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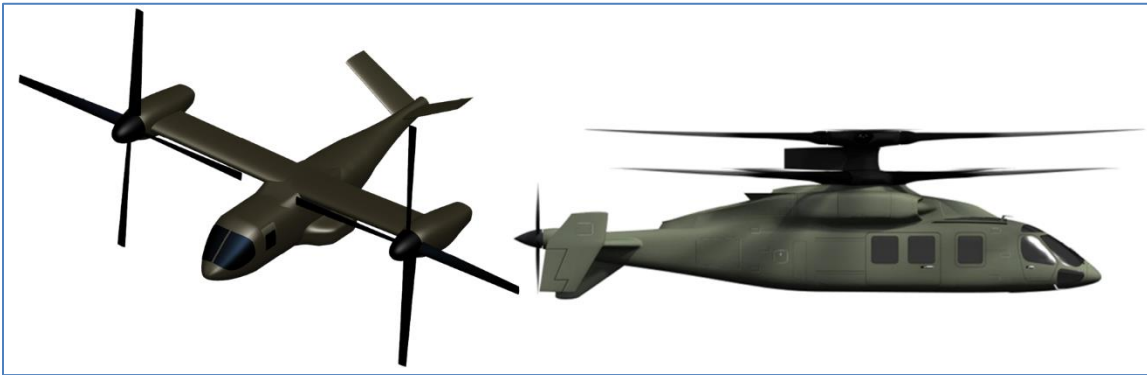
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## 1 Summary

Current and future US Army rotorcraft will rely on significant technological advancements to deliver improved performance capabilities to the future warfighter of tomorrow. One critical needed technology is an advanced variable speed power turbine (AVSPOT) design. A robust power turbine (PT) design, capable of high-efficiency operation between 55-105% speed provides a versatile power system that is compatible with the types of future rotorcraft configurations, shown in Figure 1-1, that are currently being studied for Future Vertical Lift (FVL) applications.



**Figure 1-1: AVSPOT technology enables next-gen rotorcraft concepts to meet FVL goals.**

To conduct system-level research on the technologies required to enable this capability, the U.S. Army Aviation Development Directorate (ADD), in conjunction with NASA, issued a broad agency announcement (BAA) to industry. The goal of this BAA was to identify and mature technologies for ADD and NASA to provide to both future warfighter and civil aviation applications. GE Aviation entered into a Technology Investment Agreement (TIA No. W911W6-12-2-0012) in 2012 and provided the personnel, supplies, services, and facilities necessary to conduct research and development efforts into the design, fabrication, and validation testing of an AVSPOT rig. The research executed under this TIA builds on the research conducted with ADD in 2005 on the Advanced Power Turbine (APT) program. That program successfully advanced the state of the art in conventional PT design in a similar size class.

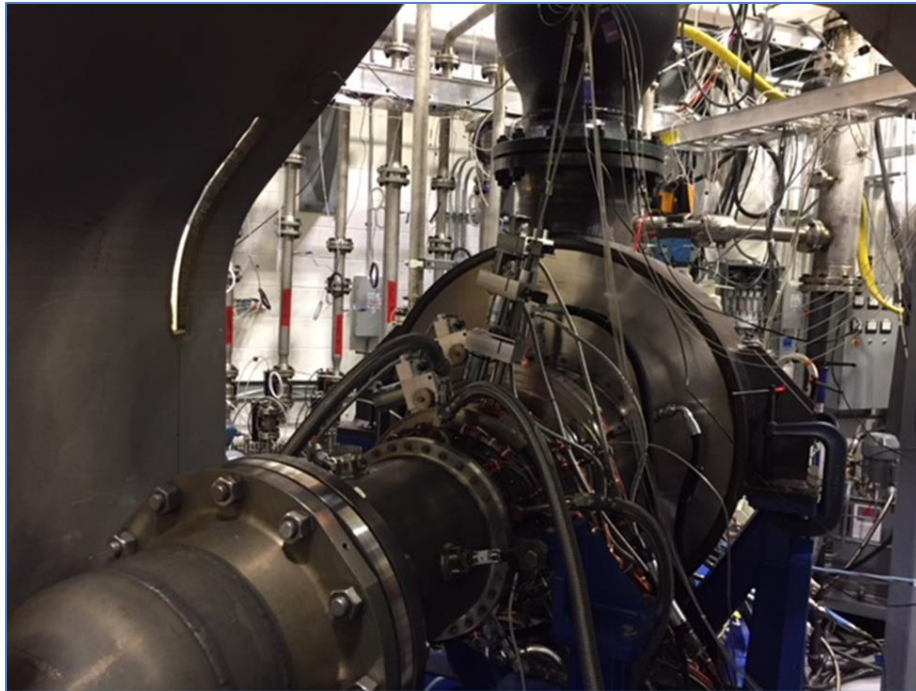
The performance objective of the AVSPOT Program is the development of a PT with:

- Output speed range:  $55\% \leq N_{PT} \leq 105\%$
- Adiabatic efficiency at engine conditions:
  - $\eta \geq 90\%$  at Cruise at 25,000 ft., Max Continuous Power, 55%  $N_{PT}$
  - $\eta \geq 92\%$  at Takeoff/Hover, Max Rated Power, 100%  $N_{PT}$
- Life/Durability as stated in the BAA at 4K/95F operating conditions
  - 6,000-hour mission life
  - LCF life greater than
    - 15,000 cold start double hump (CSDH) cycles
    - 7,500 CSDH cycles for turbine blades
- Minimal system weight and complexity

The final AVSPOT design is a simple, compact configuration incorporating advanced airfoil technology coupled with an optimal primary aero design point (ADP). This design approach accommodates the blade incidence angle and other aerodynamic changes across the speed range and delivers significant performance improvement at 55% speed relative to a baseline conventional design. The notional application (vision system) for this technology is an engine with a state of the art (SOA) conventional PT developed by GE using Advanced Affordable Turbine Engine (AATE) Program learnings. This is used as the baseline for all comparisons to the AVSPOT results.

A component test rig was designed for the aerodynamic equivalent full-scale size of the final AVSPOT design. The rig configuration and instrumentation package were defined to collect steady state data across the operating range to generate a performance map, as well as steady traverse data at the stage exit locations, and unsteady traverse data at the turbine exit to better understand the complex flow physics both on and off design.

The aero validation testing was completed at the Notre Dame Turbomachinery Laboratory (NDTL) in South Bend, Indiana from March through May of 2018 and all primary test points and objectives were achieved successfully. The rig is pictured in the cell in Figure 1-2. Data from the rig test validates the aerodynamic technology employed in the turbine.

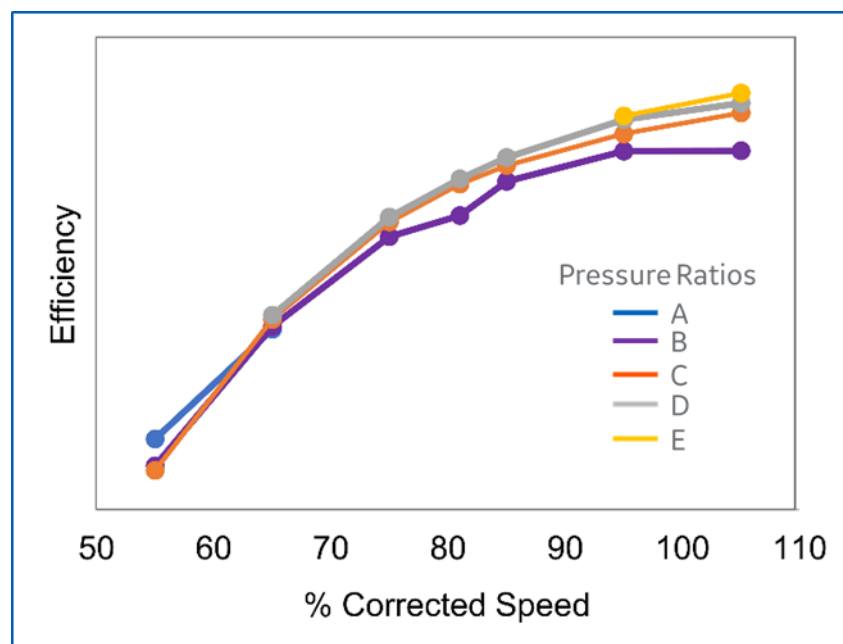


**Figure 1-2: AVSPOT PT rig installed at NDTL**

The AVSPOT power turbine aero rig test successfully achieved all main objectives:

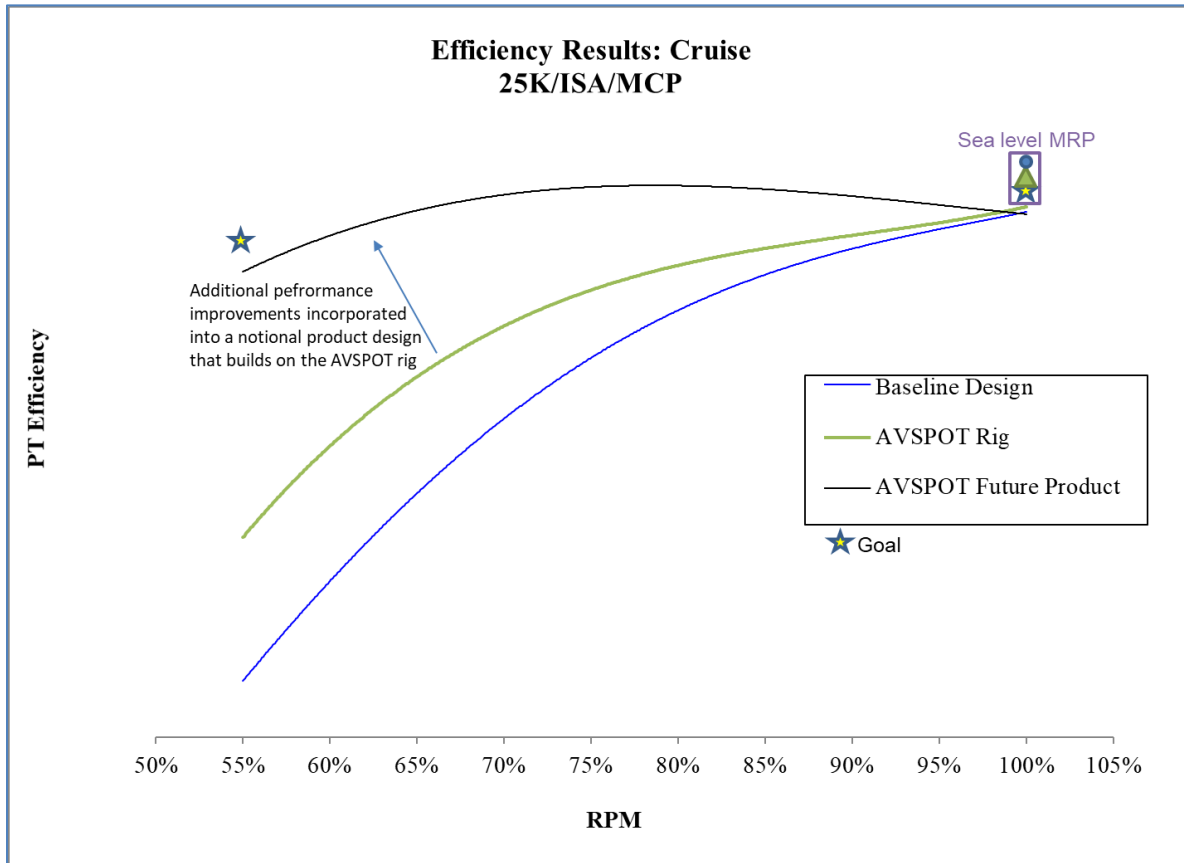
- ✓ Understood key performance derivatives, including Reynolds number, purge flows, and tip clearances
- ✓ Measured PT performance trends vs. speed at multiple pressure ratios (PR) to produce PT map and validate analytical trends.
- ✓ Measured airfoil static pressures on two vanes to validate airfoil design and analytical tools.
- ✓ Completed flow visualization.

A complete turbine map, shown in Figure 1-3 was collected. This map will enable future system-level studies of FVL-relevant propulsion systems, ensuring all operational performance requirements can be met with an optimized AVSPOT design. In addition, high fidelity traverse data was also collected at three key speeds, providing flow field insights at far off-design operating conditions for use in further design refinement studies. The data shown in Figure 1-3 is as measured rig data and is therefore not directly comparable to the AVSPOT engine condition program goals.



**Figure 1-3: AVSPOT altitude performance map of efficiency plotted as a function of turbine speed from 55%-105%**

The demonstrated AVSPOT configuration delivers performance improvements relative to a conventional design across the entire 55%-105% speed range. In order to meet the full AVSPOT performance goals, GE has developed a path to further improve performance and meet program goals in the future. Incorporating the AVSPOT rig learnings and leveraging the validation of additional advanced technologies on adjacent GE development programs results in a final AVSPOT product configuration. Figure 1-4 shows the demonstrated performance of the AVSPOT as tested configuration, as well as the projected performance of a future design that incorporates technologies in excess of the incidence tolerant advanced airfoils tested in this TIA.



**Figure 1-4: Product design incorporates learnings from AVSPOT rig test and other relevant GE development efforts.**

This report details the aerodynamic and mechanical design of the variable speed PT concept and the aerodynamic rig design and test results. Overall, the design efforts and the data collected on test will form the foundation for continued development of additional technologies to enable successful turbine designs that maximize performance for FVL applications.

## 2 Conclusions, Key Learnings, and Recommendations

The AVSPOT design achieved the program goal of advancing the state of the art in wide speed turbine design. The program scorecard is shown in Table 2-1.

**Table 2-1: AVSPOT Program Scorecard**

Criteria	BAA Goal	Demonstration	Future Product
Engine Size class	2,000-10,000 SHP		
Operational Speed Range	55% - 105%		
Efficiency at 25K/ISA Cruise, MCP	90% @ 55%N		
Efficiency at Takeoff, MRP, 100% PT Speed	92%		
LCF (cycles) – All Parts	15,000		
LCF (cycles) – Turbine Blades	7,500		
Structural Life (hours)	6,000		
Weight Impact	Optimize		
Durability Impact	Optimize		
Cost Impact	Optimize		
Rig Test demonstration of advanced PT	Demonstrate PT performance across the full speed range in a representative rig environment		

The AVSPOT Program successfully matured incidence tolerant airfoil technologies required for efficient wide speed PT operation. GE believes these technologies are sufficiently mature to proceed into a development program as a result of the design and testing activities completed to date. A number of other conclusions, learnings, and recommendations for future development activities are a direct outcome of the AVSPOT Program. These include:

### Design Technology:

- Initial design efforts were directed towards a solution which did not meet the program goals without further technology improvements. To focus the design efforts on a lightweight, engine-relevant package, the activity reverted to a design that fit within a similar installation envelope as the baseline turbine.
- Airfoil technology was applied to the first turbine blade through the last stage vane. The last stage blade design was highly constrained, so the technology was not applied there. Additional benefits are likely when the technology can be expanded to the last blade.
- Multi-point airfoil profile optimization – minimizing loss across a range of operating points while minimizing thickness – for the advanced airfoil designs provided a significant reduction in the airfoil max thickness relative to prior profiles designed for

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wide speed operation. Minimizing weight while optimizing performance is a key factor for a product relevant design.

