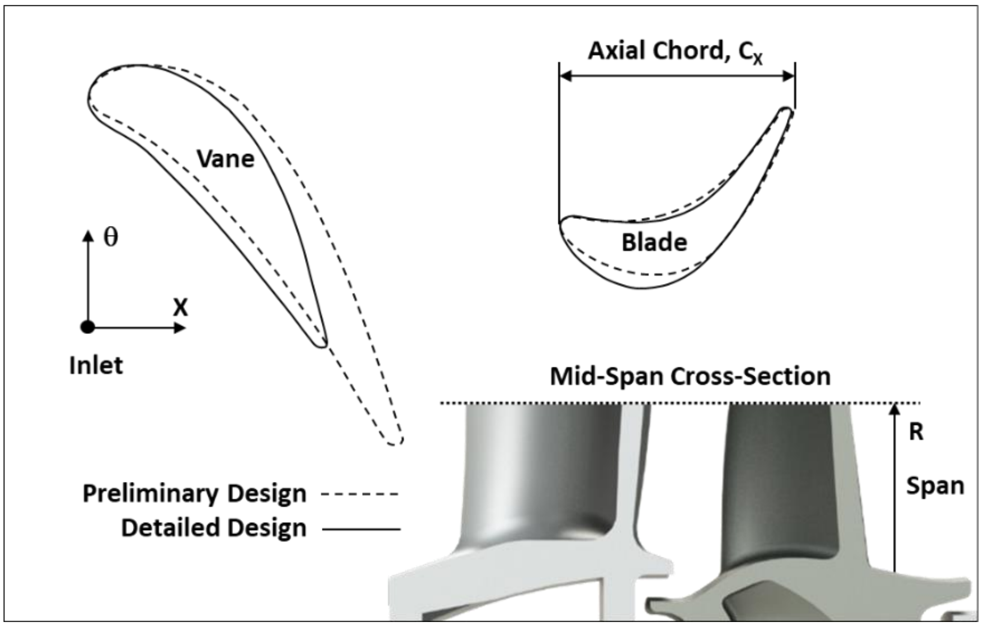


Figure 2. Preliminary and detailed designs of the NExT vane and blade cross-sections at mid-span, scaled consistently.

The aerodynamic shape of the NExT rotating blade was iteratively designed to target a turbine-exit work distribution from root to tip that is peaked near mid-span and simultaneously produces a high stage efficiency, similar in concept to the results from Ciepluch et al. [2]. The blade profile includes a relatively large cross-section near the root that tapers gradually thinner with increasing span. The leading edge region includes a size and shape that varies from root to tip, which was the result from an iterative design analysis that focused on mainstream flow incidence angles with respect to the blade metal walls and corresponding airfoil static pressure distributions.

The heat transfer and cooling methodology for the NExT airfoils was also designed to be consistent with modern first-stage high-pressure turbine vanes and blades. Figure 3 shows the internal and external cooling methodology within the vane and blade from the DDR results. At the airfoil leading-edge region, both the vane and blade include internal impingement cooling flow from a dedicated supply channel and external showerhead cooling using multiple rows of film cooling holes. The showerhead film cooling holes are oriented in the radially outboard direction with surface break out angles near 30 degrees, similar to geometries studied Albert and Bogard [14] and Nathan et al. [16].

The center-region of the vane includes a large single internal supply channel that feeds multiple rows of 7-7-7 shaped film cooling holes, from Schroeder and Thole [1], that are located along the airfoil exterior pressure and suction surfaces. Trip strips are also placed along the internal channel walls to enhance heat transfer. The trip strip designs within both the vane and blade internal channels were selected based on the results from published studies, for example Wright et al. [17] and Alkhamis et al. [18], that examined the performance of trip strip height and pitch spacing to improve heat transfer and reduce pressure loss. The center region of the blade also incorporates a single channel but with multiple u-bends alternating radially inboard and outboard, along with trip strips placed along the channel walls.

The u-bend channel feeds cooling flow to multiple rows of 7-7-7 shaped film-cooling holes that are placed along the pressure and suction surfaces.

The trailing-edge region of both the vane and blade is characterized by a dedicated supply channel that feeds cooling flow through three major geometric features, similar to the concept published by Town et al. [19]. The first is a radial row of impingement cooling holes that direct the cooling flow to a second central pin-fin array, after which the cooling flow passes through a third radial row of exit slots consisting of exterior pressure-side cutbacks.

