NASA/CR—2012-217424 TR2011-02-28-0724

Variable-Speed Power-Turbine for the Large Civil Tilt Rotor

Mark Suchezky and G. Scott Cruzen
Williams International Co. LLC

February 2012

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include creating custom thesauri, building customized databases, organizing and publishing research results.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at *http://www.sti.nasa.gov*

- E-mail your question via the Internet to *help@sti.nasa.gov*

- Fax your question to the NASA STI Help Desk at 443–757–5803

- Telephone the NASA STI Help Desk at 443–757–5802

- Write to:
  NASA Center for AeroSpace Information (CASI)
  7115 Standard Drive
  Hanover, MD 21076–1320

NASA/CR—2012-217424 TR2011-02-28-0724

Variable-Speed Power-Turbine for the Large Civil Tilt Rotor

Mark Suchezky and G. Scott Cruzen
Williams International Co. LLC

Prepared under Contract NNC10BA15B

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

February 2012

Available from

NASA Center for Aerospace Information
7115 Standard Drive
Hanover, MD 21076–1320

National Technical Information Service
5301 Shawnee Road
Alexandria, VA 22312

Available electronically at http://www.sti.nasa.gov

Contents

List of Tables

List of Figures

1.0 Introduction

The Large Civil Tilt-Rotor (LCTR) is part of NASA's Heavy Lift Systems Investigation. This proposed 90 passenger aircraft would offload short to medium range air traffic from large airports and/or runways. Due to its vertical takeoff and landing capability, only a helipad would be needed within existing airport infrastructure (Figure 1.1).

The proposed vehicle has four turbo-shaft engines powering two rotors. Each engine is to develop 7,500 hp for a total 30,000 hp. The mission would require high rotor rpm at sea level take off (650 ft/s tip speed) and significantly lower rpm at cruise (350 ft/s tip speed) (Ref. 1). That is, the cruise rpm of the main rotors is 54 percent of the SLTO rpm. This requirement comes from the fact that the main rotors are more efficient at low rpm during the altitude cruise but require high rpm during sea level take-off (SLTO). The turboshaft engines will drive the main rotors through a gearbox enabling the high rpm power turbines (PT) to spin the low rpm (103 to 191 rpm) main rotors. Each main rotor is driven by two engines. There are two possible methods for achieving the required rpm sweep.

1. Two (or higher) gear-ratio transmission: with the power turbine operating at near constant rpm.
2. Fixed gear-ratio transmission: with the power turbine experiencing the full 54 to 100 percent speed range.

For method 1, the complexity of designing a flight weight, 15,000 hp transmission (two engines X 7,500 hp each), while obtaining high life and reliability is a formidable task. The method for changing gears (ex. torque converter, clutch, etc.) would also need to be addressed. This method is not within the scope of this study and will not be further considered.

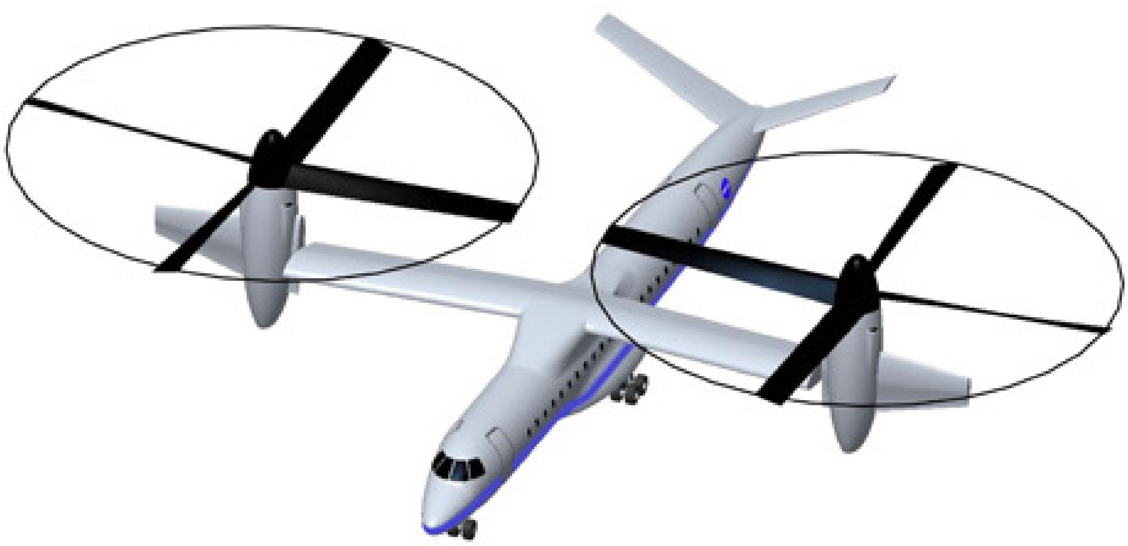


Figure 1.1—NASA LCTR Concept

Nomenclature

AN^2	See Appendix B
Cm/U	Flow Coefficient
Cx/U	Flow Coefficient
$\Delta h_0/U^2$	Work Coefficient
FOM	Figure of Merit
h_0	Total Enthalpy
LCTR	Large Civil Tilt-Rotor
LE	Leading Edge
η	Efficiency (see Appendix G)
NPSS	Numerical Propulsion System Simulator
PT	Power Turbine
SLTO	Sea Level Take Off
TE	Trailing Edge
U	Wheel Speed (usually associated with midspan)
VSPT	Variable Speed Power Turbine

2.0 VSPT Concept Development

2.1 Figure of Merit

In this study various techniques are investigated to improve efficiency and off-design characteristics of a power turbine operating in the LCTR mission. The relative performance of each design modification needs to be assessed using some form of figure of merit (FOM). The FOM chosen for this study is overall fuel burn during the mission. The overall mission profile is not well established at this time so a fictitious but representative mission needs to be assumed. Based on the work of Snyder and Thurman (Ref. 1), a study engine simulation was generated using the Numerical Propulsion System Simulator (NPSS). This simulation software has the ability to predict engine performance throughout the flight envelope based on performance maps of the individual engine components. Four output points were generated from this model and made available for this study. These four flight conditions are:

Point 1

SLTO;	100% PT Speed,	100ft,	0.0 Mach,	Std. Day

Point 2

Climb;	100% PT Speed,	2,000ft	0.0 Mach	+45 °F

Point 3

Start Cruise;	100% PT Speed	28,000ft	0.51 Mach	Std. Day

Point 4

Cruise;	54% PT Speed	28,000ft	0.51 Mach	Std. Day

A detailed output from the NPSS cycle model is included in Appendix A. These four points are the only points currently available from the model and therefore a mission made up of only these four points was assumed. The actual mission will deviate significantly from this mission, but this mission is used as a starting point (Table 2.1).

This mission was made to mimic the mission shown in Figure 2.1, provided by C. Sndyer of NASA at contract start.

TABLE 2.1—LCTR MISSION SEGMENTS

Point	Description	Δtime	Cycle PT	Power	Wf	PT	Fuel Burned	
		Minutes	ETA	hp	lbm/hr	Speed	lbm	
1	SLTO;100% PT Speed,100ft,0.0 Mach, Std. Day	2	0.85	7500	2581.28	100.0%	86.0	
2	Climb;100% PT Speed,2,000ft0.0 Mach+45°F	2	0.8266	4639.6	1761.6	100.0%	58.7	
3	Start Cruise;100% PT Speed 28,000ft 0.51Mach Std. Day	30	0.8485	2651.5	836.01	100.0%	418.0	
4	Cruise;54% PT Speed 28,000ft 0.51 Mach Std. Day	180	0.7859	2345.4	805.23	54.0%	2415.7	
3	Start Cruise;100% PT Speed 28,000ft 0.51Mach Std. Day	30	0.8485	2651.5	836.01	100.0%	418.0	
2	Climb;100% PT Speed,2,000ft0.0 Mach+45°F	2	0.8266	4639.6	1761.6	100.0%	58.7	
	TOTALS	246	Minutes				3455.2	lbm
		-or-						
		4	hours					
		6	minutes					

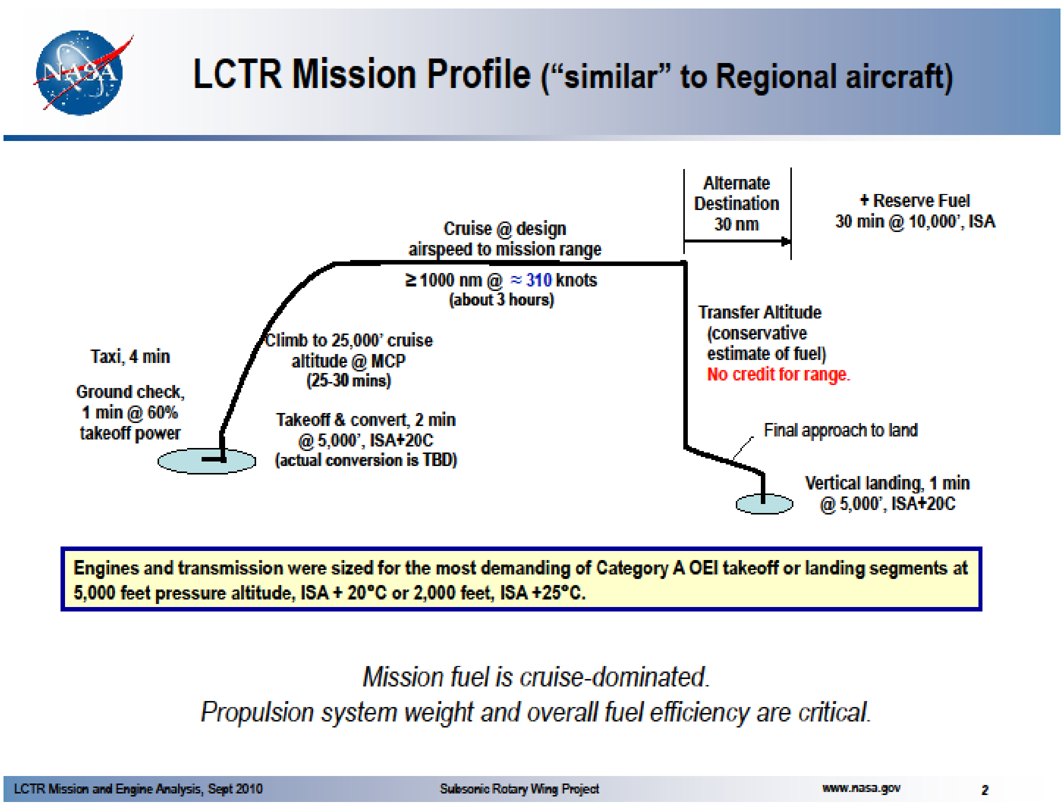


Figure 2.1.—LCTR Mission Profile

Unfortunately, cycle points such as idle and taxi were not available to use in this cycle so there is some error introduced. The mission used in this study (Table 2.1) includes a long cruise segment of 3 hr with ½ hr of climb condition before and after. There is also some high power SLTO time at the beginning and end of the mission to simulate vertical takeoff and landing.

Given the cycle predicted fuel burns at each condition and the assumed duration of each segment, the fuel burned can be integrated. (Eq. (1))

$$W_{fuel} = \sum_{seg=1}^{nseg} \dot{W}_{fuel} \times \Delta Time \tag{1}$$

Table 2.1 shows that the predicted fuel burn would be 3455.2 lbm of fuel per engine over the 4 hr and 6 min flight. Because all of the power to drive the main rotors comes from the power turbine, the fuel burn at any condition will be proportional to PT efficiency. Therefore we can evaluate the impact of predicted PT efficiencies (η_{PT}) throughout the mission by scaling the fuel flows by the ratio of predicted η_{PT} to cycle η_{PT}.

$$W_{fuel} = \sum_{seg=1}^{nseg} \frac{\eta_{predicted}}{\eta_{cycle}} \dot{W}_{fuel} \times \Delta Time \qquad (2)$$

Using this technique, a prediction for η_{PT} can be input into Equation (2) for each of the four cycle points and an overall mission fuel burn can be calculated. Comparing the new predicted fuel burn back to the cycle prediction (3455.2 lbm) yields the FOM used in this study.

2.2 Efficiency Prediction Technique

Efficiency predictions are made by the use of a ‘meanline’ analysis. The meanline used is proprietary to Williams International and is referred to as ‘MeanTurb’. MeanTurb is a row by row analysis tool that tracks the mean particle through each airfoil row. All three components of velocity are modeled which makes the tool very general and can be used for axial, mixed flow, or radial turbines. The velocity triangles are solved with the loss system, cooling flows (if applicable), gas properties, and seal leakages all converged simultaneously. The solution technique is to solve each blade row independently and then use small-change effects (Jacobian matrix) and Newton’s Method to close on continuity, angular momentum, and energy. The loss system used in this study is a combination of various public domain loss systems (Kacker and Okapuu (Ref. 4) and Moustapha, Kacker and Tremblay (Ref. 5)) with modifications based on Williams International experience.

The technique used to predict turbine efficiency is two parts. The first part is referred to as ‘design mode’. In this phase a simpler design-mode meanline called “Falcon” is used. This meanline is different from MeanTurb in that you specify mass-flow, power, pressure reaction and airfoil loading coefficient (Zweifel). The velocity triangles are calculated using nearly the same loss system as MeanTurb with several simplifying assumptions. Falcon is wrapped with a graphical user interface which allows for intuitive design as well as optimization functionality. Figure 2.2 is a screen shot of the interface.

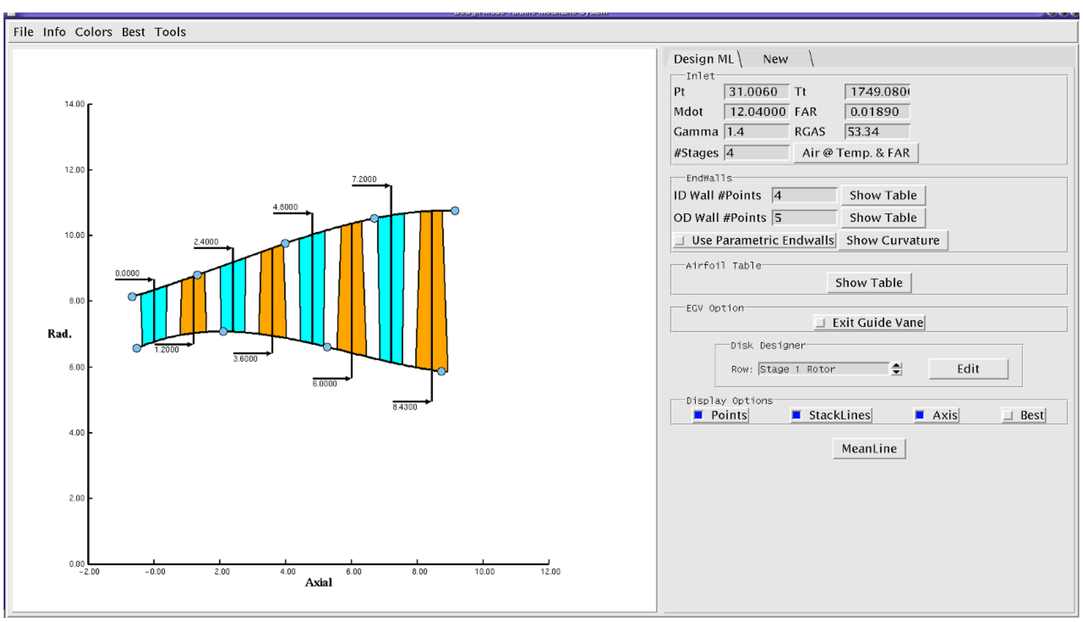


Figure 2.2—Falcon Meanline Code Interface

The second part of the efficiency prediction process begins after a satisfactory design has been produced in Falcon. Falcon writes out an off-design input file for MeanTurb. At this point the geometry is assumed fixed and parameters such as power, work split, reaction, mass-flow and efficiency are outputs of MeanTurb. One important point in this study is that the LE metal angles are assumed fixed so the impact of off-incidence design is captured in the MeanTurb calculations.

2.3 Structural Constraints

The 100 percent speed condition must be structurally viable. This study used aggressive AN^2 and Rim Speed limits of 60. E9 $in^2{\cdot}rpm^2$ and 1200 ft/s respectively as upper limits. (See Appendix B for definitions.) The most challenging structural design will be the last stage blade which will have the largest span and highest pull stress. Fortunately it is also the coolest airfoil which aids in creep rupture life. Although challenging, these limits should be achievable for a long life application. After designing several flowpaths to this criterion, a sanity check calculation was performed. A meanline analysis was run for Point 1 (the hottest and fastest of the four performance conditions used) with the inlet temperature raised by 100 °F to simulate deterioration and hot day operation. The average blade pull-stress was estimated at 68 ksi and metal temperature at 1190 °F. Based on proprietary material databases, there are several commercially available alloys capable of >20,000 hr of useful life at these conditions. Over-speed protection in the event of a gearbox or coupling failure has not been addressed. It is possible that failure analysis may require more structural conservatism.

2.4 Exhaust Constraint

Choosing the exit annulus area determines the exit Mach number from the turbine (last blade, absolute frame of reference). The four cycle points given have nozzle (tail pipe) exit Mach numbers of about 0.27. This very low exit Mach number corresponds to a design philosophy of extracting as much energy out of the power turbine as possible and achieving nearly no thrust from the nozzle. Achieving such low exit Mach numbers at the exit of a gas turbine is difficult and results in large, heavy turbines operating at low rpm. It is more advantageous to design to an exit Mach number of .4 to .55 and diffuse through the exhaust system. For the purposes of this study, Mach numbers in this range will be used. In a more formal detailed design, a trade study between nozzle exit Mach number, turbine weight, exhaust system weight and fuel burn should be performed to find the best overall system trade.

It can be shown that the combination of the structural and exhaust constraints sets the turbine rpm and the last stage flowpath. That is: picking a Mach number exiting the turbine sets the turbine exit annulus area because of continuity (although swirl angle and boundary layer blockage play a role). Then, with AN^2 already chosen, the rpm falls out. (See Appendix B for more information)

$$\text{A} = \text{function(PT, TT, Mdot, Mach, Swirl)} \tag{3}$$

$$\text{rpm} = \sqrt{\frac{\text{AN}^2}{\text{A}}} \tag{4}$$

The Rim Speed can be used to calculate the last blade trailing edge hub radius:

$$\text{Rim Speed(ft/s)} = \text{Radius}_{\text{Hub}}\,\text{(in.)/12.} * \text{rpm} * \pi / 30. \tag{5}$$

Then the trailing edge tip radius can be determined by the annulus area.

$$\text{Radius}_{\text{Tip}} = \sqrt{\frac{\text{A}}{\pi} + \text{Radius}^2_{\text{Hub}}} \tag{6}$$

From the above relations it is clear that selecting structural criteria and an exit Mach number uniquely defines the exit of the turbine and the rpm. In a more detailed engine design exercise, the front of the power turbine would need to mate to the exit of the previous turbine which would further define the flowpath. In this work, no special attention is given to the proceeding turbine. Detailed design of the overall turbine section is out of scope.

2.5 List of Analytical Studies

Several analytical studies have been performed to gain confidence and reduce risk in designing a power turbine capable of nearly a 2X speed variation while maintaining acceptable efficiency levels.

1. Flow Path Selection
   a. CX/U
   b. Work Coefficient
   c. Number of Stages
2. Loss System Validation via CFD
3. Incidence Tolerant Design
   a. LE Shape
   b. Airfoil Thickness

2.6 Flow Path Selection: Cx/U

Turbine Flow Coefficient, commonly referred to as Cx/U, is the ratio of through-flow velocity to mean wheel speed. Often Cx/U is referred to as axial velocity over wheel speed but in this study the radial velocity is taken into account. The meridional velocity is used instead and defined as:

$$V_{\text{meridional}} \equiv \sqrt{V_{\text{axial}}^2 + V_{\text{radial}}^2} \tag{7}$$

For the purposes of this study, Cx/U and Cm/U will be used synonymously and is defined as:

$$\text{Cm}/\text{U} = \text{Cx}/\text{U} \equiv \frac{\sqrt{V_{\text{axial}}^2 + V_{\text{radial}}^2}}{\omega\bar{r}} \tag{8}$$

where:

all values are calculated at the TE plane of the turbine blade
$\bar{r}$ equals the average of the hub and tip radius of the blade TE

The Flow Coefficient, Cx/U is a good indicator of the velocity triangles. Low Cx/U designs are characterized by high turning and relatively low velocity whereas high Cx/U designs tend towards low turning (camber) and higher velocities. The airfoil shapes can be dramatically different as shown in Figure 2.3.

The off-incidence loss generated at the LE of an airfoil is a function of two factors: 1) Loss Coefficient and 2) Inlet dynamic head. Low CX/U designs have lower LE Mach number but higher swings in incidence. High CX/U designs have lower excursions in incidence but always operate at higher inlet Mach number. Therefore it is reasonable to assume that there is an optimum CX/U for off incidence performance. Figure 2.4 and Figure 2.5 show a simplified example of velocity triangle for Low versus High CX/U designs.

For the VSPT, the corrected speed variation is from 54 to 100 percent. This implies that the wheel speed (U) varies from 54 to 100 percent but velocity triangle analysis shows that the Cx is nearly constant. Therefore, CX/U is approximately inversely proportional to speed.

Two flowpaths were generated to look at the impact of CX/U on mission fuel burn. The design philosophy was to follow the structural and exhaust constraints as given in the previous section and build turbine flowpaths that have good cruise velocity triangles and airfoil loadings. Once the flowpaths are established, MeanTurb is run to investigate the off design characteristics. Very good cruise performance (>90 percent) is achieved with four stage turbines. See Figure 2.6.

