Project 092 Advanced Two-stage Turbine Rig Development

The Pennsylvania State University

Project Lead Investigator

Reid Berdanier
Associate Professor
Department of Mechanical Engineering
The Pennsylvania State University
START Lab, 3127 Research Drive
State College, PA 16801
814- 863-3972
rberdanier@psu.edu

University Participants

The Pennsylvania State University (Penn State)

- P.I.: Dr. Reid Berdanier
- FAA Award Number: 13-C-AJFE-PSU-104
- Period of Performance: January 1, 2023, to March 14, 2025
- 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 two-year effort, the Federal Aviation Administration (FAA) provided $2,000,000 and matching funds of $2,125,000 were provided by Pratt & Whitney® and Penn State.

Investigation Team

Reid Berdanier (P.I.), Management, reporting, and oversight of all technical tasks
Karen Thole, Affiliate Professor, Tasks 1–3
Tom Houck, Project Manager, Tasks 1–3
Assoc. Res. Prof. Michael Barringer, Research Advisor, 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

® Pratt & Whitney is a registered trademark of RTX Corporation, Farmington, Connecticut.

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

Task 1 – Oversee New Turbine Rig Design

The Pennsylvania State University

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 new building construction (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 ft^2 of space to the START Lab to house the new research equipment, rig, and turbine.

Research Approach

The START Lab, Penn State's lead architect, and the Office of Physical Plant (OPP) drafted a specific request for proposal (RFP) to hire a new engineering firm to create the START⁺ building design. After reviewing proposals from firms all over the United States, Gannett Fleming (GF) was selected. They were the lowest cost and had the best technical proposal. A kickoff meeting was held on February 5, 2024, and since the team has made significant progress. The team worked together to layout all rooms and equipment using cloud drafting software and reviewing them during weekly updates. During early 2024, the floor plan, building concept, and storm water preliminary designs were completed that are shown in Figures 1 through 3.

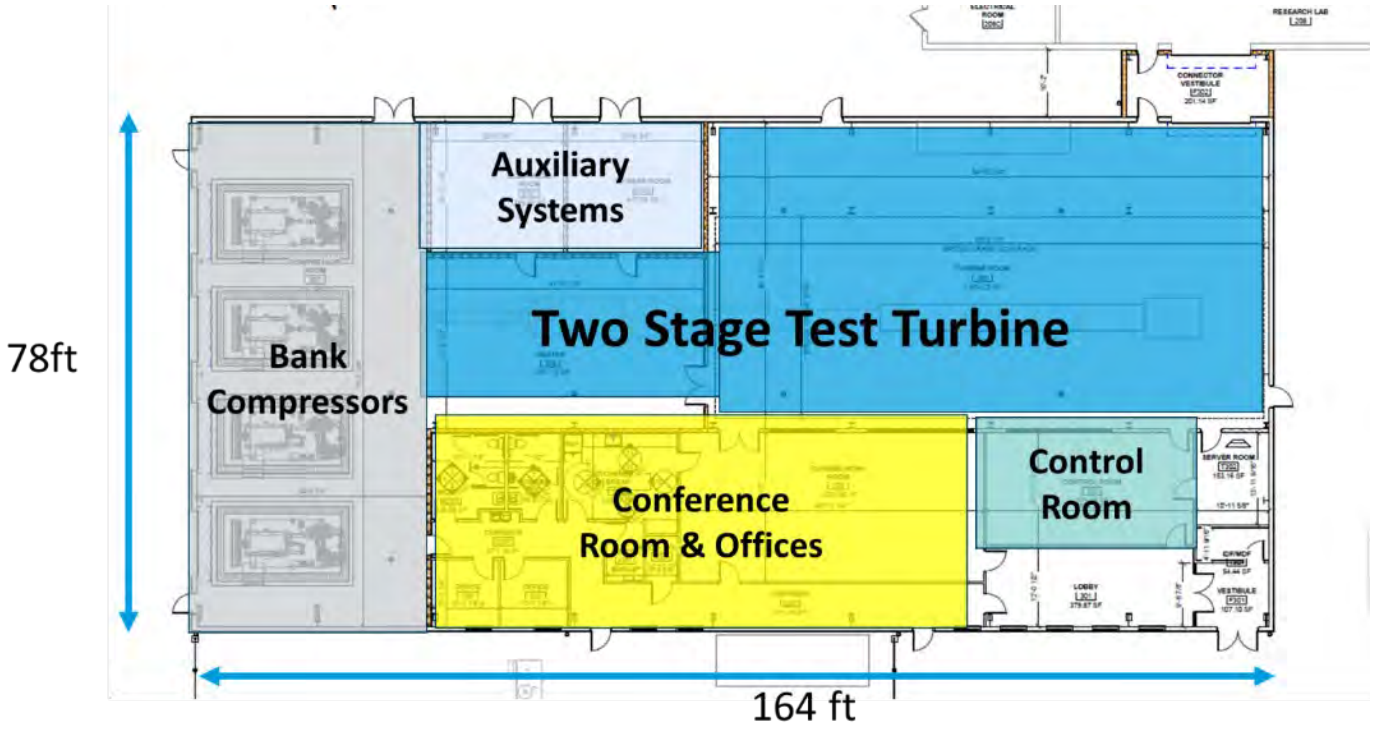

Figure 1. Floor plan of START⁺.

Figure 2. Conceptual START⁺ building.