The platform cooling design integrates concepts similar to those published by Knost and Thole [20] and Shiau et al. [21] along both the vane inner and outer endwalls, as well as the blade platform. Film cooling hole rows are located on the endwalls and platforms upstream of the stagnation point, while hole rows within the passage are placed mostly upstream of the airfoil throat along both the pressure and suction sides. The wall surface along the blade tip was designed to incorporate a full squealer with a central recessed platform that includes a series of cooling holes. The blade tip wall is also cooled from the airfoil pressure side using a series of cooling holes located radially near the tip. These blade tip cooling features are similar to concepts published by Bunker [22] and Christophel et al. [23].

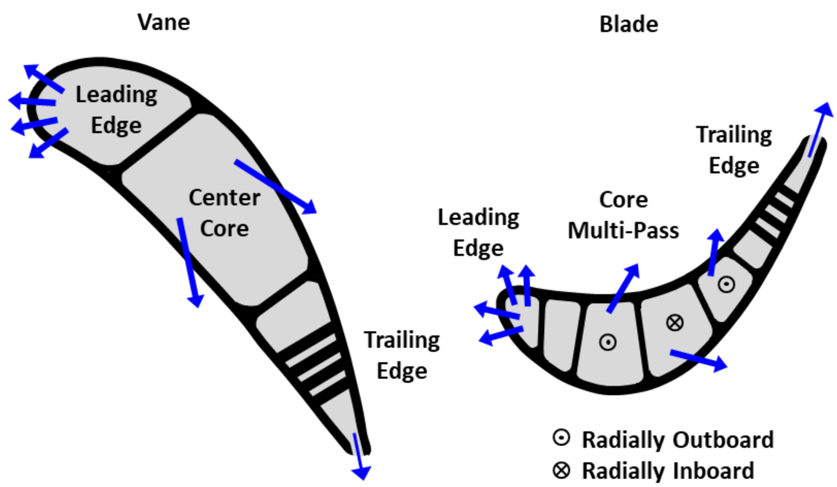


Figure 3. Detailed design results of the cooling methodology for the NExT vane and blade.

VI. Steady Thermal Aero Research Turbine (START) Facility

The START research facility was designed to study turbine aerodynamics, heat transfer, and secondary air systems using true-scale engine hardware at continuous and steady engine-relevant testing conditions. The facility is named on this fundamental operating principle and is called the Steady Thermal Aero Research Turbine (START) laboratory. The research facility was established in 2011 through an initial collaborative interaction between U.S. academia, industry, and government to advance the development of modern gas turbine engines supporting the aircraft propulsion and land-based power generation industries. Funding to construct the facility and turbine test article was provided by three primary research sponsors: Penn State University, Pratt & Whitney, and the U.S. Department of Energy National Energy Technology Laboratory.

The current START test section includes a proprietary one-stage turbine (vane / blade) operating at Mach numbers and Reynolds numbers representative of modern gas turbine engines in a fully matched aero-thermal environment. This one stage proprietary design will be replaced by the NExT design. The facility is outlined by Barringer et al. [24] and Berdanier et al. [25], and a graphical overview is presented in Figure 4. Significant facility infrastructure provides the necessary elevated air flow pressures and temperatures for properly testing the turbine hardware. Two large air compressors together deliver continuous and steady air flow rates up to 25 lb_m/s (11.3 kg/s) at supply pressures of 60 - 80 psia (400 - 550 kPa) to test turbines in the size range of 16 - 24 inches (0.4 - 0.6 m) diameter at rotational speeds up to 11,000 rpm. The electrical requirements to generate the compressed air flow rates corresponds to over 3,000 horsepower (2.2 MW).

Substantial heating and cooling capabilities establish a meaningful temperature difference between the main gas path air flow and secondary cooling air entering the turbine, which allows engine-realistic heat transfer testing to be conducted with matched air density ratios. An inline natural gas heater rated to 12 x 10^6 Btu/Hr (3.5 MW) can raise the temperature of the entire 25 lb_m/s main gas path air flow up to 750°F (675 K), and an industrial process chiller with a capacity near 60 tons reduces the temperature of the secondary cooling air to approximately 40°F (275 K). These heavy-duty operating conditions required integration of advanced safety and control systems to maintain the turbine shaft speed and allow the turbine to operate at engine-relevant ratios of axial to circumferential air flow velocities. Additional operating parameters for typical START turbine testing are provided in Table 3.