- The ADP was set to balance the off-design performance characteristic between cruise condition and sea level takeoff condition.
- Future engine system evaluations with a variable speed power turbine need to consider the flow function change with shaft speed.

#### **Test Design:**

- Use of “stabbed and brazed” rig vane designs results in excessive manufacturing complexities.
- Designing “engine-like” seals and rotors on the rig eliminates the need for complex corrections back to the engine configuration, since leakages and associated windage losses are consistent from rig to engine.
- Incorporating a rigorous balance plan leveraging successful engine experience into the rig design results in very low levels of imbalance on test.
- Designing the instrumentation package and associated routing features in parallel with the rest of the rig reduces costly and risky part re-work and ensures that there are no unexpected clashes during assembly.

#### **Test:**

- The area traverse data collected were very high quality and compared well with the more traditional exit rake measurements.
- Surface flow visualization was conducted, and qualitative results highlighted the flow conditions on the critical surfaces.
- Losses in the rig exhaust scroll need to be modeled more effectively.

#### **Tools:**

- Rig data indicated that the design was less sensitive than expected based on the 1D models. 3D CFD was more effective at capturing the measured trends, but still underpredicted the performance. The rig captured the complete interaction of all the loss mechanisms.
- Reynolds lapse was measured at a range of incidence angles – this data is not currently available in literature, so it will provide a key calibration dataset for the design tools.

### **3 Aerodynamic Design**

The three main aerodynamic challenges in designing a variable speed PT optimized for high altitude flight are off-design incidence effects, Reynolds number losses, and stage loading impacts. Airfoil incidence angle swings across a wide range, from negative at high speed to positive at low speed. Reynolds numbers are low at very high altitudes on small turbomachines such as those designed for AVSPOT and begin to approach the transitional flow range. Stage loading, a function of work extraction and pitchline speed, increases as the PT slows down, increasing secondary flow and profile losses. The AVSPOT design incorporates aerodynamic technologies focused on minimizing these effects. Below is a brief summary of the aerodynamic

tools and methods used in the program, the trade studies completed, and the final aerodynamic design of the turbine.

### 3.1 Design Procedure

The design procedure consisted of the following steps:

1. Preliminary Design: A 1-D meanline code was used to develop the preliminary turbine flowpath and free-vortex vector diagram.
2. Flowpath and Vector Diagram: An axisymmetric streamline curvature solver was used to develop the 2-D vector diagram.
3. Detailed Airfoil Geometry: The airfoils were designed on surfaces defined by the 2-D code streamlines using a parametric airfoil design tool.
4. Flow Field and Performance Evaluation: Multi-row CFD models were used to evaluate the advanced design.

### 3.2 Baseline Design Space Evaluation

Several aerodynamic design iterations were completed early in the program. First, a configuration utilizing conventional airfoil technologies was designed in order to establish a performance baseline for a concept that used existing technologies to address PT operational efficiency across a wide speed range. These studies were completed early in the program to better understand the design space for the AVSPOT technologies. The 1-D model was used to evaluate trades on stage count, flowpath geometry, design speed, worksplit, airfoil counts, and overall PT performance. The AVSPOT inlet was constrained to align with the APT to allow reuse of the existing rig inlet section. The exit case radius was constrained by the max allowable tip speed and the  $AN^2$  constraint then set the hub radius.

The primary performance challenges for a constant-power, variable speed turbine operating from 55% to 105% speed are the incidence and the stage loading impacts. To balance the off-design loss due to incidence, the range of angles the blade experiences must be biased to the negative side, as shown by the fundamental incidence loss characteristic in Figure 3-1.

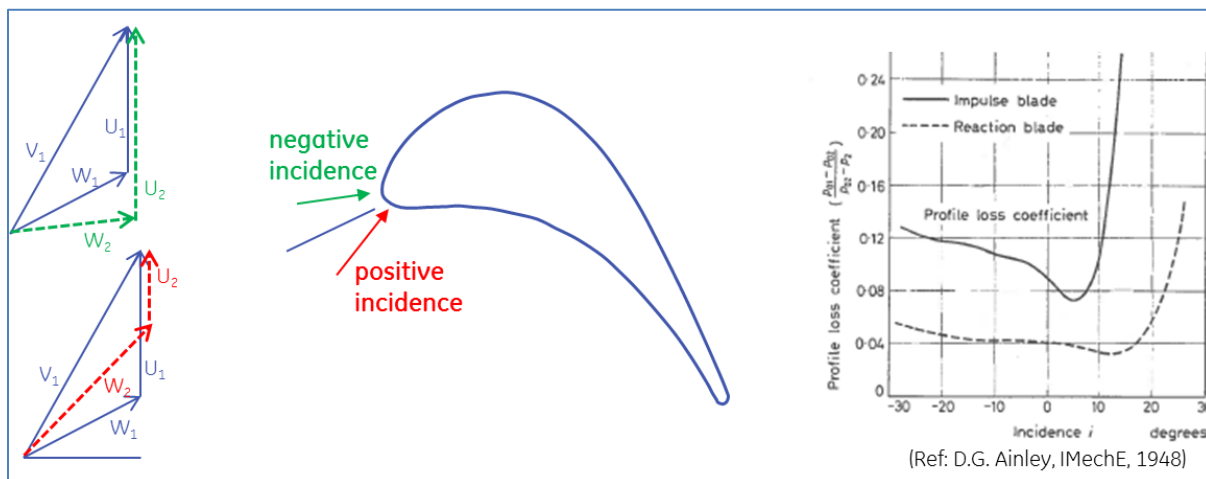


Figure 3-1: Vector diagrams and the definition of incidence on the airfoil (left), and the loss bucket as a function of incidence angle (right)

The stage loading variation with speed shows that at 55% speed the stage loading increases by more than 3x compared to 100% speed. The impact of the stage loading level on performance can be shown on the industry standard Smith chart, which clearly shows the performance challenge operating at the 55% speed condition.

After completing the 1D design space evaluation, the design proceeded through the normal process outlined above, culminating with multi-bladerow steady CFD model runs for the baseline design at the MCP operating condition with PT speeds of 55%, 65%, 75%, 85%, 100% and at MRP 100%N. The CFD highlighted that the impact of operating slower than design speed is captured by the stagnation point shifting to the pressure side of the airfoil (positive incidence). The associated overspeed around the leading-edge suction side front loads the airfoil and produces higher passage MN's. In contrast, a shaft speed higher than design intent is represented by the stagnation point shifting to the suction side of the airfoil (negative incidence). The negative incidence reduces the pressure side cove diffusion and lowers the passage MN's. On a global PT performance basis, the efficiency and flow trends from CFD are compared to the 1D model on Figure 3-2 and Figure 3-3.

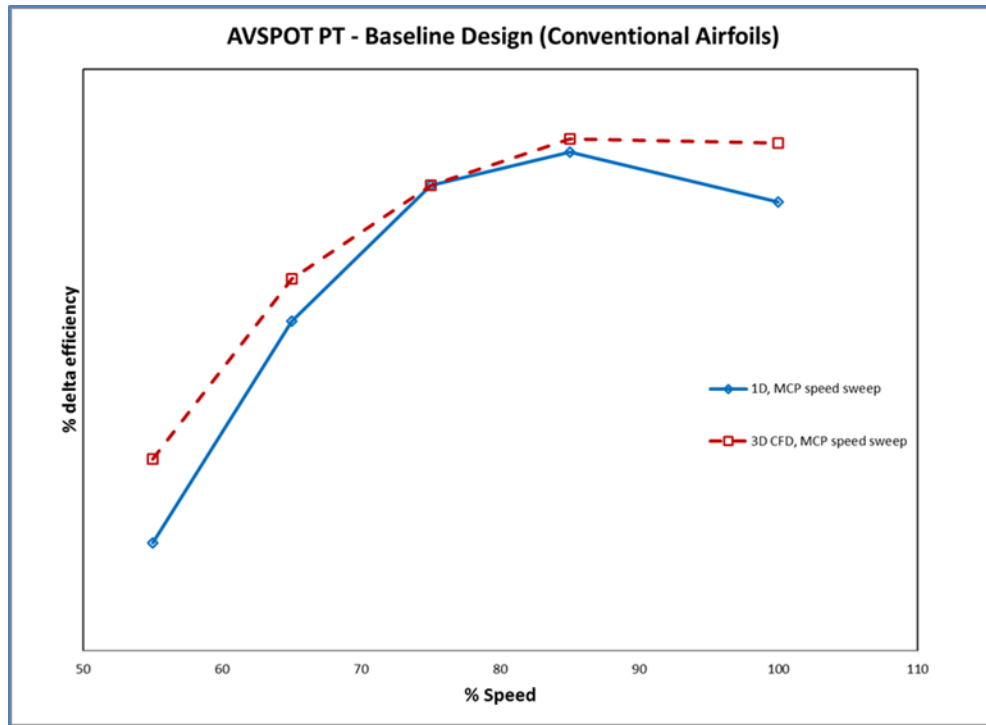
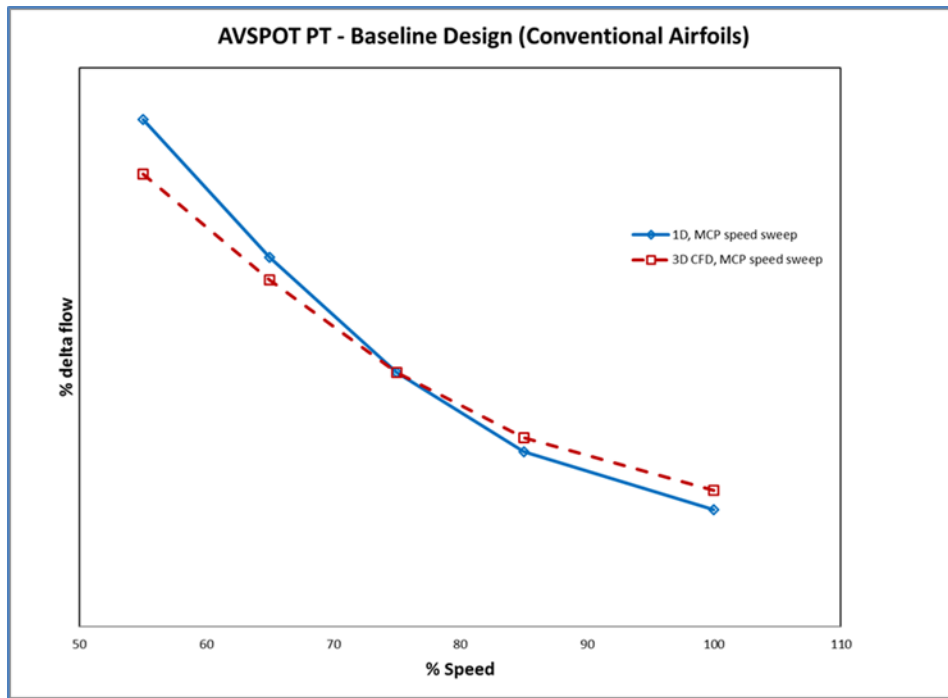


Figure 3-2: Comparison of %Delta Efficiency as a Function of Speed (%N) for 1D (solid, blue circles) and 3D CFD Models (dashed, red squares)



**Figure 3-3: Comparison of %Delta Flow Function as a Function of Speed (%N) for 1D (solid, blue circles) and 3D CFD Models (dashed, red squares)**

The comparison shows agreement in the trends, the CFD is slightly more optimistic with a smaller fall off in efficiency and flow at the off-design operation. This study showed that the tools used in GE’s conventional design suite were still representative far off design and allowed an existing PT to be selected as the baseline for the AVSPOT studies.

The baseline SOA PT was selected to be an aero design based on the previously mentioned APT program that incorporated all relevant learnings. All of the advanced design performance parameters were compared back to this baseline. A planned PT rig program to test the baseline design was executed prior to the AVSPOT test, providing detailed test data for use in evaluating the effectiveness of the tools used in the designs. The presence of both baseline and AVSPOT test data also further validates the off-design performance improvements between the baseline and AVSPOT.

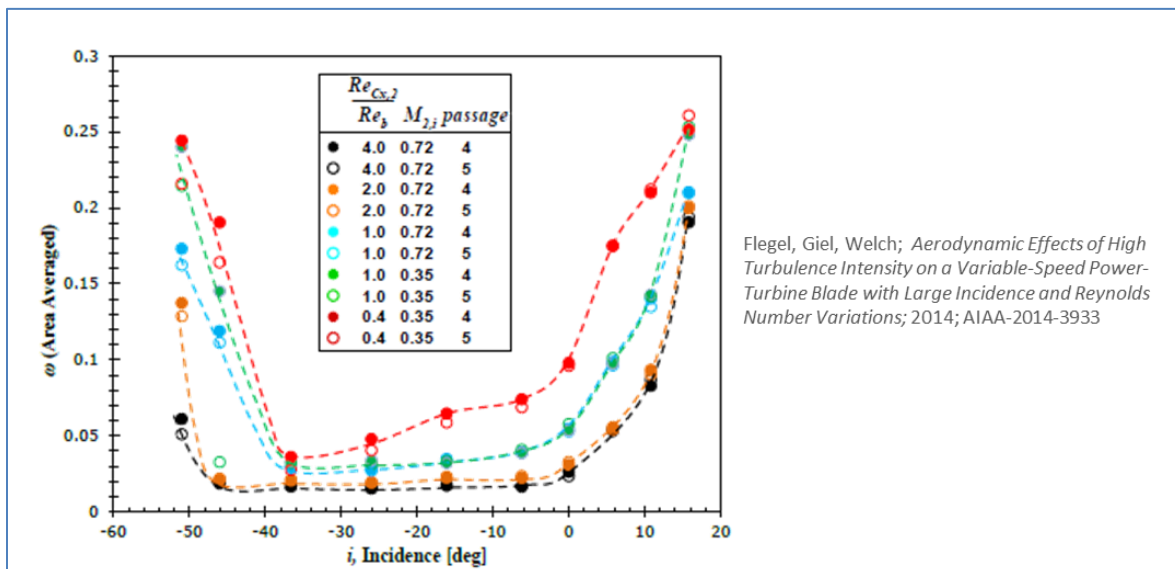
Following the establishment of this baseline model, an iteration applying an advanced airfoil concept was designed to address the high loading levels. However, the technology underperformed relative to the baseline model in this size class. The aerodynamic design team then progressed through a series of new design concepts, and while models showed a relative flattening of the PT efficiency profile throughout the operational range, several included unfavorable architecture and size changes to meet the desired goals. These early technology studies and resulting turbines were not ideal solutions and it became apparent that additional aerodynamic modifications were required to achieve a well-balanced system as discussed in the next section.