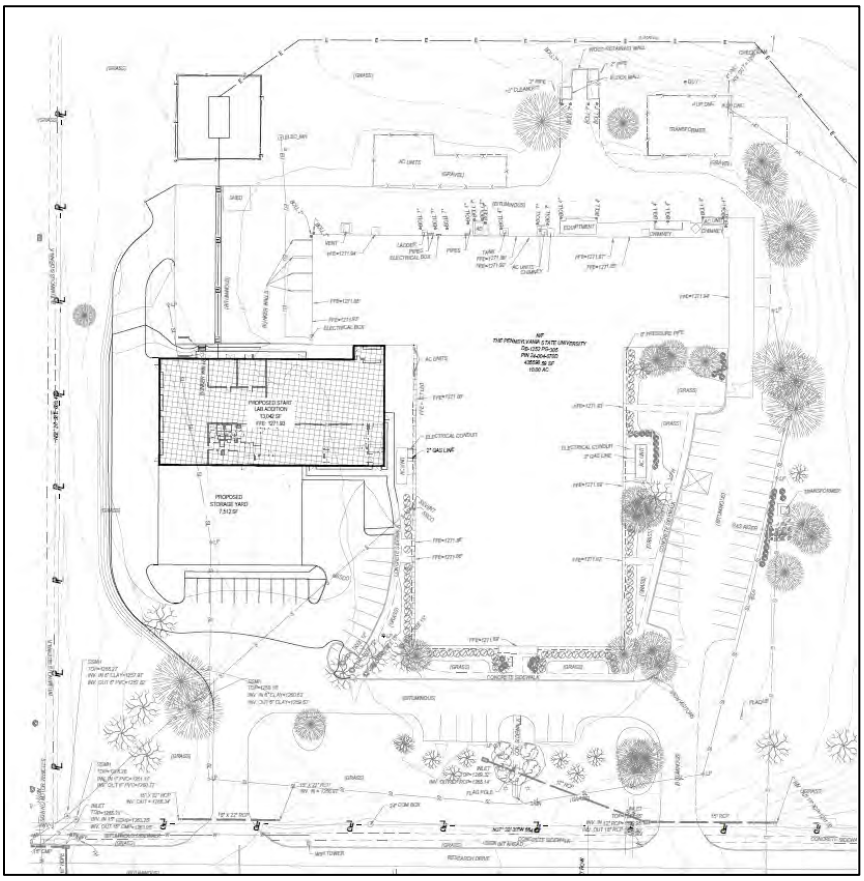

Figure 3. First submission of the START⁺ stormwater design.

The geotechnical engineering study of the START⁺ property site was generated during 2024 by GF related to the project critical path for the storm water design permit. The study was submitted to the local municipality government for their review and was approved. Water infiltration testing within selected basins on the property site was also completed. Because of the approval of the geotechnical study by the local government and the satisfactory infiltration testing results, the legal permit for the storm water management design was issued. Final land development permits by the local municipality are anticipated for issue during late 2024.

The START research group also worked during 2024 with GF to accomplish the 60%, 90%, and 100% completion milestones for the detailed design of the START⁺ laboratory addition. Significant progress was made on the detailed designs of the building addition, property stormwater management, and electrical systems including developing all details of the facility architecture, civil and structural designs, electrical and lighting plans, plumbing, fire safety, and telecommunications. Example excerpts from the detailed design completion package are shown in Figure 4. An updated solid model of the new START⁺ building addition is shown in Figure 5. After the detailed design 100% completion milestone was met, the project began coordinating the open-bidding process during the end of 2024 for construction companies to submit their proposals.

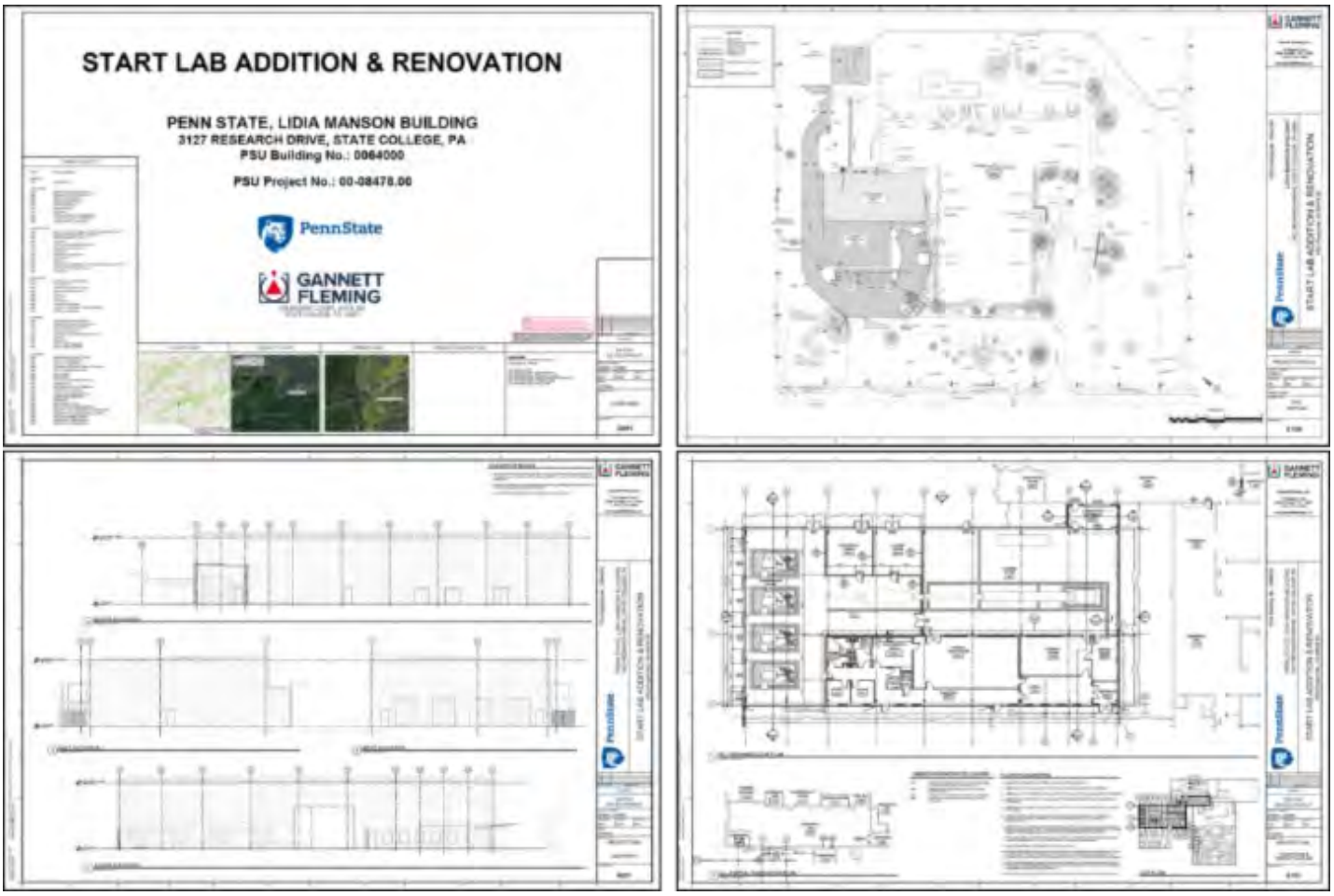

Figure 4. Detailed design of START⁺ (example excerpts).