Overall, the START team and the associated turbine research facility promote collaborative interactions within the gas turbine community with a goal to advance gas turbine technology development at a reduced cost and accelerated timeframe. Another important goal of the START facility is to provide a platform for training U.S. students to become future turbine scientists and engineers. The research and test programs conducted within START help to support graduate level Masters and PhD students toward their degrees. In summary, the START facility currently has a wide range of research activities that investigate turbine vane and blade cooling, rim cavity sealing, and stage efficiency. Turbine performance is measured and evaluated using cutting-edge precision data systems, additive manufacturing methods, and advanced instrumentation.

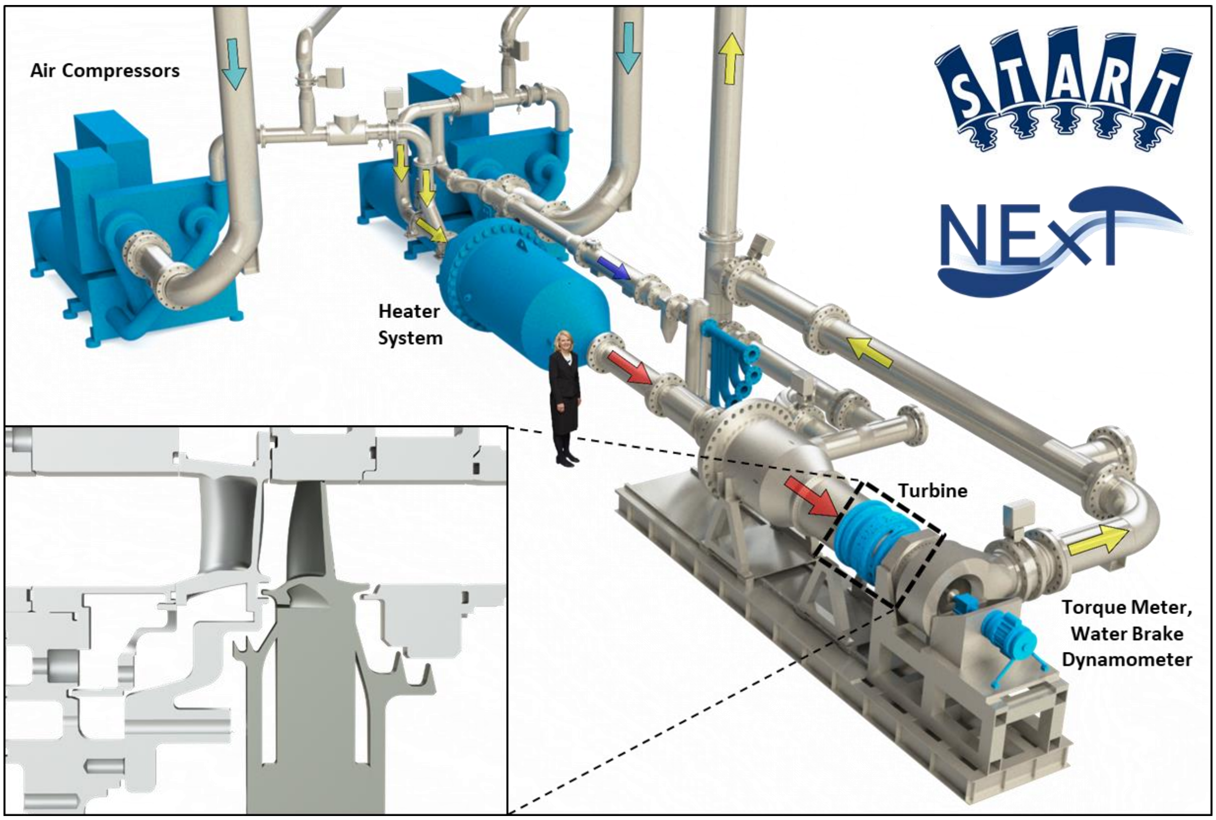


Figure 4. Overview of the Penn State START research facility.

