Project 092 Advanced Two-stage Turbine Rig Development

The Pennsylvania State University

Project Lead Investigator

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University Participants

The Pennsylvania State University (Penn State)

- P.I.: Dr. Reid A. Berdanier
- FAA Award Number: 13-C-AJFE-PSU-125
- Period of Performance: January 1, 2023, to September 30, 2026
- Tasks:
  1. Oversee new turbine rig design
  2. Design motor generator to dissipate the turbine power
  3. Order remaining air compressor components and complete manufacturing

Project Funding Level

For the three-year effort, the Federal Aviation Administration (FAA) provided $5,900,000 and matching funds of $6,150,000 were provided by Pratt & Whitney® and Penn State.

Investigation Team

Reid A. Berdanier (P.I.), Management, reporting, and oversight of all technical tasks
Assoc. Res. Prof. Michael Barringer (co-PI), Research Advisor, Tasks 1–3
Karen Thole, Affiliate Professor, Tasks 1–3
Tom Houck, Project Manager, Tasks 1–3
Justin Brumberg, Research Engineer, Tasks 1–3
Jeremiah Bunch, Engineering Technician, Tasks 1–3
Asst. Res. Prof. Matthew Meier, Research Engineer, Tasks 1-3

Project Overview

This project will significantly advance the efficiency levels of small-core gas turbines relevant to current engines, as well as future propulsion architectures such as hybrid electric propulsion systems for large single- and twin-aisle aircraft. The motivation for this research is aimed at reducing the carbon footprint of aviation through increasing turbine thermal efficiency, while maintaining or even improving component durability. This project will expand the infrastructure and research scope of the Steady Thermal Aero Research Turbine (START) Lab at Penn State, in which a two-stage, small-core, test turbine will be designed, manufactured, commissioned, and put to use in acquiring the necessary data to meet the proposed goal. The new infrastructure will be referred to as START⁺. The proposed expansion will result in a research

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turbine facility like no other in the world and will situate turbine research in the United States (U.S.) at the leading edge in efficiency improvement and emissions reduction for future propulsion applications.

Task 1 – Oversee New Turbine Rig Design

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Objectives

The objectives of this task include (1) overseeing the design of the new START⁺ turbine rig and laboratory expansion, (2) integrating the entire facility by having the mechanical engineering firm work with the building design firm to layout piping, building penetrations, supports, and ensure proper access for lab personnel, (3) ensuring the new compressors and test turbine can be appropriately accommodated in the new laboratory building, and (4) beginning the preliminary design of the rig layout, and confirming with Pratt & Whitney the entire scope of the test turbine.

In the oversight of the design of the new START turbine rig and laboratory expansions, this objective includes pursuing the selection of a turbine engineering firm by interviewing multiple firms and creating a request for quotation, to enable selection of the firm that best meets the cost, schedule, and quality requirements of the program. The construction of the new building (which is funded by the Penn State and Pratt & Whitney cost share) is required to meet the research objectives of this project since the current START Lab does not have enough space for the new START⁺ two-stage turbine rig and compressors. The new START⁺ building expansion will add more than 10,000 ft² of space to the START Lab to house the new research equipment, rig, and turbine.

Research Approach

During the current reporting period, design proposals were received and reviewed by Penn State from multiple engineering design firms to perform the main design work on the START⁺ turbine integration plan. Upon reviewing all proposals for acceptable cost, schedule, and design content, the engineering design firm Belcan was selected. This turbine integration plan includes the design firm working closely with both the START team and Pratt & Whitney to perform the detailed design of the hardware components that define the primary test section of the new two-stage turbine rig. The design scope for the START⁺ turbine test section is shown in Figure 1.