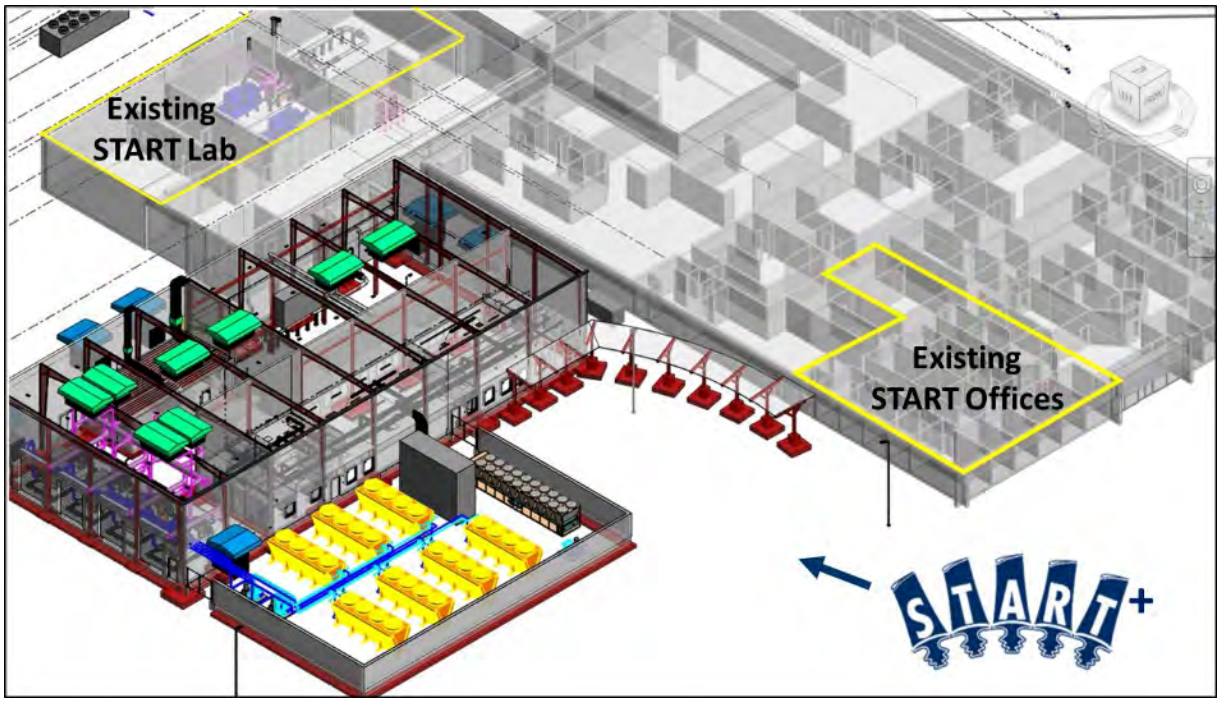

Figure 5. Updated solid model rendering of the new START⁺ building addition.

A schedule was developed in 2024 by the Penn State START team that enables the selection of an engineering design firm by the end of 2024 to begin design work on the START⁺ turbine integration plan. This 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 6. A statement of work (SOW) and RFP were generated by the START team which were then submitted to multiple engineering design firms for review. The proposal bids from the design firms are due to Penn State at the end of November 2024 at which time they will be evaluated enabling the selection of the final design firm to take place.

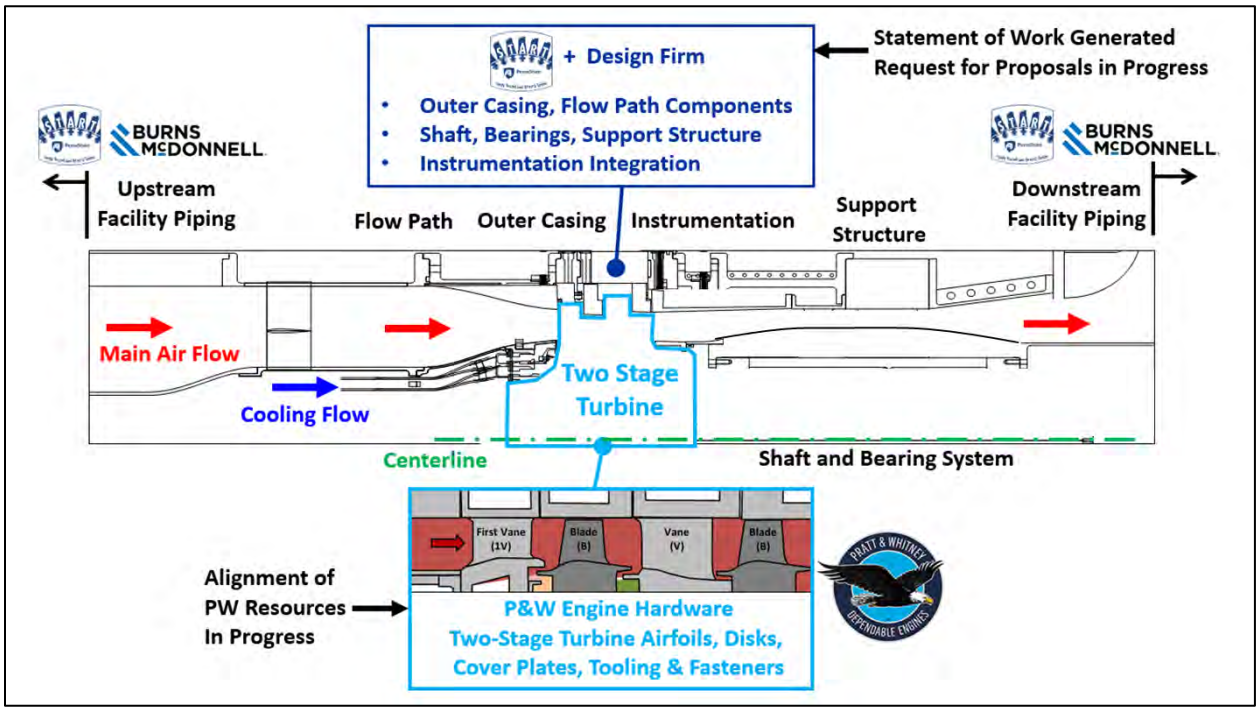

Figure 6. Design scope for the START⁺ two-stage turbine test section (cross-section diagram).