### 3.3 Final Advanced Design

A key factor in the engine design for VTOL applications is engine weight and package size. The ultimate objective is to provide the variable speed aerodynamic performance benefit in the most compact package. Therefore, the AVSPOT design applied the learnings from the early studies and optimized them into a compact configuration that delivers a significant improvement in performance at 55% speed compared to a conventional design. The final AVSPOT ADP power class, operating condition, and speed is sized specifically for FVL applications. The optimization studies focused on biasing performance to the points where preliminary studies have shown certain future rotorcraft will likely cruise. Advanced blading is used to accommodate flow angle and other aerodynamic parameter swings across the speed range. The airfoils are designed using multi-objective design optimization, which adjusts the individual blade shape to achieve the optimal performance across the speed range. Testing this configuration provided detailed performance insights into the behavior of the design at high loading levels and forms a new baseline to advance the technology and fulfil mission requirements. The final AVSPOT ADP power, operating condition, and speed are sized specifically for FVL applications that GE identified with other industry members.

#### 3.3.1 1D Design

The ADP selection is crucial in setting the incidence range experienced by the airfoils. The selection was informed by the NASA research in Reference 2, shown in Figure 3-4.



**Figure 3-4: NASA research shows the impact of incidence loss on one type of airfoil design considered for variable speed operation (Reference 2)**

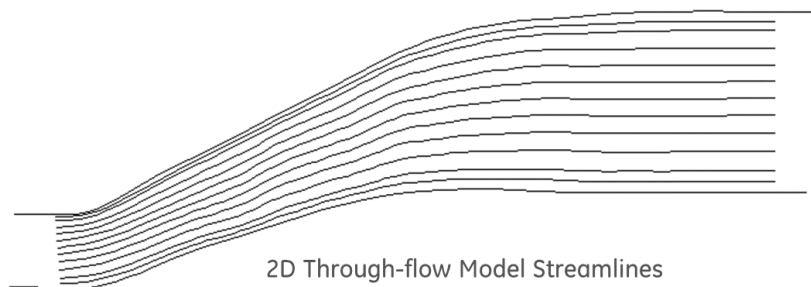
The flowpath is a modification to the baseline. Certain physical constraints were imposed to ensure product relevance and force the design to remain as compact as possible. The worksplit was shifted slightly forward relative to the baseline and the hubline radius increased to provide acceptable blade turning levels. The reaction levels were increased to improve some blade hub section convergences. The setting of reaction and worksplit also accounted for the limits of exit

swirl and MN. The airfoil count and chord were then set to provide acceptable Zweifel loading levels at low speed operation.

The 1D model efficiency prediction for the altitude speed sweep shows that AVSPOT design provides a significant benefit in the low shaft speed region relative to the baseline design, however the 1D efficiency is short of the goal at 55%N. An itemization of the loss accounting from the 1D model guided the technologies leveraged from the early studies and applied in the detailed design to improve performance. The 1D loss accounting also shows that running this size class PT at 25K ft altitude results in low Reynolds number conditions and the shaft speed range produces high MN levels. The combination of the high exit MN and low Reynolds number pushes the AVSPOT PT outside of typical GE engine experience. The 1D model identified this as a potential performance risk and important conditions to replicate and collect data in the rig test program.

### 3.3.2 2D Design

The 2D axisymmetric through-flow model domain is shown in Figure 3-5. The inlet boundary distributions were taken from the baseline design and shifted to match the AVSPOT design point operating condition.



**Figure 3-5: Flowpath with 2D through-flow solution streamlines used to complete airfoil design (Bottom)**

The 2D model mass average conditions of  $rVu$ ,  $Pt$ ,  $Tt$  and pitchline reaction were matched to the 1D model meanline conditions in addition to mass flow at the airfoil leading and trailing edge stations. This process provides a consistent design to the stage energy extraction, pressure ratio and individual airfoil row loss and acceleration (reaction). The disk purge flows are also aligned in the 2D and 1D models for mass flow match up. As noted in the Design Procedure section the through-flow model also accounts for airfoil force terms by using blockage and lean terms from the airfoil design.

The airfoil shapes were designed using a design of experiments (DOE) based optimizer built on top of the parametric airfoil design tool. All airfoils were designed on 5 sections defined by the streamlines, and the parametric tool optimized the advanced airfoil geometry.

The optimizer solved for minimum airfoil cross section area that provides a performance characteristic equal or better than the starting reference geometry. An example of the results achieved by this process on a simple airfoil is shown on Figure 3-6.

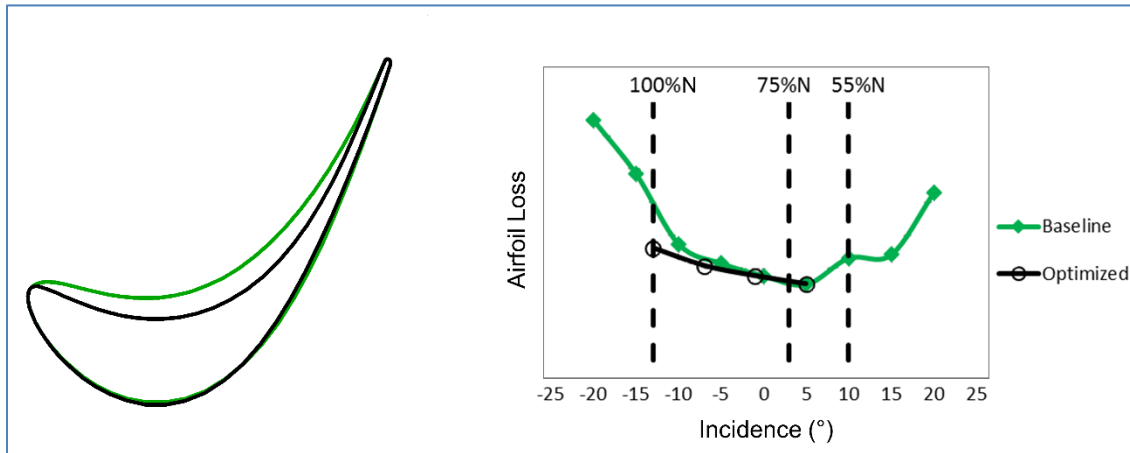
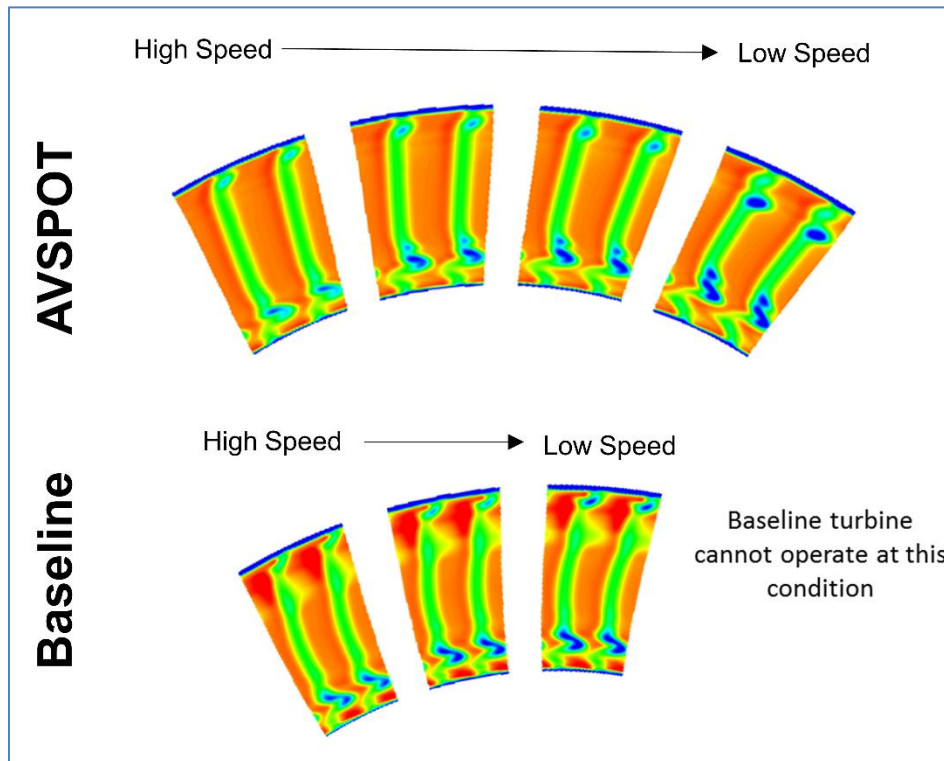


Figure 3-6: Example of multipoint optimization on a simple airfoil.

### 3.3.3 3D Design

Multi-row CFD was used to assess the flow field and turbine performance with the optimized profiles. An evaluation of the CFD capability to predict losses due to incidence effects was made using the cascade geometry from Reference 3 and data set from Reference 2. This data provided confidence that the CFD results would be representative for GE’s unique advanced airfoil design.

The AVSPOT multi-row model domain total grid count for the model was 55 million cells, and the domain inlet boundary conditions of total temperature, total pressure, swirl, and turbulence intensity are radial profiles taken from the exit of the HPT model used for the baseline turbine design. Model solutions were obtained at several operating conditions, and the AVSPOT efficiency contours are compared to the baseline design at several speeds in Figure 3-7. The red and orange shades indicate high efficiency, and the green and blue indicate flow has more loss.



**Figure 3-7: Multistage CFD Efficiency Contour Comparison to Baseline**

The CFD and 1D predicted efficiency trends show that while the two models agree very well, the CFD for the AVSPOT design deviates from the 1D model in the far off-design regions most impacted by the advanced airfoil design. Both models show that the AVSPOT design provides a significant performance improvement relative to the baseline.

#### **4 Engine Design**

The AVSPOT engine PT vision system is a compact, modular design that delivers significant improvements in high altitude, low PT speed performance while minimizing system impacts on weight, durability, and takeoff performance. The technology package, coupled with the optimized design point and advanced airfoil technology, contribute to make the notional AVSPOT product PT a robust advanced propulsion system that is an enabling technology for future rotorcraft concepts.

In addition to the aerodynamic design work discussed in detail in Section 3, several mechanical and system design trades studies were completed during the AVSPOT Program. Early studies showed that stage count had an important impact on PT cost, weight, length, aircraft installation, and engine maneuver tolerance. All these factors were considered in defining the AVSPOT configuration.

The AVSPOT architecture leverages learning from the Advanced Power Turbine (APT) Program in 2005, and incorporates lessons learned from the AATE demonstrator engine tests. AVSPOT applies these learnings to a PT sized for variable speed operation that incorporates additional

advanced materials and manufacturing processes to minimize weight and improve both performance and durability.

This section details the engine system and mechanical implementation of the final aerodynamic design in a notional engine environment, and demonstrates how the configuration balances performance, cost, weight, and engine complexity while meeting all durability and dynamics requirements. While the configuration of this notional product PT design was explored under AVSPOT, none of the technologies identified in this notional design, aside from the aerodynamic design of the turbine airfoils, was completed directly under the AVSPOT program.

## **4.1 Cycle Design**

To provide boundary conditions relevant to an FVL application, GE generated the cycle conditions used in the AVSPOT design from its state of the art demonstrator programs. The AVSPOT cycle incorporates several features specifically focused on variable speed PT platform performance to ensure the design has product relevance. The final AVSPOT ADP SHP, operating condition, and speed is sized specifically for FVL applications that GE identified with industry members.

One major point of focus was the selection of the physical RPM range of operation. The final speed selection strategy is consistent with a design optimized for wide speed range operation. When operating at CRP, MRP, and IRP the engine is assumed to run at 105% PT speed. Operation at these power settings will likely occur for takeoff/hover type maneuvers that need a high main rotor speed for lift. For MCP and lower power conditions, the PT speed is set at a realistically conservative upper bound on PT speed for cruise. The incorporation of the conservative cruise speed assumption in the durability assessments lets the overall speed range to be set at an appropriate physical RPM while still delivering a light weight, durable mechanical solution.

All mechanical assessments of the product design utilized a “lifing cycle” that includes data at key points in the durability missions. It is also run as a 2/3rd deteriorated engine with field margin and production margin included, ensuring all life results are generated at representative temperatures for a product application.

## **4.2 Component Design**

### **4.2.1 Airfoils**

AVSPOT consists of blades and vanes that balance the performance, creep/rupture, low cycle fatigue (LCF) and aeromechanic requirements. The airfoils incorporate proven materials to improve upon conventional, fielded turbine airfoil technology and achieve US Army goals. The trailing edges on all stages are designed to minimize flowpath blockage, improving stage efficiency.

The PT blades are made from materials used in other current production engines combined with successfully manufacturing approaches to deliver a robust product. One of the challenges of the AVSPOT designs is increased weight and chord length of some airfoils. The increase in low-speed performance makes this weight trade acceptable, and future advances in advanced casting

technologies will eventually lead to approaches that can minimize the weight penalty of the advanced designs.

#### **4.2.2 Rotor Structure**

The PT disks are sized to deliver a lightweight and highly capable design. The PT disks are generally sized by burst with consideration for LCF at bolt holes and air holes and dovetail creep capability. The chosen material offers the highest ultimate tensile strength for materials that meet the other requirements and therefore is the lightest weight solution. The rotor meets all US Army burst and durability goals. The PT blade retainers are designed not only to locate the blades, but also to meter the flow through the system and control cavity purge temperatures.

The PT shaft interfaces with the output drive assembly and is optimized to limit PT dynamic clearance closures throughout the operating range for maximum performance. The PT shaft is also sized to meet the US Army max torque goals. The shaft thickness is set to deliver the torque and tune the PT bending critical speed so that it falls outside of the operating range.