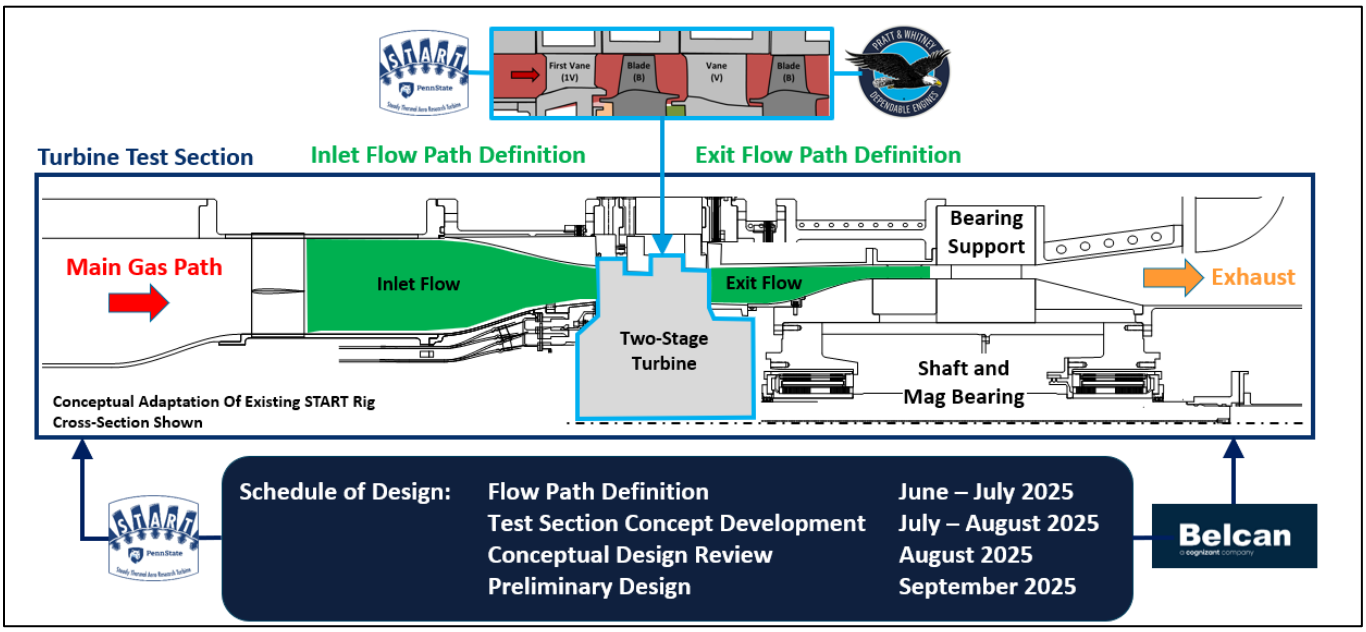

Figure 1. Design work status and schedule for the START⁺ two-stage turbine test section.

The hardware interface control plan that was presented in the previous reporting period is summarized briefly here. The two-stage turbine hardware design including the airfoils, disks, cover plates, and fasteners will be sourced by Pratt & Whitney directly from one of their current production aircraft engines. Pratt & Whitney, in conjunction with the selected design firm, Belcan, are responsible for designing any modifications to enable the engine hardware to be installed and operated within the START+ turbine test section. The hardware components that define the outer casing walls, inner flow path walls, rotor shaft and bearing system, and the bearing support structure are the responsibility of the START research group and Belcan.

The Penn State START team worked with Pratt & Whitney to complete a design kick-off meeting in December 2024 related to the hardware interface control plan. This meeting included several team members from START and Pratt & Whitney to begin review of the hardware components described above.

Following the kick-off meeting, weekly meetings were scheduled to review status of the design work. The conceptual instrumentation plan was progressed into a detailed instrumentation plan that is currently in progress covering the entire turbine test section. Additional design review meetings were held during the current reporting period between START and Pratt & Whitney to refine the key learning parameters associated with the research objectives for aerodynamics, durability, efficiency, and secondary flow systems. These meetings included the Penn State START team as well as managers and design engineers from Pratt & Whitney.

Special consideration was given to design options that enable all the two-stage turbine hardware to be frequently assembled and disassembled to and from the shaft. Since the intent of the new two-stage turbine rig is to conduct research, the frequent assembly and disassembly is an important consideration in the design process to provide access for turbine vane and blade airfoil design changes, as compared to an in-service gas turbine engine that remains fully assembled during its use in the field. The progress of the design work was presented during a June 2025 on-site meeting at the Penn State START facility for our annual Pratt & Whitney Center of Excellence partnership. This meeting included the Penn State START team as well as senior managers and design engineers from Pratt & Whitney. The conceptual instrumentation plan progressed into a detailed instrumentation plan that is currently in progress covering the entire turbine test section.

Belcan's design of the turbine test section started with a project kick-off in March 2025. A design requirements document was created by the START team and was provided to Belcan, which outlined the purpose and key design requirements for the new turbine test section. Design details incorporated into the document included the target turbine operating conditions, design ownership responsibilities, hardware interfaces, and instrumentation needs. During the current reporting period, START and Belcan began the conceptual design process which included a review of several 'lessons learned' from designing the existing single stage START turbine rig. The conceptual design work also included generating an initial geometry layout of the primary air flow path (main gas path) extending from upstream of the turbine to downstream of the turbine. Preliminary definition of instrumentation locations and quantities were also assessed to characterize measurement capabilities. Design work progressed in quarter (Q)2 to further develop the stationary hardware components that comprise the upstream part of the turbine test section in Figure 1 and the outer diameter casing pieces. The upstream part of the turbine test section includes the upstream settling chamber, the inner diameter core pieces that include the cooling air delivery system, and the strut section that physically connects the inner diameter core pieces to the outer diameter casing pieces. Concepts for the cooling air delivery system were also designed during this reporting period including cooling path quantities, locations, and egress routes.

A detailed conceptual instrumentation plan was also developed in Q3 associated with the complete turbine test section shown in Figure 1. This detailed conceptual instrumentation plan includes measurement locations, probe types, probe quantities, and probe wire and tube egress paths to fully characterize the two-stage turbine performance.