An interface control plan was also developed in 2024 related to the ownership of hardware design for the START⁺ two-stage turbine test section. All facility piping and equipment located upstream and downstream of the turbine test section will be the design responsibility of the Penn State START research group and design firm Burns and McDonnell (BMCD). The two-stage turbine hardware 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 will be responsible for designing any modifications to enable the engine hardware to be installed and operate within the START⁺ turbine test section. The hardware components within the turbine test section that define the outer casing walls, inner flow path walls, rotor shaft and bearing system, and bearing support structure will be the responsibility of the START research group and selected design firm. A summary of this interface control plan is shown in Figure 6.

The preliminary design of the rig process and equipment arrangements were also finalized during 2024 for the pipe network related to the large air compressors. The pipe network includes the air flow pipes and equipment necessary to deliver air flow from the compressors to the turbine test section, as shown in Figure 7. For each compressor, there are three main pipe branches including an inlet, exit, and unloading bypass. The inlet pipe branch directs air flow from outdoors to the compressor inlet using an intake filter housing located outdoors, a muffler silencer located indoors, and interconnecting pipes. The exit pipe branch directs airflow from the compressor exit to the turbine using a flow control valve and interconnecting pipes all located indoors. The unloading bypass branch is used temporarily each day during the startup and shutdown of the compressor and includes a flow control valve and muffler silencer both located indoors, and an exhaust pipe located outdoors. In addition to completing the preliminary design of the compressor pipe network, a RFP document was generated by the START research group and was submitted to BMCD that enabled the transition from preliminary design to the detailed design phase of their project work scope. Their proposal package was then received and is currently being reviewed by the START team to enable the detailed design work to begin as soon as possible.

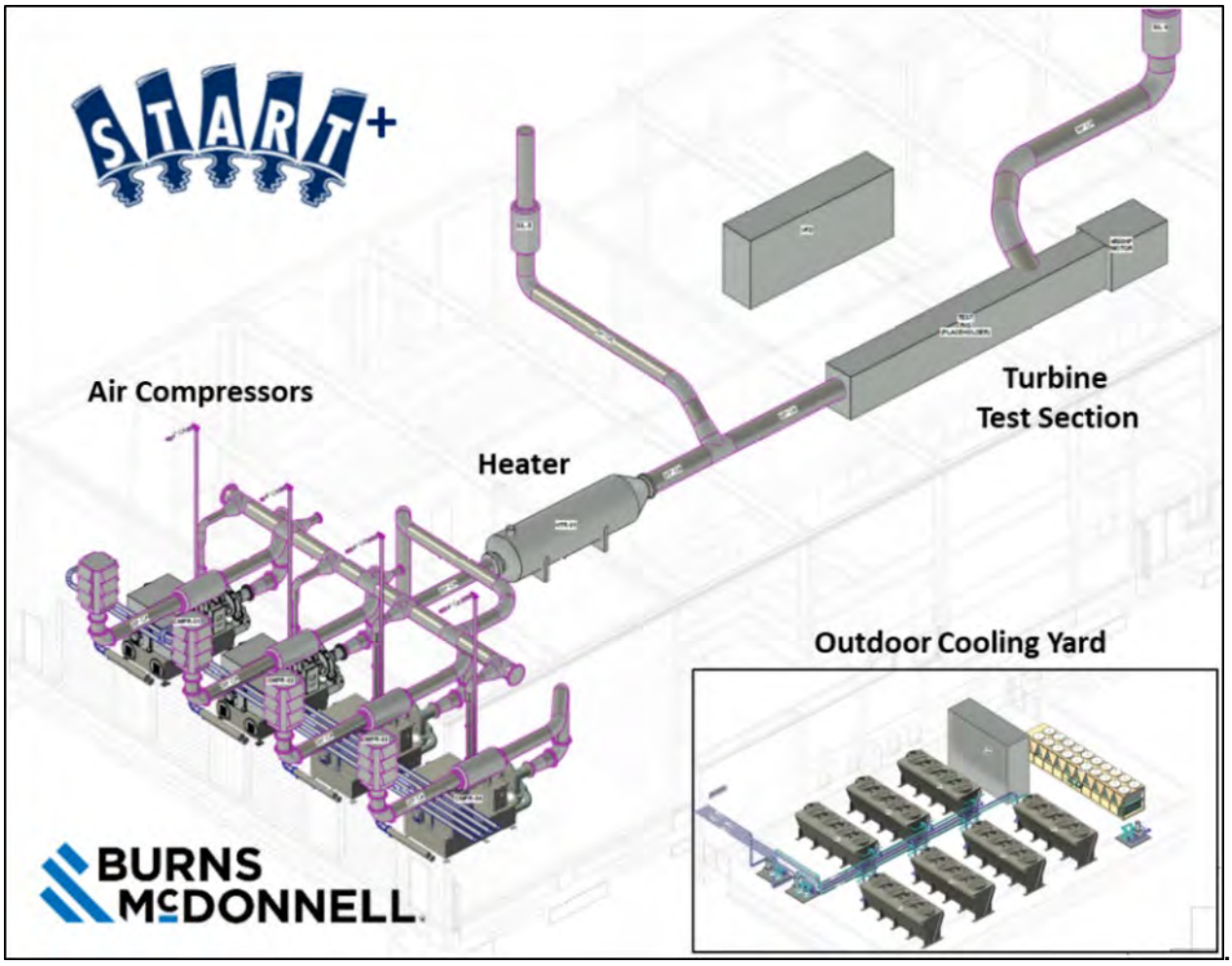

Figure 7. Preliminary design layout of the START⁺ rig piping and equipment integration.