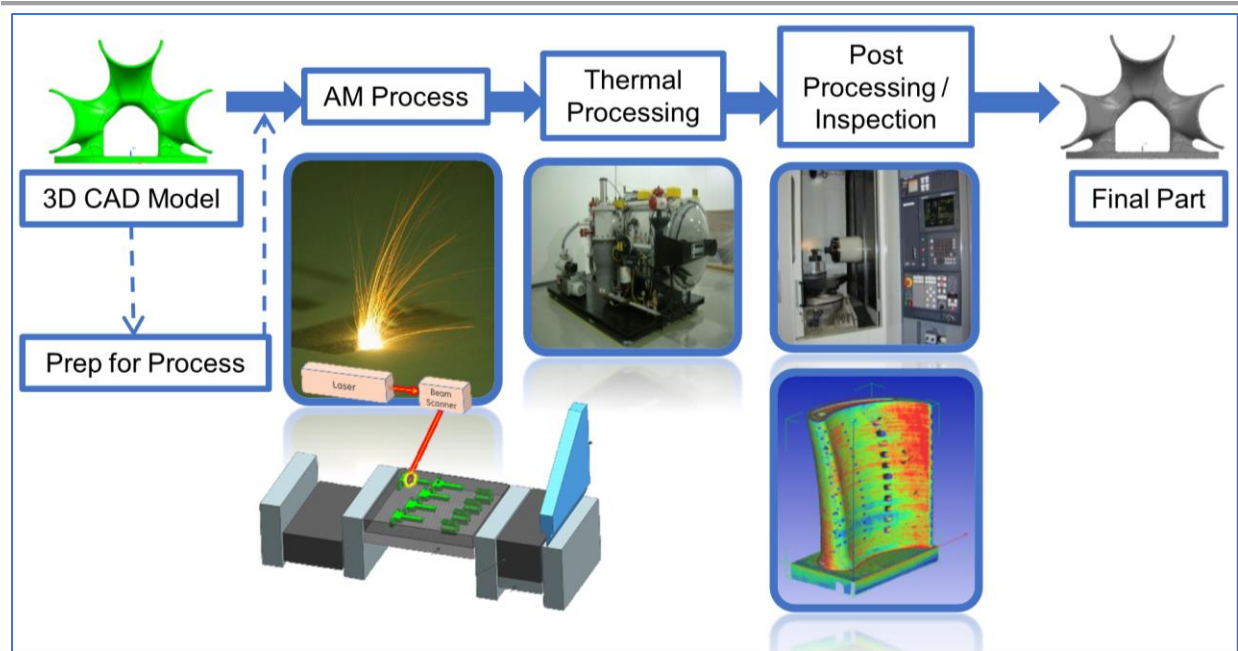
#### **4.2.3 Static Structure**

The AVSPOT architecture optimizes bearing and frame placements to enable a simple, light-weight flowpath transition between the GGT and PT. The stator utilizes targeted cooling flow, advanced materials, and cutting-edge manufacturing processes to deliver a light weight, high performing and durable configuration. The case is sized for containment and buckling and provides anti-rotation features for the shrouds and vanes. The duct material selection allows for the implementation of a design that reduces weight, improves durability, and creates a clean, simple aerodynamic flowpath between the GGT and PT. The frame and sump are designed to reduce part count, weight, and leakage while delivering the required system stiffness. The frame supports the bearing structure and the PT speed sensor and provides rotor cooling flow and sump oil services through the hollow struts.

#### **4.2.4 Advanced Material Technology**

Additive manufacturing is an enabling technology for the AVSPOT stator. Additive manufacturing enables light weight designs by eliminating manufacturing constraints of traditional casting and machining methods, and by allowing advanced system designs that replace traditional multiple part assemblies. Additive manufacturing allows the minimum thickness of non-load bearing walls on structural components to be reduced compared to traditional sand or investment casting processes. Further, since it eliminates casting cores, additive manufacturing allows for the design of the more complex internal passages that can reduce overall part weight without incurring additional cost. Multi-part assemblies can be combined into one additively manufactured part, eliminating the fasteners and reducing interface wall thicknesses. Additive manufacturing also enables production of optimized weight reduction features, including scallops, without the cost and cycle time of final machining operations.

GE uses the Direct Metal Laser Melting (DMLM) additive manufacturing process in production on the commercially certified turbofan LEAP engine fuel nozzle. The process used to manufacture the AVSPOT hardware, shown in Figure 4-1, is the same as the LEAP production process.



**Figure 4-1: Additive manufacturing process.**

AVSPOT also strategically incorporates Ceramic Matrix Composites (CMC), which have 1/3 the density of typical turbine metallic alloys and enhanced high temperature capability. The use of CMCs in the AVSPOT design reduces module weight compared to an all-metallic design. AVSPOT benefits from GE’s experience designing CMC components on the LEAP, FATE, and T700 programs, and all design best practices, including those from successful demonstration and certification testing, will be applied to this design. GE has over 1 million flight hours on commercial CMC and additive parts fielded on the LEAP engines.

#### **4.2.5 Component Durability**

Component durability is assessed consistently with the BAA requirements. All parts meet the 6,000-hour mission life as well as the 15,000 CSDH cycle LCF requirement (7,500 cycles for blades). Specifically, lives are calculated using  $-3\sigma$  material properties, 4,000 ft. 95°F operating conditions, the cycle discussed in Section 4.1, and the usage spectrum and LCF cycle definition provided in the BAA. The PT speed distribution used in the durability mission best represents operation of a VSPT application. CRP, MRP and IRP conditions are assessed at 105% speed because operation at these power settings will likely occur for takeoff/hover type maneuvers that need high speed operation. In contrast MCP and lower power conditions are assessed at 85% a realistically conservative upper bound on PT speed for cruise.

#### **Aeromechanics**

One of the major mechanical challenges of a variable speed PT is the increased speed range of concern for aeromechanical resonances. The airfoils are tuned to move resonances to acceptable speed ranges, by ensuring that either the crossing is outside of the operating range or that the response of the mode is acceptable. The designs leverage best practices and lessons learned from both turboshaft and turbofan engine designs to ensure the airfoils are robust and have sufficient vibratory capability.

## **Airfoil Stress and Life**

A stress and life assessment was completed on the critical airfoil and rotating components of the AVSPOT product, and all parts meet the BAA goals. The airfoils and rotor were selected for these assessments as they are typically the limiting components in PT durability.

Blade bulk creep life fraction used (LFU) results are tabulated for 5 airfoil span locations at each point in the BAA specified lifting mission. Creep is typically the limiting failure mode for PT blades, and assessments show that the blades meet requirements as stated in the BAA. 1D stress models and accompanying LCF assessments were also completed for each blade, and the life results all meet BAA goals.

The vanes were also assessed for durability. Due to the complexity of analyzing PT vanes, which have boundary conditions that are highly dependent on system architecture details, durability assessments. These conservative assessments show that the vanes are capable of meeting BAA life goals. Again, boundary conditions were not optimized for the AVSPOT-specific cycle and configuration, and since the vane bands are very sensitive to small changes, an AVSPOT product would be optimized to meet durability requirements using more refined analysis.

## **Rotor Sizing**

The disks are sized to match the bulk average and maximum unconcentrated stresses of a baseline design that meets all durability goals in the BAA. The AVSPOT product would have similar rotor bulk temperatures and uses the same materials as this baseline, and the architecture and stress concentrations are similar between the two designs. Using this sizing approach, the AVSPOT design will maintain similar LCF, overspeed, and burst capability as the baseline design. Sizing the AVSPOT rotors to match maximum unconcentrated and disk average stress of a configuration that meets the applicable durability requirements reduces risk of durability shortfalls.

## **4.3 System Design**

Several system level design studies were also completed as part of the product design. In addition to the dynamics, clearances and weight studies detailed below, consideration was given to the control system required for variable speed operation.

Since future vertical lift aircraft require significant improvement in vertical lift, range, speed, payload, survivability, and reliability, they must be able to seamlessly utilize the AVSPOT-provided capabilities. To maximize the impact of an efficient variable speed PT, it must be coupled with variable main rotor speed (NR) control system capabilities. With variable NR controls, future vertical lift aircraft will be able to set NR through the PT speed to any level between 55% and 105% to optimize the specified leg of the mission flown. High speed operation, increased range and increased endurance may require low speed PT operation, while mission legs requiring high maneuverability and increased hover payload may require high speed PT operation. Variable NR control was studied as part of the RAEICS Program, which GE conducted in collaboration with ADD.

## **Dynamics**

A baseline dynamics model was modified to capture the AVSPOT geometry and predict PT critical speeds. The model is used to predict critical speeds, imbalance, maneuver, and blade-out loads and clearance closures, inter-shaft clearances, and external excitation/vehicle induced vibration responses. Model outputs from a variety of these loading cases serve as boundary conditions for the mechanical design of the frames, sumps, bearings, carcass bolted joints, and rotor structural flanges to ensure capability to requirements.

The AVSPOT rotor system dynamic response is acceptable throughout the entire speed range. The PT Shaft 1<sup>st</sup> bending mode frequency is optimized to avoid the 55% speed operating point.

In addition to critical speed assessments, the response of the system under maneuver loading was assessed. The maneuver closures are more severe for AVSPOT compared to a conventional PT, as expected given the increased weight and inertia of the AVSPOT rotor. However, the bearing and PT shaft stiffness can be optimized to reduce these deflections and the clearances can be sized to ensure the performance impact of a maneuver is the same or better than a conventional PT.

### **Clearances**

One of the challenges inherent in variable speed PT operation is the increased tip clearances associated with low speed operation. Tip clearances are typically sized to achieve optimal performance at the aerodynamic design point. In a conventional engine the PT mechanical deflections are fixed, and the tip clearance is a function of the thermal environment of the turbine. However, in a VSPT application the speed of the PT is varied independent of the turbine inlet temperature, creating conditions where the stator thermal deflections are near their maximum and the rotor mechanical deflections are significantly reduced. This mechanical deflection reduction correlates directly with clearance increase, which negatively impacts performance.

Blade tip clearances have a strong impact on the performance of the PT. Increased clearances allow more bypass flow around the blade tips, which also introduces a mixing loss when it re-enters the flowpath downstream of the seal. A robust product design must consider and address this clearance challenge.

### **Weight**

The AVSPOT design adds a modest amount of weight compared to a conventional design, driven mainly by the airfoils, which are thicker and have a longer chord than those in a single speed PT. Because of this, several other engine components have an increased weight to accommodate the new flowpath and to meet product durability requirements with more airfoil weight. To mitigate this, a number of weight reductions are incorporated into the AVSPOT design, and several future technologies could further reduce product weight, but they are not included in the current study. Technology trades of weight vs. risk would be a major part of a follow-on engine program.

## 5 Rig Design and Predictions

The AVSPOT rig is a full scale aero rig designed to demonstrate variable speed PT capability for future rotorcraft propulsion applications. The warm air rig is aerodynamically equivalent to the engine design presented in Section 3. The rig design enables a single-build test to effectively quantify performance across a matrix of speeds, pressure ratios, clearances, Reynolds numbers, and purge flows, with minimal configuration changes on the associated instrumentation package between air periods. The overall test vehicle borrows heavily from the APT and FATE GGT rig set ups, including the skid, frames, and water brake. Figure 5-1 shows the full rig assembly model.

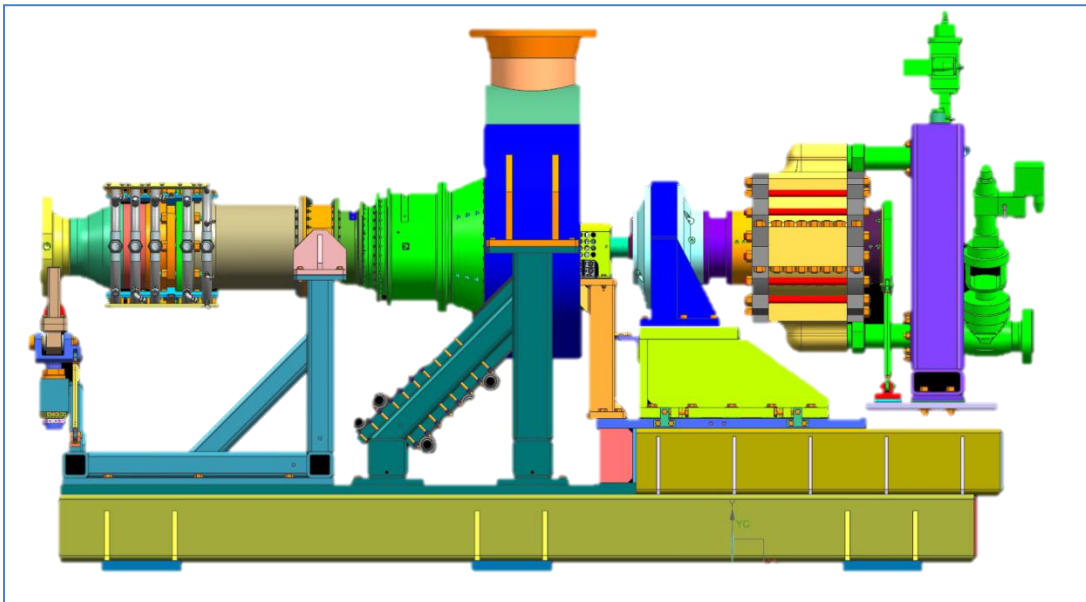


Figure 5-1: Rig Test Vehicle

### 5.1 Rig Mechanical Design

The AVSPOT rig architecture leverages the successful APT design, but incorporates targeted changes to improve producibility, control costs, and ultimately deliver higher quality test results. One improvement is the use of “engine-like” rotors, which provide more realistic purge flow interactions by preserving real features. Other improvements include an integral shroud and exhaust case to allow for clearance probes. In addition to leveraging the basic architecture of APT, AVSPOT also reused some of the as-run APT hardware.

The expansive speed and pressure ratio ranges of the AVSPOT map require some points to be tested at higher inlet temperatures. The higher inlet temperature allows a higher physical speed to be used to capture an equivalent corrected speed and helps keep the test points within the allowable water brake load map. However, this inlet temperature change adds complexity to the mechanical design of the rig hardware. Certain criteria are now limited by different points based on the speed/temperature combinations. To account for this, 4 unique conditions were assessed, allowing the full design space to be evaluated and ensuring safe operation at all points.

The major requirements imposed on the rig mechanical design were derived from GE's component test design practice and have proven effective for recent successful test campaigns on similar commercial programs. To ensure safe operation, robust analysis methods were applied to the rig design. The compliance approaches employed on the AVSPOT program were consistent with GE's rig design best practices.

## **5.2 Rig Pre-Test Predictions**

A series of pretest measurements and inspections were completed to accurately capture the pedigree and geometry of the as-tested hardware.

### **Dynamics**

Rotor balance was completed using the same balance machine and software used for production rotors. The final imbalances are well within the 1 gr-in limit specified on the rotor assembly drawing and had no impact on the predicted dynamic response of the vehicle.

### **Clearances and flows**

Cold build clearances were measured and compared to nominal to calculate an associated hot running clearance change at ADP. The deviations from nominal are captured in the pre-test prediction and verified on test via clearanceometers on one stage. No direct measurements were taken on the lab seal clearances, and therefore there was no change to the predicted secondary flows in the rig.