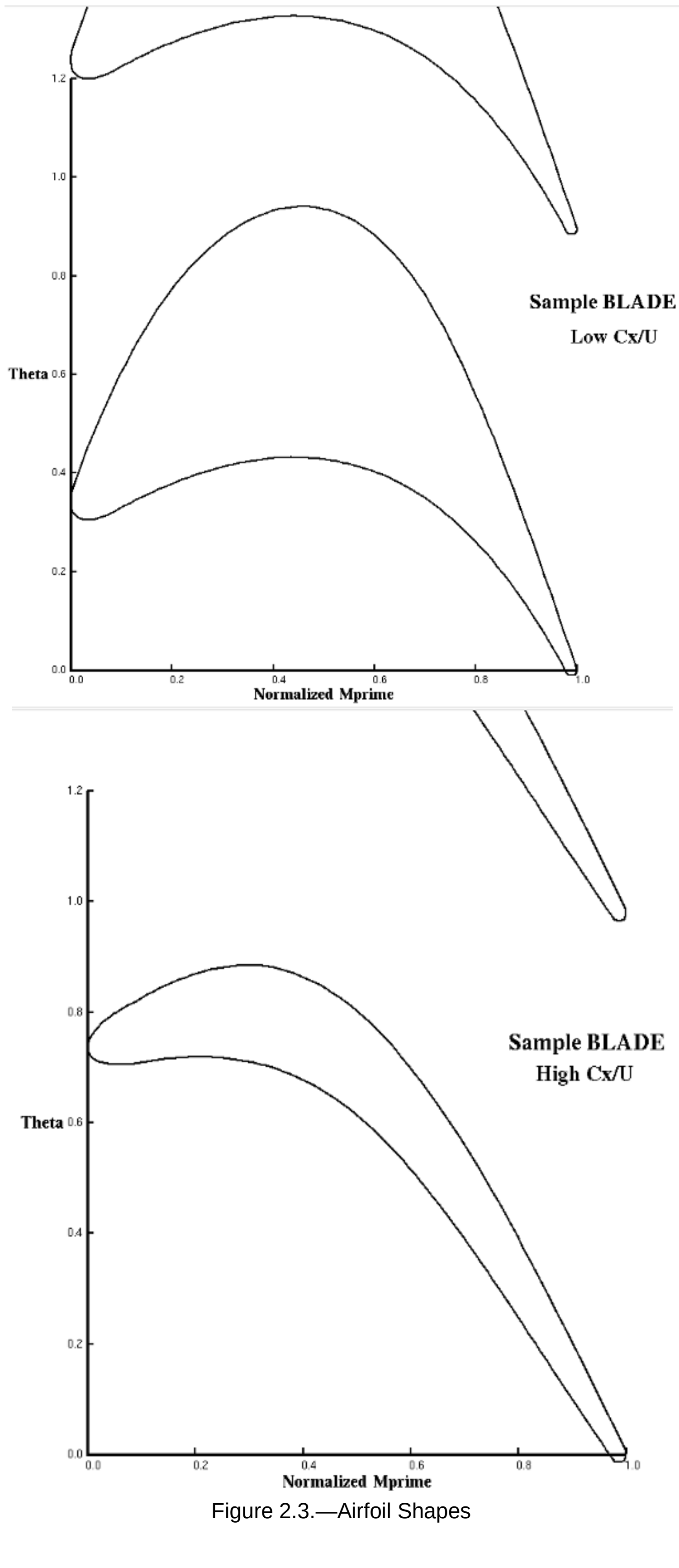


Figure 2.3.—Airfoil Shapes

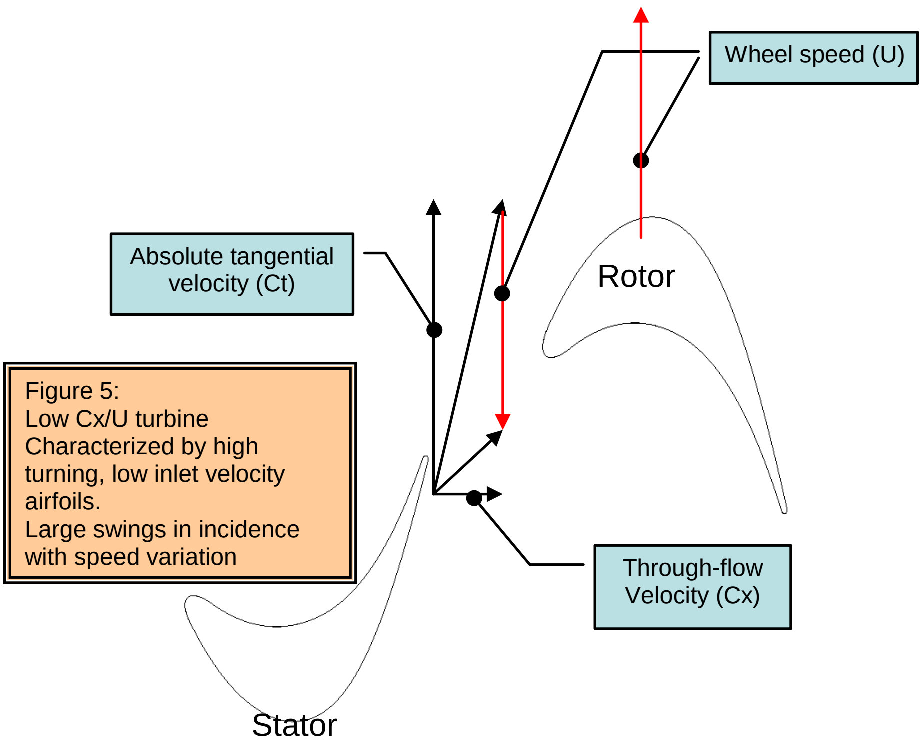


Figure 2.4.—Low CX/U Design Velocity Triangles

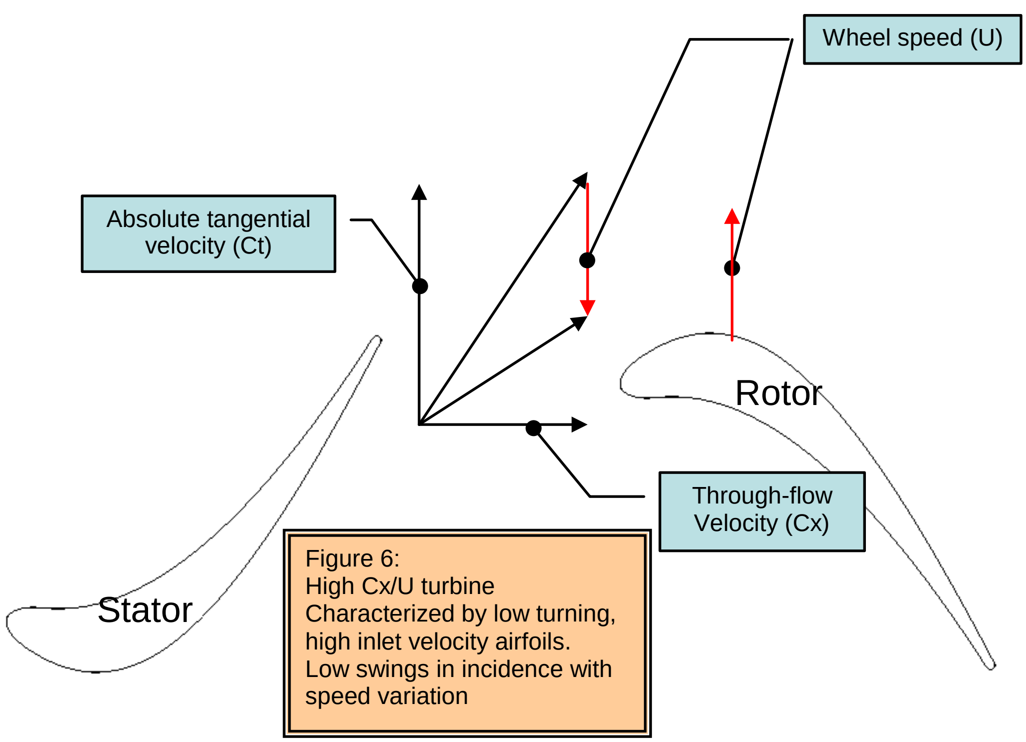


Figure 2.5—High CX/U Design Velocity Triangles

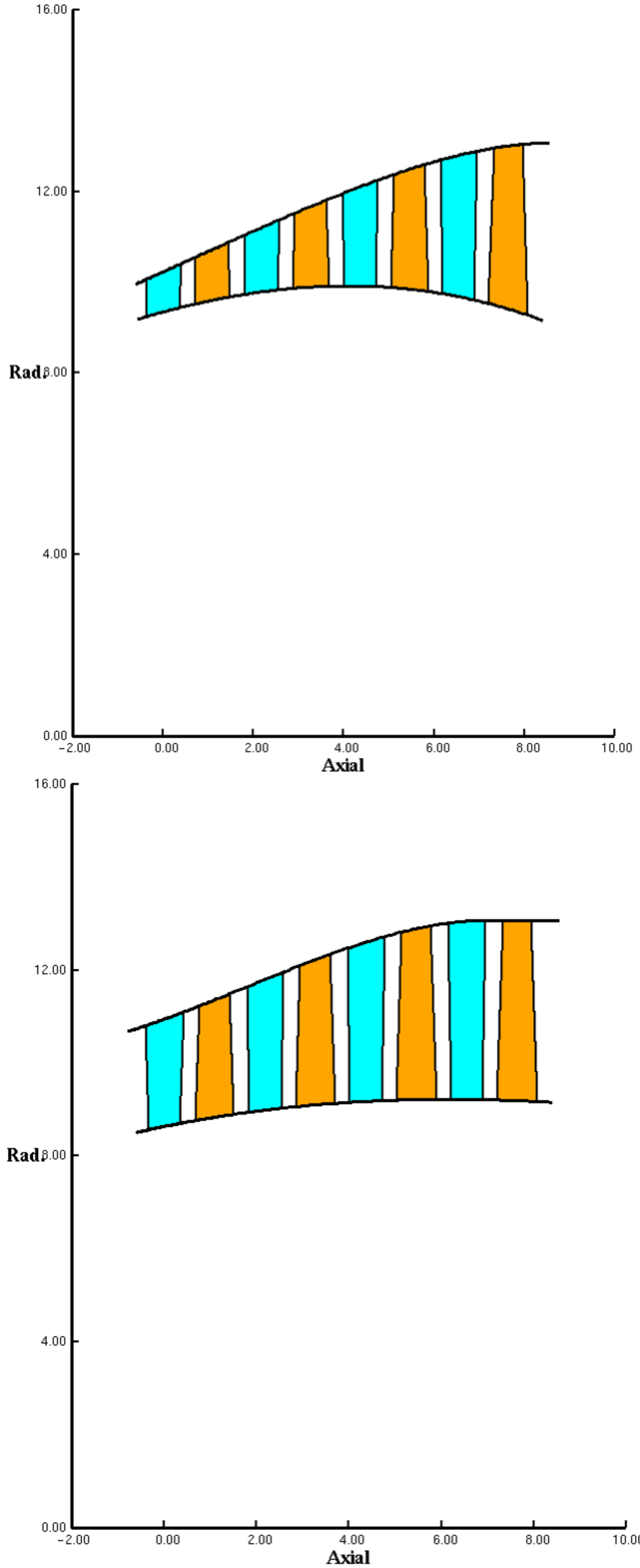


Figure 2.6.—Comparison of High and Low CX/U Flowpaths

If the turbines in Figure 2.6 were designed for the low speed cruise condition (54 percent speed), they would have predicted efficiencies of 91.4 and 90.2 percent respectively when operating at that design point. Unfortunately, each of these turbines is predicted to have an efficiency of 69.3 percent when operating at the high speed cruise condition (100 percent speed). Likewise, if the two turbines were designed for the 100 percent speed condition, the efficiencies would be 92.8 and 91.4 percent respectively. These turbines both would have very low efficiencies (<58 percent) when operating at the 54 percent speed conditions. Of course, these off-design efficiency predictions are highly dependent on the empirical loss system used in the meanline prediction system. Nonetheless, a compromised design point somewhere between 54 and 100 percent would most likely be a good compromise. A method for determining the optimal design point was developed. Four design speeds were chosen: 54, 69, 85 and 100 percent speed. A preliminary design was produced for each of these turbines at each of these speeds. This preliminary design process sets the LE metal angles and blade counts for the velocity triangles corresponding to that speed. Each of these designs was then run off-design using MeanTurb to the four different mission points in order to predict the efficiency. The resulting efficiencies are available in Table 2.2. For each of these designs, the resulting efficiencies for points 1, 2, 3, and 4 were used in Equation (2) (via spread sheet) and the overall impact to mission fuel burn was calculated, the results of which are also included in Table 2.2.

The results of Table 2.2 are plotted in Figure 2.7. From this plot, the best design practice is to pick a design point that is compromised between the low speed and high speed cruise but favoring the low speed cruise condition. An unexpected outcome of this study is the fact that both the High CX/U design and the Low CX/U design optimize at about the same speed and result in about the same overall fuel burn. Neither design philosophy appears to have an advantage. There is no compelling evidence from this study that CX/U (in of itself) is a determining factor in the design of this type of turbine.

TABLE 2.2.—FUEL BURN COMPARISON FOR HIGH AND LOW CX/U DESIGNS

High CX/U

% Speed	Design RPM	Fuel Burn%	ETA 1	ETA 2	ETA 3	ETA 4
53.8	8045	-3.29	73.34	68.62	69.34	91.39
69.2	10343	-7.88	88.33	84.71	84.12	88.62
84.6	12642	1.41	92.95	90.84	90.63	74.87
100.0	14941	23.20	91.25	91.58	92.80	57.42

Low CX/U

% Speed	Design RPM	Fuel Burn%	ETA 1	ETA 2	ETA 3	ETA 4
53.8	8045	-2.22	69.98	66.62	69.30	90.20
69.2	10343	-7.80	87.58	83.60	82.85	89.14
84.6	12642	-1.84	92.00	89.60	89.44	78.75
100.0	14941	24.30	89.29	89.78	91.43	57.00

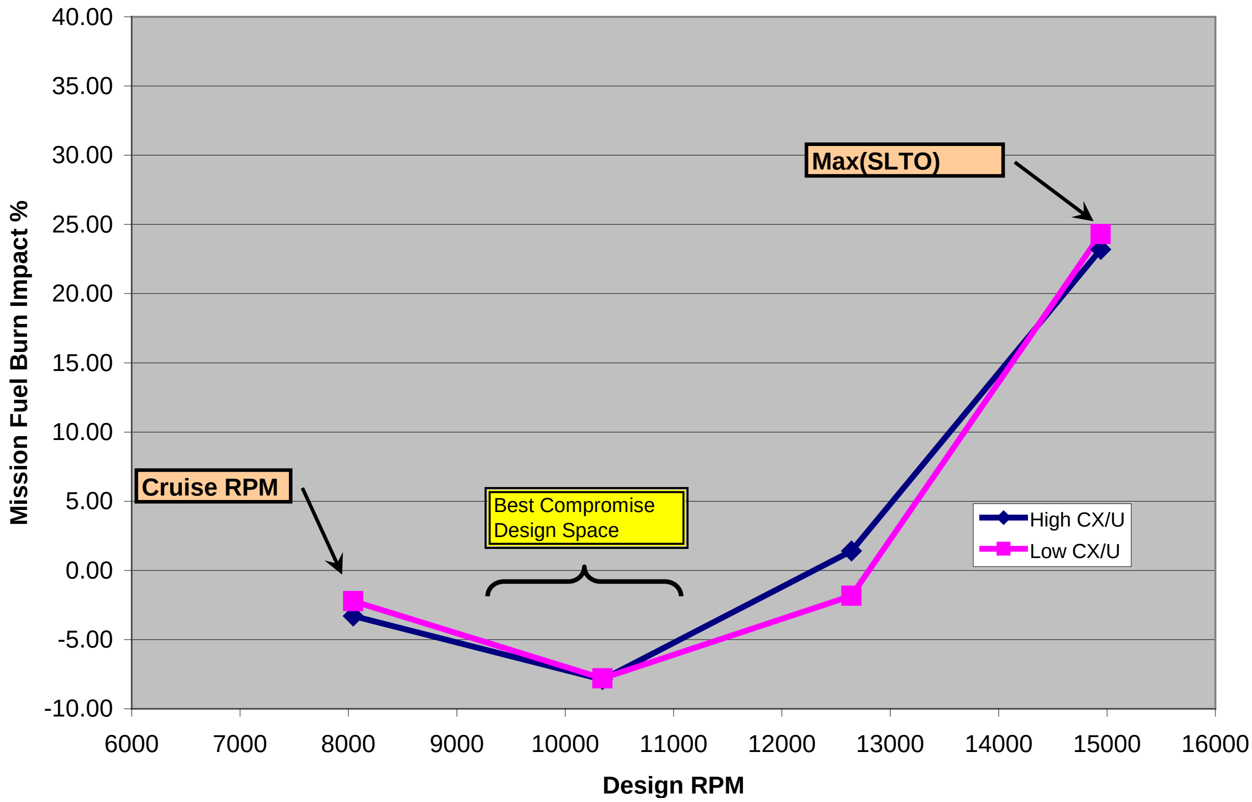


Figure 2.7.—Design Speed Selection for High and Low CX/U Designs

2.7 Work Coefficient

The Work Coefficient ($\Delta h_0/U^2$) is a dimensionless parameter relating the turbine work to the mean wheel speed of the turbine. The use of Work Coefficient (Wcoeff) combined with Flow Coefficient (Cx/U) was popularized by Smith (Ref. 6) with his correlation of turbine efficiency using both parameters. Smith showed that there was an optimum relationship between the two parameters. There is no indication that Smith's 1965 correlation considered turbines operating far off-design so it is not obvious whether his correlation is helpful in determining optimum velocity triangles for the LCTR power turbine application when operating at its full range of speeds. The Smith correlation was presented (Ref. 6) as a plot and Figure 2.8 is a reproduction produced by digitizing the figure in his paper.

Assuming the LCTR power turbine is designed at the 54 percent cruise condition, then as the turbine transitions from 54 to 100 percent speed, the Flow Coefficient (Cx/U) and Work Coefficient ($\Delta h_0/U^2$) change considerably. MeanLine and cycle analysis confirm that $\Delta h_0/U^2$ is nearly proportional to 1/rpm^2 and Cx/U is nearly proportional to 1/rpm. Therefore the Wcoeff increases by $1/.54^2$ or 3.4 times when the rotor speed drops from 100 to 54 percent rpm. Likewise the Cx/U increases by a corresponding factor of 1/.54 or 1.85. If Smith's correlation indicates optimum relationships between these two parameters, it is reasonable to assume that it may provide some guidance in designing a turbine that transitions over a large swing in these parameters. The two turbines in the Cx/U study were placed on the Smith correlation in Figure 2.9.

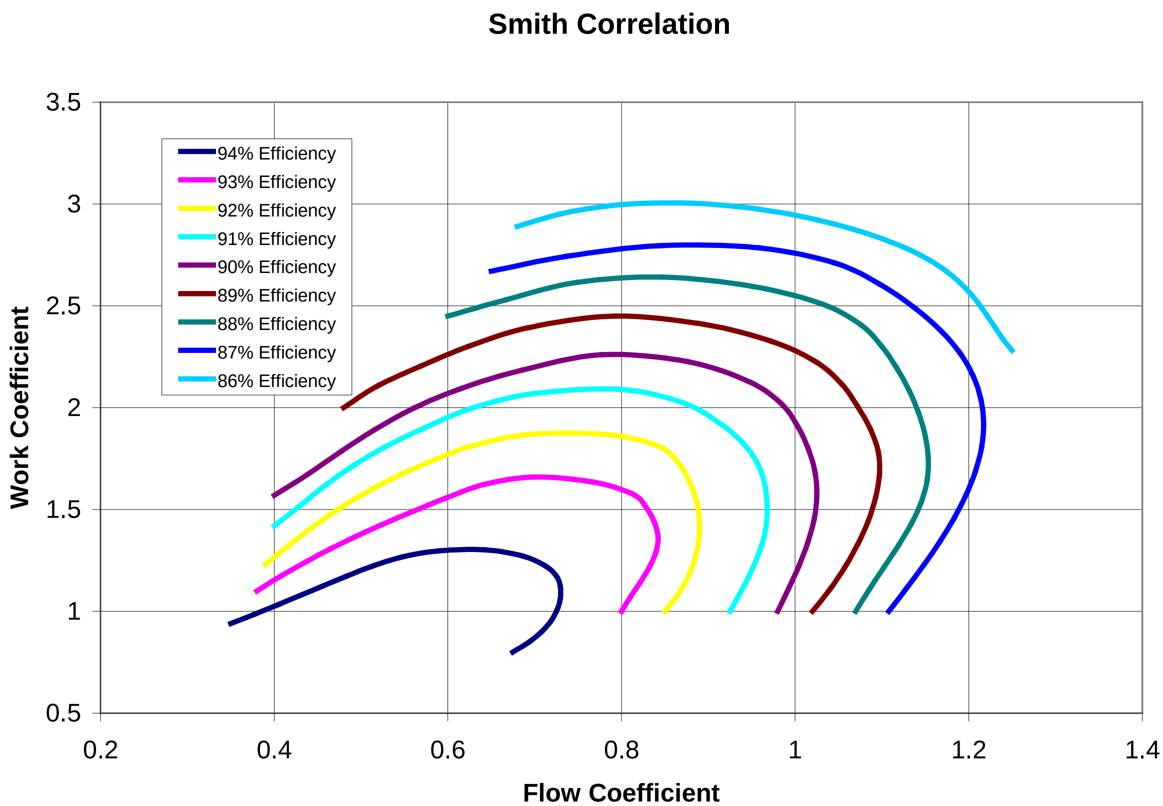


Figure 2.8.—Work Coefficient Versus Flow Coefficient

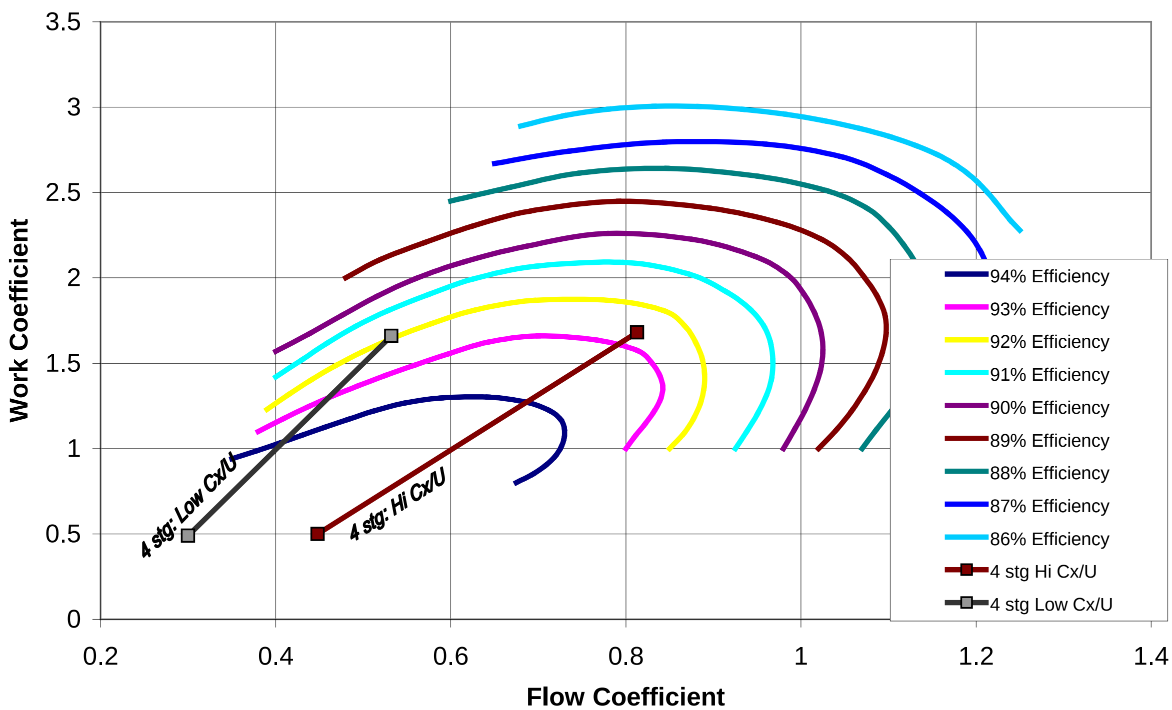


Figure 2.9.—Work Coefficient Versus Flow Coefficient

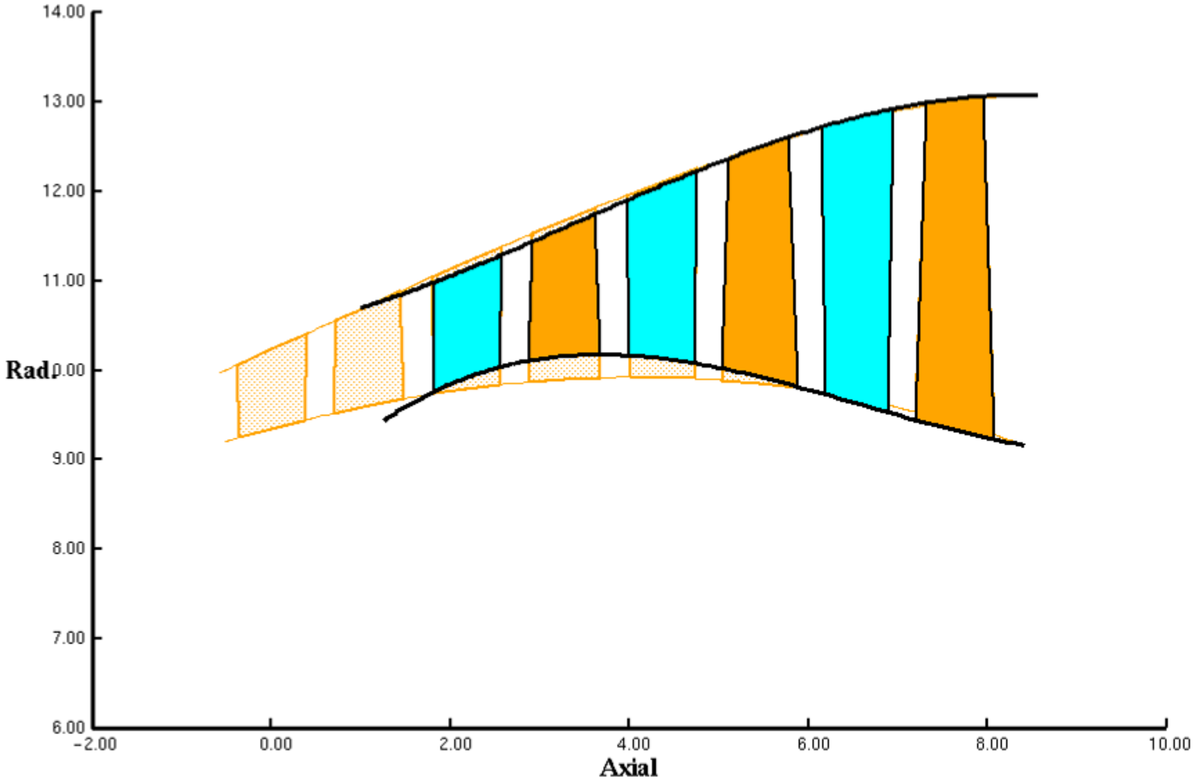


Figure 2.10.—Comparison of Three Stage and Four Stage Turbine Flowpaths

From this plot, the high Cx/U flowpath is shown to transition through the heart of the efficiency islands while the low Cx/U is in a non-optimum part of the correlation.