Table 3. Representative Operating Parameters for START

Parameter	Value
Stage Total Pressure Ratio	2
Mass Flow Rate (kg/s)	11.3
Inlet Total Temperature (K)	380 – 675
Inlet Total Pressure (kPa)	400 – 550
Rotational Speed (RPM)	≤ 11,000
Coolant to Mainstream Density Ratio	2

VII. Instrumentation Plan

The START rig test section features an extensive instrumentation suite monitoring facility conditions and turbine performance. Dedicated systems monitor nearly 200 channels each of temperature and pressure, condition monitoring such as vibrations and clearance gaps, and redundant high-accuracy measurements of speed and torque. Multiple probe traversing devices enable spatially-resolved flow field measurements (e.g., pressure, temperature, velocity) at several measurement locations throughout the turbine test section. A magnetic bearing system offers tunable control for system rotor dynamics, and a unique capability to adjust rotor position (axially or radially) in real time. Furthermore, the facility is dedicated to advanced diagnostics development and integration. Areas of ongoing development include thin film heat flux gauges for time-resolved measurements of temperature on airfoil surfaces, telemetry for sensors installed on the rotating reference frame, thermal imaging for spatially-resolved temperature measurements on stationary and rotating components, and fast-response probes for measurements of pressure, velocity, and turbulence parameters.

Initial measurements for the NExT program will focus on quantifying aerodynamic and heat transfer performance for the turbine design. These efforts will require complimentary instrumentation packages to build a broad understanding of turbine performance and serve as a baseline for future design iterations. Figure 5 shows a combined representation of the planned instrumentation layouts for future test programs; sensor placements shown in Figure 5 may change for individual test section builds depending on installed hardware limitations and specific test campaign needs.

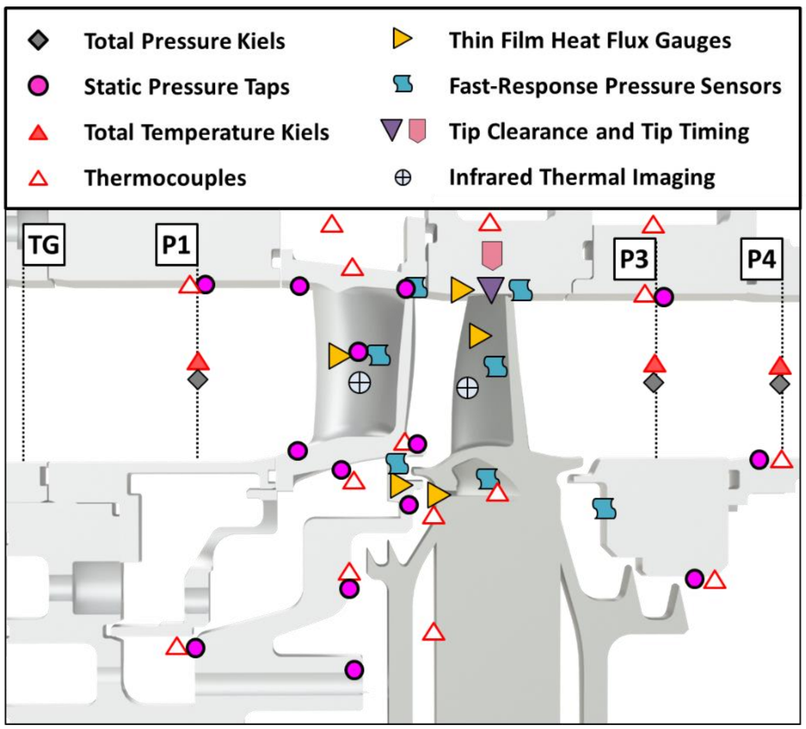


Figure 5. Example instrumentation layout for NExT programs.

A. Aerodynamic Flowfield Measurements

Aerodynamic performance will be characterized using a combination of fixed instrumentation and flow field traverses. Probe access upstream of the vane (P1) enables measurement of stage inlet conditions at multiple locations around the circumference. Sector traverse hardware can also be mounted at this position to quantify pitch wise variations or characterize imposed non-uniformities. Radial and circumferential mapping of total temperature and total pressure will define experimental stage performance metrics and boundary conditions for computational comparison efforts. More advanced sensors such as hotwires and multi-hole pressure probes inserted at P1 have been historically used to measure turbulence intensity and flow angle. These verifications will continue throughout the NExT test campaigns, particularly as turbulence grids (TG) are installed and removed from the test section at location TG upstream of the P1 measurement plane. The test section is designed for probe flexibility, so fast response aerodynamic probe (FRAP) equipment and other custom sensor designs can also be installed for time-resolved measurements at the turbine stage inlet.

Probe access at the stage exit plane immediately downstream of the rotor (P3) is similar to the stage inlet plane through flexibility for probe installations at several circumferential locations and accommodations for two circumferential traversing sectors. Proximity of P3 to the blade enables measurements such as time-resolved measurements of the blade exit flow field [26]. Design considerations allow this measurement plane to be used in the one-stage (vane/blade) configuration, or for inter-passage measurements of the second vane in a 1.5-stage configuration (vane/blade/vane). Either one-stage or 1.5-stage test section builds can also utilize measurements at the exit plane (P4), which accommodates additional probe access and wider circumferential sector capabilities.