### **Aerodynamics**

Prior to executing the rig, a pre-test prediction was completed to assess the efficiency and flow function for where the rig was expected to run. This analysis includes losses due instrumentation, flowpath geometry features not accounted for in the 1D model, and manufacturing variation that deviates from the hardware design intent. The efficiency walk was discussed at the test readiness review (TRR).

The starting prediction is a model updated from engine conditions to rig conditions (inlet conditions, purge flows and temperatures, fuel to air ratio, etc.). The stack from initial rig model to predicted rig conditions yields an expected rig efficiency that can be compared to actual test results. The flow function was also evaluated pre-test and shown at the customer TRR.

## **6 Rig Test**

The AVSPOT PT aero rig test successfully achieved all main objectives:

- ✓ Understand key performance derivatives, including Reynolds Number, purge flows, and tip clearances
- ✓ Measure performance trends of PT vs. speed at multiple PRs to produce PT map and validate analytical trends.
- ✓ Measure airfoil static pressures to validate airfoil design and analytical tools.
- ✓ Flow visualization
- ✓ Determine the efficiency of the PT at the ADP and other key rating points

- ✓ Identify opportunities for refinement for future engine applications.

This testing was performed on an aerodynamically equivalent, full scale turbine rig and was conducted in Notre Dame Turbomachinery Laboratory (NDTL) Test cell number 0400. GE generated the assembly and instrumentation drawings, and GE Aviation Lynn shipped the fully assembled and instrumented rig to NDTL. The NDTL test team assembled plugs, terminated instrumentation leads, and conducted the test procedure with engineering support. The testing was to be completed in 12 air periods, 2 of which were for mechanical checkout.

## 6.1 Set-up

To ensure a successful test campaign, the AVSPOT rig leveraged all relevant lessons learned from GE’s extensive recent rig test experience. The rig was tested at Notre Dame Turbomachinery Laboratory (NDTL) Cell 0400. The test facility overview is shown in Figure 6-1.

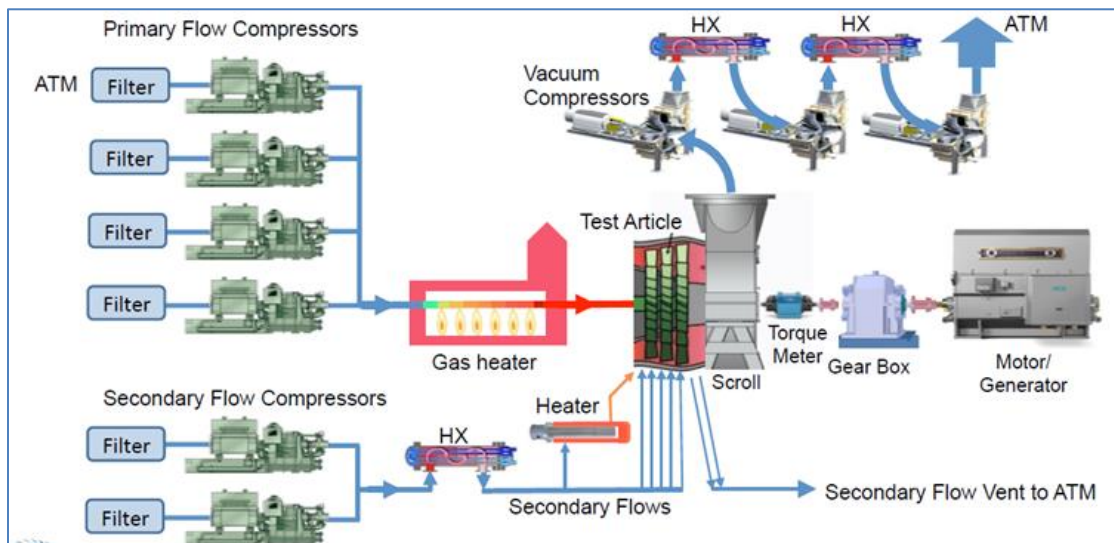


Figure 6-1: NDTL facility overview

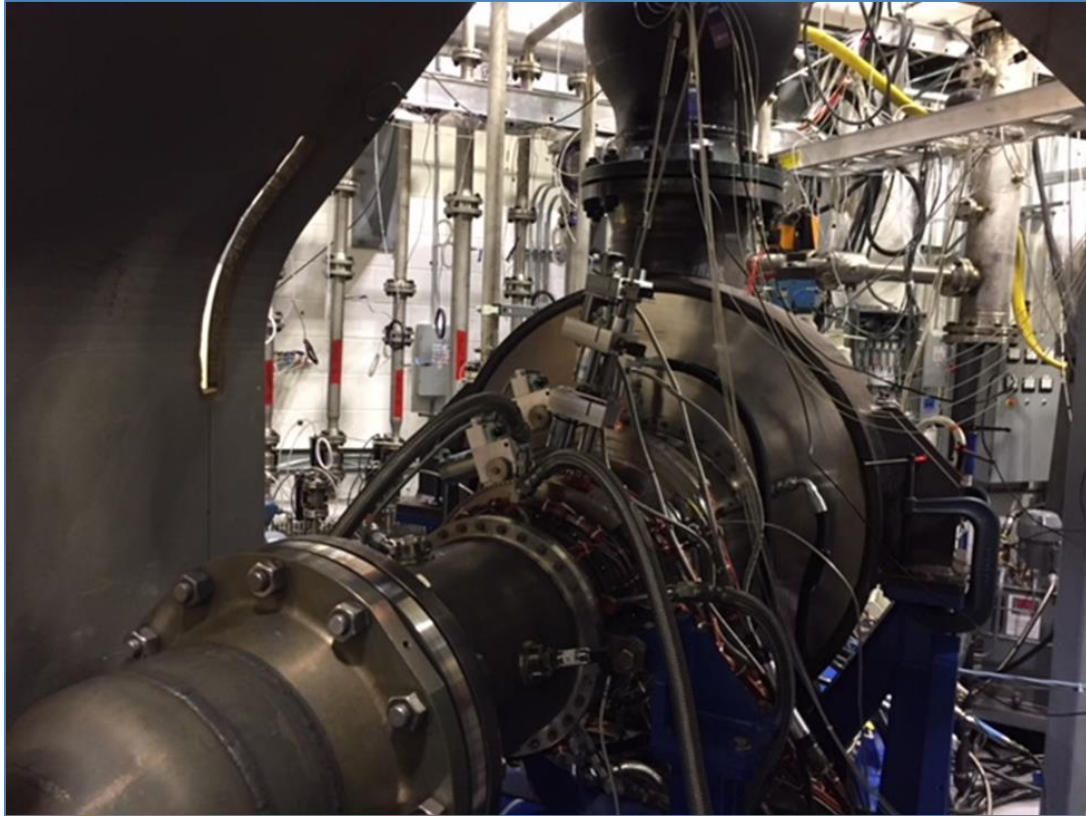
Air is drawn in from a climate-controlled room by “push” side compressors. NDTL has six available compressors for both primary and secondary flow circuits.

In the primary circuit, the air proceeds to a heater where it can be heated by an indirect heat exchanger to up to 1200°F. The fluid is then transported via the hot header circuit to the test cell. Upon entering the test cell, the hot header fluid will enter a mixing chamber where the fluid is mixed with cold secondary circuit air to reduce the overall temperature to the specified AVSPOT inlet temperature. The exiting fluid from the mixing chamber is metered by a calibrated Venturi and proceed to the test article.

From the secondary circuit, the temperature is regulated by heat exchangers and electric heaters to reach the desired temperature. The secondary fluid proceeds to the test cell where it is used for secondary air supply for the test article. A branch of the secondary circuit also goes to the previously mentioned mixing chamber.

After passing through the test article, the fluid is collected in a collector scroll before going to the pull side compressors. Three pull compressors are arranged in series. Upon exiting the third compressor, the fluid is ejected to the atmosphere.

The installed AVSPOT rig is shown in Figure 6-2.



**Figure 6-2: AVSPOT PT Rig installed at NDTL**

### **Instrumentation**

The AVSPOT instrumentation is designed to achieve the following deliverables:

- Establish rig inlet conditions, PT, TT, flow, and Ps. PT measurement traverse at inlet just aft of pre-swirl ring.
- Measure inter-stage cavity rim Ps and TT; also, additional cavity Ps and TT as needed for rotor thrust balance and safety.
- Measure PT and TT forward of the inlet rating plane via stick probes at different radial immersions.
- Measure PS on vanes along the pressure and suction side.
- Measure main flow and secondary flow amounts, TT and PT.
- Perform exit traverses and measure annulus wall statics on all tests to characterize the flow field.
- Measure turbine exit PT & TT with exit rakes.

- Measure clearances at one stage.
- Measure torque and RPM.
- Measure static pressures on the hub and case of the flowpath.

## **Planned Test Procedure**

In general, the test procedure was developed to balance technical risk and prioritize key data collection early in testing. Initial testing will be completed at the nominal inlet temperatures to ensure successful data collection early in testing. Key turbine performance data is prioritized over derivative testing to ensure a minimum viable data set is collected as early in testing as possible.

## **6.2 Test Operations**

The test team consisted of a minimum of eight people to staff each of the test stations. The eight stations were:

- Test Director – issues the test commands by directing each test personnel of their required actions to bring the test article to operating point as defined by the test matrix. The test commands are standardized so that there is no confusion in the intent of the command. For example, the commands include, but are not limited to: return to idle, back-off, hold, and stop. The director is also responsible for all personnel, test article, and lab safety.
- Pilot – commands all the test cell and test article related valves at the direction of the test director.
- Air Plant Operator – commands all air plant related valves at the direction of the test director.
- Water Brake Operator – controls the water brake as needed. The operator will alert the test director of any unsafe limits as they are neared.
- Mechanical Drive Train Monitor – monitors the mechanical drive train related variables. This monitor is responsible for ensure adequate oil flow and temperatures are being provided to the test article and water brake bearings. The monitor will ensure that sufficient oil scavenge levels are being attained to avoid an oversupply of oil.
- Low Speed Data Acquisition System Operator – acquires low frequency data at the direction of the test director and aerodynamics monitor. The operator is also responsible for operating the traverse system.
- High Speed Data Acquisition System Operator – acquires high frequency data at the direction of the test director and aerodynamics monitor. The operator will monitor vibrations and relay critical “no-spin” zones to the test director.
- Aerodynamics Monitor – monitors the aerodynamic operating points. The aerodynamics monitor will identify when the desired operating point has been achieved and when to acquire data.

## **Log Files**

Log files were created for documentation. Logs were maintained during all phases of testing (before, during, and after). The log files are detailed and archived in such a way to assist in future discussions of any AVSPOT related testing. Main log files include:

- **Change Log:** Configuration changes were logged using a change log. Logged changes include any changes to the rig configuration not controlled by the drawing specification. This includes all instrumentation, facility, test article, and data acquisition system related changes. Logs were maintained and updated on a regular basis to ensure accurateness.
- **Test Log:** A daily test log was also kept. Test logs detailed date, time, data description, file name, reading number, and transient type. The rig rotation start and end times were also recorded on the same document. The test logs are also used for instrumentation fault tracking in the comments section. Upon a note being made, the GE/NDTL team will determine if that fault is a “fix immediately,” “fix before next run,” or “fix when able” based on criticality to safety, performance, and availability of redundant measurements.
- **IOI:** A daily Items of Interest (IOI) was documented by NDTL and distributed by the GE Test Focal.

### **Data Processing and Handling**

A sequence of test data processing and handling occurs from the time the data is physically measured at the test article. Those physical measurements are converted to an analog or digital signal as appropriate by a transducer. Any analog measurement is eventually converted to a digital signal. A data acquisition system is used to collect the data. NDTL used Safran Test Cells Cyres software for low frequency and Apex for high frequency data acquisition.

### **6.3 Summary of Completed Testing**

The AVSPOT test campaign began with first roll over on March 27, 2018. All required testing was completed on May 17, 2018. The test campaign included first roll-over session, two mechanical check-out sessions, and a combined total of 10 air periods. The 10 air periods included 9 full day air periods and 2 half day air periods.

The run summary of the rig is shown below:

- Total AVSPOT Bearing Time: 125 hours 54 minutes
- Total AVSPOT Air Plant Time: 174.5 hours
- Total Rig Starts: 21
- Maximum Speed Range Cleared: 105%

The main test objectives were accomplished as shown below:

- 
- ✓ System safety integration prove out - COMPLETE
  - ✓ Mechanical check out - COMPLETE
  - ✓ Initial performance data collection - COMPLETE
  - ✓ Spec point traverses - COMPLETE
  - ✓ Exit Traverses - COMPLETE
  - ✓ Reynolds effect map - COMPLETE
  - ✓ Mapping - COMPLETE
  - ✓ Purge flow and clearance derivatives - COMPLETE
  - ✓ High T<sub>in</sub> points - COMPLETE
  - ADDED: High P<sub>in</sub> points - LIMITED BASED ON RIG/CELL CAPABILITY
  - ✓ Flow Visualization - COMPLETE

Due to facility, water brake, and personnel availability limitations, the executed rig test plan migrated from the planned testing procedure discussed at TRR. The inlet condition characterization and aero design point data was collected followed by the altitude map points as intended. Due to personnel availability, some exit traverses could not be completed as early as planned and they were moved later in the testing schedule. The purge and tip clearance derivative testing moved forward due to the low risk and ease of completion. The heated conditions for the low speed points remained at the end. All the key points and most of the map points were collected, resulting in a successful rig test campaign.

### **Test Lessons Learned**

While testing was completed smoothly and overall successful in hitting all key objectives, a number of issues were identified throughout the course of the test campaign. The issues were addressed at the time of occurrence to mitigate risk and impact, allowing the team to proceed to close out the test campaign. As such, all required data and objectives were met.

Some of the issues that were discovered during the test campaign include:

- Vacuum Capability
  - Minimum exhaust pressure was higher than expected from analysis at rig exit. It was determined that losses were mainly in the rig scroll due to an oversimplified analysis of the exit conditions. Including deswirlers may have helped in static pressure recovery to help reduce losses through the rig collector scroll.
- Inlet Pressure
  - Cold and hot header mixing chamber introduced losses that capped inlet pressure. The mixing chamber was required to reach the desired inlet temperature condition. Using the hot header only was not possible because the heater in the hot header circuit could not deliver a stable temperature at the required AVSPOT mass flow rate. As a result, the hot header heater output a higher temperature fluid. That warmer fluid was then mixed with the cold header fluid in the mixing chamber to achieve the desired AVSPOT inlet temperature.
  - A maximum inlet pressure of the mixed flow would have been sufficient for the original test plan. However, with the discovered vacuum capability issue that resulted in a fixed, obtainable minimum back pressure,

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AVSPOT was not able to achieve some ratio operating points. Therefore, raising the inlet pressure would have assisted in getting closer to those operating points.