Both flowpaths developed in the Cx/U study have similar Work Coefficients which drop to very low levels when the rotor rpm is at 100 percent. These low levels are outside of normal gas turbine design experience. Another study was conducted to investigate the impact of running to higher Work coefficients in order to assure operation within the traditional design space. A new flowpath was generated by removing the first stage but holding the same rpm and about the same overall radius of the last three stages. This Three Stage turbine has the same power and speed as the two four stage turbines already analyzed but the average work per stage is higher (by the ratio of 4/3). Figure 2.10 compares the Three Stage turbine with the High Cx/U four stage design from the previous study.

The same process of picking four design speeds, calculating efficiency at each of the four mission points, and integrating the fuel burn across the mission was performed with the Three Stage design. Table 2.3 documents the results and Figure 2.11 plots the Three Stage turbine results against the results of the Four Stage Cx/U study.

The Three Stage does not show a predicted improvement in overall fuel burn relative to the lower work four stage designs, but it does show a significantly different trend. Figure 2.11 shows that the Three stage turbine is more forgiving than any of the Four Stage designs in choosing the design speed. It also indicates that the optimal design speed is closer to the SLTO rpm which is different than the previous two designs and is not the expected result. In Figure 2.12, the Three Stage turbine is shown on the Smith Correlation compared to the two Four Stage designs. The Three Stage falls between the two Four Stage designs. If the Smith Correlation were a good indicator of off-design capability, then it could be expected that the Three Stage design would have off-design performance characteristics between the two Four Stage designs: which it clearly does not.

The large difference in character between the Three Stage and Four Stage designs begs the question as to what makes the Three Stage so different. The difference in Work Coefficient appears to have played a significant role. At 54 percent speed, the Work coefficient of the Three Stage turbine is about 2.1 which is well within design experience. Designing to higher Work Coefficient may further improve performance. Higher Work Coefficients are generally more challenging to design because they result in higher airfoil turnings and Mach numbers. The practical limit is approximately 3.0, above which the design becomes very challenging. To assess whether higher Work Coefficient is better for overall mission fuel burn, a High Work Four Stage turbine was designed (Figure 2.13). The Work Coefficient at the 54 percent cruise speed was set at 2.83 and the Flow Coefficient was set to 1.0 in an attempt to stay in the center of the Smith Correlation. After the same process of picking four design speeds, calculating efficiencies, and integrating mission fuel burn, this design proved to be the best out of a total of 8 flowpaths that were examined (Table 2.4). The flowpath is reduced in radius relative to the designs presented so far, making it smaller and lighter, which is an added benefit. (Figure 2.14)

The fuel burn calculation versus speed plot for this turbine is shown in Figure 2.14.

The corresponding Smith Curve correlation is shown in Figure 2.15.

TABLE 2.3.—Three-STAGE TURBINE RESULTS

3 Stage

% Speed	Design RPM	Fuel Burn%	ETA 1	ETA 2	ETA 3	ETA 4
53.8	8045	-1.11	70.57	66.14	67.52	89.72
69.2	10343	-4.51	78.24	74.89	74.04	89.63
84.6	12642	-7.19	93.53	91.76	91.60	84.44
100.0	14941	-6.36	92.35	92.49	93.53	66.26

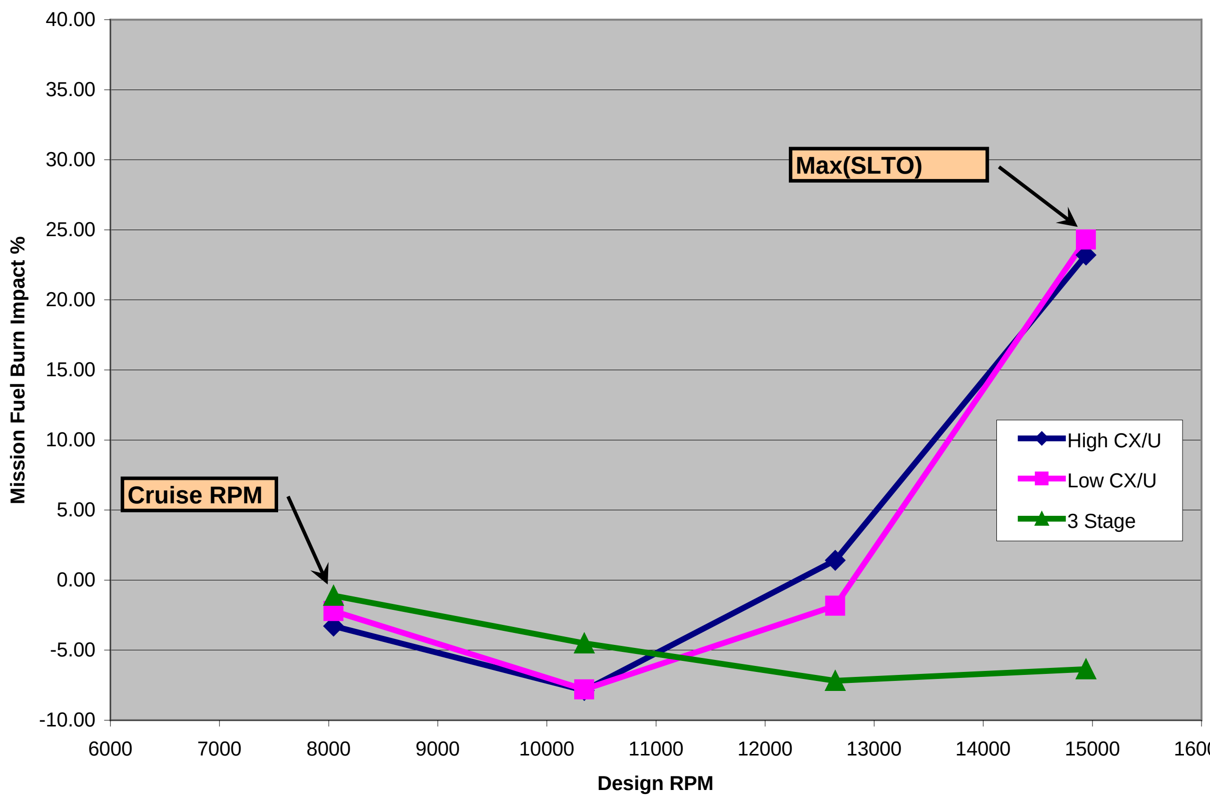


Figure 2.11.—Turbine Design Speed Selection

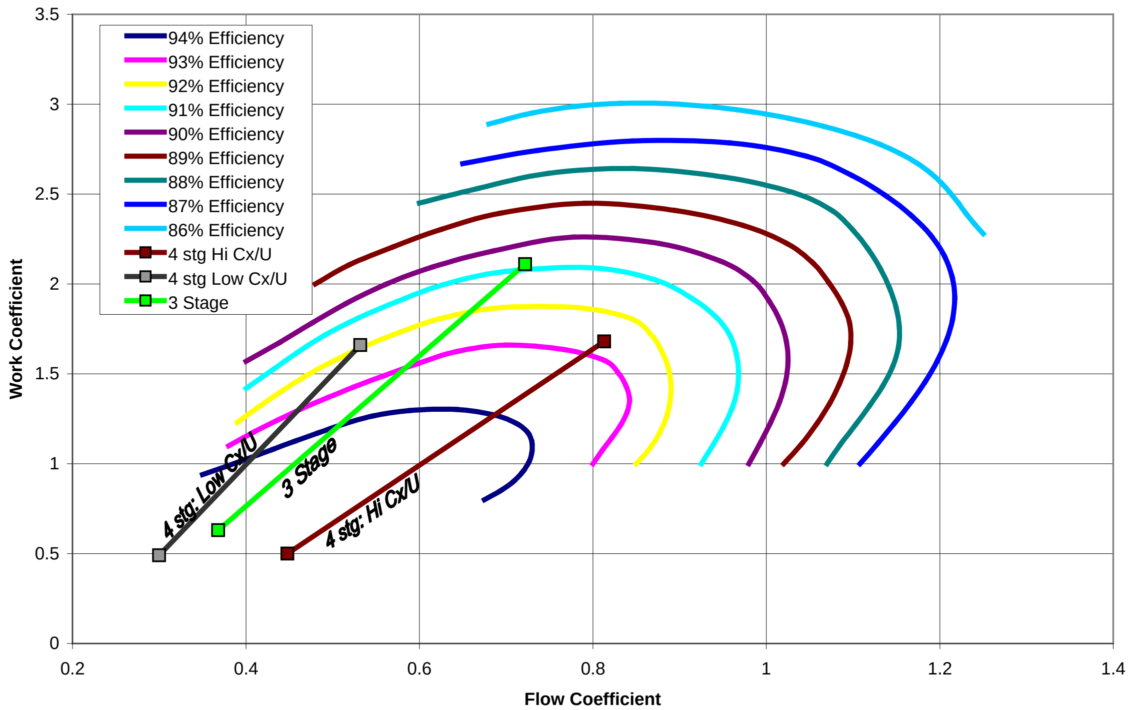


Figure 2.12.—Smith Correlation for Three Turbines

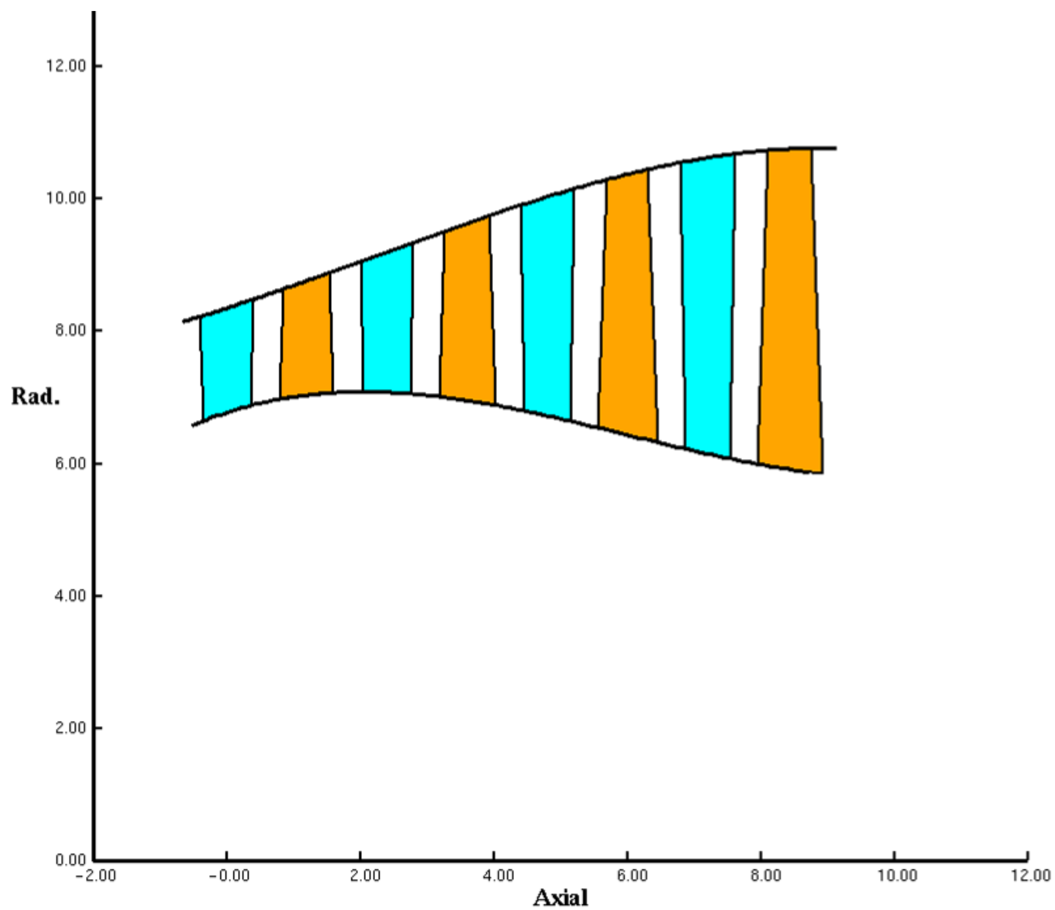


Figure 2.13.—Four-Stage Turbine Flowpath

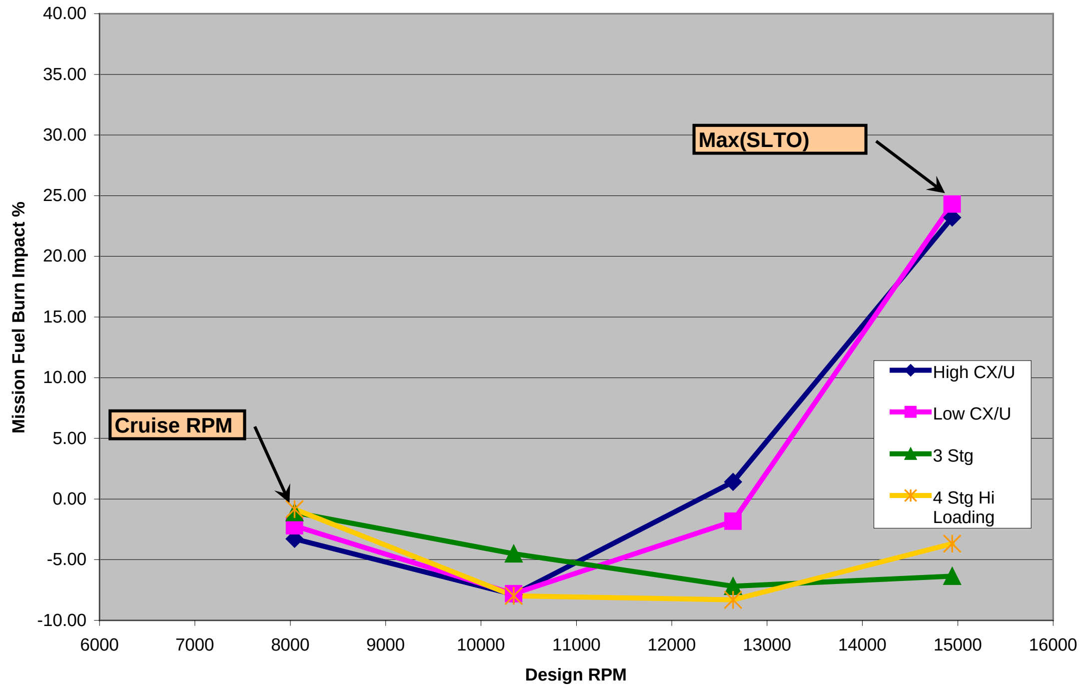


Figure 2.14.—Design Speed Versus Segment Fuel Burn

TABLE 2.4.—FOUR-STAGE TURBINE SEGMENT FUEL BURN

4 Stg Hi Loading (1)

% Speed	Design RPM	Fuel Burn%	ETA 1	ETA 2	ETA 3	ETA 4
53.8	8045	-0.84	78.77	71.42	69.10	87.45
69.2	10343	-7.98	90.15	87.28	87.13	87.37
84.6	12642	-8.31	93.67	92.32	92.37	85.64
100.0	14941	-3.68	93.96	93.59	94.26	79.31

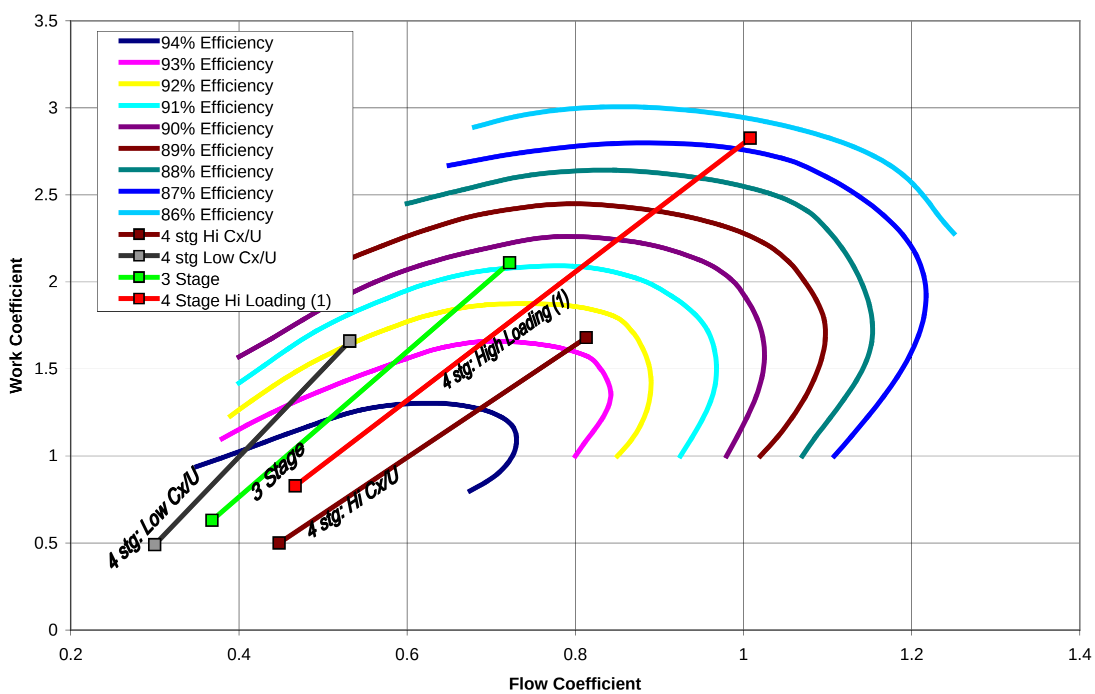


Figure 2.15.—Smith Correlation for Four Study Turbines

A complete description of the 8 flowpaths examined in this study is provided in Appendix C.

This flowpath (Four Stage: High Loading 1) emerges from the flowpath study as having the best potential to minimize mission fuel burn. This conclusion is based on the assumption that the meanline loss model and, more specifically, the off-design loss model adequately predict the efficiency characteristics through a significant range in incidence and loading. Presumably, the design is centered in the design space such that the turbine will not rapidly lose performance as speed and loading change throughout the flight envelope. In order to gain confidence in this conclusion, a 3–D design was executed at 75 percent speed (11174 rpm) and investigated in various CFD simulations. Appendix D contains both the 3–D and 1–D analysis summaries for the design conditions. An additional summary of the meanline predictions for 54 and 100 percent design speed is presented in Appendix E. This is provided to illustrate the large impact of the full speed variation and its implication to the design velocity triangles.

2.8 3–D Design Execution

Airfoils were designed consistent with the chosen flowpath (Four Stage: High Loading 1). The design was executed at 75 percent speed, i.e., 11174 rpm. The basic methodology for executing the 3–D design was as follows:

- Each of the 8 airfoils is designed by stacking three 2–D design sections, i.e., a hub section, a mean section and a tip section. (Figure 2.16)
- Each 2–D section is manually designed in an interactive design tool called “FoilGen”. (Figure 2.17) FoilGen has a variety of tools that allow for simple structural analysis, 2–D aerodynamics, 3–D stacking and airfoil internal core validation if applicable.
- Design iterations are passed through an in-house 3–D solver called VORTEX. VORTEX has an inviscid mode with an empirical loss model which aids in establishing the correct velocity triangles in the absence of viscous effect. This solver runs fast enough to execute several design iterations per day.
- Designs are validated via viscous simulation. VORTEX can be run with the full Navier Stokes equations turned on. The turbulence model is the κ-ω model with integration to the walls (no wall functions). A steady state mixing plane assumption was used at the interface between stators and rotors.

The full Four Stage design was executed at 75 percent speed which is consistent with Figure 2.14. This places the design point approximately half way between the cruise (54 percent speed) and the SLTO (100 percent speed) conditions. The airfoil geometry was not refined to a final status for all 8 airfoils, but only to a satisfactory level for further study. The third Stage was chosen as a representative stage for more in-depth analysis. The third Stage design was pulled out and further refined (Figure 2.18). Calculations were performed using boundary conditions from the full Four stage calculation. A detailed review of the full four stage 3–D CFD run is documented in Appendix D.