Belcan, the Penn State START team, and Pratt & Whitney held a conceptual design review meeting in August 2025. The meeting was successful in enabling the design to progress into the preliminary design phase. A review meeting for the preliminary design will take place in the timeframe of November 2025 that will cover an end-to-end engineering review of the complete turbine test section. A detailed design review will take place in the timeframe of January 2026. The goal is to enable manufacturing from January through the summer of 2026.

The design of the START+ rig air piping and equipment integration to be located upstream and downstream of the turbine test section are the responsibility of the Penn State START team and the design firm Burns & McDonnell (BMCD). Penn State

initiated a purchase order with BMCD to perform the detailed design phase of the work. Their scope includes detail design to integrate major equipment systems including the compressors, combustor, air piping network, turbine test section, dynamometer, and outdoor cooling yard.

Figure 2 shows the detailed design work that the Penn State START team conducted with BMCD regarding the layout of the large air compressors and outdoor cooling yard equipment. A set of high priority design tasks were developed to enable an efficient progression from the preliminary design phase into the current detailed design phase. These specific design tasks focused on the air piping network, cooling piping network, physical supports and foundations, electrical and utility connections. The equipment installation and their integration will take place in the latter half of 2026 as originally planned.

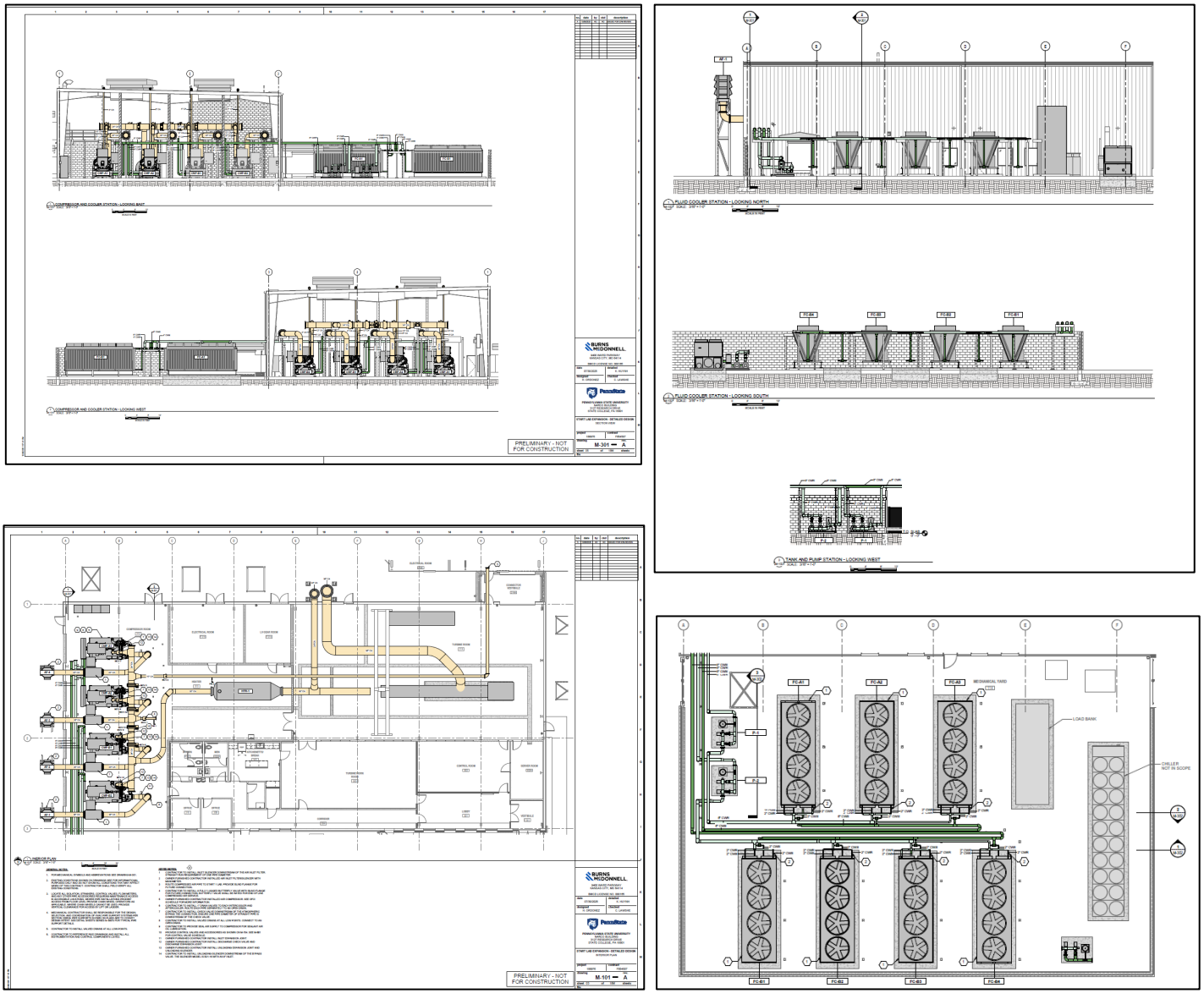

Figure 2. Drawing examples of the detailed design work for the major equipment system integration.