- A modification to reduce the pressure loss through the mixing chamber was implemented obtain a higher inlet pressure but running at the elevated inlet pressure resulted in other limits being hit.
- With all modifications and safe limits in place, all mapped speed lines included a number of points sufficient to generate a full map.

As the issues were discovered, the test team addressed them as required. Required lessons learned were documented and shared across GE and NDTL.

## **7 Rig Test Results**

### **7.1 Key Mechanical Results**

#### **Dynamics**

During mechanical check out, a GE rotor dynamics engineer was on site to verify high-speed data acquisition setup and to monitor dynamics instrumentation consisting of 18 accelerometers, 3 DC clearanceometers, and 4 proximity probes. During the mechanical checkout period, rig demonstrated stable operation well within limits at all test speeds up to 105%. The rig traversed sub-idle rotor critical with less than 0.2 ips peak vibration on all vibes and less than 0.5 mils peak 1/rev closure on the clearance probes, indicative of a well-balanced and straight rotor assembly. Maximum vibratory response was 0.5 ips peak at forward cartridge bearing vertical plane accelerometer at the 105% speed point. Following mechanical checkouts, a daily health check data recording was transferred for offsite review by GE rotor dynamics; the dynamic behavior of the rig did not substantially change at any point during testing, and all instrumentation remained well within limits through test completion.

#### **Clearances**

The blade tip clearances were monitored during test using clearance probes. A clearance model that makes an estimate of the blade tip clearances based on the test condition and rig instrumentation readings was developed to validate the clearance probe readings. The variables in the clearance model include cold clearance, rotor speed, inlet and exit temperature, case metal temperature, and purge flow temperature. The blade and disk metal temperatures are calculated using thermal effectiveness scaling from the inlet and exit temperatures. The model and clearance probe matched pre-test predictions at all operating points.

#### **Leak Check**

A leak check was performed prior to testing the rig in order to identify the location and size of leaks in the rig to determine the impact to the overall flow rate and efficiency. The rig was sprayed with soap and inspected the formation of bubbles or jets. Leaks that were present were then sealed as effectively as possible using RTV prior to testing. The leak check and sealing process was repeated several times to confirm mitigation of the leaks. A final step was to quantify the total remaining leakage magnitude using an effective area calculation. The leakage

was found to be small and therefore the rig flow measured did not require a flow measurement correction and there was no impact to flow function or efficiency measurements.

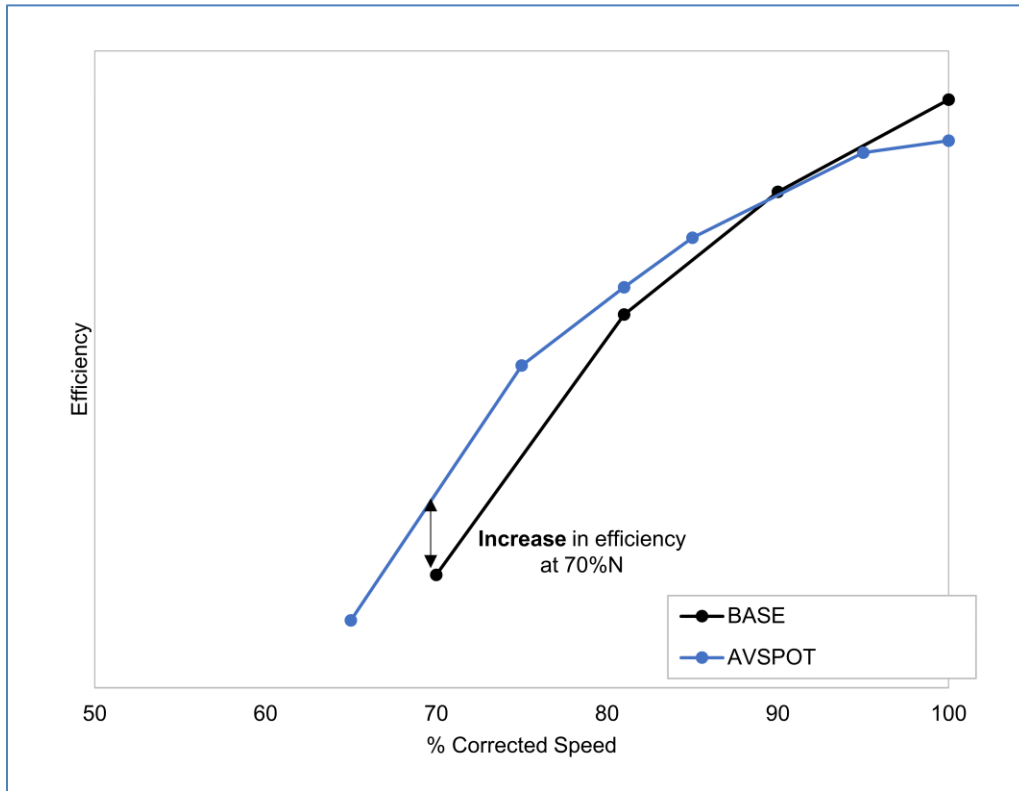
## **7.2 Aerodynamic Data Summary**

The AVSPOT turbine rig ran successfully over the course of 2 months at NDTL. The overall speed lapse results show an improvement at low speeds over a traditional baseline turbine design. Several data sets were collected during the rig test campaign to support this result. The following sections show that the vehicle performed consistently and as intended over the course of the 2 months. ADP inlet conditions were as expected, the results of collecting the same point over the course of 2 months was repeatable, and the exit conditions were as expected for both ADP and the key off design speed conditions. The map results trends were similar to expectations, but showed a wider range of performance than predicted at off design conditions. Finally, the collection and understanding of the key derivatives were critical in order to generate a physically correct and consistent map.

### **Single Speed Line Lapse**

The key outcome from the AVSPOT test data was quantifying the performance impact of the advanced airfoils. Test results exhibited an improved lapse rate with speed compared to the baseline turbine. The baseline results were measured in a PT rig that was tested with a similar set-up and instrumentation package. It was designed for peak efficiency at its respective design point at its 100% speed. As with most traditional designs, the performance starts to decrease as the turbine migrates off-design and speed is reduced. The AVSPOT design optimization traded a relatively lower efficiency at the 100% speed point to improve performance at off-design, lower speed conditions. This fundamental design philosophy, trading peak efficiency at a single design point for improved off-design performance by setting ADP at a part-speed condition was validated by the test data.

Figure 7-1 below shows the tested AVSPOT efficiency lapse as a function of speed. The test data validates the efficiency improvement of the AVSPOT configuration at low speed. Traverse data collected at the last stage blade exit is also shown at three key speeds, demonstrating the type of detailed flowfield data gathered during the rig test campaign. This data provides high-fidelity understanding of the flow field at the far off-design operating conditions and will be covered more in depth in Section 7.3.3. The data shown in Figure 7-1 is a comparison of as measured rig data for 2 rigs corrected to a common point and is therefore not directly comparable to the AVSPOT pre-test prediction or engine condition program goals.



**Figure 7-1: AVSPOT test data validates intended performance improvements at low speed relative to the base design**

### 7.3 Rig Aerodynamic Validation

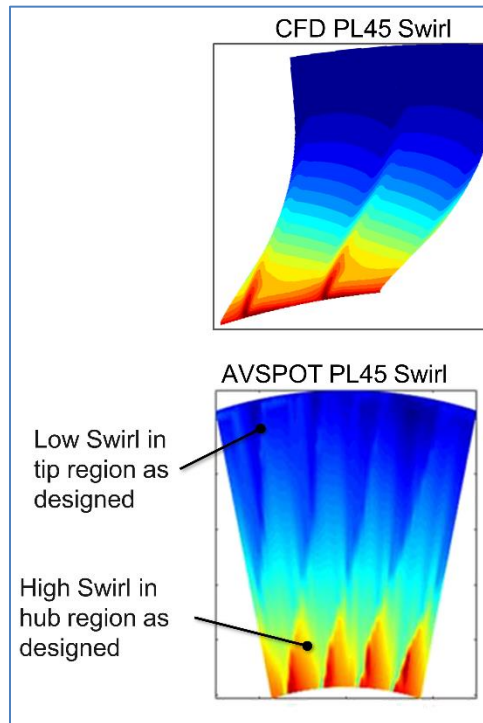
To gain confidence in the rig results, day-to-day variation is examined in the following sections along with inlet and exit profile comparisons to expectations. The rig performed as expected with very minimal day-to-day variation. This is validated by repeatable ADP data from various days of the test campaign. The inlet swirl from the pre-swirler provided the intended swirl profile into the turbine, and consistent and repeatable inlet conditions and operation of the vehicle yielded consistent exit conditions for both ADP and off design conditions.

#### 7.3.1 Inlet condition characterization and stability for Aero Design Point

The AVSPOT test exhibited stable and repeatable operation across the entire test campaign, which is critical for developing a quality map and derivative relationships without excessive corrections for run-to-run variability. Repeatability for rig parameters were taken at health check points (ADP conditions) on 5 different days, totaling 44 steady state readings during the rig test campaign. Inlet pressure, temperature and flow, and rig overall pressure ratio, were consistent to less than 0.4% 1-sigma variation, which leads to a peak-to-peak variation in measured efficiency below the instrumentation uncertainty. Overall, the rig demonstrated excellent run-to-run repeatability.

An area traverse was completed behind the pre-swirler to characterize the duct inlet condition. The pre-swirl vane was designed to produce a smooth, representative GGT exit swirl distribution

entering the duct, with higher swirl levels present near the inner wall. In Figure 7-2, the contours are shown relative to the CFD expectations.



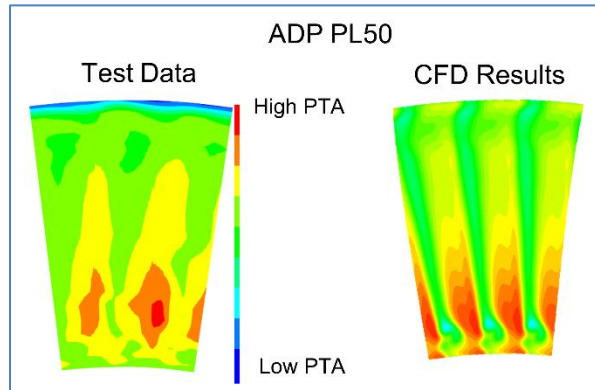
**Figure 7-2: PL45 5-hole vs. CFD Swirl Match behind Pre-Swirler**

The rig swirl contours across the traverse arc are shown on the bottom. Red indicates high swirl and blue indicates low swirl. The CFD shown on top shows a very similar result to what was measured in the rig. This indicates that the pre-swirler design met its intent.

### 7.3.2 Exit Contours and Profiles

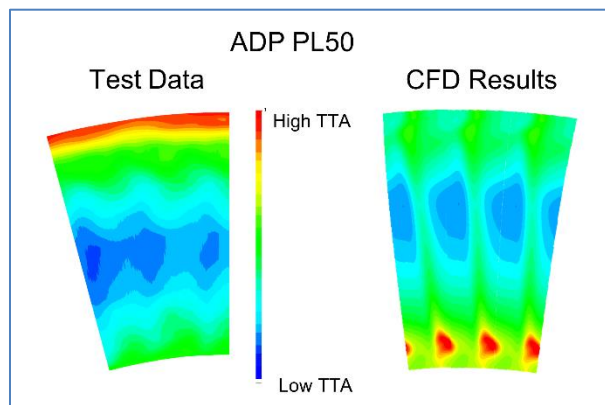
Traverse data was collected at the exit plane in order to validate the rig performance. Data collected included pressure, temperature, and swirl. In each case, the test data is compared to a CFD model ran at rig conditions with design intent rig hardware. The rig results match the CFD reasonably, thus increasing confidence in the quality of the rig data.

Contour plots in Figure 7-3 below show the exit absolute total pressure (PTA) data collected. The test data and CFD contours are again normalized by the average PL50 PTA. Note that the data is collected steady-state with a stationary probe, so the contours are showing the vane wakes after passing through the blade, compared to the CFD which is showing the blade wakes. Circumferential averages are comparable between the two.



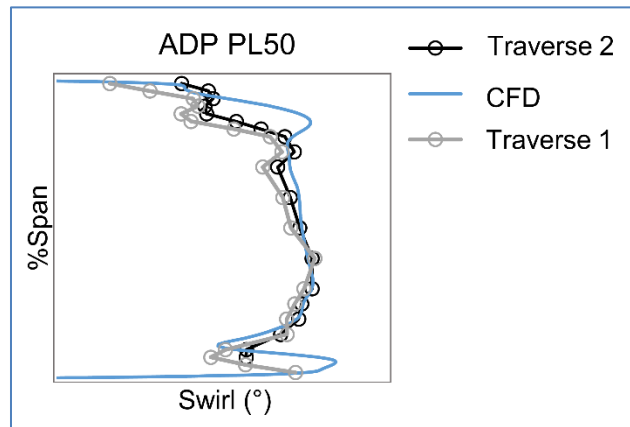
**Figure 7-3: Absolute Total Pressure (psia) measurements show good agreement with CFD predictions.**

Contour plots in Figure 7-4 below show the exit absolute total temperature (TTA) data collected. The contours are again normalized by the average PL50 TTA. The test results were in the stationary frame of reference, CFD results were in the rotating frame of reference (but absolute total temperature was plotted). All of the measurements and the CFD show the expected “C” shape in the temperatures – along with lower efficiency in the airfoils near the endwalls, fluid that leaks through the tip seals was not worked, so has higher temperature than the fluid passing through the blading; at in the inner spans, the cavity purge flows were warmer than core fluid as it was expanded through the turbine.



**Figure 7-4: Absolute Total Temperature (°R) measurements agree with CFD predictions**

Circumferential average swirl plots in Figure 7-5 below show the exit swirl data collected compared to the CFD model. The blue line is CFD and the black and grey lines are 2 traverse readings.



**Figure 7-5: Swirl (°) measurements show very good agreement with CFD predictions**

The CFD model matched the mid and inner span characteristics well. There was a larger difference between the measurements and CFD near the outer spans, perhaps due to the simplified tip seal in the CFD model.

In summary, multiple measurement techniques were used to assess the flowfield at the exit of the turbine. All of those measurement techniques were generally in agreement about the flow behavior as the speed was reduced. The CFD model did demonstrate some shortcomings in modeling the flowfield, especially at the low speed off-design condition where positive incidence was present on the airfoils. Other than the modeling challenges, the detailed measurements taken indicated that the rig was operating as expected across the speed range, with no major uncertainties, and represents a quality data set that performance maps can be built from.