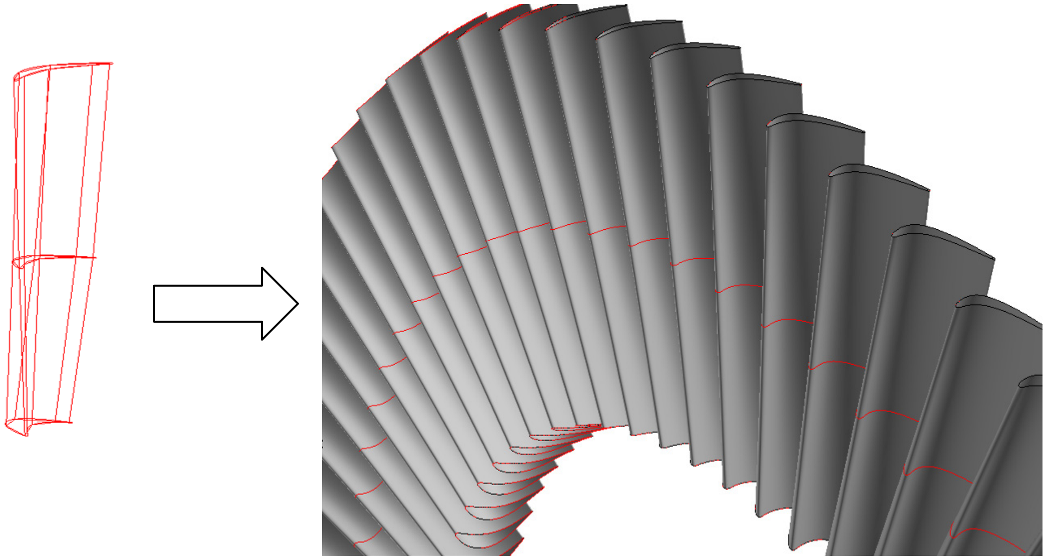


Figure 2.16.—Airfoil Stacking

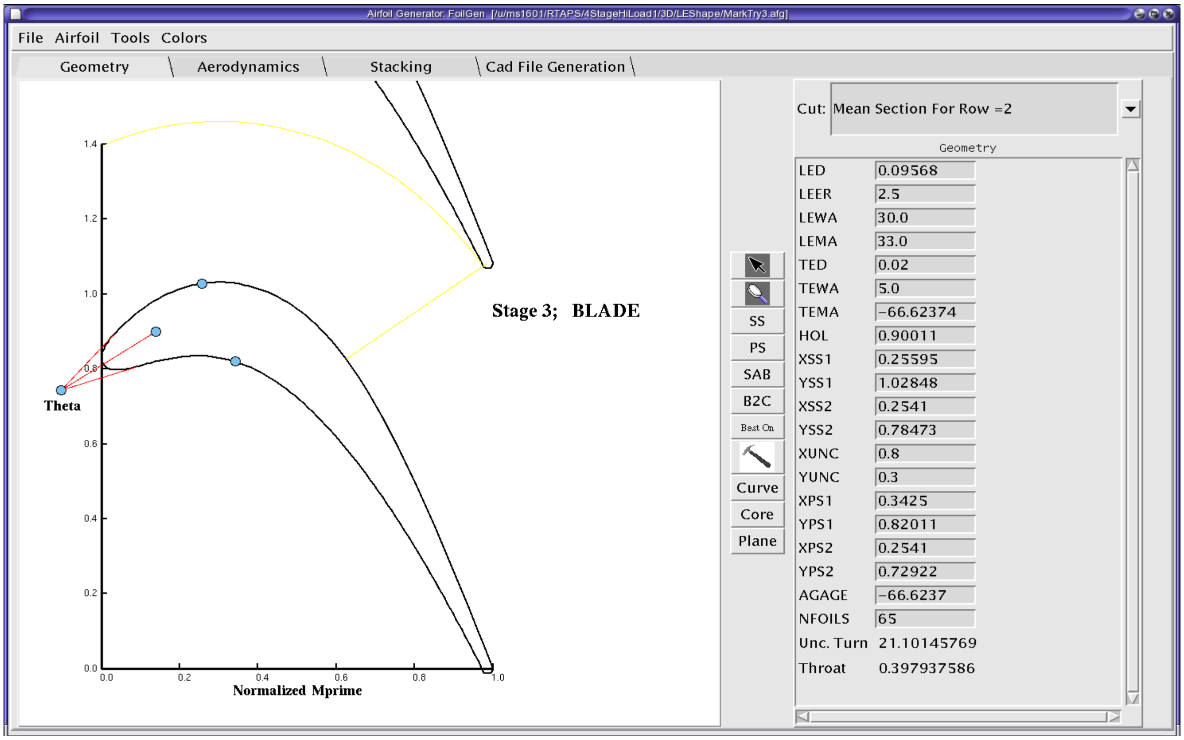


Figure 2.17.—FoilGen Output

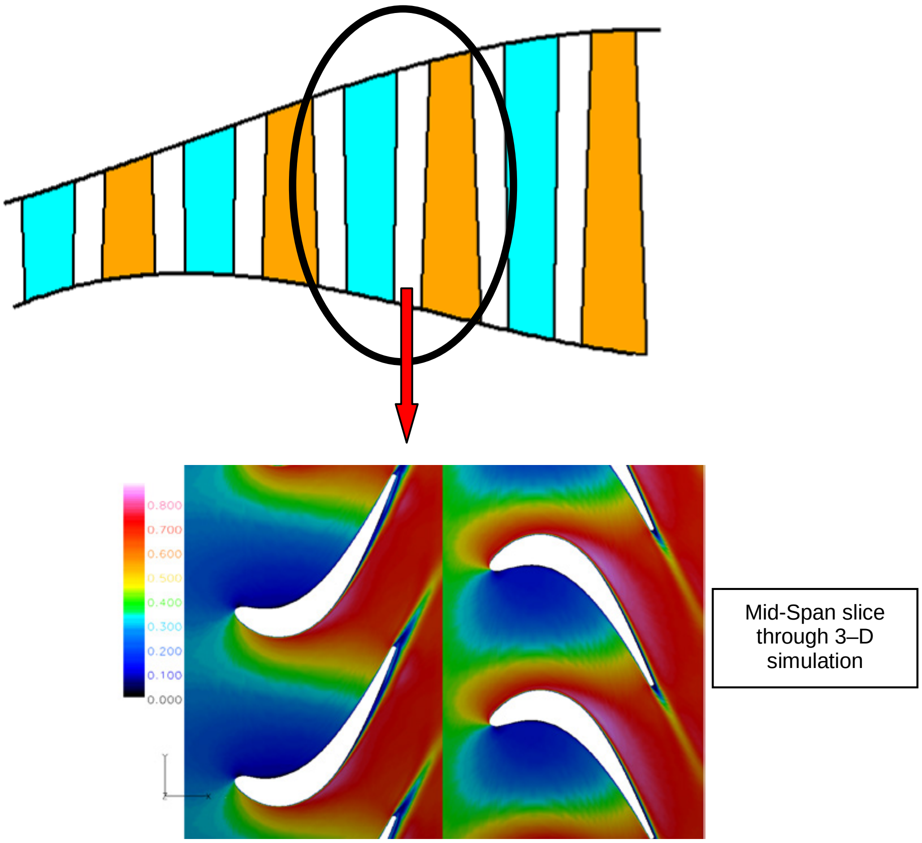


Figure 2.18.—Third Stage extracted from full simulation to investigate off-design performance

2.9 Loss System Validation via CFD

The optimum flowpath selected for this turbine and the choice of design speed relies on the off-design predictive capability of the meanline analysis. In order to assess the validity of this model, various CFD models were exercised. The third stage vane and blade were chosen as a representative set of airfoils. Two separate studies were performed. The first study addresses the incidence tolerance of the third blade and the other adds the vane and assesses the third stage together. The blade study was performed with two different blade thicknesses.

2.10 Turbine Blade Incidence Study

The third stage vane and blade were run together through a series of CFD runs. All CFD runs are based on steady state assumptions using mixing planes to account for time averaging between stationary and rotating frames. The inlet conditions (Total Pressure, Total Temperature, and gas angles) to the third vane were held fixed and the exit static pressure from the third blade was also fixed. The CFD was then run over a sweep of rpm. This analysis will simulate the incidence and loading sweeps that the blade would undergo throughout the operating envelope while the vane remains fixed at design point. The meanline was run exactly the same way to predict the efficiency changes as the speed changes. Both the meanline and the CFD assume no leakage flows, cooling flows or tip clearance. The meanline has a real gas model while the CFD runs assume ideal gas. The CFD confirms the large incidence swing and loading changes that are expected as the rpm is varied. Four different CFD simulations were performed; each one was swept through the speed range. All four simulations predict better incidence tolerance than the meanline correlation. This result is particularly satisfying because the meanline prediction was better than the cycle simulation. If actual incidence tolerance is better than the meanline characteristic, than overall engine performance should surpass the NPSS simulation.

The four CFD simulations used are:

1. VORTEX (Williams International proprietary solver). κ-ω turbulence model, integrated through boundary layers to the wall.
2. FLUENT (ANSYS, Inc.) κ-ε realizable, using wall functions
3. FLUENT κ-ω turbulence model, transitional flow model
4. FLUENT κ-ω turbulence model, SST

All FLUENT calculations used a density based, implicit solver while VORTEX used a density based explicit solver. FLUENT version 6.3 was used.

Figure 2.19 compares the meanline prediction and the four CFD runs. Inside of the design speed range, all four CFD simulations predict flatter efficiency trends than the meanline. There is considerable variability in the predicted level of efficiency among the FLUENT turbulence models. VORTEX and the Std, κ-ω SST model are very similar and close to the meanline level. The transitional flow model for κ-ω predicts unrealistically low efficiency even at the design point. VORTEX was run to a more broad speed range to search for an incidence cliff. It did reveal a very rapid fall off in efficiency at 40 percent speed when the loading was high enough to cause suction side separations. At that condition, the efficiency fall off was more rapid than predicted by the meanline.

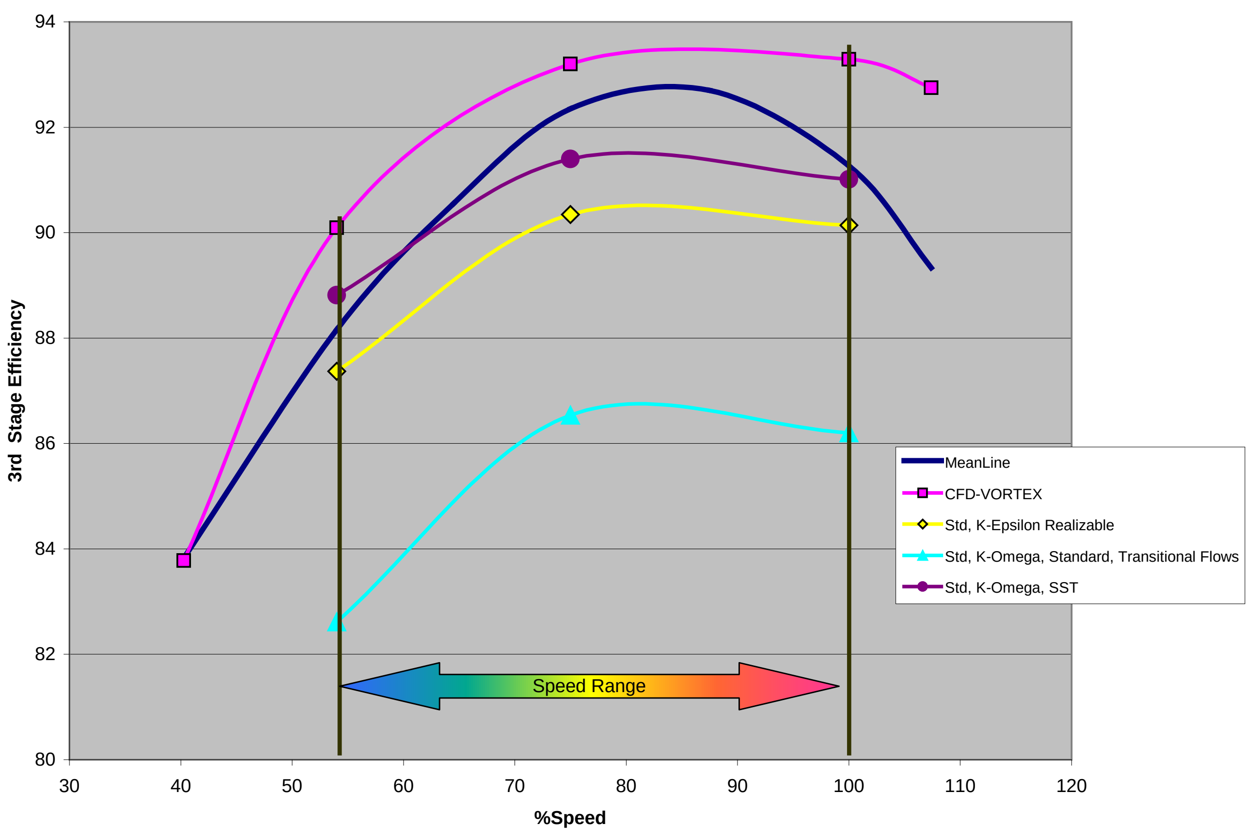


Figure 2.19.—Efficiency Comparisons for Four Turbine Designs

Figure 2.19 is good testimony to the fact that CFD is still paced by the lack of fidelity in turbulence modeling. The level of efficiency predicted by various turbulence models is significant. However, all four models predict a very similar efficiency trend with speed. The results give some confidence that the design may meet its incidence tolerance goals but is not adequate to completely mitigate risk. If it were necessary to chose between a fixed speed turbine and a variable speed turbine, a turbine rig test would still be recommended to determine if this design can truly meet the incidence tolerance goals. Another observation from Figure 2.19 is that the turbine blade is more tolerant to negative incidence than positive. This would lead us to move the design speed lower (higher camber airfoils) and allow the turbine to run off-design further on the negative side than the positive.

2.11 Thin Turbine Blade Incidence Study

Traditional airfoil design philosophy would indicate that larger leading edge diameters are more incidence tolerant than smaller diameters. While this is well established for airfoils in a free-stream, it is not nearly so obvious for airfoil cascades where the internal flow between the airfoils is more like channel flow than external flow. When a cascade airfoil has a larger LE diameter, the entire airfoil must be thicker. Thicker airfoils have higher through flow velocities and therefore (by intuition) generate more viscous scrubbing losses. Although this statement seems straight forward and logical, the high camber inherent in gas turbine blades complicates the situation.

Consider the airfoil shown in Figure 2.20. The throat of the airfoil cascade spans from the TE of one airfoil to the suction side of an adjacent airfoil. The passage between the two airfoils is bounded by the suction side of one airfoil and the pressure side of the adjacent. This passage controls the through-flow Mach numbers of the gas as it passes through the airfoils. It is desirous for this passage to be separation free and as low loss as possible. In this figure, the design philosophy is to produce a smooth, converging passage through the airfoil to the throat. To illustrate this passage convergence, a line of the same dimension as the throat is shown in orange. It is swept forward in the direction of the green line perpendicular to the suction side resulting in the orange trace. This gives a visual cue to the convergence through the passage as well as how the airfoil pressure side can impact the channel convergence.

Now consider the airfoil shown in Figure 2.21. This cascade has the same suction side as Figure 2.22 but a pressure side that results in a thinner airfoil. The airfoil passage now has a non-smooth area distribution through the channel. After the leading edge of the airfoil, the pressure side diffuses and then converges to the airfoil throat. Experience with this type of cascade would predict pressure side separation and reattachment as sketched in light grey. If the resulting separation bubble is large enough, the resulting blockage may result in through-flow Mach numbers similar to the airfoil in Figure 2.20. Separation bubbles that occur at relatively low velocities and are followed by strong acceleration generally do not generate high pressure loss. However, in the case of a rotating blade, the low momentum fluid trapped in a separation bubble can be centrifugally pumped outward due to the high rotational acceleration field. This can cause much higher loss than in the case of a stationary airfoil.

A study was executed to determine if a thin blade could potentially improve overall fuel burn by lowering through-flow velocity or would a separation bubble out-weigh any perceived benefit. Again the third stage was used as a representative stage. The blade was redesigned to be thinner but still maintain the same suction side as the nominal blade.

Figure 2.22 shows visually the change made to the blade. The brown line in the background indicates the nominal blade pressure side.

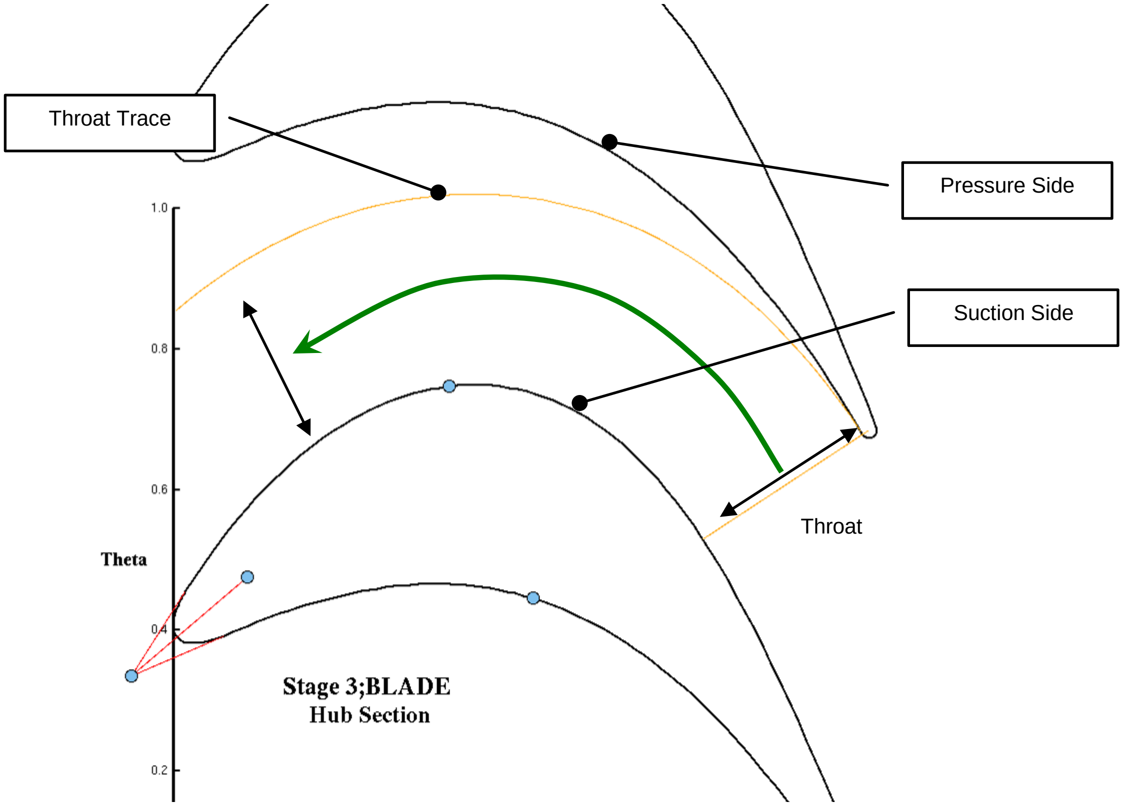


Figure 2.20.—A Simple Turbine Blade Cascade

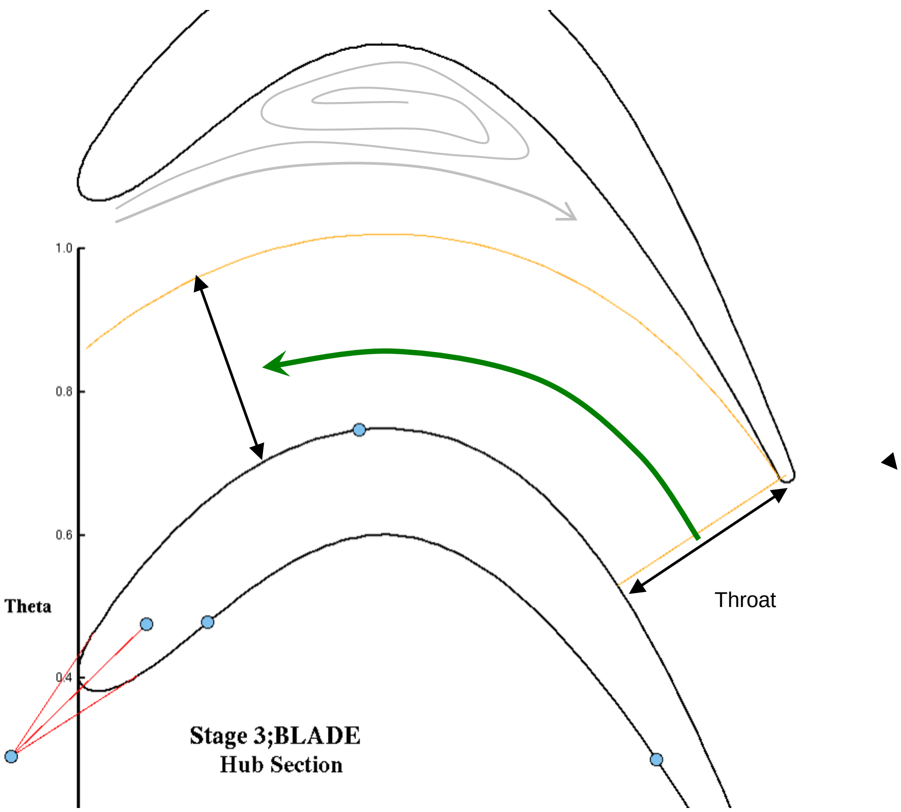


Figure 2.21.—A sample thin blade cascade

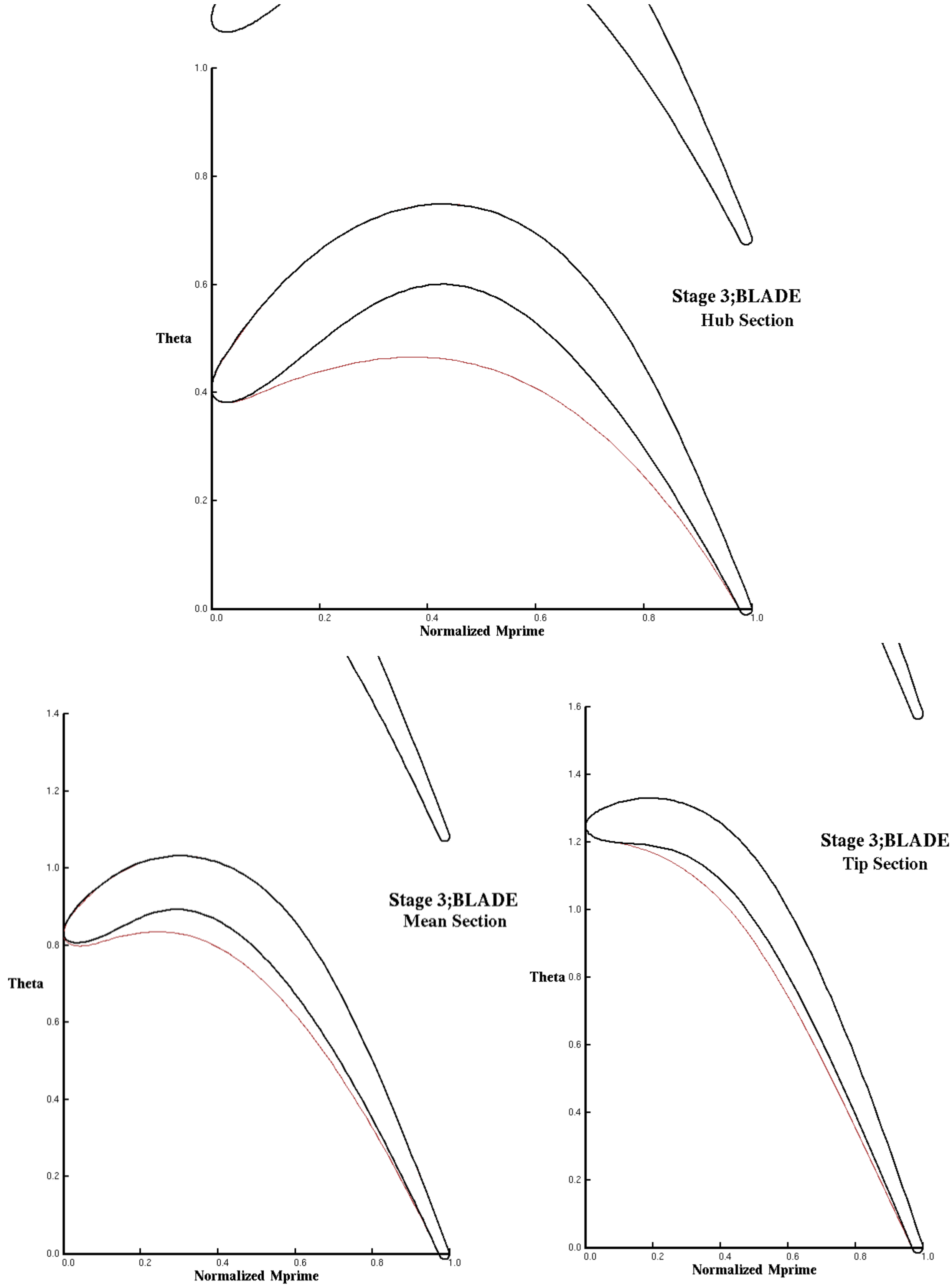


Figure 2.22.—Blade Profile Modifications

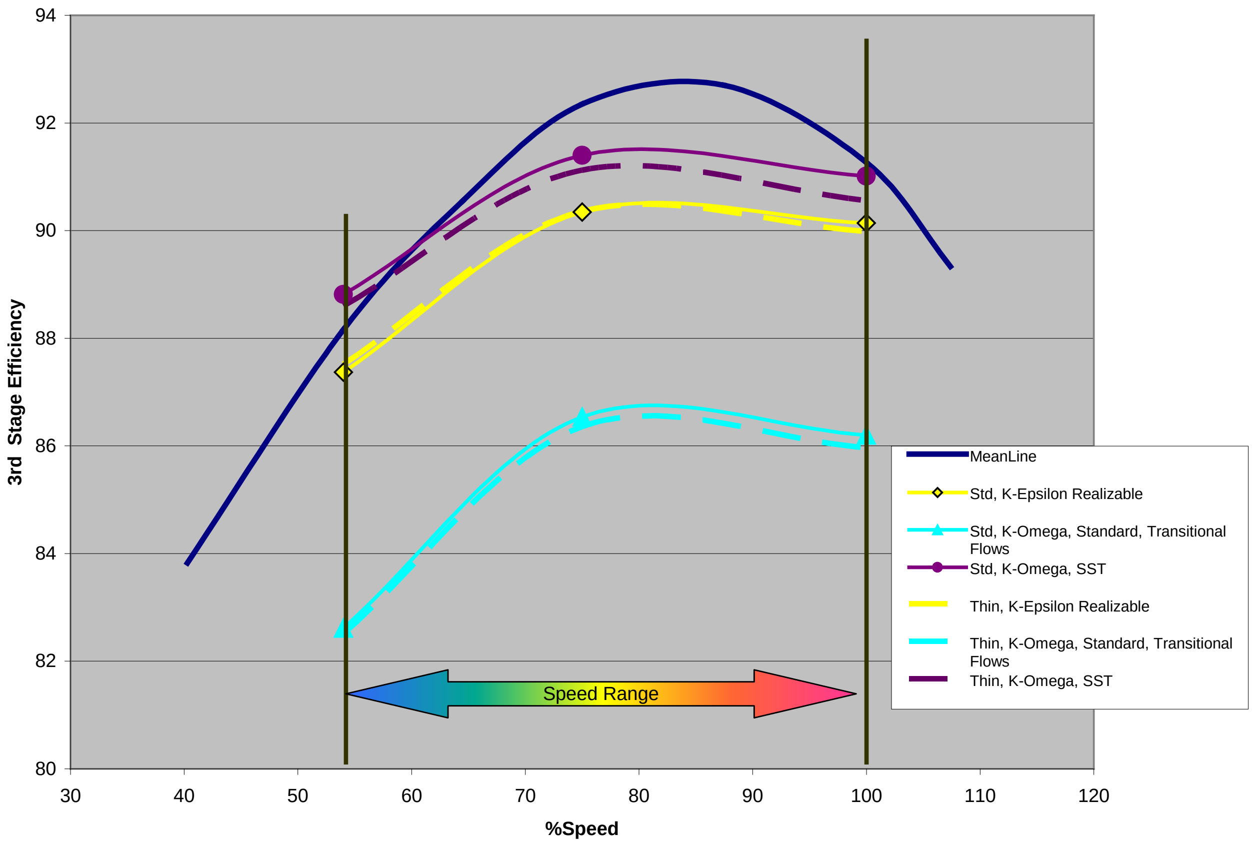


Figure 2.23.—Thin turbine blade geometry compared to nominal

The thin blade should be more susceptible to pressure side separation at high negative incidence (high speed). At positive incidence (low speed), the air impinges on the airfoil in a more favorable way for the pressure side and may not separate. We would therefore expect a thin blade to be similar or better at low speed but potentially worse at high speed. The airfoil in Figure 2.22 was run through FLUENT in a consistent manor with Figure 2.19. The results are shown in Figure 2.23. The dash lines indicate the results of the thin airfoil and are color consistent with the nominal blade run to the same turbulence model. The results are very similar with the thin blade overall slightly higher in loss. All three analyzes hint that low speed performance trends better than high speed performance. Based on this study there is no compelling evidence to depart from normal design philosophy (i.e., smooth channel convergence).