An isometric view of the new START+ turbine room is shown in Figure 3 that illustrates a concept equipment layout that was developed including the air piping, turbine test section components, and supporting equipment. The primary air flow from the compressors enters the turbine room from the left and passes towards combustion chamber where the air is heated up to the target temperature levels. The air flow is then directed towards the test turbine, after which the air flow enters a downstream collection volute chamber and is redirected towards the main exhaust silencer. A bypass air pipe system is shown to enable air flow to be routed around the turbine for specific objectives including startup, emergency, and cool down periods.

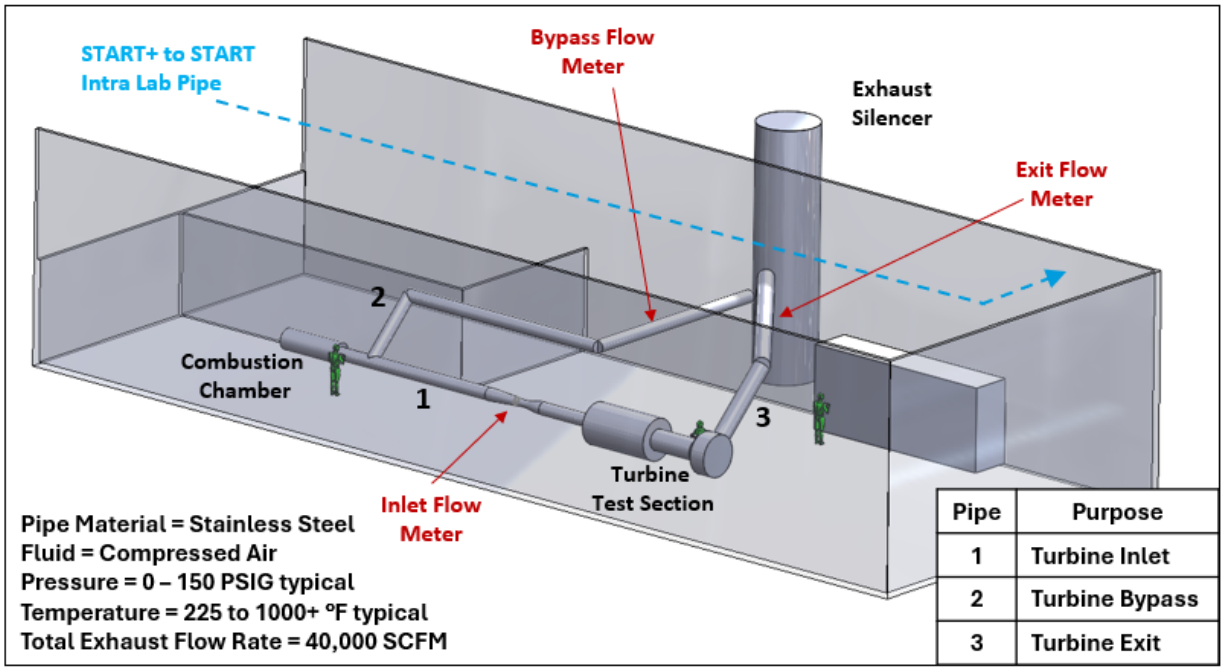

Figure 3. Drawing showing the concept equipment layout within the turbine room. START: Steady Thermal Aero Research Turbine.

Construction on the main building and cooling yard began at the new START+ facility property site in June of 2025. Figure 4 shows photographs of the construction zone before (June 2025) and during the construction work (July through September 2025). The construction work has recently focused on installing the building foundation that includes a facility wide concrete slab on grade, and isolated concrete block foundations for select major equipment systems. The steel support beams, exterior walls, and roof system are planned for installation during the timeframe of October and November 2025. At time of writing this report a significant completion of the steel support beams was achieved. The detailed design and construction of the START+ laboratory addition is funded by other project partners to support this work.

Figure 4. Photographs show the construction zone in progress for the START⁺ building expansion that will house the two-stage turbine rig and facility.

Task 2 – Design Motor Generator to Dissipate the Turbine Power

The Pennsylvania State University

Objectives

The objectives of this task are to create a request for quotation for a motor generator system to dissipate the turbine power, review all bids, and select the company that best meets the cost, schedule, and quality requirements of the program. Collaborate with the selected vendor to develop manufacturing drawings so the turbine and motor generator system layout can be completed.