The baseline sound study for outdoor noise on the property was also performed. This baseline study was performed by the START research group and the acoustics consulting firm SLR, which included sound level measurements at multiple locations on the property while the existing START laboratory had its equipment active in operational mode. The results of the baseline study indicated acceptable sound levels within the 54-62 dBA range as shown in Figure 8. The baseline results were combined with the sound level specifications of the new START⁺ equipment items in order to establish a total sound model and map for both the existing START rig and the START⁺ rig operating simultaneously. The new sound model and map were completed by SLR during 2024.

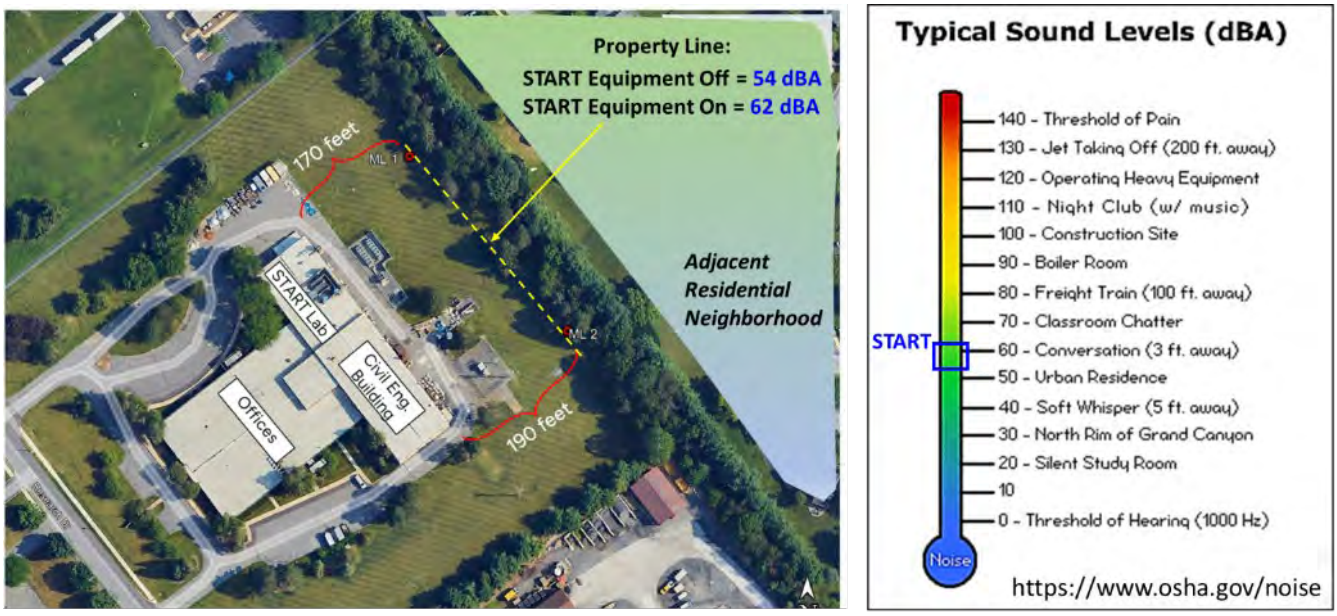

Figure 8. A baseline sound study was conducted for the existing START lab operation.

The START team worked with the exhaust vent silencer vendor to iterate on the preliminary design of the main exhaust silencer for air flow exiting the new START+ turbine. The focus was centered on the base structure and overall height of the vent silencer stack. The base structure will be designed for high temperature capability to avoid excessive thermal stress to the concrete foundation. The height of the silencer outlet from ground level was shortened to help reduce direct line of sight to the property line. The acoustics consultant firm SLR that was added to the team used their baseline sound survey results of the existing START lab operation and combined the results with the sound specifications and layout of the new equipment for the START+ addition. The combined acoustics information was used to create a new detailed sound model of the entire START and START+ operation, which was used to identify additional noise mitigation measures needed to meet the sound ordinance for the property. A few of these noise mitigation measures include (1) extending the sound curtains on the existing roof platform to completely obstruct direct line of sight of all equipment items, (2) wrapping the existing START facility vent silencers with additional noise reduction material, and (3) installing at ground-level sound curtains adjacent to specific pieces of heat rejection equipment.

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

To help with the mechanical equipment design for START+, the team continued to collaborate in 2024 with BMCD. BMCD is a large engineering firm with past experience in designing turbine test facilities similar to START+. BMCD and START selected ACS to provide a motor generator solution. The ACS proposal met all technical requirements and was over $1 million less expensive than other vendor quotes. ACS will provide a 4,500-hp motor generator solution shown in Figure 9 that can absorb the targeted testing conditions from the START+ turbine. The solution also includes the auxiliary equipment required such as a gear box, oil system, variable frequency drive, and load bank to dissipate the power. The START Lab confirmed with the West Penn Power electric company that sending the turbine power back to the local

electricity grid is not an option for this project. West Penn Power requires continuous operation throughout the year. A purchase order was submitted to ACS in 2024 to perform the detailed engineering phase of the motor generator system. A preliminary layout plan of the motor generator equipment was also developed including the physical arrangement of the equipment components in the new turbine room as shown in Figure 10. An official project kickoff meeting was also held to review the preliminary design concept of the motor generator system components and overall project schedule.