2.12 Third Stage Combined Incidence Study

The third Stage combined study was conducted in similar fashion as the third blade only study. The simulation was composed of the second blade, the third vane and the third blade. (Figure 2.24) The inlet conditions into the second blade were held fixed in the absolute frame of reference simulating the exit conditions of the second vane. The exit condition of the third blade was a free vortex boundary with the average static pressure iterated to match the proper exit corrected flow. In order to assess the third stage performance, the efficiency of the second blade was ignored and the third stage was calculated based on its inlet and exit conditions in the converged solution. The meanline analysis was performed in exactly the same manor so that the CFD and meanline results may be compared directly. The speed was varied in a similar way as was done in the blade only study. There was no tip clearance, leakage or cooling modeled. In this calculation both the third vane and third blade experience the incidence swing associated with the speed change, therefore the efficiency impact with speed is higher than the previous study. Figure 2.25 compares the resulting meanline efficiency to the CFD prediction. The conclusions are generally the same as the blade only calculations. The CFD prediction is more incidence tolerant than the meanline prediction and also indicates that negative incidence (high speed) is more forgiving than positive incidence.

The third vane total pressure loss was extracted from the CFD and compared to the meanline prediction as well (Figure 2.26).

The vane exhibits a similar trend as the blade in that it is more incidence tolerant at high speed (negative incidence) rather than low speed. The vane is exceptionally tolerant at negative incidence because the pressure side separation bubble is: 1) very small (less than ½ the thickness of the airfoil), and 2) completely reattached at relatively low Mach number before the airfoil throat (Figure 2.27). Unlike the blade, the vane is not subject to the high centrifugal acceleration field and therefore the low momentum fluid trapped in the separation bubble is not transported radially.

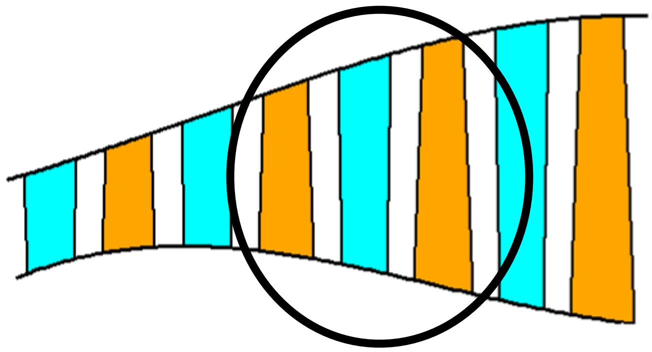


Figure 2.24.—Third Stage Speed Study composed of Three airfoils

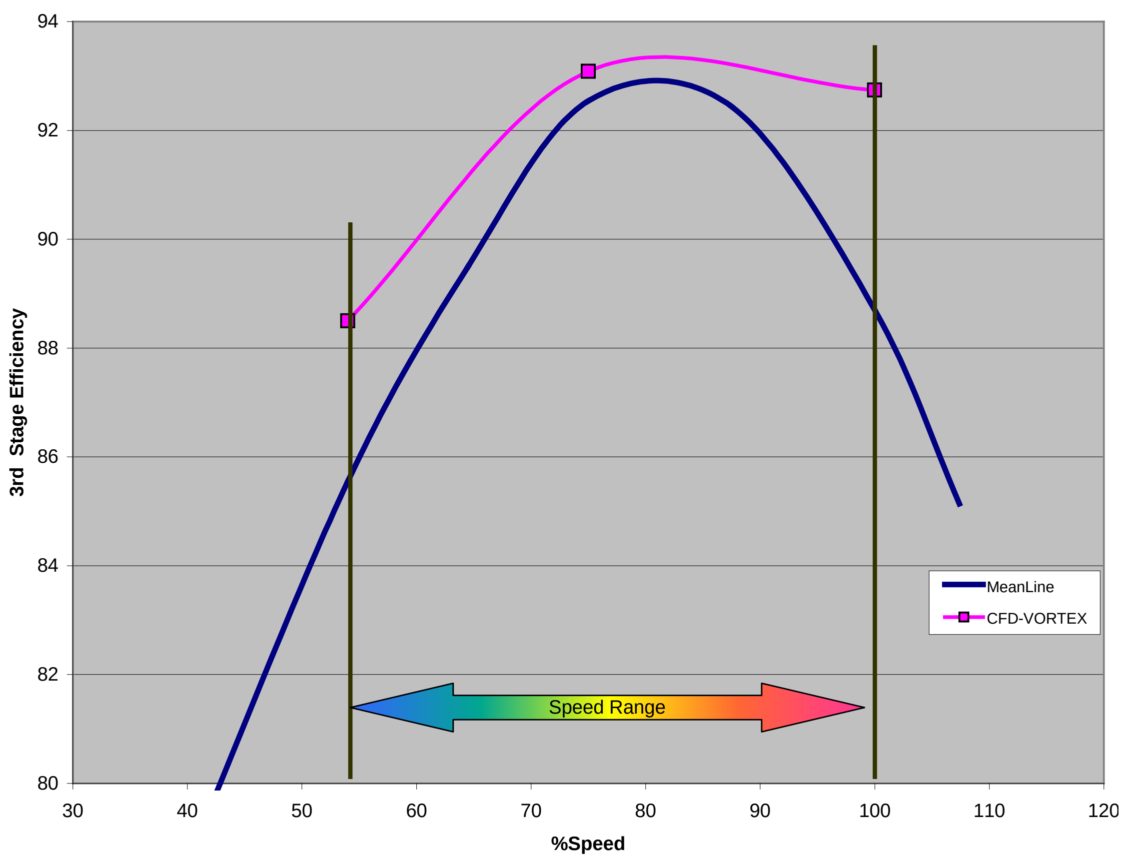


Figure 2.25.—Third Stage Performance

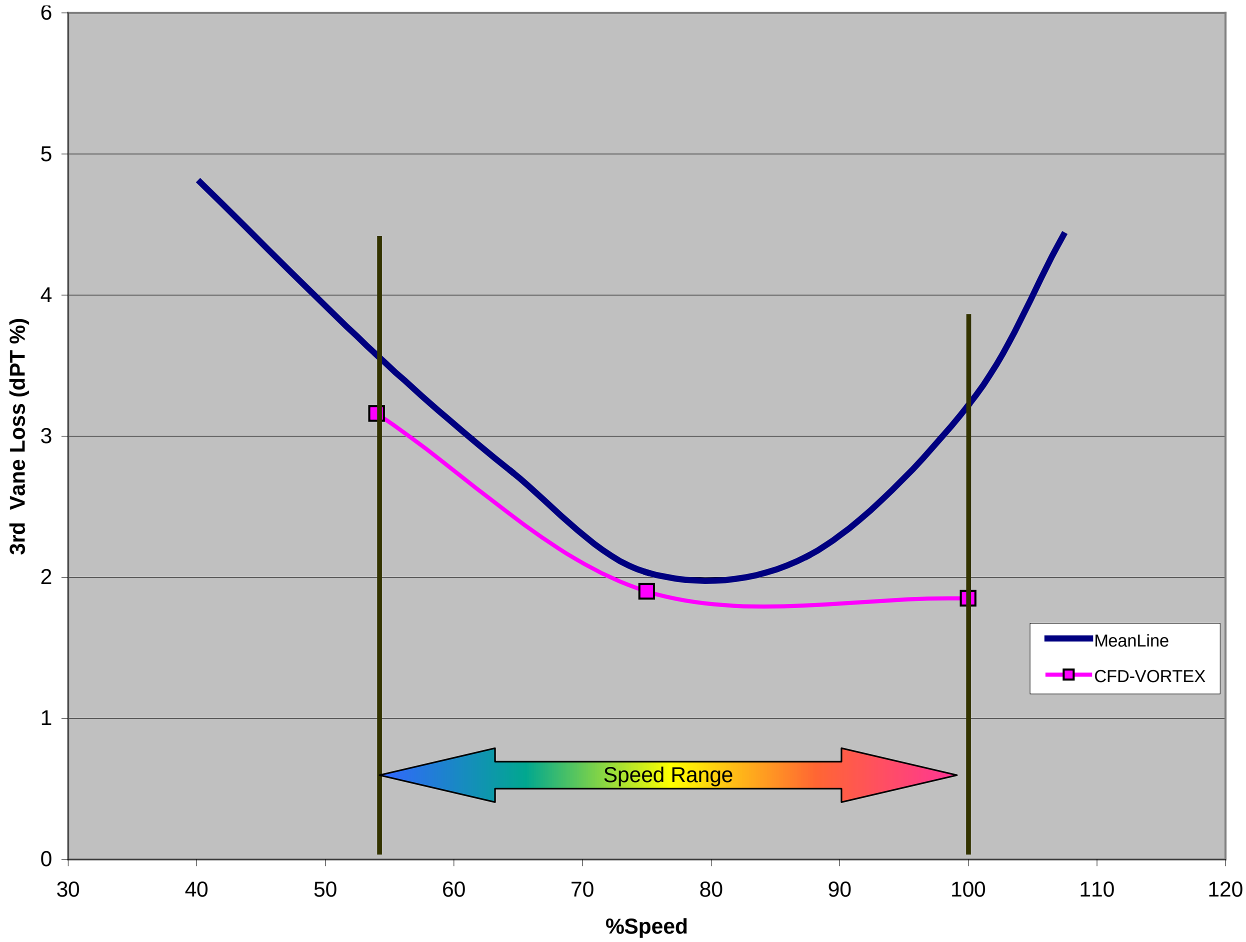


Figure 2.26.—Third Vane Pressure Loss

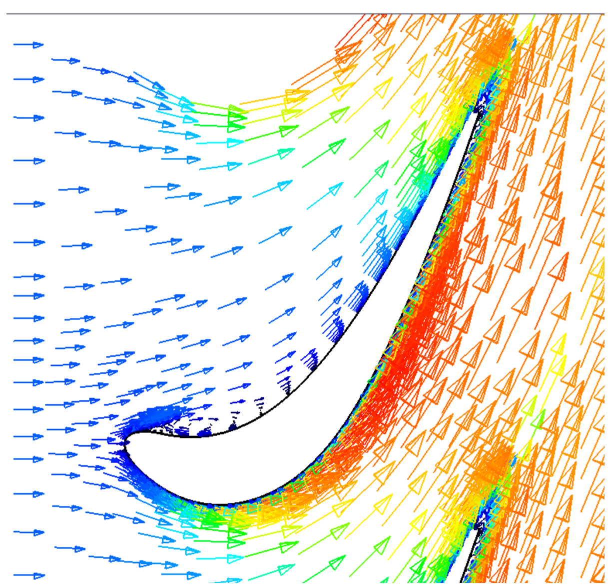


Figure 2.27.—Vane Velocity Vectors

All the CFD work performed suggests that mission fuel burn is improved by designing for relatively low corrected speed. In this present work, the design speed chosen was 75 percent speed, or approximately half way between low speed cruise (54 percent) and high speed take-off (100 percent) based on meanline predictions. The CFD suggests that the turbine is: 1) more forgiving than the meanline predictions and 2) able to tolerate higher negative incidence. A lower design speed may further improve overall mission fuel burn. Figure 2.14 would suggest a design speed of 70 percent as a logical compromise or next design iteration. Designing for lower speed also results in airfoils with higher camber. This is an added benefit because higher camber airfoils are generally stiffer and more resilient to high cycle fatigue.

2.13 Airfoil Leading Edge Geometry

The aviation industry routinely designs wings for variation in loading and incidence. From the largest commercial aircraft to the private general aviation airplane, variable geometry (flaps and/or LE slats) are employed to increase loading coefficient and wing area during take-off and landing. Zenith Aircraft Company uses a fixed LE slat (Figure 2.28) to make their STOL CH 701 stall resistant to very high angles of attack. The completely passive nature of their design is very attractive from a cost and complexity standpoint. Similarly, in this VSPT design, it would be very desirable to include features that improve tolerance while being completely passive. Turbine airfoils are relatively small and made from investment castings. It would be impractical to attempt to cast them with such intricate details. It would however be very advantageous to design turbine airfoils with a LE shape that was inherently incidence tolerant. One concept investigated in this study is to attempt to smooth the LE curvature distribution as much as possible in order to allow the air to smoothly transition from the LE to the airfoil pressure and suction sides.

Turbine airfoils are typically designed with an elliptical LE connected to a curved pressure and suction side. See Figure 2.29. Although the intersection of the ellipse and airfoil curves is designed to match point and slope, it does not typically match curvature and can in fact be discontinuous. In order to assess the impact of this discontinuity, a smoothing algorithm was developed and applied to the third blade from the previous studies. The algorithm calculates the curvature as a function of surface length (S-distance) and calculates a local correction factor based on the gradient in curvature from one point to the next. Each point is moved normal to the surface in the direction to smooth the gradient by a small amount. The process was iterated 200 times until a smooth curvature distribution was obtained. See Figure 2.30. The actual change in the surface profile required to smooth the curvature distribution is well within any reasonable casting profile tolerance. As shown in Figure 2.30(b) it is nearly within the thickness of a line when plotted at a reasonable viewing size. Figure 2.30(c) clearly shows the discontinuity in curvature at the tangency points and the result of running the smoothing algorithm. Nonetheless, it is still desirable to establish the best possible design shape and apply manufacturing tolerance about that nominal shape rather than a less optimal design. In order to determine if the smooth shape is in fact better, the smoothed third blade was run through the same set of CFD calculations as in the blade incidence study.

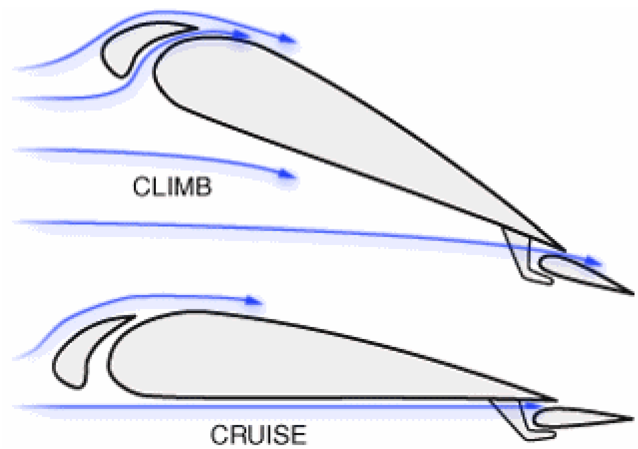


Figure 2.28.—Fixed geometry LE slats. Used with permission from Zenith Aircraft Company, Mexico, Missouri, 65265-0650.

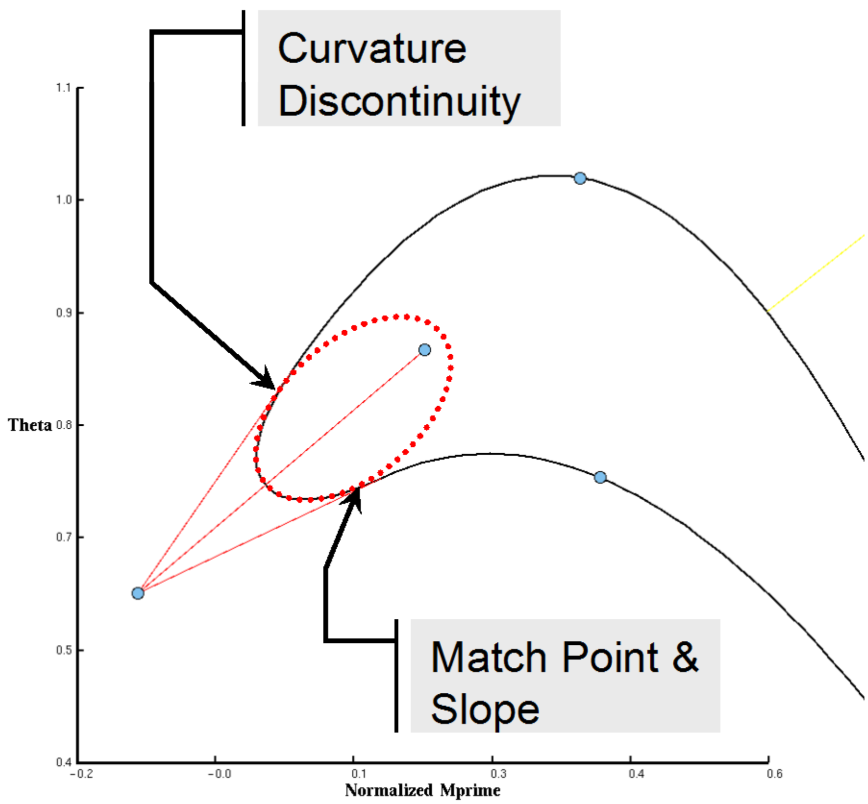


Figure 2.29.—Typical Turbine Airfoil Leading Edge Profile

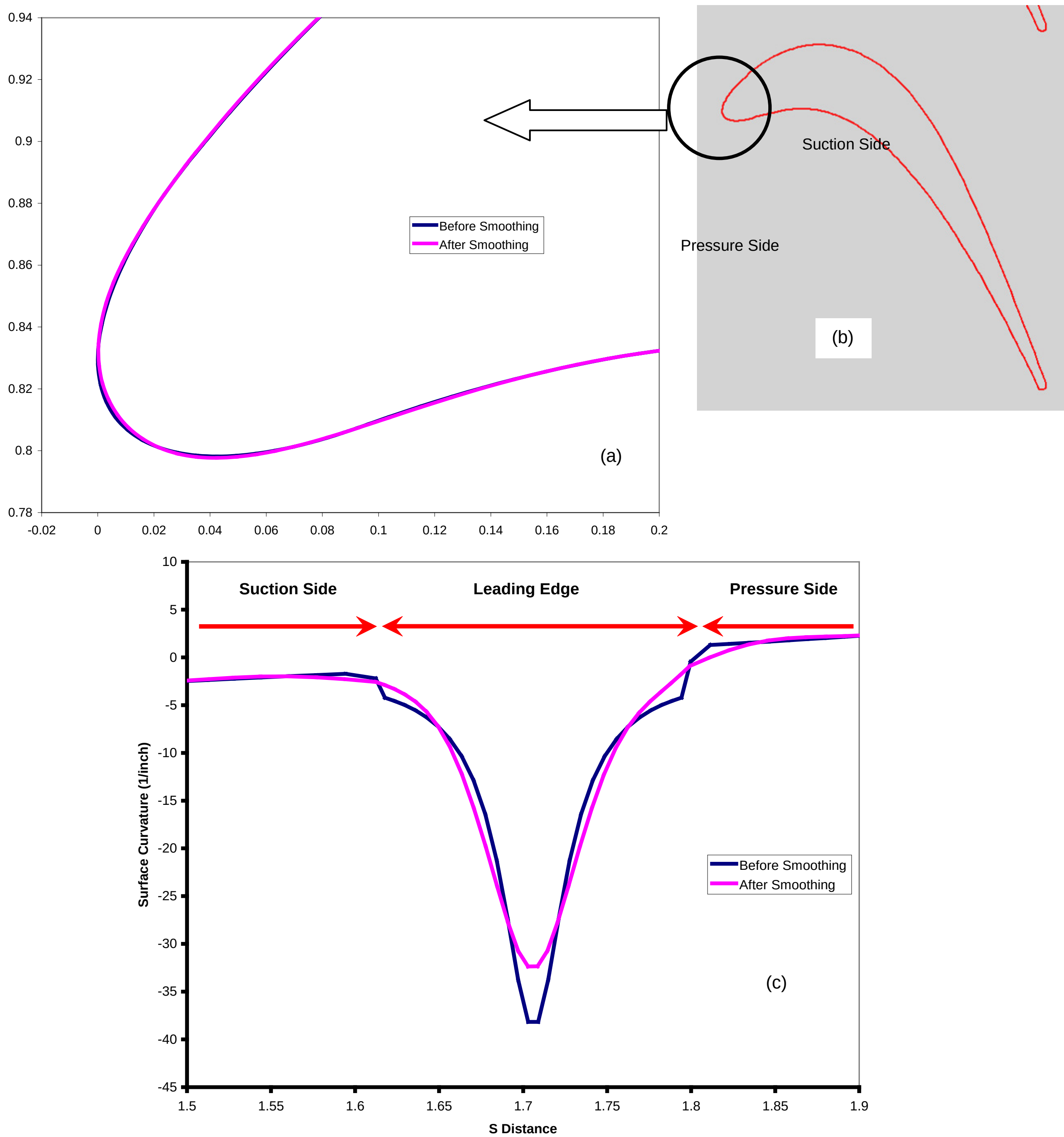


Figure 2.30.—Third Blade Mean, surface curvature smoothed

The changes to the geometry and CFD mesh were basically imperceivable to the eye. The global CFD results (i.e., efficiency and flow) for the third Blade at design speed (75 percent) were virtually unchanged relative to the non-smoothed blade. Figure 2.31 gives the mid-span surface static pressure loading also showing nearly identical results. Despite this disappointing result, the CFD was run at high and low speed to investigate off-incidence tolerance. The resulting efficiency trend with variation in speed was surprising. See Figure 2.32. Shown in green, the smoothed LE contour maintained better incidence tolerance at low speed relative the non-smoothed baseline configuration shown in pink. In order to understand this, a detailed investigation into the flow field was performed. At the design speed, no significant flow field changes were evident. This was also true at negative incidence (high speed), but at low speed, the smoothed LE resulted in an improved flow field. At approximately 80 percent span, the airfoil suction side loading is highest. As the airfoil loading is increased, this is the most likely location for the airfoil to separate.