Research Approach

As noted in the previous annual report, the START research group selected the company ACS to provide a dynamometer motor generator solution to dissipate the two-stage turbine power. The ACS proposal met all technical requirements and was cheaper than other vendor sales quotes. The purchase order from Penn State to ACS was successfully completed to have ACS perform the detailed engineering phase of the complete dynamometer system including the alternating current (AC) motor generator, gear box, oil system, variable frequency drive (VFD), and load bank, all of which are needed to dissipate the turbine power. Preliminary costs and timeline schedules associated with procuring each piece of the dynamometer system equipment noted above were then obtained from multiple vendors and reviewed. Two of the five vendors provided equipment solutions that were reasonably aligned with the project budget and schedule, while the other three vendor solutions were well above the available project budget.

The START team worked with ACS to size a 4,500-horsepower motor generator solution that can absorb the operating conditions of the START+ turbine. Specifically, two options were discussed and identified to support the operation of the dynamometer system. The two options for the method of operation include (1) a non-regenerative power mode and (2) a regenerative power mode. The first optional method includes a dissipative electrical load bank that is sized for the full 4,500 horsepower of the AC motor generator, in which all power being absorbed from the turbine by the VFD drive is electrically directed and dissipated into the outdoor load bank system. The second optional method includes a much smaller-sized load bank, in which most (or all) power being absorbed from the turbine by the VFD drive is directed back into the facility electrical switchgear system for medium voltage (4,160 V) that supports the electrical operation of the four large air compressors. The second option essentially recycles the power absorbed from the turbine and sends the power back to operate the air compressors, with any residual power being offloaded to the smaller-sized load bank. The electrical infrastructure design required to support both options was determined and provided to Penn State. At the time of writing this report, the START research group is preparing to present the two options to university administrators for evaluation to determine which of the two options will be acceptable and pursued.

The dynamometer system will mostly be used to absorb the power that is produced by the two-stage turbine during research testing. In some instances, while preparing for research testing, the dynamometer VFD system will be used to supply power to the AC motor in order to rotate the turbine shaft at relatively slow speeds (approximately 0 – 1000 rpm) without air flow. This infrequent style of operation in supplying power to drive the turbine shaft will be focused mainly on (1) confirming rotor dynamic balancing of the turbine rotating hardware assembly and (2) inspecting the operability and functionality of instrumentation sensors mounted on the test turbine. The START research team worked with ACS to confirm that this low-speed style of operation is suitable for the various equipment.

Work continued into Q2 with a focus on the preliminary design of the system components including component selection, sizing, and vendor pricing. The primary components include the large AC motor generator, VFD system, gearbox, high and low speed drivelines, electrical load bank, riser support structure, and cooling systems. Identifying the primary instrumentation and electronics controls logic necessary for safely operating the dynamometer system with the new START+ test turbine was also performed. A preliminary design review was then held in February of 2025 that summarized all identified components and their specifications. The START team then held preliminary internal meetings to begin preparations for procuring the large AC motor generator and VFD drive system.

Design of the dynamometer system was completed in Q3, and a detail design review meeting was held including Penn State START and ACS. A solid model drawing of the dynamometer system is shown in Figure 5 including the AC motor generator, gearbox, shaft drivelines, and support table system. A separate image is also shown of the VFD that will be used to control the AC motor generator. Purchase orders for long-lead items including the AC motor generator and VFD have been coordinated, and purchase order preparations for the remaining shorter lead-time equipment items are in

progress. The remaining equipment includes the gearbox system, a central electronic controller and computer system, a hydraulic oil skid, and a thermal conditioning coolant system.