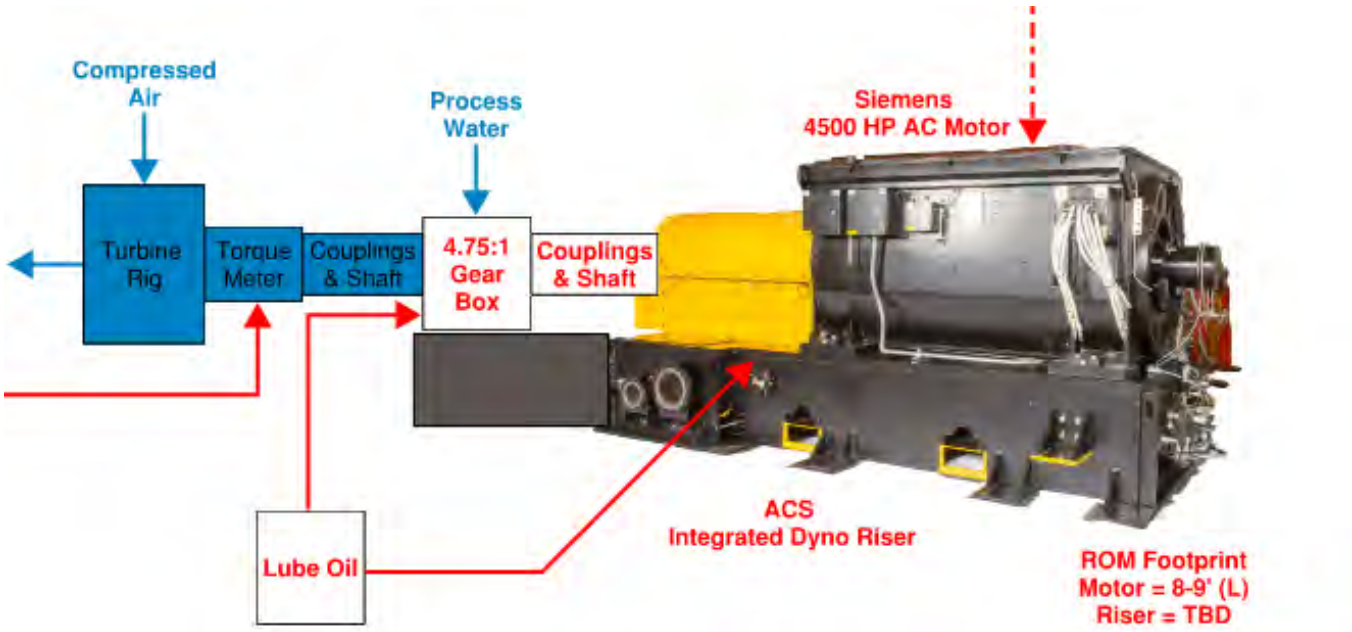

Figure 9. The ACS motor generator solution for START+ turbine power control.

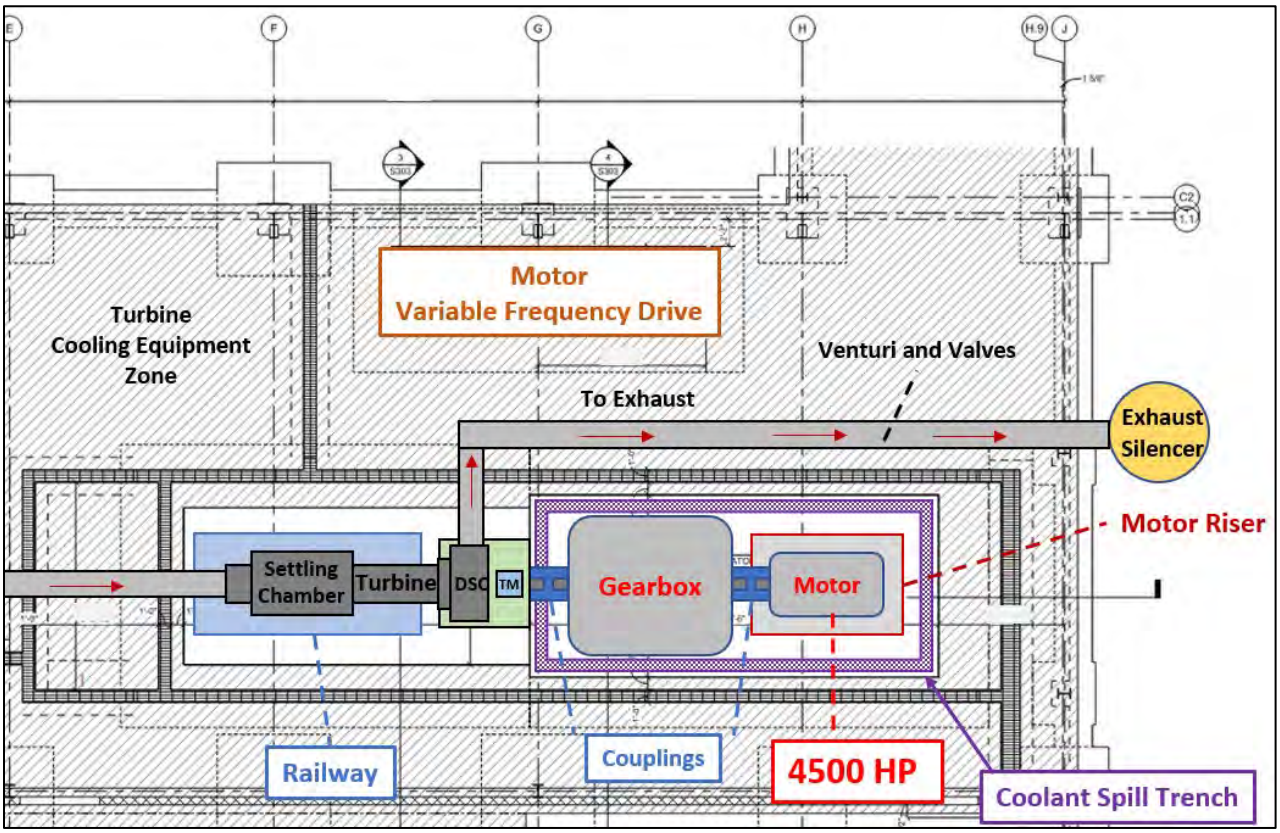

Figure 10. Preliminary layout of the motor generator equipment in the START⁺ turbine room.

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

The Pennsylvania State University

Objectives

The objectives of this task are to (1) review manufacturing quality documents related to the compressor starters, variable frequency drive (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 research group continued to work in 2024 with the compressor manufacturer F.S. Elliott to complete the engineering design of the new air compressors and their subsystem equipment. Drawings of the compressors, motors, motor starters, and electronic control systems were obtained and reviewed. Drawings of the air intake systems, sound silencers, valves, and cooling systems were also obtained and reviewed. An updated sales quotation was obtained to allow a new purchase order to be submitted for manufacturing the compressors and subsystem equipment. A relatively small (5%) inflationary increase in cost was noted for the compressors in the updated 2024 sales quotation, compared to the original preliminary August 2023 quotation. However, this cost adjustment was able to be managed without any change overall project cost. A summary of the new START⁺ compressor designs is shown in Table 1 in relation to the existing START lab compressors. A drawing of the new F.S. Elliott air compressor that will be installed in START⁺ is shown in

Figure 11 in its three-stage centrifugal configuration, along with selection notes for the compressor motor and motor starter.