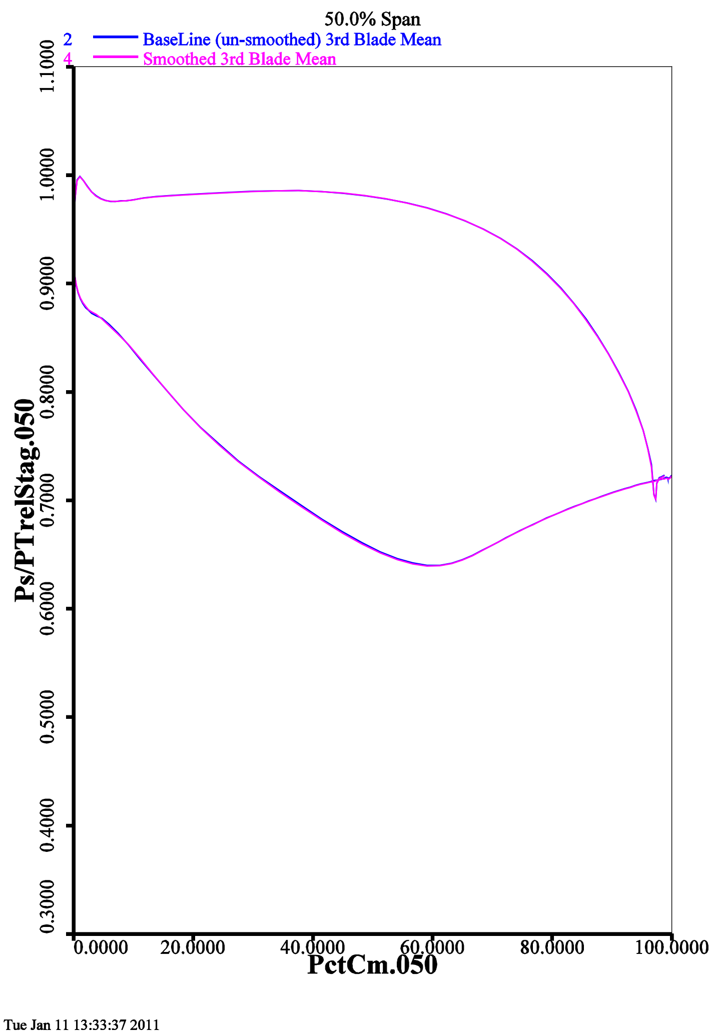


Figure 2.31.—Third Blade mid span static pressure distribution

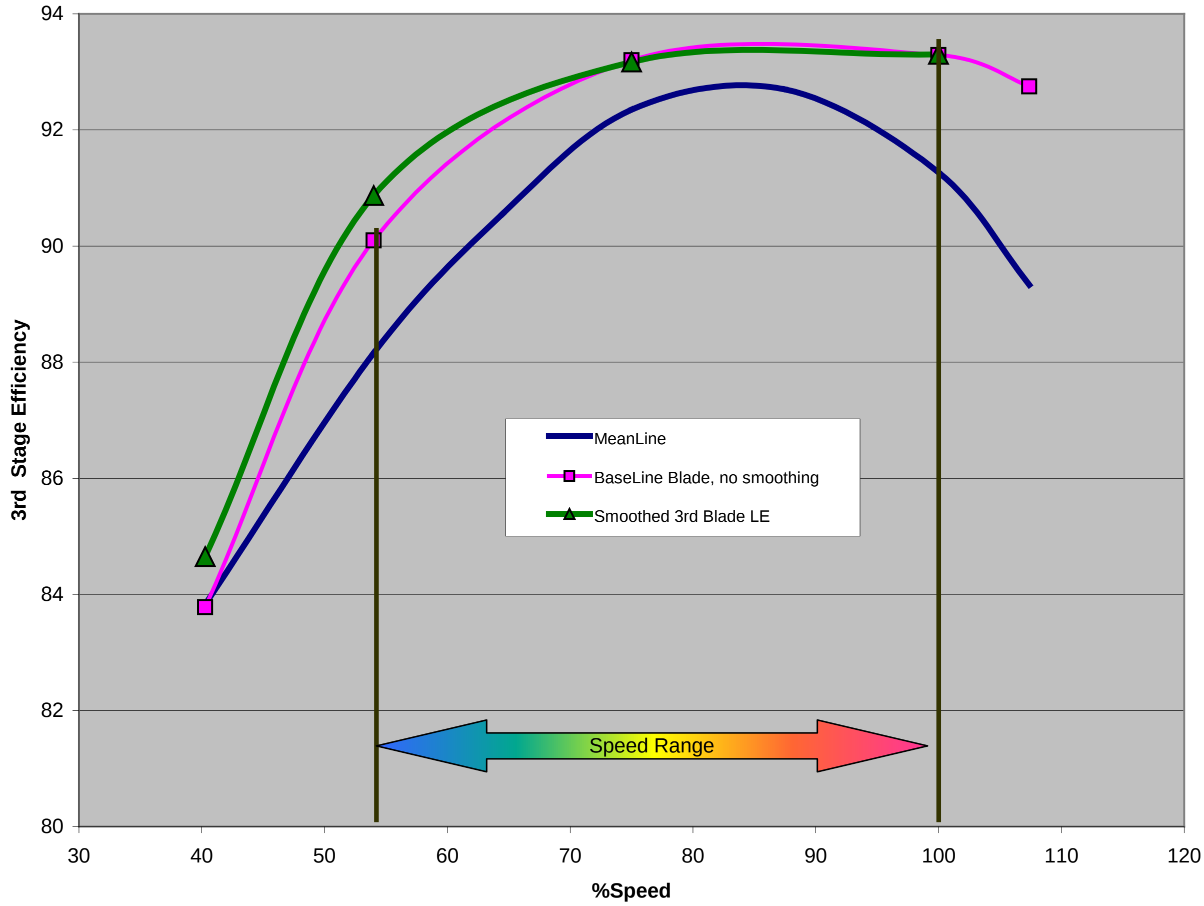


Figure 2.32.—Smoothed third Blade Efficiency Trend with Speed

Combing through the velocity vectors did reveal a separation in this location for the baseline (unsmoothed) blade. The easiest way to visualize this is to capture the separation bubble with a constant Mach number surface.

In Figure 2.33, the non-smoothed blade is compared to the smoothed blade. An iso-Mach number surface was generated for each calculation. The yellow-green surfaces shown are surfaces of Mach number equal to 0.15. Since the through-flow Mach numbers are all much higher than 0.15, all of the flow beneath the surfaces shown are boundary layers or separations. The non-smoothed blade has a separation bubble near the tip that is nearly completely removed after the blade is smoothed. The separation bubble is visually interacting with the secondary flow field near the shroud line.

This result is based on a single solver and turbulence model. No further CFD modeling was performed within this study. It is not know how transition from laminar to turbulent flow may be impacted by curvature smoothing. Likewise, the impact of the unsteady flow field is not known.

This work reinforces the importance of maintaining boundary layer health upstream of diffusing flowpaths. These results are encouraging: they suggest careful design of LE geometry can improve airfoil incidence tolerance. Additional, this completely passive design does not change the design point methodology. The design point analysis was completely unaffected by the incorporation of the smoothing algorithm. Addition research in this area may result in airfoil shapes that are inherently more incidence capable.

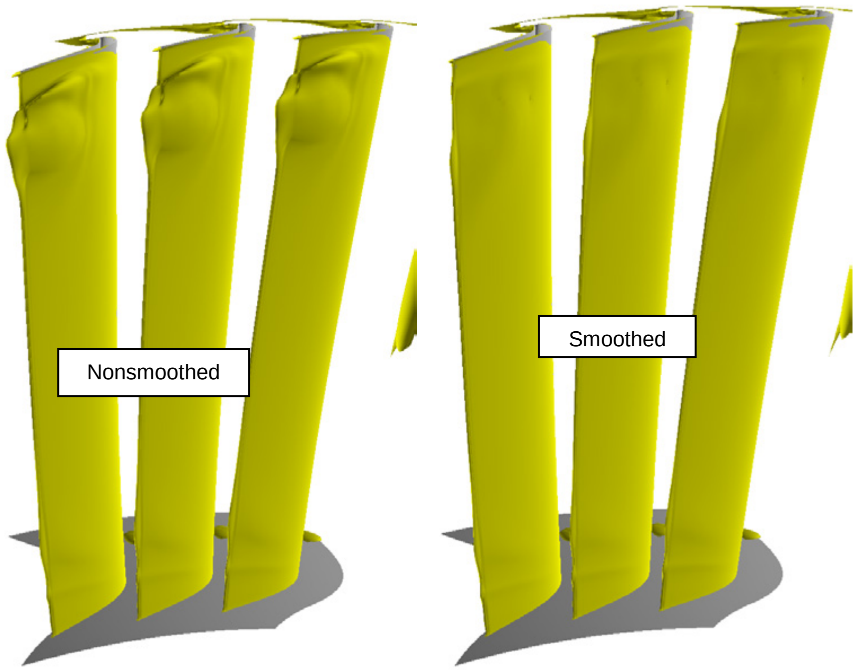


Figure 2.33.—Separation bubble visualization

3.0 VSPT LCTR Mission Performance Modeling

A thermodynamic cycle model was developed to study the performance impact of various power turbine designs. The basis of this study was the TS2-NPSS model provided by the NASA Glenn Research Center. The model was originally created March 5, 2010, and has description: "two-spool turboshaft about equal work for LPC/HPC, HPC is PR=1.3 axial + centrifugal - includes update for turbine cooling (best guess for number turbine stages)". The model was updated from NPSSv1.6.5 to NPSSv2.3 and the output of the model was enhanced. A copy of the updated model was provided to NASA to assist in adopting the latest version of NPSS consistent with NASA's overall goals. The only performance feature of the cycle model that was modified was the Power Turbine maps.

Three turbine designs were evaluated at the three critical mission points defined in the LCTR "Design" Mission Profile. These mission points define the design conditions for the overall cycle and present some challenges for the turbine design because of the wide range of shaft speeds. Table 3.1 summarizes the flight conditions and shaft speeds.

TABLE 3.1.—CRITICAL MISSION POINTS

Mission Segment	Takeoff hot	Climb	Cruise
Time, hr	0.07	1.00	3.00
Power, hp	7859	2646	2351
N3, rpm	15000	15000	8077
Ambient			
Mach Number	0	0.51	0.51
Altitude, ft	0	28000	28000
Delta T from standard conditions, F	45	0	0
VTAS, knot	0	303	303

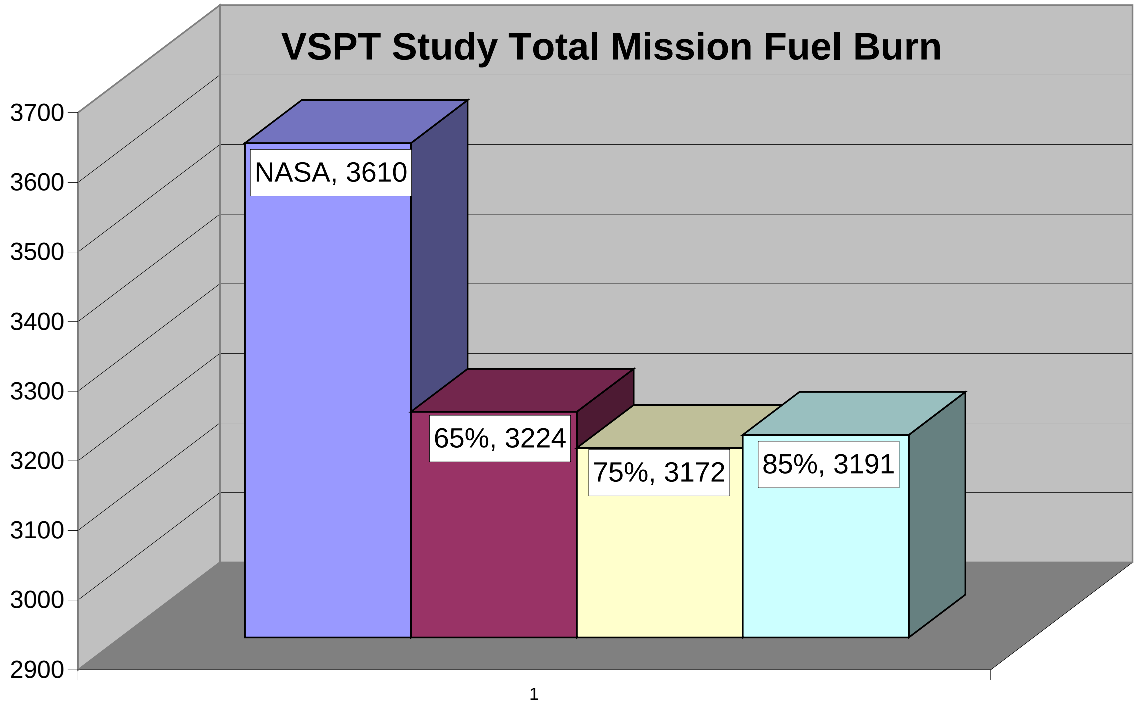


Figure 3.1.—VSPT Total Mission Fuel Burn for Three Williams International Designs

The Takeoff hot condition requires the maximum power at high rotor speed, but the amount of time at that condition is limited to 3 min for takeoff and 3 min for landing with an additional minute for taxi. The climb is represented by the top of climb condition at high rotor speed and represents 30 min to climb plus an additional 30 min to fly to an alternate destination. The cruise condition is represented by the same flight condition as the climb point, but at shaft rpm that is 54 percent of the full throttle condition and also at high power output for 3 hr.

The power turbine map provided with the NASA model was run at the three flight conditions and the power output was used as the requirement for each flight condition. Three power turbines were designed to provide performance at the cruise condition and to meet the maximum shaft speed requirement. The turbine design points were set at 65, 75 and 85 percent corrected speed and are labeled accordingly. Figure 3.1 shows the total mission fuel burn for the three designs.

The three proposed designs have significantly reduced mission fuel burn compared to the baseline power turbine design. The 75 percent design has the lowest mission fuel burn and is the best design on this basis. The 75 percent design uses 1.6 percent less fuel than the 65 percent design and 0.6 percent less fuel than the 85 percent design. The 75 percent design uses 12.1 percent less fuel than the baseline design and is the best overall design based on this preliminary design study. For each of the three turbine designs, the NPSS output for the three critical mission points is given in Appendix H.

In the cycle detailed output, there are 6 points presented for each turbine design. The takeoff point (T/O) is the cycle design point at takeoff power on a standard day at 15,000 rpm power turbine speed. The second point is takeoff on a hot day. The third point is at the climb condition, 15,000 rpm at the same power setting as the NASA design climb condition; however the power setting condition logic does not result in the same power output for different turbine designs. The fourth point is at the climb condition at the same power output as the NASA design to allow fuel flow comparisons. The fifth point is at the Cruise condition at reduced shaft speed of 8,077 rpm at the NASA power setting. The sixth point is at the Cruise condition at the NASA power level and is used for the fuel flow comparison.

4.0 Development of a Cost-Effective Approach to an LCTR-Relevant VSPT Component Experiment

Testing of a power turbine presents unique challenges in that it is not self-supporting. In order to test a power turbine, inlet compressed air is required that requires heating to at least several hundred degrees F to avoid ice formation on exhaust structures and instrumentation. A power sink is also required that has excellent control characteristics in order to set rpm and avoid overspeeds. Ideally, the power turbine should be tested at full scale to minimize Reynolds effects and so that key inter-stage instrumentation can be inserted without unduly affecting the flow conditions in the local area. Since the VSPT for the LCTR will be relatively large, full scale testing will require a test facility that can provide continuous flow of large volumes of heated inlet air with substantial power absorption capability. Use of an existing engine as a gas generator testbed for testing the VSPT was considered as an option, but ruled out because the engine operating line would severely limit the range of power turbine entrance conditions that could be achieved during test. The optimum approach appears to be to develop a dedicated VSPT rig to mate to the single-spool turbine test facility at NASA GRC. The capabilities and limits of the single-spool turbine facility, listed in Table 4.1, provide more than sufficient capability to produce the entrance and exit conditions needed to evaluate the LCTR VSPT design concept at full scale.

There are two basic engine configurations that can provide power to the rotor system, and both have been used successfully in large numbers of turboshaft and turboprop systems. The gas generator can be mounted with the compressor facing in the direction of flight, or opposite to the direction of flight. The aft-facing compressor configuration, similar to that used by the Pratt & Whitney PT-6 turboprop, provides a very large advantage in that the power turbine shaft can be very short and large in diameter since the power turbine module is adjacent to the reduction drive gearbox, compared to the long, thin shaft needed by the forward-compressor configuration, which needs to pass the turbine shaft through the center of the gas generator shafts. This greatly reduces or eliminates the rotordynamics and torque limitations issues associated with the long, thin shaft. The disadvantage of this configuration is that the airflow must be turned 180° prior to entering the inlet, and once again in the exhaust duct. This is necessary to avoid having the inlets face the ground during VTOL operation. An advantage is that it provides a simple method for rejecting ice, birds, or other foreign matter before it can enter the gas generator. The forward-facing compressor configuration requires an S-duct inlet and can use an axial exhaust, which have lower aerodynamic losses. The aft-facing compressor design also provides a much easier approach to an inertial separator design for ejecting ice and solid objects, another distinct advantage. Mostly because of the reduced rotordynamics concerns, the compressor-aft configuration is recommended for the LCTR application. Figure 4.1 is a schematic of this configuration for a twin-pack LCTR design. The spacing between the power turbine exhaust and the reduction drive gearbox is the minimum required to provide a low-loss turn in the exhaust duct.

TABLE 4.1.—NASA GRC SINGLE-SPOOL TURBINE TEST FACILITY CAPABILITIES

• Maximum Turbine Inlet Pressure	50 psia
• Minimum Exhaust Pressure	2 psia
• Maximum Inlet Air Temperature (from in-line vitiated natural gas combustors)	940°F
• Maximum Primary Air Flow Rate	27 pps
• Secondary Air (150 psig supply): » 2 Legs – 1.5 pps each up to 550ºF » 4 Legs – 0.08 to 1.19 pps each up to 250ºF » 6 Legs – at 70ºF	
• Maximum Turbine Rotational Speed (with maximum Gear Ratio, G.R., of 7.87)	14,000 rpm
• Maximum Turbine Torque	36,217 ft·lb_f/G.R.
• Minimum Gear Ratio, G.R. = 1.51 (N_{max}= 2,718 rpm; $Torque_{max}$= 24,000 ft·lb_f)	
• Maximum Test Article Diameter	52 inch

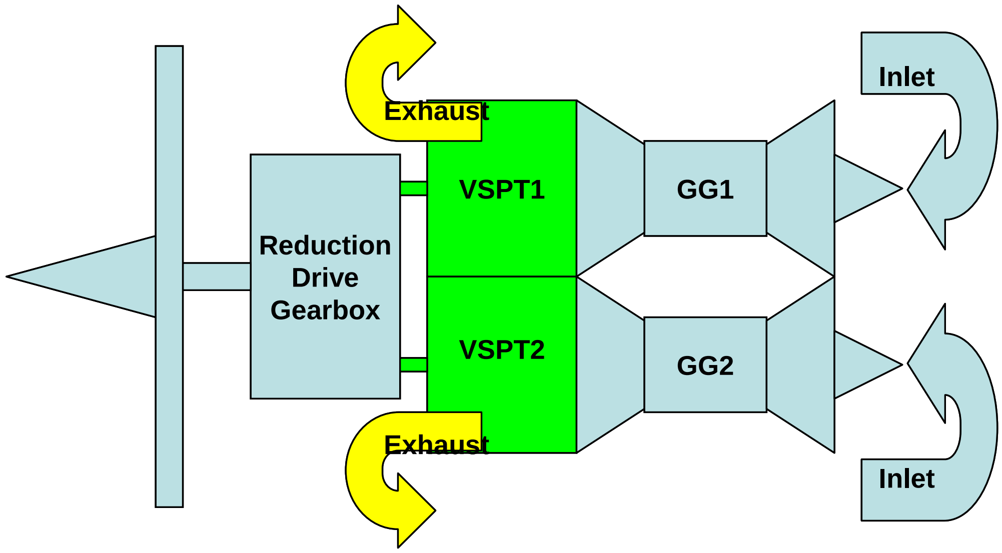


Figure 4.1.—Schematic of Recommended Engine Configuration for LCTR

Rotordynamics of turboshaft machinery such as tilt rotors are generally divided up into two categories, lateral and torsional. Each has its own set of typical challenges.

Lateral challenges typically involve long flexible drive shafts that operate above the first flexible critical mode, i.e., supercritical rotors. Inadequate damping at the bearings results in damaging vibrations when traversing the lateral critical modes of drive shaft. Controlling run-out and wall thickness variation of long hollow flexible shafts at reasonable cost is often challenging. Misalignment of drive shaft between gearbox and power-turbine adds further complexity that must be addressed. Last and perhaps most important the large overhung tilt rotor makes the system sensitive to rotating unbalance.

Torsional challenges typically involve shock from start up and elevated transient loading through the drive shaft. Unloading of gear teeth during surge events, back lash, gear run out, random vibration due to gear inaccuracies and rolling element defects, and closed loop control system instabilities have all been known to lead to torsional failure modes. All of these issues need to be addressed as part of the full engine and test article designs.

Figure 4.2 shows a layout of the proposed full scale VSPT test article mated to the NASA GRC single spool turbine test facility dynamometer drive frame. Locations are indicated for multi-element instrumentation rakes at the inlet and exit of the VSPT, and for cylindrical radially-translating flow angle sensors at each of the three interstage locations. The rig inner and outer flowpaths are a combination of formed sheet metal and machined details, with the inner flowpath and bearing support structures supported by an exit guide vane row set well behind the last stage rotor. The four-stage turbine is overhung on the front of the shaft, supported by an aft roller bearing and forward ball bearing to react thrust loads. As shown, the thrust loads are intended to be reacted through the front bearing and out into the outer frame structure through the exit guide vane row. The bearing cartridge in the SSTTF has sufficient load capacity to support the VSPT test article as an entirely overhung mass, so an alternative approach would be to eliminate the VSPT bearings altogether and hang the VSPT off the front of the drive spindle. If feasible, this arrangement would simplify the system and eliminate the bearing lubrication requirements, as well as reducing the cost of the design and hardware. It will be necessary to analyze the shaft system to ensure that critical speeds are not an issue and displacements do not drive excessive tip clearances in the test article. The preliminary aero and structural design tasks in the experimental program will determine if it will also be necessary to include one or more balance pistons to offset some of the thrust load.