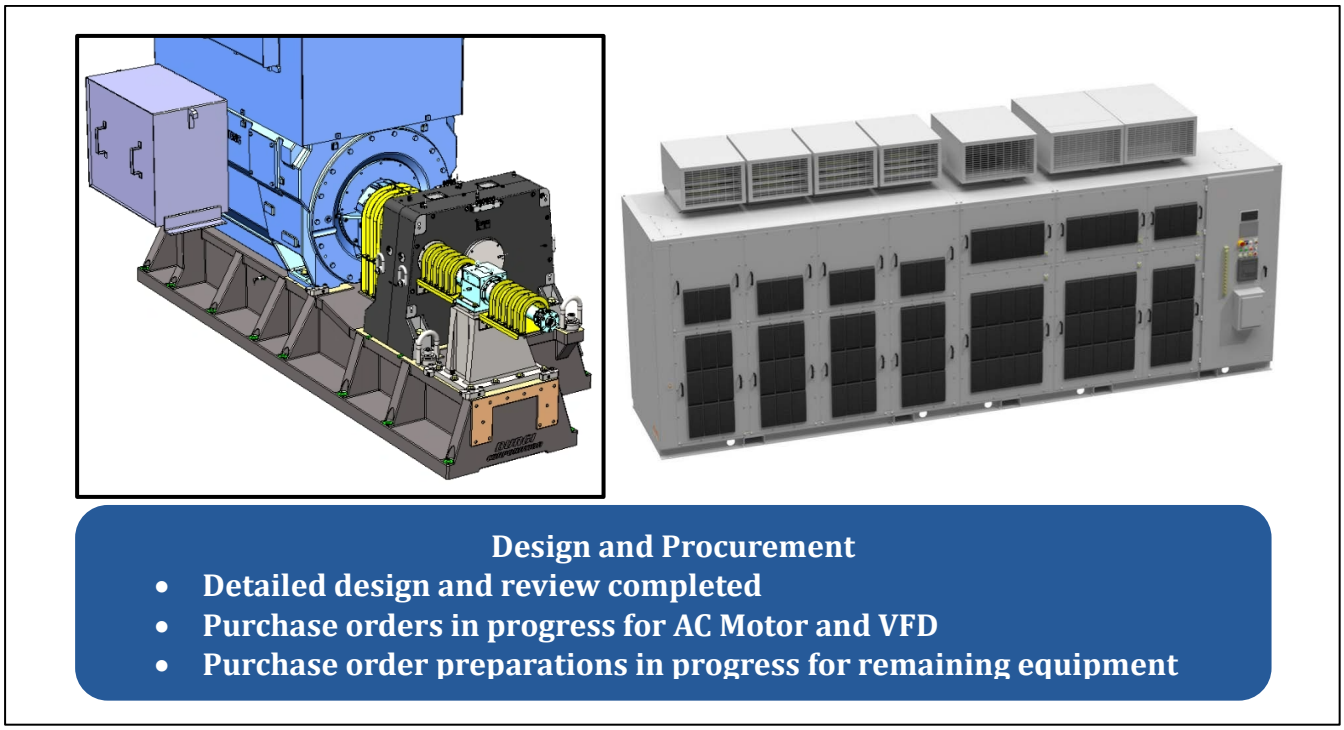

Figure 5. Drawing of the alternating current (AC) motor generator, gearbox, shaft drivelines, and variable frequency drive (VFD).

Recently, options were investigated for mounting the equipment system to a steel bed plate as shown in Figure 6 that is rigidly embedded into an isolated concrete foundation. During the current reporting period, the purchase of the equipment was divided into two separate acquisitions including one for the AC motor generator and VFD, and a second for the gearbox and subsystem equipment. The delivery estimate for all the equipment is in the latter half of 2026 corresponding to building occupancy.

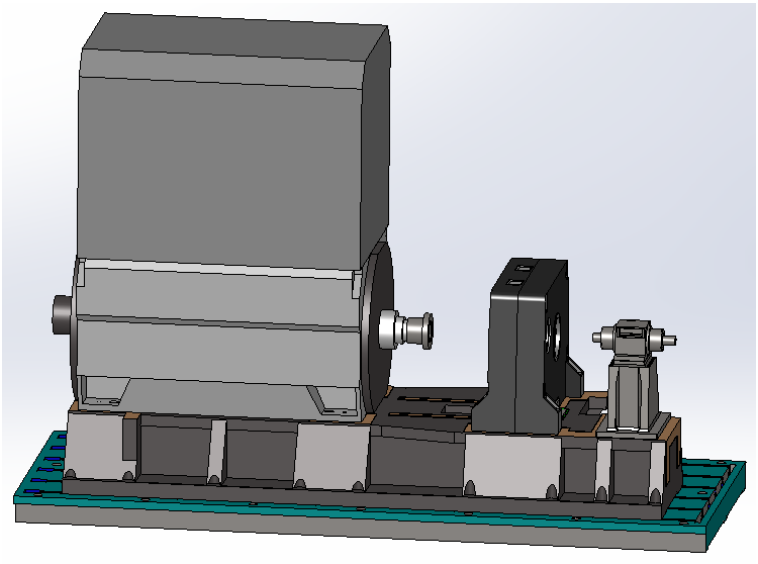

Figure 6. Drawing of the primary dynamometer equipment anchored to a steel foundation.

Task 3 – Order Remaining Air Compressor Components and Complete Manufacturing.

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Objectives

The objectives of this task are to (1) review manufacturing quality documents related to the compressor starters, VFD layout, cooler general arrangement drawings, and manufacturing reports, as well as to resolve non-conformances and approve final inspection reports, (2) attend factory performance testing and ensure the compressors meet all of the quoted performance metrics, review testing data such as hydrotests, flow, and pressure results, and (3) oversee the installation of equipment in START⁺ to ensure the compressors fit on their anchor bolts, are grouted in to place per the compressor vendor's requirements, and all lifting requirements are met.

Research Approach

The START team successfully processed a purchase order for the compressors. Manufacturing has continued as planned and the manufacturing of the outdoor cooler fan banks has been completed and delivered. Delivery of the air compressors and their accessories is still scheduled to coincide with the new START⁺ laboratory occupancy in mid-2026. A summary of the air compressor systems is provided in Table 1.

Table 1. Summary of the START+ Compressor Designs. START: Steady Thermal Aero Research Turbine.