Table 1. Summary of the START⁺ compressor designs.

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

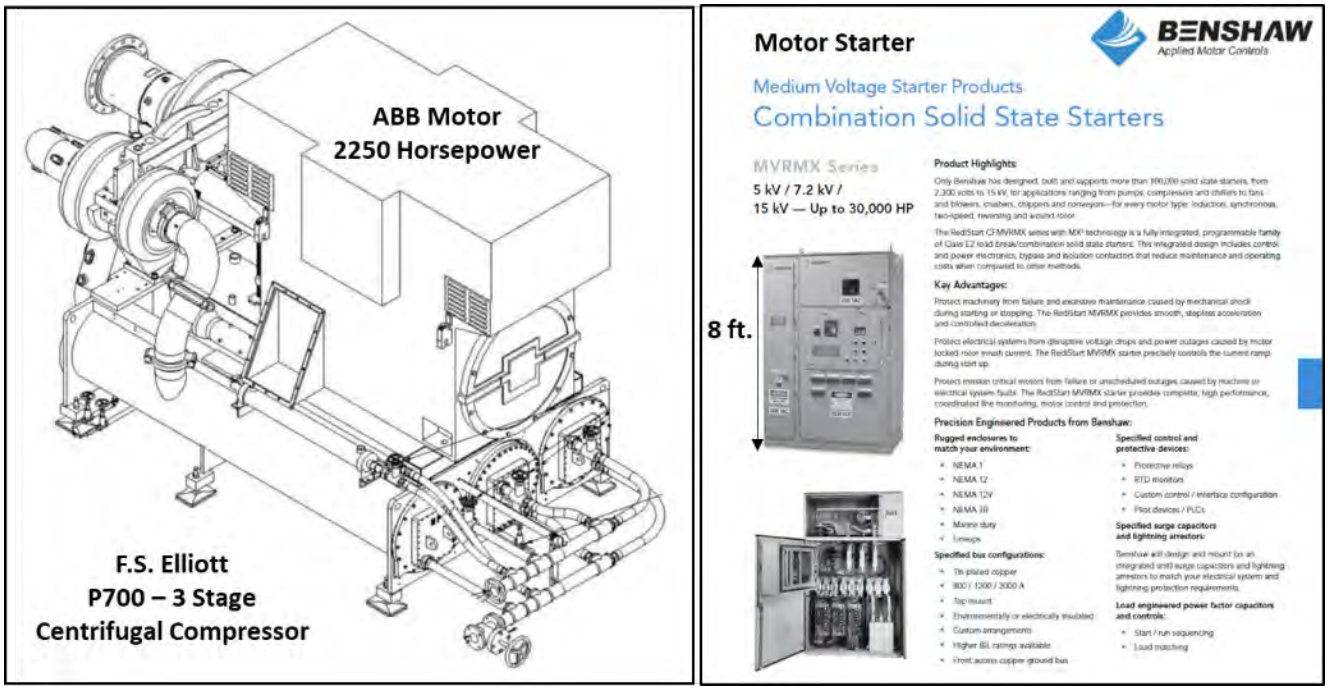

Figure 11. New START⁺ air compressor with motor and motor starter.

GF and West Penn Power completed the high voltage electrical design for supplying power to the four new air compressors. Preliminary sales quotations with lead times were obtained including 40-55 weeks for the main new 46 kV transformer that will be housed in a new substation yard shown in Figure 12. The transformer and switch gear equipment will be ordered during the initial phase of the building construction so that the overall schedule of the START⁺ project is not impacted.

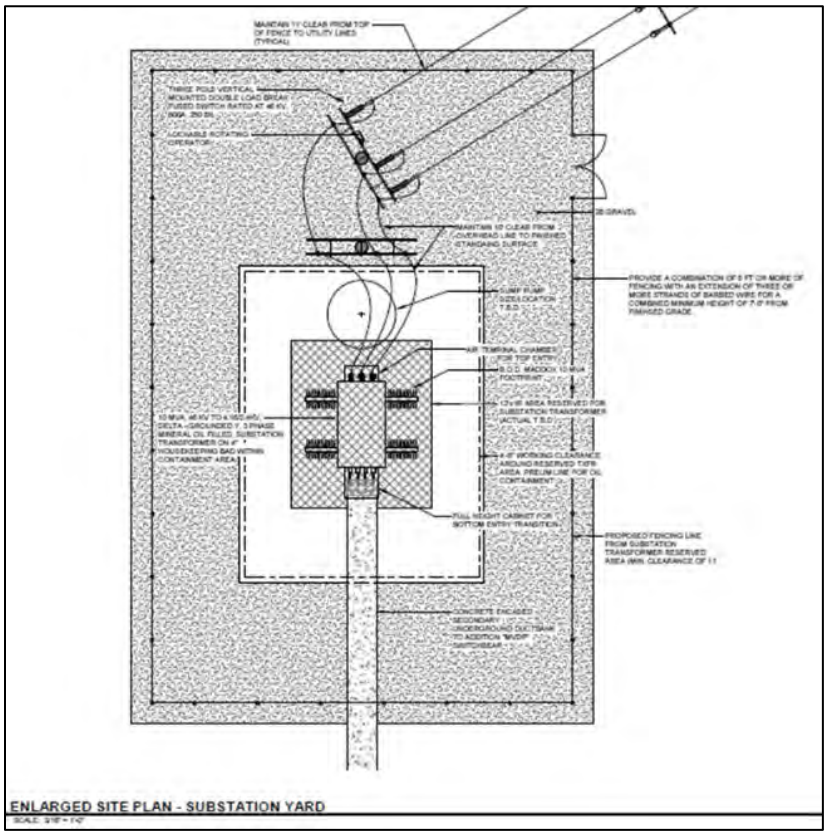

Figure 12. Design of the new electrical substation with main 46 kV transformer for the air compressors.