### 7.3.3 Airfoil Loading Measurement

Advanced airfoil design is one of the critical design aspects for the successful performance of the AVSPOT turbine at off design conditions. The airfoils were designed to improve performance specifically at lower speeds. This section highlights the rig test data that supports the successful design of airfoils at off design conditions. Pressure and suction side pressure taps were put in four airfoils vanes. The pressure taps were placed at 50% span as close to the leading edge as possible in order to measure loading.

For the most part, the CFD model matches the measured test data. The suction side is of the most interest because it experiences the largest amount of impact from the change in air angle. The case with positive incidence results in a slight overspeed as the flow accelerates around the leading edge on the suction side. At low speed, the test data shows that the suction side sees a clear saddle back feature between the LE overspeed and accelerating to the trailing edge. The ADP condition has a more ideal loading distribution where there is constant acceleration across the suction side surface. No significant issues or flow separations were noted in the measurements across the speed range, evidence the airfoils were functioning as designed.

### 7.3.4 Flow Visualization

A surface flow visualization technique was applied as has been used successfully on several GE turbine rigs. The flow visualization was conducted on the last day of testing at a low speed point

with high loading, the key point of high interest for this rig design. Images were obtained using a borescope post-test.

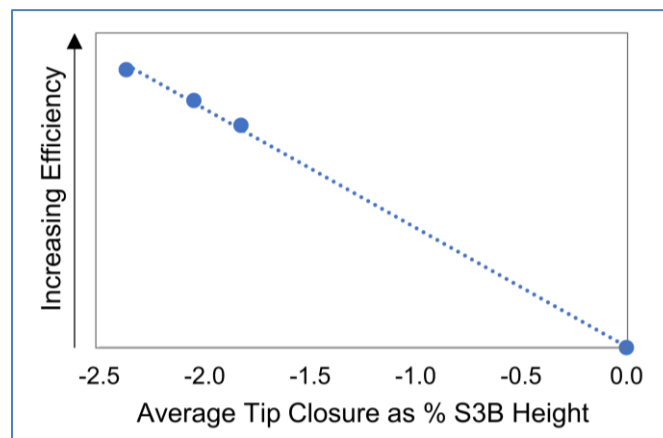
The results show expected flow conditions for airfoils operating at low Reynolds numbers. Evidence of the secondary flow loss development can be seen near the hub surface, where the flow trace tracks all the way to the airfoil trail edge. This was consistent with the increased losses measured in the traverse at the turbine exit for the same operating condition.

## 7.4 Derivatives and Reynolds Effects

Key performance derivatives including tip clearance derivatives, purge flow derivatives, and Reynolds number effects are presented below. The derivative sets are critical for correcting the test data to consistent operating conditions across the entire map, for performance comparisons and for model development.

### 7.4.1 Clearance Derivatives

A specific set of test data at a consistent operating point were taken while varying the rotor tip clearances. Performance measurements were then taken to generate a derivative curve for the turbine. An average tip clearance was used in the clearance derivative formulation.



**Figure 7-6: Measured delta efficiency vs. average clearance closure.**

The data is shown as blue circles – the measured rig clearance efficiency derivative was linear with closure, as expected. The final derivative for 1mil of average tip clearance was very close to 1D models for this effect, and the measured derivative was used to correct the map to the design intent average tip clearance.

### 7.4.2 Purge Derivatives

Constant temperature purge flow derivatives were also taken during the rig test campaign. This derivative impacts the efficiency and flow function measured in the rig. It is used to correct any variations across the test map to the intended conditions, as well as verify the turbine models. The secondary air circuits were varied by +/-25% at ADP conditions. The measured trend matches expectations. As purge flow levels decrease, there is less flow to do work so efficiency decreases. As purge flow levels increase, efficiency increases in a nearly linear relationship.

Purge flow levels also inversely impact the flow function of the turbine. All the purge flow for this rig was introduced aft of the rating plane for the turbine, so as purge flow decreases, flow function increases due to a reduction in hub blockage. Overall, the sensitive of the turbine to purge is quite small, and the variation during operation of the turbine was also small, therefore map efficiencies were not corrected for purge flows.

### **7.4.3 Reynolds Effects**

Understanding of Reynolds effects is critical for this turbine due to the engine high altitude (25kft) operating requirement. The AVSPOT rig test collected data at as low a Reynolds number possible in the facility for three speed conditions in order obtain the Reynolds lapse rate for a range of incidence angles. The lapse is then used to correct the as-measured data to the engine Re and validate the 1D model. One outcome of interest was to determine if there was any sensitivity in the Reynolds lapse to speed of the turbine. Three speeds were selected to collect data at a range of incidence angles on the turbine airfoils. Selecting a wide range of incidence angles provides more data than typically collected on traditional rigs where typically only one speed is considered (usually with no incidence).

The Reynolds variation was generated in the rig by lowering the inlet pressure and subsequently lowering exit pressure to maintain pressure ratio along the speed line. The results were consistent down to the lowest Reynolds number achieved in the rig with a smooth fit through the respective data sets that matched expectations based on CFD models.

The Reynolds number lapse measurement was a key outcome from the test campaign. The test measured the lapse rate at several shaft speeds. Smooth and consistent curves were obtained that were used to provide corrections to estimate the engine PT performance at critical high-altitude flight conditions across the speed range.

## **7.5 Turbine Aerodynamic Design Validation**

With confidence in the rig test data and the effects of tip clearance, purge flows, and Reynolds effects established, the test data and pre-test prediction are compared. The pre-test prediction discussed in Section 5 was updated with the rig derivatives in order to properly compare the model to the test data.

### **7.5.1 Aero Design Point Performance**

Starting from the pre-test prediction, the first adjustment made was to update the anticipated boundary conditions to the rig as-tested inlet conditions. This new “prediction” was then compared to the as measured efficiency result. The measured rig torque efficiency was within the predictive capability of the 1D model and represents a positive outcome from the test.

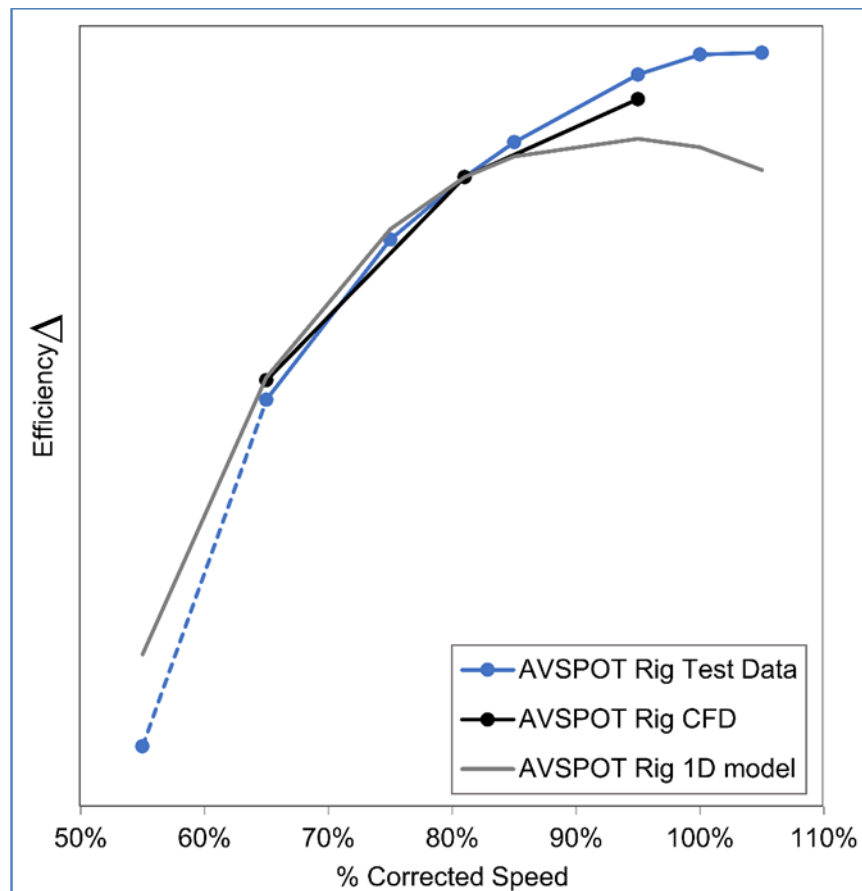
The temp to torque ratio is a consistency check on the rig power and can reveal potential issues with a torquemeter measurement. It is defined as the ratio of the rig power computed from the rig shaft torque over the rig flowpath enthalpy change. The rig result for temp to torque was very good, but indicated that the torque measurement was slightly lower than the power inferred from the thermal measurements. This indicates the potential for upside performance above the torque-based efficiency. The thermal and torque-based efficiencies bound the predicted rig performance, with the small differences between the measurements on par with the uncertainties in

determining each value. Overall, the rig performed very close to expectation and represented a successful validation of the design efficiency.

Flow function is another important indicator of how the turbine rig performed relative to design intent. The rig ran with very good agreement between the as measured and predict values, well within the GE goal of a +/-1% flow function match.

### 7.5.2 Prediction Models Comparison to Test Data for the Design PR Speedline

The AVSPOT design incorporated both 1D model and CFD results and comparing those design expectations back to measured data will improve future iterations of the design. The AVSPOT rig test data, rig CFD, and rig 1D prediction models are shown in Figure 7-7. The data is plotted as a delta to ADP efficiency for several speed cases at a constant pressure ratio. The data shown in Figure 7-7 is as measured rig data and is therefore not directly comparable to the AVSPOT engine condition program goals.



**Figure 7-7: AVSPOT design speed line efficiency lapse test data compared to CFD and 1D model predictions.**

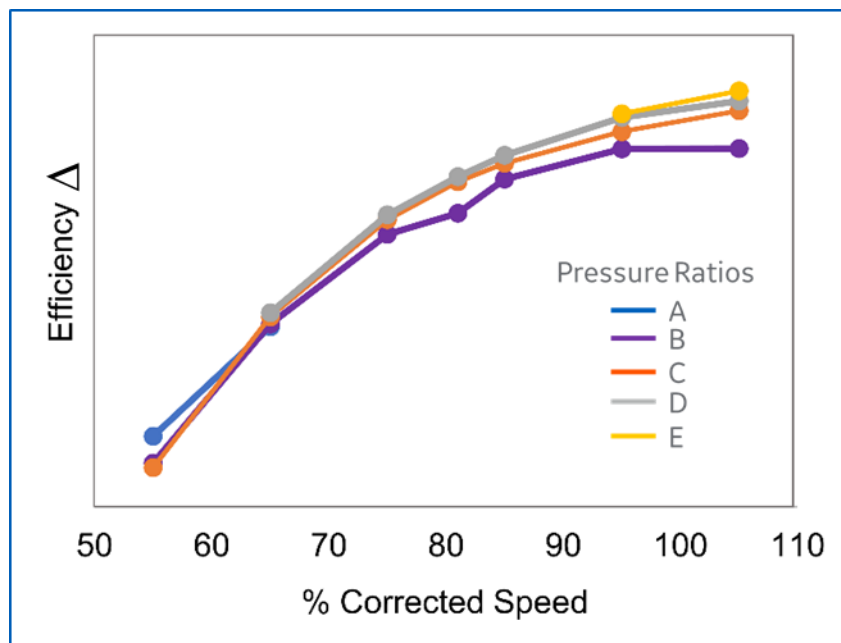
The analytical models and test data showed similar lapse characteristics at low speeds down to 65% speed. At the lowest speed point, the test data indicated that the performance falls off more steeply than the model. At high speeds the test data found a stronger improvement from the advanced airfoils than the models would predict. Performance in the rig at higher speeds peaked

near 105%. This result indicated that the design was much more tolerant of negative incidence than expected – additional evidence was found in the detailed flow surveys, where there were limited changes in the loss distributions between mid and a high speed points. The CFD model was between the 1D model and the test result, indicating that some of the physics was being captured in the CFD, but capturing the complex loss interactions requires higher-fidelity models.

## 7.6 Turbine Maps

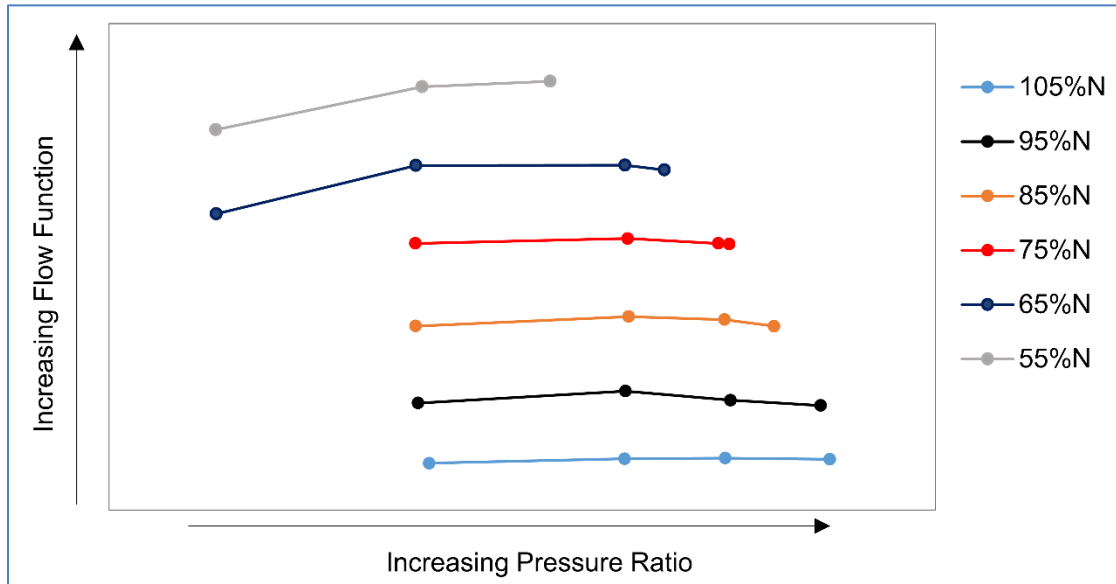
The map data generated from the rig test campaign is an important input for performance models of future engine development efforts. Multiple speed points along lines of constant  $\Delta H/T$  were taken during testing, and those results were converted to both efficiency and flow function maps.

The turbine map was completed at a rig Reynolds number and then corrected for Reynolds number and tip clearance effects using measured derivatives. All the map was corrected to the design intent tip clearance and Reynolds. Figure 7-8 shows the map data plotted as an efficiency  $\Delta$  from design point. The map shows the performance lapse with speed as a function of pressure ratio. Pressure ratio had a mild impact on performance, with lower pressure ratios reducing the performance slightly (due to the differential unloading of the turbine stages).



**Figure 7-8: AVSPOT performance map. Lines of constant Pressure Ratio.**

Figure 7-9 is the rig flow function map, corrected using the same methodology as described above. Overall, the flow function is a stronger function of speed than pressure ratio. The measured data showed only a slight sensitivity to pressure ratio at the low and high ends of the speed lines.