When stage efficiency measurements are desired for one-stage test section configurations, a unique sector traversing mechanism is installed downstream of the stage near the P4 location [26]. This system holds a set of efficiency measurement rakes with up to ten radially-distributed Kiels for total pressure and total temperature. The entire rake assembly can be traversed circumferentially through large sectors covering many vane passages to capture spatially-resolved time-averaged stage exit flow field parameters downstream of the turbine. This unique capability also enables accurate identification of spatial variations due to intentional introductions of flow nonuniformities (i.e., drop-in replacement of AM vane hardware for comparison with cast hardware). Extensions of this traversing hardware with alternate instrumentation also enable time-resolved spatial maps of flowfield parameters.

B. Heat Transfer Measurements

In addition to extensive deployment of thermocouples throughout the test section, heat transfer measurements in the START turbine test article primarily incorporate thin film heat flux gauge (HFG) and infrared (IR) thermal imaging technologies.

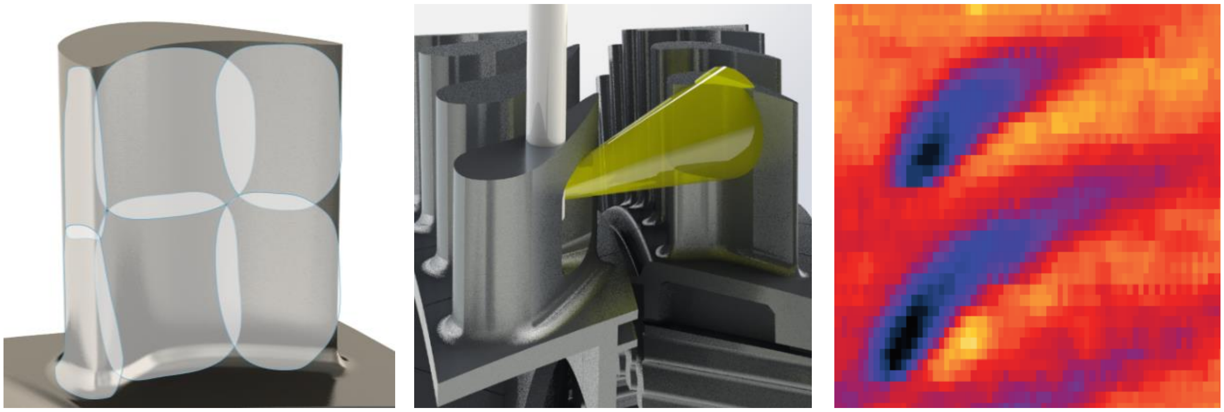
Thin film heat flux gauges have been utilized for heat transfer measurements in gas turbine applications for several decades. They provide particular value through their small packaging (typical sensors are on the order of 500 μm, but sensors have been successfully manufactured at Penn State with features as small as 4 μm), flexible packaging (typical dielectric substrates made from thin polyimide can be wrapped around complex airfoil geometries), and fast response (HFG sensors can typically perform with frequency response on the order of 100 kHz or more). Both single-sided and double-sided HFG designs have been integrated for START facility tests. Details of recent HFG maturation at Penn State have been outlined by Siroka et al. [27], and recent implementation in the turbine has been introduced as well [28].

Heat transfer measurements on rotating hardware are enabled as point-based measurements through telemetry and slipring equipment. A 64-channel digital telemetry system offers capabilities for thermocouples and heat flux gauges (as well as bridge-type sensors such as strain gauges and piezoresistive fast response pressure sensors) with individual channel configurability, and a similar 10-channel telemetry system can be installed as well. A separate slipring system with on-rotor digitization and digital data transfer can also be utilized with 64 channel capability optimized for heat flux gauge operations.

As a supplementary option for point-based temperature measurements from thermocouples and thin film heat flux gauges, the START Lab has also demonstrated the use of infrared thermal imaging to capture spatially-resolved temperatures on stationary and rotating turbine airfoils [29]. Through the use of a periscope-type optical probe entry, paired with a thermal imaging engine capable of integration times on the order of 1 us or less, phase-locked thermal images are collected with high spatial resolution and accuracies on the order of 0.5 K. A process outlined by Knisely et al. [29] also ensures optimization of integration time for the thermal imaging detector to ensure minimal errors due to blade motion, even at speeds on the order of 10,000 rpm dictated for this NExT program.