Compressor Specification	Existing START	START+
Compressor Stages	2	3
Total Horsepower	3000	9000
Flow Rate per Unit	12 lbm/s	10 - 11 lbm/s
Discharge Pressure	60-80 psia	125 psia, 165 psia
Discharge Temperature	225°F	225°F, 110°F
Number of Compressors	2	2 + 2 = 4
Number of Outdoor Fluid Coolers	2	7

Turbine Main Gas Path Flow
Turbine Cooling Air Flow + Supplemental Flow

As noted in Task 2, the dynamometer system has completed the detailed design phase and procurement of the equipment items is in progress. Purchase orders for long-lead items are being processed this November, with mid- and short-lead items being purchased in 2026.

Conceptual design work on the bearing system was performed with the vendor Synchrony during the current reporting period. A design requirements document was created by the START team and was provided to Synchrony, which outlined the goals, objectives, and key design requirements for the new turbine bearing system. The requirements included the turbine shaft operating speed range, physical design space, and rotor dynamics analysis. The magnetic bearing system progressed to the preliminary design phase. Continuing meetings are being held with the bearing vendor to review design topics including rotor dynamics analysis, bearing physical sizes, and load capacities.

The combustion heater also continued to progress through its design phase into detailed design. During the current reporting period, weekly meetings continued with the combustor vendor. The design of the combustor system has been developed to include process and instrumentation diagrams, preliminary chamber drawings, and the natural gas delivery stand. The delivery of the complete combustion system is still on track for delivery to coincide with the new START+ laboratory occupancy in mid-2026.

As noted in Task 1, design work is continuing for the complete network of air piping, valves, and the exhaust silencer system.

The chiller system has been delivered to the new START+ facility site. This chiller will enable future operation of delivering cooling air to the test turbine down to 40°F. A status summary of all major equipment systems is shown within Figure 7 for the current reporting period.

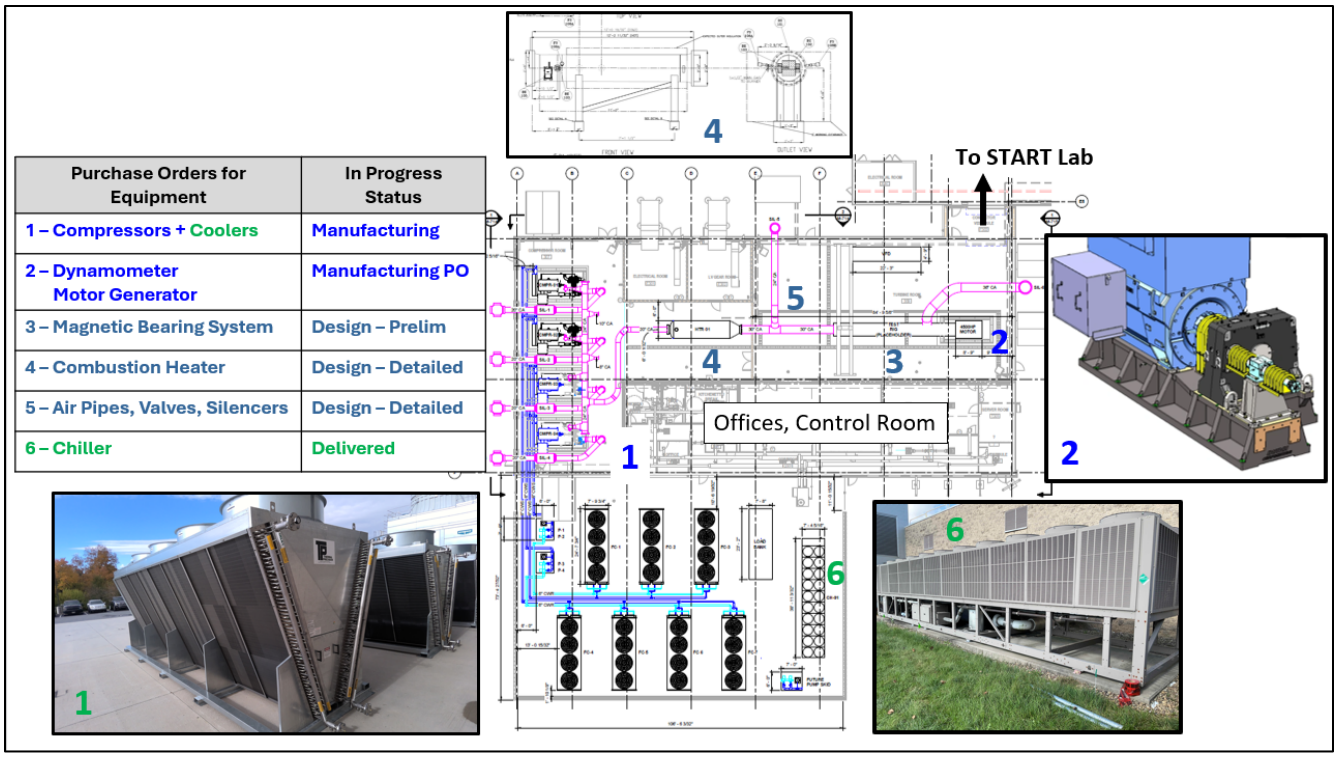

Figure 7. Status summary of the main equipment systems. START: Steady Thermal Aero Research Turbine.