**Figure 7-9: AVSPOT flow function map. Lines of Constant Speed.**

## 7.7 Rig Test Results Conclusion

The AVSPOT test successfully achieved all main objectives.

- ✓ Understood key performance derivatives, including Reynolds Number, purge flows, and tip clearances
- ✓ Measured performance trends of PT vs. speed at multiple PRs to produce PT map and validate analytical trends.
- ✓ Measured airfoil static pressures to validate the airfoil design and analytical tools.
- ✓ Completed flow visualization.

The test campaign was executed without significant issue and collected high quality data across a very wide operating range, including detailed turbine exit area traverses that provided insight into the flow behavior at far off-design conditions. The rig test demonstrated that the AVSPOT turbine out-performed the baseline design at low speed conditions and demonstrated that the advanced airfoil technology was a successful enabling technology. Overall, the data collected in this test will form the foundation for continued development of additional technologies to enable successful turbine designs for the stringent requirements of FVL applications.

## 8 Performance vs Program Goals

The AVSPOT rig demonstrated improved performance at low speed relative to a conventional design optimized at one point, validated the design point physics in the predictive models, and identified some areas for improvement in the low speed design regime. The first step in building the engine outcome is predicting the performance using the 1D modeling tool, which was validated by the test data. Starting with the measured rig efficiency, the engine tip clearance, Reynold's number, air properties, and operating conditions are applied to migrate from rig to engine conditions. The measured value is also corrected for purge flow differences, the elimination of the rakes in the inlet of the turbine, and all recoverable hardware deviations

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described in the pre-test predictions. The resulting demonstrated performance delivers exceptional performance improvements relative to a conventional design across the entire 55%-105% speed range.

The performance for the as-tested turbine design at ADP but at engine conditions is the starting point for building a comprehensive product design that combines rig test learnings with additional state of the art technologies to deliver the goal performance. The as-tested design successfully meets the 100% speed MRP goal and demonstrated a significant part-speed improvement over a turbine optimized at for a single speed.

Based on the findings in the AVSPOT rig test, several approaches exist to meet the program goals across the operating range. The key is to take the AVSPOT advanced airfoils and introduce technologies validated by other relevant rigs or other basic design modifications to combat the change in off-design loading. One potential path is to attempt to reduce the overall turbine loading by changing stage count and tip speed. By applying manufacturing technology currently under development, a path exists for designing the advanced airfoil technology in a package capable of the higher  $AN^2$  than currently employed on the rig. This loading reduction approach, coupled with technologies to reduce secondary flow and Reynold's losses, delivers a turbine that meets program goals but also changes engine length and outer diameter, requiring a new installation.

The selection of stage count and size is a function of close integration of aircraft and engine requirements, and the optimal system solution can only be achieved with greater fidelity of the application aircraft needs. With that said, from a total system perspective a design that minimizes cost, complexity, length, and weight will likely be optimal. These system implementation considerations drove the AVSPOT design towards the compact, highly loaded turbine with advanced airfoils that was tested in the rig. The rig data offers insights into what technology insertions would be needed for the design to meet key program goals within the currently defined engine length and diameter. First, a more aggressive turbine duct and increased annulus area on the front stages will achieve some of the benefits noted above but would not require changes to the installation envelope of the tested design. Durability studies discussed in Section 4.2.5 show that the components have sufficient margin to withstand this slight  $AN^2$  increase.

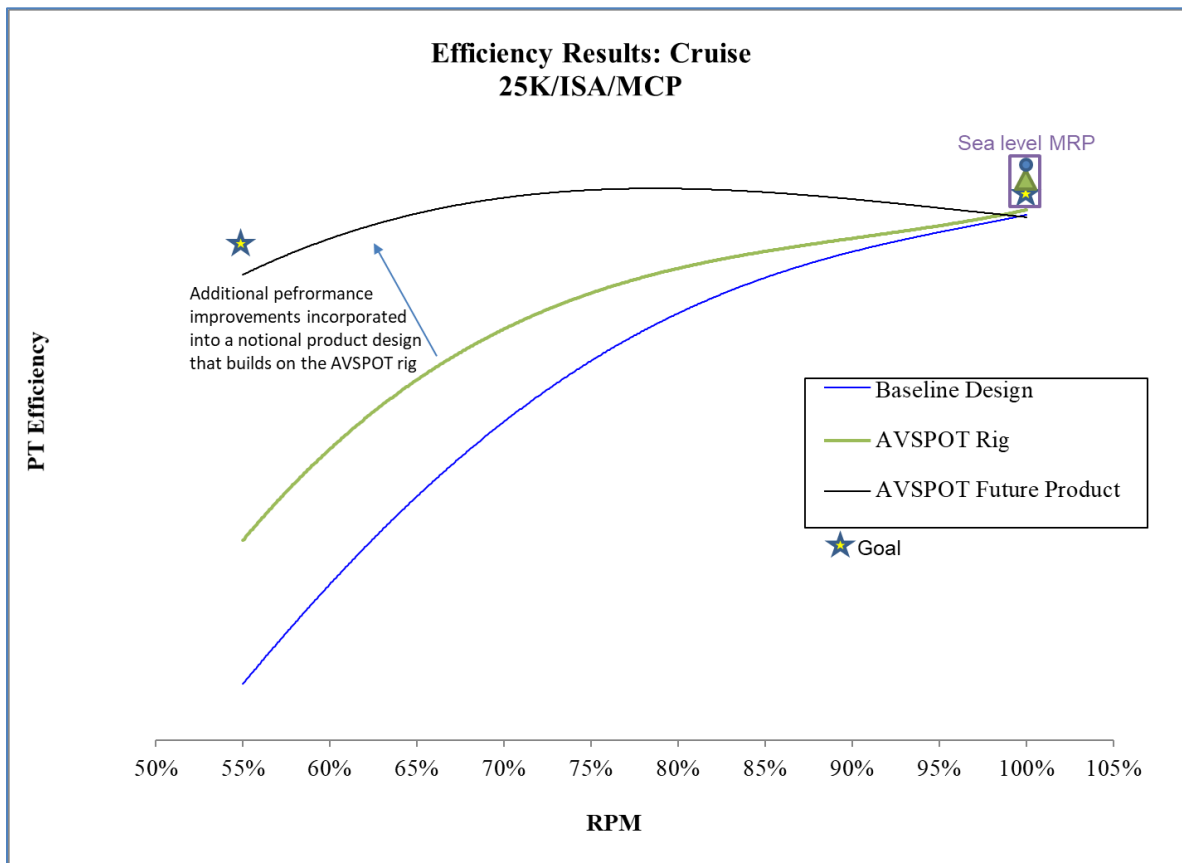
Next, a key finding from the AVSPOT rig test campaign is that the advanced airfoil designs behaved better than expected at high speed and had performance in-line with expectations at low speed. This suggests that reoptimizing the design point would further improve low speed efficiency without eroding the high speed performance.

Finally, the AVSPOT test was executed with a very targeted technologies suite to determine the fundamental physics of low speed performance for the advanced airfoil design and provide a foundation for continued development of a wide speed range turbine. In addition to the advanced airfoils, a product power turbine will incorporate a number of other advanced aerodynamic and mechanical technologies optimized at multiple part-speed conditions. These technologies are leveraged from several commercial and military development programs that have demonstrated improvements to the loss mechanisms important to wide speed operation. These development programs have also refined and validated the analytical tools and methods to design them, albeit at a single design point. In a product variable speed PT, these technologies would be advanced

from the current single-point optimization to a multi-point design optimization and applied to the AVSPOT design.

In order to project performance for this future product AVSPOT with all of the technologies discussed above, estimated performance improvements from each individual technology are added to the rig-based performance of the as-tested AVSPOT configuration at the 3 points specified in the BAA. Based on the AVSPOT test findings, the design point will be shifted, which significantly improves the turbine performance at low speed with minimal roll-off at the high-speed conditions. The individual technologies being integrated target specific loss mechanisms, the magnitudes of which vary with speed and altitude. Therefore, the magnitudes of the efficiency impact of these technologies also change with speed and altitude. For example, low Reynolds technology is designed to maximize impact at points where Reynolds losses are the most severe.

The resulting final product projected performance is shown in Figure 8-1. This design includes the multi-point design optimization of aero technologies validated on recent GE rigs, coupled with an optimized ADP a small flowpath flair compared to the rig tested configuration.



**Figure 8-1: Product design incorporates learnings from AVSPOT rig test and other relevant GE development efforts.**

In conclusion, a plan has been created for a compact, lightweight VSPT to meet the FVL needs of the Army. A foundational first step was taken by testing a product-representative rig that

incorporated advanced airfoil technology to generate a performance map. The results can easily be projected to a slightly higher performance, but heavier and more expensive, design, depending on aircraft requirements. One key finding from the test was that the design models were reasonable on the low speed loss behavior, but conservative on the high-speed side. With that finding and validation of further performance technologies in adjacent programs, the next steps in the evolution of the AVSPOT product can be determined.

The AVSPOT Program successfully matured the aerodynamic technologies required for efficient wide speed PT operation. The demonstrated technologies are sufficiently mature to proceed into future development programs as a result of the design and testing activities completed to date. An engine-level demonstration focused on mechanical risks is one option to further reduce risk for FVL applications. This yet-to-be-determined engine demonstration of this AVSPOT product, possibly coupled with a re-build of the initial turbine rig, would further risk reduce the integration of all required technologies in a compact, efficient and lightweight turbine package.

## 9 References & Definitions

### 9.1 References

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2. McVetta, A., Giel, P., Welch, G., “Aerodynamic Measurements of a Variable-Speed Power-Turbine Blade Section in a Transonic Turbine Cascade at Low Inlet Turbulence,” ASME GT2013-94695, July 2013.
3. Ford, A., Bloxham, M., Turner, E., Clemens, E., Gegg, S., “Design Optimization of Incidence-Tolerant Blading Relevant to Large Civil Tilt-Rotor Power Turbine Applications,” NASA/CR-2012-217016, Dec. 2012.
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### 9.2 Acronyms and Definitions

**Table 9-1: Acronyms and Definitions**

Acronym	Definition	Acronym	Definition
AATE	Advanced Affordable Turbine Engine	ADD	Aviation Development Directorate
ADP	Aerodynamic Design Point	AETD	Adaptive Engine Technology Development
APT	Advanced Power Turbine	ASME	American Society of Mechanical Engineers
ATD	Aviation Test Data	AVSPOT	Advanced Variable-Speed Power Turbine
BAA	Broad Agency Announcement	BTU	British Thermal Units
CAD	Computer Aided Design	CDRL	Contract Data Requirement List
CFD	Computational Fluid Dynamics	CIP	Component Improvement Program
CMC	Ceramic Matrix Composite	CMM	Coordinate Measuring Machine

Acronym	Definition	Acronym	Definition
CRP	Contingency Rated Power	CSDH	Cold Start Double Hump
DAQ	Data Acquisition	DC	Direct Current
DES	Detached Eddy Simulation	DHTQTL	Total Torque
DMLM	Direct Metal Laser Melting	DOE	Design of Experiments
ETATTT	Torque based efficiency	ETAXTT	Thermal Based Efficiency
FATE	Future Affordable Turbine Engine	FEA	Finite Element Analysis
FF	Flow Function (also called Wp)	FVL	Future Vertical Lift
GGT	Gas Generator Turbine	HCF	High Cycle Fatigue
HMI	Human-Machine Interface	ID	Inner Diameter
IRP	Intermediate Rated Power	ISA	International Standard Atmosphere
KSI	Pounds per square inch, thousands	LCF	Low Cycle Fatigue
LE	Leading Edge	LES	Large Eddy Simulation
LFU	Life Fraction Used	LL	Lean Lab (GE Aviation development shop)
LPT	Low Pressure Turbine	LTD	Large Turbine Development
MA	Massachusetts	MATLAB	Matrix Laboratory (software)
MCP	Maximum Continuous Power or Multi-Core Processor	MN	Mach Number
MRP	Maximum Rated Power	NASA	National Aeronautics and Space Administration
NCORXL	Corrected Speed, RPM/ $\sqrt{TT}$	ND	Nodal Diameter
NDE	Non-Destructive Evaluation	NDTL	Notre Dame Turbomachinery Lab
NG	Gas Generator Speed	NGR	Corrected Core Speed
NP	Power Turbine Speed or Average Cyclic Crack Propagation	NPT	Power Turbine Speed
NR	Rotor Speed	OD	Outer Diameter
OPR	Overall Pressure Ratio	PL	Plane
PR	Pressure Ratio	PS	Static Pressure
PSI	Pounds per Square Inch	PT	Power Turbine
PTA	Total Pressure Profile	PTR	Power Turbine Rotor
RAEICS	Rotorcraft Advanced Engine Integrated Control System	RANS	Reynolds Averaged Navier Stokes
RPM	Revolutions Per Minute	RTV	Sealing Epoxy
SETT	Second Engine To Test	SFC	Specific Fuel Consumption
SHP	Shaft Horsepower	SL	Sea Level
SLS	Sea Level Static	SOA	State Of The Art
SS	Steady State or Stainless Steel	TFE	Test Facility Engineering
TIA	Technology Investment Agreement	TO	Take Off
TR	Transient	TRL	Technology Readiness Level
TRR	Test Readiness Review	TS	Static Temperature or Turboshaft
TT	Total Temperature	TTA	Absolute Total Temperature
US	United States	UTS	Ultimate Tensile Strength
VSPT	Variable Speed Power Turbine	VTOL	Vertical Takeoff & Lift
YS	Yield Strength	ZWI	Zweifel Number
<b>Other units and parameters</b>			
ktas	Air Speed (knots)	psia	pounds per square ince (absolute)

Acronym	Definition	Acronym	Definition
psid	pounds per square ince (delta)	psig	pounds per square ince (gage)
ft	foot	lbf	pound force
lbm	pound mass	in	inches

**Table 9-2: Turbine Descriptive Parameters**

Parameter	Definition
$P'/P'$	Total-to-Total Pressure Ratio
$P'/P$	Total-to-Static Pressure Ratio
$\frac{W\sqrt{\theta}}{\delta}$	Corrected Flow, lb/sec
$\frac{\Delta H}{\theta}$	Corrected Work, Btu/lb
$\frac{N}{\sqrt{\theta}}$	Corrected Speed, RPM
$\eta$	Efficiency
$\eta_{TT}$	Total-to-Total Efficiency
$\eta_{TS}$	Total-to-Static Efficiency
$\eta_{temp}$	Efficiency Derived from Total Temperature Drop
$\eta_{torq}$	Efficiency Derived from Torque
$W_{chg}$	Chargeable Flow, lb/sec
$W_{4.8}$	Inlet Flow, lb/sec