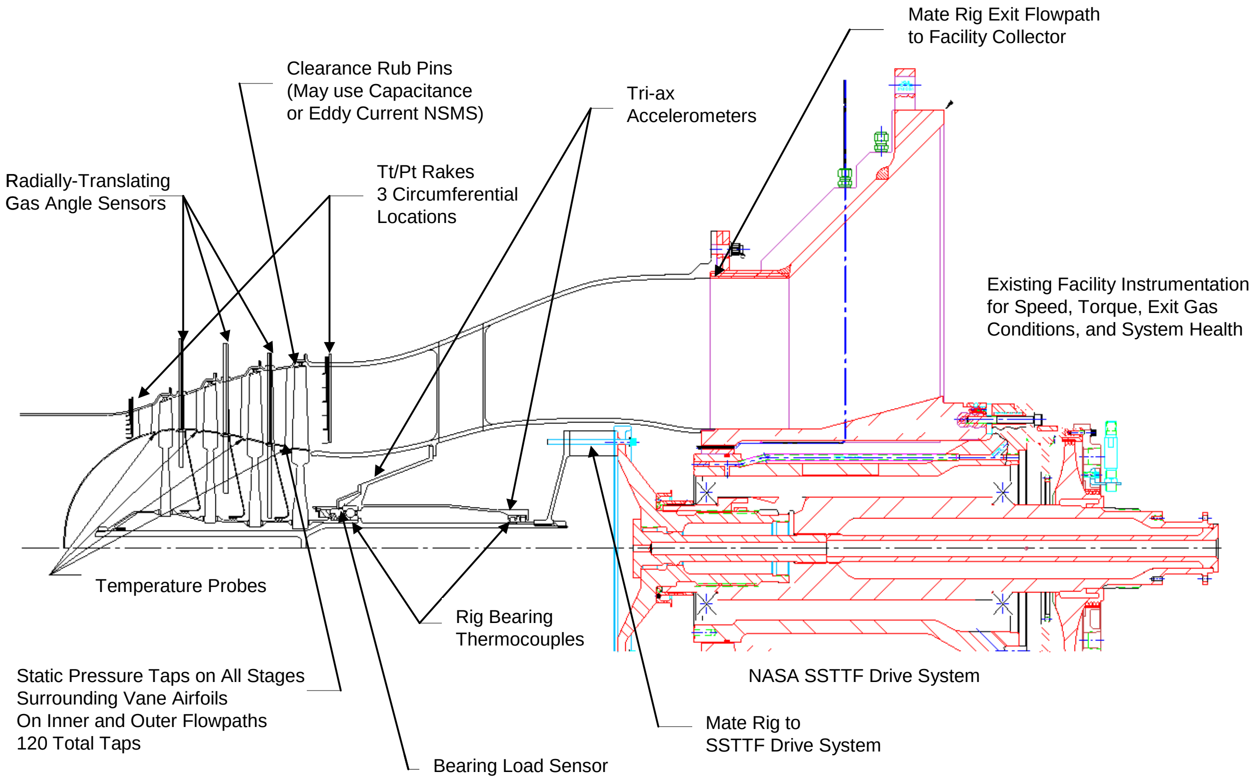


Figure 4.2.—VSPT Test Article Mated to NASA-GC Single Spool Turbine Test Facility

The four-stage rotor is shown as a clamped assembly with the clamp loads applied at the hub through curvic couplings. This was done in order to make it possible to use the cylindrical wake angle sensors. This type of sensor has performed very well in past tests and has the advantage of being much smaller in diameter than traditional cobra probe sensors because it is supported at both ends of the flowpath rather than cantilevered from the outer wall. This greatly minimizes blockage but imposes some limitations on the design of the test component. Since the sensing position on the probe has to transit the entire span from the outer to the inner wall, provisions must be made for the probe body to penetrate an equal distance beneath the inner flowpath when the inlet holes are at the innermost radial position. This makes it impossible to use with a drum rotor configuration. A detailed rotordynamic analysis of the rotor/shaft system will be a key part of the experimental program and its results will determine whether this approach is feasible or if a drum rotor configuration with conventional probes is required to achieve sufficient speed and frequency margins relative to the operating speed range. The spacing between stages and between vane and blade rows shown in the figure is notional and would be optimized during the test article design process to provide access and routing for all of the planned instrumentation.

4.1 Experimental Test Plan and Instrumentation List

The proposed operating conditions of the VSPT vary from 54 to 100 percent speed. Therefore, it would be beneficial to develop a turbine map that fully describes the turbine efficiency within this range. The proposed test plan to characterize this turbine would include a pressure ratio sweep from 3.0 to 7.0 and a speed sweep of 40 to 120 percent (Table 4.2). Generally speaking, it is easier to change speed than PR in a test facility so the order of operations would be to set PR and then increment through the speed range to develop lines of constant PR.

TABLE 4.2.—PROPOSED MAP/TEST PLAN

	PR								
Speed%	3	3.5	4	4.5	5	5.5	6	6.5	7
40									
50									
60									
70									
80									
90									
100									
110									
120									

The turbine map should be developed at both high and low Reynolds number where “high” is equivalent to a SLTO condition and “low” is equivalent to the cruise condition.

Low Reynolds number cruise at highest corrected speed is most challenging condition, and requires vacuum. For similitude in Reynolds number, PR, Corrected Flow and Corrected speed, the following table defines the 100 percent speed conditions for the turbine:

	Engine	Proposed Rig
Inlet PT	31.01 psia	20.6 psia
Inlet TT	1749.1°R	1260.°R (800 °F)
Inlet Mass Flow	12.04 lbm/s	9.425 lbm/s
Power	2740 hp	1525 hp
Exit PT	5.35 psia	3.55 psia
rpm	14898	12645
First Vane Reynolds Number	178,000	172,000
Last Blade Reynolds Number	61,000	61,000

The SLTO (high Reynolds Number) condition requires the following parameters:

	Engine	Proposed Rig
Inlet PT	88.49 psia	45 psia
Inlet TT	2166.3°R	1260 °R (800 °F)
Inlet Mass Flow	9.41 lbm/s	20.6 lbm/s
Power	7500 hp	3350 hp
Exit PT	15.43 psia	7.76 psia
rpm	14898	12645
First Vane Reynolds Number	395,000	377,000
Last Blade Reynolds Number	130,000	134,000

These rig conditions are within the advertised capability of the New Single Spool Turbine Facility proposed by NASA to replace W-6A Warm Core Turbine Facility.

In order to simplify the rig as much as possible, the rig would be uncooled. The proposed warm inlet temperature of 800 °F should allow for nearly no cooling flow. This allows for simple turbine efficiency calculations based only on measured inlet and exit total pressure and total temperatures. The Turbine efficiency can be calculated as follows:

$$\eta = \frac{\Delta T}{T_{in}\left(1.0 - PR^{\frac{1.0-\gamma}{\gamma}}\right)}$$

where γ is the ratio of specific heats calculated at the average of the inlet and exit temperatures.

The corrected speed is calculated as:

$$\mathrm{rpm_{corr}} = \mathrm{rpm}\sqrt{\frac{518.67}{T_{in}}}$$

where 100 percent is defined as $\mathrm{rpm_{corr}} = 8113$.

Of great interest is the turbines performance at the two design conditions (54 and 100 percent) speed. At these conditions, inter stage gas swirl angle and total pressure profiles will be measured and compared back to predictions. The use of a cylindrical probe between the stages is proposed to measure gas angles behind rotors with minimal blockage. It is significantly more difficult to measure the gas angles behind stators because the circumferential variation in angle and pressure complicates the measurement and therefore it is not recommended.

Table 4.3 comprises an initial recommendation for instrumentation required to collect the desired test data.

TABLE 4.3.—PROPOSED INSTRUMENTATION LIST FOR VSPT COMPONENT EXPERIMENT

Sensor type	Objective	Location	Quantity	Required accuracy
Radially translating cylindrical gas angle sensor	Measure flow angles exiting each turbine stage	Nozzle vane Leading Edge	1 per stage, 3 total	± 1°
Six-element total pressure rake	Measure total pressure at entrance and exit of VSPT	Inlet and exit	6	±0.5%
Static pressure taps	Determine pressure distribution around vanes	Outer and inner wall, at root of nozzle vane	20 OD, 20 ID, 3 locations, 120 total	± 0.5%
Six-element total temperature rake	Determine stage temperature drop	Inlet and exit	6	± 1 °F
Bearing Thermocouple, type K	Monitor bearing health	Outer race	2 per bearing, 4 total	± 10 °F
NSMS or capacitance probe	Actively monitor tip clearance	At tip of each blade row	4	± 0.001 in.
Rub Pins	Verify min tip clearance	At tip of each blade row	2 per row, 8 total	± 0.001 in.
Triax accelerometer	Monitor vibes for rig health	On fwd and aft bearing housing	2	± 1g
Real Time Spectrum Analyzer	Monitor vibes and frequencies for rig health	Accelerometer output	1	N/A
Oil sump thermocouple, type K	Monitor oil temperature	Oil sump	1	±10 °F
Strain gage thrust ring	Monitor bearing thrust load	Fwd bearing	2	± 10 lbf
Facility Speed pickup	Monitor speed	facility	2	±10 rpm

4.2 VSPT Component Experiment Program Plan, Schedule, and ROM Cost

A program to provide experimental validation of the proposed LCTR VSPT using the NASA GRC Single Spool Turbine Facility can be accomplished in 36 months, of which 33 months are required for the technical effort and 3 months for reporting. Figure 4.3 shows a notional program schedule to accomplish this effort. During the preliminary design task, the concept for the VSPT will be refined to the point where all key aspects of the component and rig designs have been defined in sufficient detail to ensure that no key risk items are likely to force substantive design changes during detailed design. This requires that a comprehensive layout be produced, from which a bill of materials and parts list can be generated. Preliminary aerodynamics will be defined for each blade and vane row, from which structural models will be prepared. The aerodynamic, structural, and dynamic design of the blades, vanes, and other flowpath elements needs to take into consideration the actual operating conditions the VSPT would see in operation behind the gas generator, not just the relatively cold rig operating conditions, since it would do no good to test a component design which has no chance of surviving the actual operating conditions in the real engine. Rotordynamic analyses will be required as a part of the preliminary design in order to ensure that sufficient speed and frequency margins can be obtained with the proposed configuration. For a power turbine module that interfaces with the reduction gearbox directly rather than by extending a shaft through

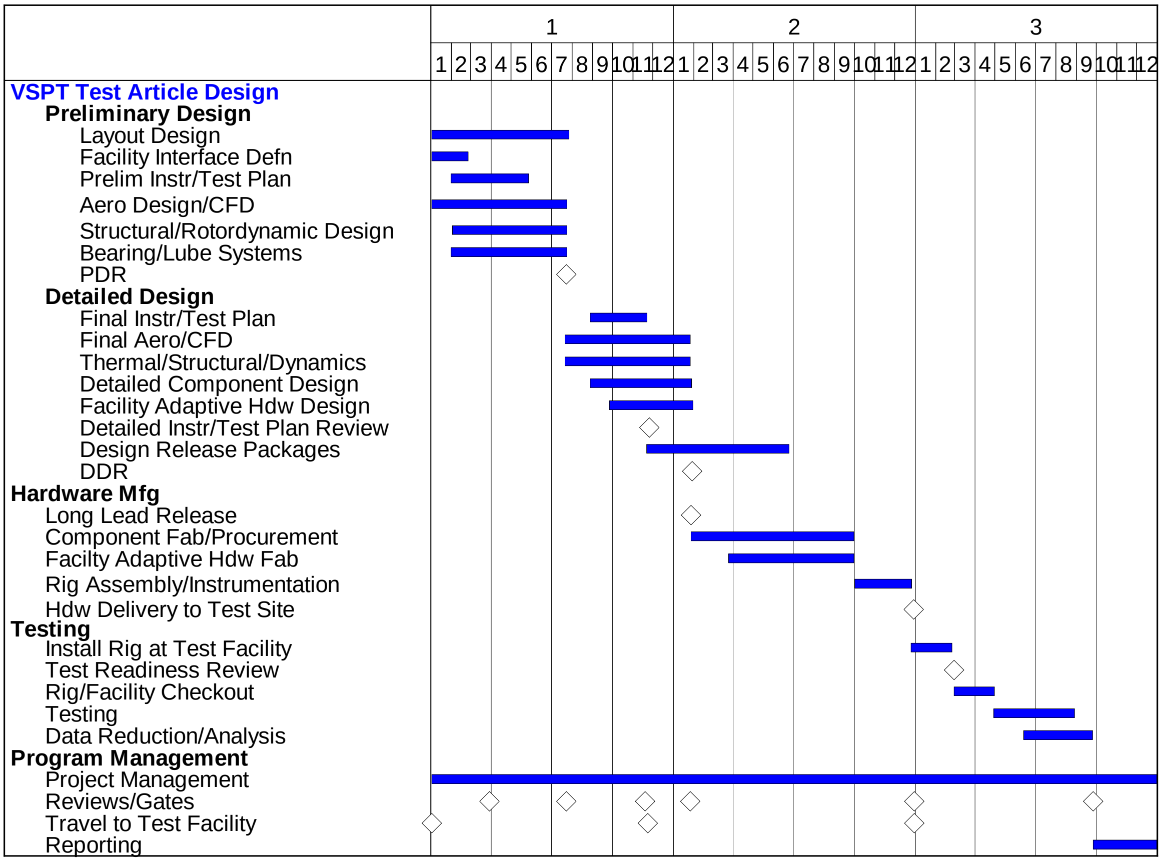


Figure 4.3.—Proposed Schedule for VSPT Experiment

the gas generator (e.g., PT-6 configuration) there is substantial freedom in the design and opportunity to vary shaft characteristics and bearing spacing to achieve sufficient margins, so the risk of not achieving acceptable margins is fairly low. To reduce risk, a Design Failure Modes and Effects Analysis (DFMEA) will be conducted during preliminary design. This will help identify any potential failure modes and define mitigation approaches early enough in the program so they can be incorporated into the design and test plan.

The rig configuration will be driven by the requirements to obtain the key data for validating the design, and by the interfaces with NASA's single spool turbine facility. At the outset of the preliminary design task, Substantial coordination with the NASA technical team will be required to define the rig/facility interface requirements, as well as routing for instrumentation and secondary systems plumbing and rig and facility safety requirements.

The lubrication and secondary air systems will also be defined in the preliminary design. For the rig, a conventional jetted recirculating oil lubrication system will be used. Facility pumps will provide motive flow and scavenge and these will be sized according to the predicted requirements of the rig across its operating range of speed and power output. Purge air flow and pressure requirements for bearing compartments and to prevent flowpath air ingestion will also be defined. The preliminary design effort is expected to require 7 months to complete. At the conclusion of the preliminary design efforts, a preliminary design review with the NASA technical team is planned.

Since all of the key characteristics of the VSPT component and rig design will have been defined in Preliminary Design, the detailed design efforts will focus on substantiating the preliminary design configuration via detailed modeling and analysis. The instrumentation and test plan will be finalized and will be provided to NASA along with a 3-D external model of the test rig and all its secondary systems and plumbing. Component aerodynamics will be finalized via detailed CFD, structural, and dynamics analyses, including transient analyses to define final operating and build tip clearances. If necessary due to design changes, the rotordynamics model will be updated and exercised to finalize the design of the rotary group and bearing system. Design release packages will be produced, comprising all the design and manufacturing information needed to produce or procure the component and rig hardware. At the completion of the detailed design task, a detailed design review will be held with the NASA technical team. The DDR will include a review of the updated DFMEA based on the completed state of the design.

Once the DDR is approved, long lead hardware will be ordered and hardware fabrication will begin. Since the rig and component hardware is primarily to be made of steel and aluminum, it is likely the only long lead hardware may be the bearings. As a risk reduction approach, the rig can be designed around bearings that are already in hand and available, or are known to be available on short lead. Fabrication of rig and component hardware, as well as facility adaptive hardware, can be completed in 8 months, at which time instrumentation and assembly of the rig will begin. The milestone for delivery of the completed instrumented rig to the NASA test facility occurs at month 24.

A detailed test readiness and safety review will be conducted once the rig is installed at the test facility. This review will address all aspects of rig operation and data collection, including a review of the DFMEA.

Testing will begin at month 28 and will follow the approved test plan. Ideally, two sets of hardware with slightly different aerodynamics will be tested back-to-back to bracket the design and provide data for a sensitivity analysis. At completion of the test program, the rig and component hardware will be torn down and assessed to determine if any conditions exist that may have affected the test data, such as tip rubs or damage to any of the hardware or instrumentation. The test data will be reduced and analyzed and compared to pre-test predicted maps. The maps used in the cycle model will be updated to reflect actual performance and the mission analysis will be re-run to determine the effects of the status updates on the overall mission performance.

The program schedule shows milestones for major reviews and on-site meetings at the test facility. A final report will be compiled and submitted at month 36.

A ROM cost estimate for the proposed 36-month VSPT experiment program shown in Figure 4.3 is $4.5M, broken down as follows:

- Preliminary Design: $800,000
- Detailed Design: $1,400,000
- Component and rig hardware: $1,200,000
- Testing: $300,000
- Program management: $800,000

This ROM represents an estimate of contractor cost to perform the design, build the hardware, conduct testing, and manage the effort. It does not include an estimate of costs for use of the test facility and support from NASA and government service contractors. If it is determined that the VSPT test components can be overhung directly from the facility bearing cartridge, eliminating the need for the dedicated component bearings and lube system, the cost to design and build the components would be reduced, and the total cost of the program could potentially be lower by as much as $200,000.

5.0 Conclusions

In this study, a variable speed power turbine design was executed for a proposed Large Civil Tiltrotor. This application is unique in that it requires a turbine with far greater off-design capability than traditional propulsion related gas turbines. Airfoil incidence can change as much as 60° between the high speed and low speed rotor settings. These large changes in incidence cause airfoil separations and large loading changes resulting in reduced efficiency. In order to address these large loading swings, a study was performed in which a methodical multiple design-point process was used to arrive at a flowpath that is fundamentally speed insensitive. This is in direct contrast to other techniques such as variable geometry or a variable gear ratio transmission. The figure of merit used in this study was to minimize the fuel burn throughout the mission by weighting various performance conditions in such a way as to mimic a typical flight. Various designs were analyzed and traded against each other with a turbine meanline code and CFD calculations were used to validate the results. CFD consistently showed better negative incidence tolerance (high speed) than the 1–D meanline loss systems. This finding would suggest moving the design point selection to lower speed than the 1–D prediction. Any further research would require testing.

A component experiment program plan was proposed that can be accomplished within a 36-month period. This program would design and fabricate a stand-alone rig to mate to the NASA GRC Single Spool Turbine Test Facility and take advantage of its capabilities to run the testing at full scale for the proposed LCTR application in an economical manner. A notional component test article design was proposed that emulates the configuration recommended for the LCTR engine, and which greatly minimizes rotordynamic issues that would be major concerns for alternative configurations.

The design methodology and technology investigated in this study can provide benefits to other systems beyond the LCTR. Any system that can benefit from improved off-design performance, whether turbofan, turboshaft, or turboprop, may be able to take advantage of the proposed approach to avoid the complexity and cost associated with traditionally variable geometry approaches. This includes not only aviation engines, but also ground power and automotive engines.

Appendix A.—NPSS Outputs

TABLE A.1.—SEA LEVEL STATIC (MRP) 100 PERCENT NPT

```
*******************************************************************************************************************************
Date:08/27/10    Time:09:18:23    Model:                    AHS 2010 Govt turboshaft engine - Design pt    converge = 1    CASE:    1
Version:NPSS_1.6.5 - Rev: ->    Gas Package: Janaf    iter/pass/Jacb/Broy= 20/ 35/ 1/18    Run by:           csnyder       PC:      0

                                      SUMMARY OUTPUT DATA
    MN        alt      dTs         W          Fn      TSPC       Wfuel       VTAS      OPR       T4       T41       T47  Dyn P.
 0.000        0.1     0.00     28.69       457.5    5.6417     2581.28       0.00   42.415   3660.0    3326.8    2739.2     0.0

                                       FLOW STATION DATA
                                W        Pt        Tt        ht      FAR        Wc        Ps        Ts     Aphy      MN    gamt    gams
FL1  Ambient.Fl_O           28.69    14.696    518.67     -6.18   0.0000     28.69    14.696    518.67   ----.--   0.000  1.4002  1.4002
FL2  Inlet.Fl_O             28.69    14.696    518.67     -6.18   0.0000     28.69    13.161    502.57   132.95   0.400  1.4002  1.4004
FL22 Duct1.Fl_O             28.69    14.696    518.67     -6.18   0.0000     28.69    14.292    514.55   247.79   0.200  1.4002  1.4003
FL23 LPC.Fl_O               28.69   211.732   1202.17    161.80   0.0000      3.03   190.054   1167.67    14.19   0.400  1.3679  1.3701
FL24 ICduct.Fl_O            28.69   211.309   1202.17    161.80   0.0000      3.04   189.674   1167.67    14.22   0.400  1.3679  1.3701
FL25 HPC_axi.Fl_O           28.69   239.743   1248.88    173.74   0.0000      2.73   225.559   1228.65    16.37   0.300  1.3650  1.3663
FL26 Bld25.Fl_O             26.46   239.743   1248.88    173.74   0.0000      2.52   215.241   1213.31    11.79   0.400  1.3650  1.3672
FL27 HPC_centri.Fl_O        26.46   623.331   1661.69    282.22   0.0000      1.12   587.037   1636.42     6.75   0.300  1.3423  1.3435
FL28 Bld3.Fl_O              19.40   623.331   1661.69    282.22   0.0000      0.82   597.846   1644.07     5.85   0.250  1.3423  1.3431
FL3  Duct6.Fl_O             19.40   623.331   1661.69    282.22   0.0000      0.82   606.871   1650.38     7.22   0.200  1.3423  1.3428
FL4  Burner.Fl_O            20.12   610.864   3660.00    229.74   0.0370      1.29   554.588   3586.55     6.24   0.400  1.2553  1.2573
FL42 HPT.Fl_O               27.18   294.057   2818.32    125.14   0.0271      3.17   277.836   2782.82    19.55   0.300  1.2831  1.2841
FL43 Duct43.Fl_O            27.18   294.057   2818.32    125.14   0.0271      3.17   265.950   2755.71    15.24   0.400  1.2831  1.2848
FL44 LPT.Fl_O               29.41    88.489   2166.27    -35.05   0.0250      9.98    86.224   2153.16    89.22   0.200  1.3043  1.3047
FL45 ITduct.Fl_O            29.41    88.489   2166.31    -35.05   0.0250      9.98    79.832   2114.66    47.72   0.400  1.3043  1.3061
FL6  PowerT.Fl_O            29.41    15.431   1534.66   -215.29   0.0250     48.18    14.539   1512.08   292.50   0.300  1.3314  1.3326
FL7  Duct12.Fl_O            29.41    15.431   1534.73   -215.29   0.0250     48.18    14.539   1512.14   292.50   0.300  1.3314  1.3326
FL9  Nozzle.Fl_O            29.41    15.431   1534.79   -215.29   0.0250     48.18    14.696   1516.24   320.24   0.271  1.3314  1.3324

TURBOMACHINERY PERFORMANCE DATA
              Wc       PR      eff         Nc       TR    efPoly        pwr     SMN     SMW
LPC        28.69   14.407   0.8438  12000.000   2.3178   0.8891     -6819.3   20.00   19.59
HPC_axi     3.04    1.135   0.8863   9721.313   1.0389   0.8882      -484.8   20.00   12.62
HPC_cen>    2.52    2.600   0.8577   9537.774   1.3305   0.8739     -4061.7   20.00   18.25
HPT         1.29    2.077   0.8500    244.636   1.1355   0.8183      4546.4
LPT         3.17    3.323   0.8500    226.040   1.2528   0.8253      6819.3
PowerT      9.98    5.735   0.8500    322.278   1.4117   0.8184      7500.0

TURBOMACHINERY MAP DATA
           WcMap    PRmap   effMap      NcMap    R/Parm     s_WcDes   s_PRdes  s_effDes  s_NcDes
LPC        30.00    9.000   0.8510    100.000    2.0000    0.956433    1.6759    0.9916   0.8333
HPC_axi    30.00    1.200   0.8510      1.000    2.0000    0.100682    0.6728    1.0354   0.0001
HPC_cen>   30.00    3.200   0.8510      1.000    2.0000    0.083407    0.7273    1.0019   0.0001
HPT        30.15    6.000   0.9288    100.000    6.0000    0.042649    4.6409    0.9152   0.0179
LPT       149.90    6.000   0.9276    100.000    6.0000    0.021123    2.1523    0.9163   0.0194
PowerT    179.05    2.000   0.9112    100.000    2.0000    0.055750    0.2112    0.9328   0.0136

---INLETS----      eRam       Afs       Fram
Inlet            1.0000   -----.--       0.0     BLEEDS - output    Wb/Win   hscale   Pscale        W        Tt       ht        Pt
                                                 C_LPTCharg   Bl>   0.0214   1.0000   1.0000   0.6145   1248.88   173.74    88.489
```