Milestones

Milestone	Completed or planned date
Design Development Kickoff with Gannett Flemming	February 1, 2024
60% Detailed Design Completed	March 18, 2024
90% Detailed Design Completed	July 9, 2024
Geological (Storm Water) Review Completed	July 18, 2024
100% Detailed Design Completed	August 30, 2024
Board of Trustees Approval	September 6, 2024
Compressors Ordered	October 31, 2024
Parking Study Completed	November 1, 2024
Groundbreaking Ceremony	November 8, 2024
Township Land Development Permit Submitted	November 11, 2024
Project Released for Bidding (Pending)	December 9, 2024

Major Accomplishments

Task 3.1- Review manufacturing quality documents related to the compressor starters, VFD layout, cooler general arrangement drawings, manufacturing reports, as well as, to resolve non-conformances and approve final inspection reports

GF was selected as the START+ building engineering design firm. They immediately began working on the program in February 2024 and kept the new building project on schedule.

An interface control plan was developed by the START research group related to the ownership of hardware design for the START+ two-stage turbine test section. The preliminary design of the rig process and equipment arrangements were also finalized for the pipe network related to the large air compressors. A RFP document was generated by the START group and was submitted to BMCD to transition from preliminary design to the detailed design phase of their project work scope. The START research group and GF completed the 60%, 90%, and 100% detailed design milestones for the new START+ building addition. The START group and SLR completed the baseline sound study for the existing START lab operation, and simultaneously acquired detailed sound level specifications for the new START+ equipment that were incorporated into the new sound model of the entire laboratory operation.

A schedule was developed by the Penn State START team that enables the selection of an engineering design firm by the end of 2024 to begin design work on the START+ turbine integration plan. A SOW and RFP were generated by the START team which were then submitted to multiple engineering design firms for review. The START team generated a SOW and RFP related to the detailed design phase of the rig piping and equipment integration. Both the SOW and RFP were submitted to BMCD for their review, and their proposal package was then received and is currently being reviewed. The START team and GF met the 100% completion milestone for the detailed design of the START+ laboratory building addition including the final design details of the building addition and electrical systems. The geotechnical engineering study of the START+ property site was completed related to the project critical path for the storm water design permit in which water infiltration testing within selected basins on the property site were completed.

Task 3.2 - 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

START and BMCD selected ACS to provide the turbine power control solution. It will be a 4500-hp motor generator with associated equipment that will maintain the speed of the turbine and extract the energy from its shaft. A purchase order was submitted to ACS for the detailed engineering phase of the project to design the electrical motor dynamometer, gear box, oil system, variable frequency drive, and load bank to dissipate the power.

Task 3.3 - 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

An updated sales quotation was obtained for the new air compressor systems and their cooling systems to allow a new purchase order to be placed for their manufacturing. The purchase order for manufacturing was submitted in 2024.

All of the equipment details were reviewed necessary for submitting purchase orders for the engineering phase of (1) the ACS turbine motor generator system, (2) the heater chamber and process combustion system, and (3) the conceptual design of the new magnetic bearing system for the turbine rotor shaft. The purchase orders for the engineering phase of these equipment items will be submitted at the end of 2024.

Publications

Pennsylvania State University. (2024). Plan advances for addition, renovation to build START+ Lab at CATO Park. https://www.psu.edu/news/administration/story/plan-advances-addition-renovation-build-start-lab-cato-park

Outreach Efforts

Dr. Karen Thole presented in 2024 an update on the project to the American Institute of Aeronautics and Astronautics (AIAA) Science and Technology Forum and Exposition on January 9, 2024. The conference included multiple government agencies, academia, and industry representatives. On March 11, 2024, Dr. Anna Oldani, Arthur Orton, and Joshua Glottmann (all representing FAA ASCENT) visited START. Dr. Thole and the START team gave an update on the project to them along with the other START Ascent Grant. Finally, during the first quarter of 2024, the project was reviewed with multiple industry partners. The project was reviewed with Solar Turbines on January 18, 2024, during the semiannual

Center of Excellence Review. During the 2024 period, multiple Pratt & Whitney executives, including Geoff Hunt, Senior Vice President of Engineering were given updates on the project during visits to the lab.

During June 2024, the project was also presented to the several people that visited the START laboratory from the U.S. Department of Energy (DOE) National Energy Technology Laboratory including John Crane (Technology Manager). In August 2024, this project was presented to visitors from National Aeronautics and Space Administration (NASA) and Pratt & Whitney.

Dr. Reid Berdanier presented this work as part of program discussions at the Turbine Engine Technology Symposium in September 2024, in collaboration with the Propulsion Instrumentation Working Group. Dr. Berdanier also shared updates on this project at a DOE meeting in September 2024. Dr. Berdanier and Dr. Meier shared updates on the progress at a NASA meeting in October 2024.

In November 2024, an event was held at Penn State to celebrate the formal beginning of development efforts for a new construction project to house the equipment outlined in this project. The celebration was well-attended by guests from across Penn State, including the Board of Trustees, Deans, Vice Presidents, and University President. A collection of executive guests from Pratt & Whitney were also in attendance, including Senior Vice President Geoff Hunt and Senior Vice President of Engineering Michael Thacker. This event was also acknowledged through a local news report: https://www.wtaj.com/news/local-news/penn-state-announces-expansion-to-start-lab-to-expand-research/

Awards

None.

Student Involvement

Although no formal student support was included in this project for the 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

- Complete the detailed design of the two-stage test turbine.
- Begin procurement of the turbine components.
- Complete the designs of instrumentation including cameras and efficiency traverse.
- Attend weekly construction review meetings (Penn State START and OPP team) to ensure that the schedule and budget remain within the plan.
- Solve any issues as they arise between the new building contractor and Penn State OPP.
- Facilitate planning installation between the contractor and equipment vendors.
- Review quality documents to verify that all drawings and standards by the construction firm are maintained.
- Conduct walkthrough inspections with the design firm to ensure that drawing requirements and tolerances are within specifications.

During the next reporting period, the START team will also perform the following main steps to accomplish the goals and objectives of the project.

1. Oversee the beginning of construction on the new laboratory building addition.
2. Work with Pratt & Whitney and the selected design firm to begin the integration design of the two-stage turbine and primary test section.
3. Work with BMCD to begin the detailed design of the rig piping and equipment integration.
4. Oversee manufacturing and designing the major equipment items including the air compressors, cooling systems, motor generator, bearing system, and combustion heater.