Spatially-resolved temperatures will be mapped over a majority of the blade surface following a composite reconstruction shown in Figure 6(a). Measurements of the blade pressure side and leading edge can be largely accommodated by inserting the optical probe through a custom additively manufactured vane, as demonstrated in Figure 6(b). By moving the probe to focus on different areas of the blade, a desired piece-wise reconstruction of the blade is performed by mapping the two-dimensional images to the three-dimensional part geometry. A similar probe entry in a location downstream of the blade provides viewing capability for the blade suction side. An example IR temperature map showing cooling hole film traces on rotating blades is shown in Figure 6(c).

The same thermal imaging equipment and probe access capabilities demonstrated by Knisely et al. [29] for blade measurements will also be leveraged to measure spatially-resolved temperatures on the cooled vane for the NExT program. By operating in a vane-only configuration, the probe will be installed downstream of the vane and turned upstream to image the vane suction surface; additional provisions will enable imaging of other regions of the vane, such as the leading edge and the pressure surface.



(a) (b) (c)

Figure 6. Infrared thermal imaging in the START facility from Knisely et al. [29]: (a) Example composite view; (b) Blade pressure side and leading edge access through an optical probe inserted into a custom additively manufactured vane; (c) Example thermal image from IR system showing film traces exiting cooling holes on a rotating blade.

C. Tip Clearance and Timing Capabilities

The START turbine facility includes blade-by-blade tip clearance measurement capabilities through four capacitance-type probes positioned around the circumference of the stationary test hardware. As a supplement to these blade clearance measurements, a new non-intrusive stress measurement system (NSMS) will be integrated for use with the NExT program. This optical probe system measures blade vibration through tip timing with additional provisions for blade tip clearance. The combination of optical probes with capacitance probes provides a unique flexible capability within the NExT framework for real-time monitoring of blade clearance and vibration, while simultaneously integrating with measurement system developers to improve upon accuracy and integration strategies for each respective sensor technique. The new optical NSMS measurement system also extends the NExT hardware into a research space for turbine aeromechanics, integrating with strain gauge capabilities via telemetry hardware, and complementing the primary NExT program focuses for heat transfer and aerodynamics.

VIII. Conclusions

This paper establishes the new National Experimental Turbine (NExT) and its unique collaborative design effort between U.S. academia, industry, and government. The NExT will serve as a research baseline geometry that will allow U.S. turbine manufacturers to improve their design tools through detailed and systematic performance studies that focus on improving aerodynamics and heat transfer. The NExT is being integrated into the START laboratory testbed to take advantage of a wide variety of test operating conditions and an advanced suite of instrumentation capabilities.

The NExT baseline design is characterized by a full stage turbine with vane and blade airfoil geometries representative of modern first-stage high-pressure turbines. The OEM project partners each served an equal and critical role in the design by providing acceptable target ranges for the turbine geometric, aerodynamic, and heat transfer performance parameters. The design process was facilitated by establishing non-disclosure and confidential communication feedback between Penn State and each turbine manufacturer. The design targets were then aggregated to form a baseline turbine architecture map that allowed the turbine design firm to plan a conceptual design.

The subsequent design process included several steps to take the initial concept and transform it into a formal preliminary design with realistic airfoil sizes and features that would fit within the START infrastructure envelope. Upon conclusion of a preliminary design review, key feedback from the project partners sparked a revision to the vane design in which the vane chord length was reduced and vane airfoil quantity was increased. The motivation for the design revision was to reduce secondary flow losses within the vane passages, and to also provide a more favorable ratio of vane-to-blade airfoils for full wheel and sector CFD modeling. An in-depth detailed design was then completed that incorporated the major desired revisions to the preliminary design, along with fine-tune adjustments of cooling flow features internal and external to the airfoils. The detailed design of the cooling features included sizing, quantity, and placement of film cooling holes, pin-fin arrays, turbulator trips, exit slots, and blade tip squealers.

Manufacturing and procurement of the NExT hardware will begin in early 2021, with integration into the START facility following shortly thereafter to support the planned test program beginning in late 2021. The detailed data that will be generated from testing the NExT baseline geometry and operating conditions will enable U.S. turbine manufactures to improve their design and modeling tools. New joint research missions between U.S. academic institutions will also be made possible by providing a platform for comparing relevant turbine data. The testbed being used for the project also allows opportunities for development of new advanced sensors.

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