Milestones

Milestone	Vendor	Completion Date
Dynamometer Design Purchase Order	ACS	November 5, 2024
Magnetic Bearing System Purchase Order	Synchrony	December 19, 2024
Turbine Test Section Purchase Order	Belcan	February 27, 2025
Building Contractor Selected	Poole Anderson	March 20, 2025
Construction Kickoff Meeting	Poole Anderson	April 17, 2025
Combustion Heater Purchase Order	Alstam	April 21, 2025
Building Construction Started	Poole Anderson	June 25, 2025
Air Pipes, Valves, Silencers Design Purchase Order	Burns & McDonnell	August 8, 2025
Coolers Delivered	F.S. Compression	November 12, 2025
Dynamometer Procurement	ACS/Innomotics	Pending

Major Accomplishments

Penn State completed the open-bid process for construction companies to submit their proposal packages. Penn State reviewed all proposals and issued an official contract for the construction work to begin in the next reporting period. Poole Anderson began work in June of 2025, with a projected completion date of May 2026.

Design proposals were received and reviewed by Penn State from multiple engineering design firms to perform the main design work on the START⁺ turbine integration plan. Upon reviewing all proposals for acceptable cost, schedule, and design content, the engineering firm Belcan was selected. Penn State START team held a kick-off meeting with Belcan for

the new turbine rig design work that focused on a review of the project goals, objectives, requirements, and schedule. A design requirements document was created by the START team and was provided to Belcan, which outlined the purpose and key design requirements for the new turbine test section. START and Belcan began the conceptual design process. START staff continues to hold weekly meetings with Belcan in preparation for a preliminary design review this to held in December 2025.

The Penn State START team also worked with Pratt & Whitney to complete a design kick-off meeting related to the two-stage turbine design and integration plan. This meeting included several team members from START and Pratt & Whitney to begin review of the turbine hardware components. Weekly meetings are currently being held including START and Pratt & Whitney to identify and design specific geometry changes required to enable the engine hardware to be installed within the new START^{+} rig.

Penn State submitted a purchase order to BMCD to perform the detailed design phase of the air piping and equipment integration to be located upstream and downstream of the turbine test section. The detailed design to integrate these major equipment systems is now in progress. A concept equipment layout within the new turbine room was also completed including the air piping, turbine test section components, and supporting equipment. Weekly meetings are currently in progress.

A vendor was selected for the combustion heater. After reviewing proposals from multiple vendors, Alstam was selected for design and manufacturing. Biweekly meetings are currently underway. A preliminary design review meeting has been completed. Delivery is anticipated for February 2026.

A purchase order was issued to ACS to perform the detailed engineering phase of the complete dynamometer system to dissipate the turbine power. The detailed design of the dynamometer system was completed, and a detail design review meeting was held including Penn State START and ACS. Purchase orders for long lead-time items including the AC motor generator and VFD were coordinated, and purchase order preparations began for the remaining shorter lead-time equipment items. Long-lead item purchase orders are anticipated for November 2025.

The manufacturing of the compressors continued as planned, and the manufacturing of the outdoor cooler fan banks was completed and delivered. Procurement of the dynamometer system equipment is in progress. The magnetic bearing system continued progress through its preliminary design phase. The combustion heater also continued to progress through its design phase into detailed design.

Publications

None.

Outreach Efforts

Dr. Reid Berdanier presented updates on this project to gas turbine industry representatives from Pratt & Whitney, Solar Turbines, Siemens Energy, Honeywell Aerospace, Mitsubishi Heavy Industries, GE Aerospace, GE Vernova, EPRI, Howmet Aerospace, IHI Corporation, Baker Hughes, Collins Aerospace, and more. Similarly updates for U.S. government agencies were shared to the Department of Energy, National Aeronautics and Space Administration, Office of Naval Research, Air Force Research Laboratory, and National Science Foundation.

Awards

Dr. Reid Berdanier was elected as an Associate Fellow of the American Institute for Aeronautics and Astronautics (AIAA).
Dr. Karen Thole was awarded the 2025 Kate Gleason Award from the American Society of Mechanical Engineers (ASME).

Student Involvement

Although no formal student support was included in this project for this reporting year, the students in the START Lab are provided regular updates on the status of this project through weekly team meetings.

Plans for Next Period

- Oversee and complete construction of the new START^{+} laboratory building addition.
- Continue working with Pratt & Whitney and Belcan to complete the integration design of the two-stage turbine and primary test section.

- Continue working with BMCD to complete the detailed design of the rig air piping and equipment integration.
- Integrate major equipment, including industrial compressors and associate subsystems.
- Begin procurement of test section hardware for a two-stage turbine.
- Execute purchase orders for motor/generator and associated electrical systems.

Disclaimer

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