TABLE A.1.—Concluded.

```
----DUCTS----  dPnorm      MN     Aphy      C_LPTUncharg Bl>   0.0563   1.0000   1.0000     1.6163   1248.88   173.74   294.057
Duct1          0.0000  0.4000   132.95      C_HPTCharg   Bl>   0.0916   1.0000   1.0000     2.4239   1661.69   282.22   294.057
ICduct         0.0020  0.4000    14.19      C_HPTUncharg Bl>   0.1751   1.0000   1.0000     4.6347   1661.69   282.22   610.864
Duct6          0.0000  0.2500     5.85
Duct43         0.0000  0.3000    19.55
ITduct         0.0000  0.2000    89.22
Duct12         0.0000  0.3000   292.50

---SHAFTS----   Nmech  trq in   pwr in
HP_Shaft      14800.0  1613.4   4546.4
IP_Shaft      12000.0  2984.7   6819.3
LP_Shaft      15000.0  2626.1   7500.0

---BURNERS---   TtOut     eff   dPnorm    Wfuel      FAR    EINOx     ppm
Burner        3660.00  1.0000   0.0200  0.71702  0.03695

---NOZZLES---      PR     Cfg     CdTh       Cv       Ath     MNth     Vact      Fg
Nozzle          1.050  0.9900   1.0000   0.9900    320.24    0.271    500.5   457.5
```

TABLE A.2.—2,000 ALTITUDE, +45 °F DAY, HOVER (NOT AT MAXIMUM POWER) 100 PERCENT NPR

```
*******************************************************************************************************************
Date:08/27/10     Time:09:18:25     Model:                 Generic turboshaft engine - Off-design    converge = 1    CASE: 114
Version:NPSS_1.6.5 - Rev: ->    Gas Package: Janaf    iter/pass/Jacb/Broy-  4/ 15/ 1/ 2    Run by:          csnyder       PC:     35

                                        SUMMARY OUTPUT DATA
    MN        alt       dTs          W          Fn       TSFC       Wfuel       VTAS       OPR       T4       T41       T47  Dyn P.
 0.000     1999.9     45.00      21.13       338.8     5.1997     1761.60       0.12    32.845    3516.1    3199.7    2634.0     0.0

                                         FLOW STATION DATA
                                   W        Pt        Tt        ht       FAR        Wc        Ps        Ts     Aphy      MN     gamt     gams
FL1  Ambient.Fl_O              21.13    13.665    556.54      2.91    0.0000     23.54    13.665    556.54   -----.--  0.000  1.3997  1.3997
FL2  Inlet.Fl_O                21.13    13.665    556.54      2.91    0.0000     23.54    12.745    545.58    132.95  0.317  1.3997  1.3998
FL22 Duct1.Fl_O                21.13    13.665    556.54      2.91    0.0000     23.54    13.414    553.60    247.79  0.163  1.3997  1.3997
FL23 LPC.Fl_O                  21.13   157.430   1194.47    159.84    0.0000      2.99   141.778   1161.19     14.19  0.394  1.3684  1.3705
FL24 ICduct.Fl_O               21.13   157.115   1194.47    159.84    0.0000      3.00   141.495   1161.19     14.22  0.394  1.3684  1.3705
FL25 HPC_axi.Fl_O              21.13   178.300   1240.86    171.69    0.0000      2.69   168.045   1221.32     16.37  0.296  1.3655  1.3667
FL26 Bld25.Fl_O                19.49   178.300   1240.86    171.69    0.0000      2.48   160.616   1206.58     11.79  0.394  1.3655  1.3677
FL27 HPC_centri.Fl_O           19.49   448.807   1636.08    275.35    0.0000      1.13   421.830   1610.32      6.75  0.305  1.3435  1.3447
FL28 Bld3.Fl_O                 14.29   448.807   1636.08    275.35    0.0000      0.83   429.876   1618.15      5.85  0.254  1.3435  1.3444
FL3  Duct6.Fl_O                14.29   448.807   1636.08    275.35    0.0000      0.83   436.588   1624.58      7.22  0.203  1.3435  1.3440
FL4  Burner.Fl_O               14.78   439.831   3516.12    227.00    0.0342      1.29   399.216   3444.48      6.24  0.399  1.2602  1.2622
FL42 HPT.Fl_O                  19.98   211.768   2708.62    125.92    0.0251      3.17   200.056   2674.04     19.55  0.300  1.2873  1.2883
FL43 Duct43.Fl_O               19.98   211.768   2708.64    125.92    0.0251      3.17   191.472   2647.68     15.24  0.400  1.2873  1.2891
FL44 LPT.Fl_O                  21.62    66.179   2092.41    -23.97    0.0232      9.64    64.601   2080.51     89.22  0.193  1.3081  1.3085
FL45 ITduct.Fl_O               21.62    66.179   2092.46    -23.97    0.0232      9.64    60.194   2046.08     47.72  0.383  1.3081  1.3098
FL6  PowerT.Fl_O               21.62    14.348   1558.00   -175.66    0.0232     38.38    13.835   1543.95    292.50  0.234  1.3313  1.3321
FL7  Duct12.Fl_O               21.62    14.348   1558.06   -175.66    0.0232     38.38    13.835   1544.01    292.50  0.234  1.3313  1.3321
FL9  Nozzle.Fl_O               21.62    14.348   1558.12   -175.66    0.0232     38.38    13.665   1539.29    255.10  0.271  1.3313  1.3323

TURBOMACHINERY PERFORMANCE DATA
              Wc       PR       eff          Nc        TR    efPoly        pwr     SMN     SMW
LPC        23.54   11.521    0.8564   11309.372    2.1462    0.8953    -4691.4   21.06   21.55
HPC_axi     3.00    1.135    0.8893    9597.988    1.0388    0.8912     -354.2   19.71   11.97
HPC_cen>    2.48    2.517    0.8579    9416.842    1.3185    0.8736    -2858.1   22.75   21.37
HPT         1.29    2.077    0.8502     245.635    1.1376    0.8209     3212.4
LPT         3.17    3.200    0.8516     225.094    1.2476    0.8285     4691.4
PowerT      9.64    4.612    0.8266     327.916    1.3431    0.7964     4639.6

TURBOMACHINERY MAP DATA
           WcMap    PRmap    effMap       NcMap    R/Parm     s_WcDes   s_PRdes  s_effDes  s_NcDes
LPC        24.61    7.278    0.8637      94.245    1.8331    0.956433    1.6759    0.9916   0.8333
HPC_axi    29.63    1.200    0.8542       0.987    1.9397    0.100682    0.6728    1.0354   0.0001
HPC_cen>   29.62    3.086    0.8515       0.987    2.0262    0.083407    0.7273    1.0019   0.0001
HPT        30.15    5.998    0.9290     100.408    5.9980    0.042649    4.6409    0.9152   0.0179
LPT       149.98    5.735    0.9294      99.582    5.7349    0.021123    2.1523    0.9163   0.0194
PowerT    172.96    1.763    0.8861     101.749    1.7630    0.055750    0.2112    0.9328   0.0136

---INLETS----     eRam       Afs       Pram
Inlet           1.0000   -----.--       0.1      BLEEDS - output   Wb/Win   hscale   Pscale        W        Tt       ht        Pt
                                                 C_LPTCharg   Bl>   0.0214   1.0000   1.0000   0.4525   1240.86   171.69    66.179
```

TABLE A.2.—Concluded.

```
----DUCTS----  dPnorm      MN     Aphy      C_LPTUncharg B1>  0.0563  1.0000  1.0000   1.6163  1248.88  173.74  294.057
Duct1          0.0000  0.4000   132.95      C_HPTCharg   B1>  0.0916  1.0000  1.0000   2.4239  1661.69  282.22  294.057
ICduct         0.0020  0.4000    14.19      C_HPTUncharg B1>  0.1751  1.0000  1.0000   4.6347  1661.69  282.22  610.864
Duct6          0.0000  0.2500     5.85
Duct43         0.0000  0.3000    19.55
ITduct         0.0000  0.2000    89.22
Duct12         0.0000  0.3000   292.50

---SHAFTS----   Nmech  trq in   pwr in
HP_Shaft      14800.0  1613.4   4546.4
IP_Shaft      12000.0  2984.7   6819.3
LP_Shaft      15000.0  2626.1   7500.0


---BURNERS---   TtOut     eff   dPnorm     Wfuel      FAR   EINOx     ppm
Burner        3660.00  1.0000   0.0200   0.71702  0.03695


---NOZZLES---      PR     Cfg     CdTh      Cv       Ath    MNth    Vact     Fg
Nozzle          1.050  0.9900   1.0000  0.9900    320.24   0.271   500.5  457.5
```

TABLE A.3.—CRUISE MISSION 1, 303.4 kn, 28,000 ALTITUDE, +0 °F DAY, INITIAL CRUISE POWER LEVEL, 100 PERCENT NPR rpm/650 ROTOR TIP SPEED

```
 (this is just before shift, power turbine at 100% mechanical, 110% corrected speed from engine, power is a touch higher to match
rotor efficiency loss @ 650 fps (75%) vs. 350 fps )(84.8%) at cruise speed)
*******************************************************************************************************************************
Date:08/30/10    Time:11:24:01    Model:                         Generic turboshaft engine - Off-design    converge = 1    CASE: 115
Version:NPSS_1.6.5 - Rev: ->    Gas Package: Janaf    iter/pass/Jacb/Broy=  4/ 15/ 1/ 2    Run by:            csnyder      PC:    47

                                           SUMMARY OUTPUT DATA
   MN        alt      dTs         W         Fn       TSFC       Wfuel      VTAS      OPR       T4       T41       T47  Dyn P.
 0.510   28000.0    -0.00     11.74      -20.3    --.----     836.01    511.85   40.872   3105.0   2816.5   2302.6   125.3

                                            FLOW STATION DATA
                               W        Pt        Tt        ht      FAR        Wc        Ps        Ts      Aphy      MN     gamt     gams
FL1  Ambient.F1_O          11.74     5.705    440.66    -24.88   0.0000     27.88     4.776    418.82   107.32   0.510   1.4010   1.4011
FL2  Inlet.F1_O            11.74     5.705    440.66    -24.88   0.0000     27.88     5.147    427.87   132.95   0.386   1.4010   1.4010
FL22 Duct1.F1_O            11.74     5.705    440.66    -24.88   0.0000     27.88     5.557    437.36   247.79   0.194   1.4010   1.4010
FL23 LPC.F1_O              11.74    80.217   1019.82    115.84   0.0000      3.02    72.108    990.31    14.19   0.396   1.3795   1.3813
FL24 ICduct.F1_O           11.74    80.057   1019.82    115.84   0.0000      3.02    71.963    990.31    14.22   0.396   1.3795   1.3813
FL25 HPC_axi.F1_O          11.74    90.864   1060.53    126.01   0.0000      2.72    85.549   1043.16    16.37   0.297   1.3770   1.3780
FL26 Bld25.F1_O            10.83    90.864   1060.53    126.01   0.0000      2.50    81.693   1030.03    11.79   0.396   1.3770   1.3789
FL27 HPC_centri.F1_O       10.83   233.165   1416.67    217.21   0.0000      1.13   219.298   1394.07     6.75   0.302   1.3550   1.3563
FL28 Bld3.F1_O              7.94   233.165   1416.67    217.21   0.0000      0.83   223.430   1400.93     5.85   0.252   1.3550   1.3559
FL3  Duct6.F1_O             7.94   233.165   1416.67    217.21   0.0000      0.83   226.879   1406.57     7.22   0.201   1.3550   1.3556
FL4  Burner.F1_O            8.17   228.501   3105.04    178.28   0.0292      1.29   207.187   3039.09     6.24   0.397   1.2738   1.2756
FL42 HPT.F1_O              11.06   109.688   2369.77     88.37   0.0214      3.17   103.594   2338.53    19.55   0.298   1.2998   1.3008
FL43 Duct43.F1_O           11.06   109.688   2369.82     88.37   0.0214      3.17    99.130   2314.75    15.24   0.398   1.2998   1.3016
FL44 LPT.F1_O              11.97    32.595   1799.93    -46.75   0.0198     10.06    31.746   1788.36    89.22   0.200   1.3219   1.3224
FL45 ITduct.F1_O           11.97    32.595   1799.98    -46.75   0.0198     10.06    29.350   1754.45    47.72   0.401   1.3219   1.3239
FL6  PowerT.F1_O           11.97     5.015   1225.88   -203.25   0.0198     53.94     4.645   1201.58   292.50   0.338   1.3530   1.3545
FL7  Duct12.F1_O           11.97     5.015   1225.94   -203.25   0.0198     53.95     4.645   1201.64   292.50   0.338   1.3530   1.3545
FL9  Nozzle.F1_O           11.97     5.015   1226.01   -203.25   0.0198     53.95     4.776   1210.48   358.41   0.269   1.3530   1.3539

TURBOMACHINERY PERFORMANCE DATA
              Wc       PR       eff         Nc        TR    efPoly        pwr     SMN      SMW
LPC        27.88   14.061    0.8467  11891.743    2.3143    0.8913    -2337.9   19.31    19.32
HPC_axi     3.02    1.135    0.8860   9688.471    1.0399    0.8879     -169.0   19.85    12.38
HPC_cen>    2.50    2.566    0.8558   9500.707    1.3358    0.8724    -1397.3   21.32    19.72
HPT         1.29    2.083    0.8494    243.803    1.1438    0.8269     1566.3
LPT         3.17    3.365    0.8484    225.162    1.2676    0.8263     2337.9
PowerT     10.06    6.499    0.8485    353.555    1.4685    0.8139     2651.5

TURBOMACHINERY MAP DATA
           WcMap    PRmap    effMap      NcMap    R/Parm     s_WcDes    s_PRdes   s_effDes    s_NcDes
LPC        29.15    8.793    0.8539     99.098    1.9377    0.956433     1.6759     0.9916     0.8333
HPC_axi    29.90    1.201    0.8521      0.997    1.9792    0.100682     0.6728     1.0354     0.0001
HPC_cen>   29.90    3.153    0.8503      0.996    2.0213    0.083407     0.7273     1.0019     0.0001
HPT        30.16    6.027    0.9281     99.659    6.0270    0.042649     4.6409     0.9152     0.0179
LPT       149.97    6.091    0.9259     99.611    6.0905    0.021123     2.1523     0.9163     0.0194
PowerT    180.41    2.162    0.9096    109.705    2.1615    0.055750     0.2112     0.9328     0.0136

---INLETS----     eRam       Afs       Fram
Inlet           1.0000    107.32     186.8       BLEEDS - output    Wb/Win    hscale    Pscale         W         Tt         ht         Pt
```

TABLE A.3.—Concluded.

C_LPTCharg	Bl>	0.0214	1.0000	1.0000	0.2515	1060.53	126.01	32.595
C_LPTUncharg	Bl>	0.0563	1.0000	1.0000	0.6614	1060.53	126.01	109.688
C_HPTCharg	Bl>	0.0916	1.0000	1.0000	0.9920	1416.67	217.21	109.688
C_HPTUncharg	Bl>	0.1751	1.0000	1.0000	1.8967	1416.67	217.21	228.501

----DUCTS----	dPnorm	MN	Aphy
Duct1	0.0000	0.3862	132.95
ICduct	0.0020	0.3957	14.19
Duct6	0.0000	0.2515	5.85
Duct43	0.0000	0.2982	19.55
ITduct	0.0000	0.2002	89.22
Duct12	0.0000	0.3380	292.50

---SHAFTS----	Nmech	trq in	pwr in
HP_Shaft	13585.4	605.5	1566.3
IP_Shaft	10961.0	1120.2	2337.9
LP_Shaft	**15000.0**	**928.4**	**2651.5**

---BURNERS---	TtOut	eff	dPnorm	Wfuel	FAR	EINOx	ppm
Burner	3105.04	1.0000	0.0200	0.23223	0.02924		

---NOZZLES---	PR	Cfg	CdTh	Cv	Ath	MNth	Vact	Fg
Nozzle	1.050	0.9900	1.0000	0.9900	320.24	0.269	447.3	166.5

TABLE A.4.—CRUISE MISSION 1, 303.4 kn, 28,000 ALTITUDE, +0 °F DAY, INITIAL CRUISE POWER LEVEL, 54 PERCENT NPR rpm/350 ROTOR TIP SPEED—NO MULTISPEED GEARBOX

```
(reduction in speed from engine to rotor is achieved totally through speed reduction in the power turbine)
*****************************************************************************************************************
Date:08/27/10    Time:09:18:48    Model:                    Generic turboshaft engine - Off-design    converge = 1    CASE: 146
Version:NPSS_1.6.5 - Rev: ->    Gas Package: Janaf    iter/pass/Jacb/Broy=  1/  1/ 0/ 0    Run by:            csnyder      PC:    48

                                        SUMMARY OUTPUT DATA
    MN       alt      dTs         W          Fn      TSFC      Wfuel     VTAS      OPR       T4       T41      T47   Dyn P.
 0.510   28000.0    -0.00     11.81       -19.4    --.----     805.23   511.85   40.644   3039.9   2760.7   2259.4   125.3

                                         FLOW STATION DATA
                                   W         Pt        Tt        ht      FAR       Wc        Ps         Ts      Aphy     MN     gamt     gams
FL1  Ambient.Fl_O              11.81      5.705    440.66    -24.88   0.0000    28.05     4.776     418.82   107.98  0.510  1.4010   1.4011
FL2  Inlet.Fl_O                11.81      5.705    440.66    -24.88   0.0000    28.05     5.139     427.68   132.95  0.389  1.4010   1.4010
FL22 Duct1.Fl_O                11.81      5.705    440.66    -24.88   0.0000    28.05     5.555     437.32   247.79  0.195  1.4010   1.4010
FL23 LPC.Fl_O                  11.81     81.953   1026.41    117.49   0.0000     2.98    73.893     997.56    14.19  0.390  1.3791   1.3809
FL24 ICduct.Fl_O               11.81     81.789   1026.41    117.49   0.0000     2.99    73.746     997.56    14.22  0.390  1.3791   1.3809
FL25 HPC_axi.Fl_O              11.81     92.859   1067.28    127.71   0.0000     2.68    87.570    1050.28    16.37  0.293  1.3765   1.3776
FL26 Bld25.Fl_O                10.90     92.859   1067.28    127.71   0.0000     2.47    83.748    1037.50    11.79  0.390  1.3765   1.3784
FL27 HPC_centri.Fl_O           10.90    231.865   1413.31    216.33   0.0000     1.14   217.760    1390.22     6.75  0.305  1.3552   1.3565
FL28 Bld3.Fl_O                  7.99    231.865   1413.31    216.33   0.0000     0.84   221.969    1397.23     5.85  0.254  1.3552   1.3561
FL3  Duct6.Fl_O                 7.99    231.865   1413.31    216.33   0.0000     0.84   225.477    1403.01     7.22  0.203  1.3552   1.3558
FL4  Burner.Fl_O                8.21    227.228   3039.88    179.09   0.0280     1.29   206.009    2974.87     6.24  0.397  1.2763   1.2781
FL42 HPT.Fl_O                  11.12    109.465   2324.19     91.12   0.0205     3.16   103.413    2293.55    19.55  0.297  1.3018   1.3028
FL43 Duct43.Fl_O               11.12    109.465   2324.24     91.12   0.0205     3.16    98.983    2270.27    15.24  0.396  1.3018   1.3036
FL44 LPT.Fl_O                  12.04     31.006   1749.03    -45.80   0.0189    10.48    30.126    1736.72    89.22  0.209  1.3247   1.3253
FL45 ITduct.Fl_O               12.04     31.006   1749.08    -45.80   0.0189    10.48    27.613    1699.96    47.72  0.421  1.3247   1.3270
FL6  PowerT.Fl_O               12.04      5.016   1242.37   -183.50   0.0189    54.59     4.636    1217.10   292.50  0.343  1.3525   1.3541
FL7  Duct12.Fl_O               12.04      5.016   1242.44   -183.50   0.0189    54.59     4.636    1217.16   292.50  0.343  1.3525   1.3541
FL9  Nozzle.Fl_O               12.04      5.016   1242.50   -183.50   0.0189    54.59     4.776    1226.77   362.53  0.270  1.3525   1.3535

TURBOMACHINERY PERFORMANCE DATA
               Wc       PR      eff          Nc        TR    efPoly        pwr     SMN     SMW
LPC         28.05   14.366   0.8466   11919.382    2.3293    0.8915    -2379.7   17.62   17.54
HPC_axi      2.99    1.135   0.8894    9571.222    1.0398    0.8913     -170.8   19.52   11.74
HPC_cen>     2.47    2.497   0.8572    9386.157    1.3242    0.8732    -1366.3   23.43   22.14
HPT          1.29    2.076   0.8499     244.205    1.1442    0.8283     1537.1
LPT          3.16    3.530   0.8473     227.887    1.2805    0.8240     2379.6
PowerT      10.48    6.182   0.7859     193.128    1.4080    0.7428     2345.4

TURBOMACHINERY MAP DATA
            WcMap    PRmap   effMap       NcMap    R/Parm      s_WcDes   s_PRdes   s_effDes   s_NcDes
LPC         29.33    8.975   0.8538      99.328    1.8890     0.956433    1.6759     0.9916    0.8333
HPC_axi     29.53    1.201   0.8552       0.985    1.9200     0.100682    0.6728     1.0354    0.0001
HPC_cen>    29.52    3.058   0.8516       0.984    2.0308     0.083407    0.7273     1.0019    0.0001
HPT         30.15    5.993   0.9286      99.824    5.9928     0.042649    4.6409     0.9152    0.0179
LPT        149.61    6.446   0.9246     100.817    6.4463     0.021123    2.1523     0.9163    0.0194
PowerT     187.94    2.094   0.8424      59.926    2.0945     0.055750    0.2112     0.9328    0.0136

---INLETS----      eRam       Afs       Fram
Inlet            1.0000    107.98      188.0       BLEEDS - output    Wb/Win    hscale    Pscale          W         Tt        ht         Pt
                                                   C_LPTCharg   Bl>   0.0214    1.0000    1.0000     0.2530    1067.28    127.71     31.006
```

TABLE A.4.—Concluded.

```
----DUCTS----  dPnorm      MN      Aphy      C_LPTUncharg B1>  0.0563  1.0000  1.0000   0.6655  1067.28  127.71  109.465
Duct1          0.0000    0.3890   132.95     C_HPTCharg   B1>  0.0916  1.0000  1.0000   0.9980  1413.31  216.33  109.465
ICduct         0.0020    0.3900    14.19     C_HPTUncharg B1>  0.1751  1.0000  1.0000   1.9084  1413.31  216.33  227.228
Duct6          0.0000    0.2544     5.85
Duct43         0.0000    0.2972    19.55
ITduct         0.0000    0.2088    89.22
Duct12         0.0000    0.3428   292.50

---SHAFTS----   Nmech    trq in   pwr in
HP_Shaft      13464.3     599.6   1537.1
IP_Shaft      10986.5    1137.6   2379.6
LP_Shaft       8077.0    1525.1   2345.4

---BURNERS---   TtOut       eff   dPnorm     Wfuel       FAR    EINOx      ppm
Burner        3039.88    1.0000   0.0200   0.22367   0.02800

---NOZZLES---      PR       Cfg     CdTh       Cv        Ath     MNth     Vact       Fg
Nozzle          1.050    0.9900   1.0000   0.9900     320.24    0.270    450.5    168.6
```

Appendix B.—Definitions

AN^2 is an indicator of blade pull stress. This stems from the fact that the pull stress of a spinning radial cylinder is proportional to AN^2. A good rule of thumb is that blade stress will be proportional to AN^2 at the rate of 10 ksi per 10E9 AN^2. For example, a well designed turbine blade with nickel based alloys operating at 50E9 AN^2 will have an average pull stress of about 50 ksi.

$$AN^2 \equiv (\text{Flowpath Annulus area in.}^2) \text{ X } (\text{rpm}^2)$$

Rim speed combined with AN^2 is an indicator of disk loading. Rim speed is calculated using the TE hub radius.

$$\text{Rim Speed(ft/s)} = \text{Radius}_{\text{Hub}} \text{ (in.)/12.} * \text{rpm} * \pi / 30.$$

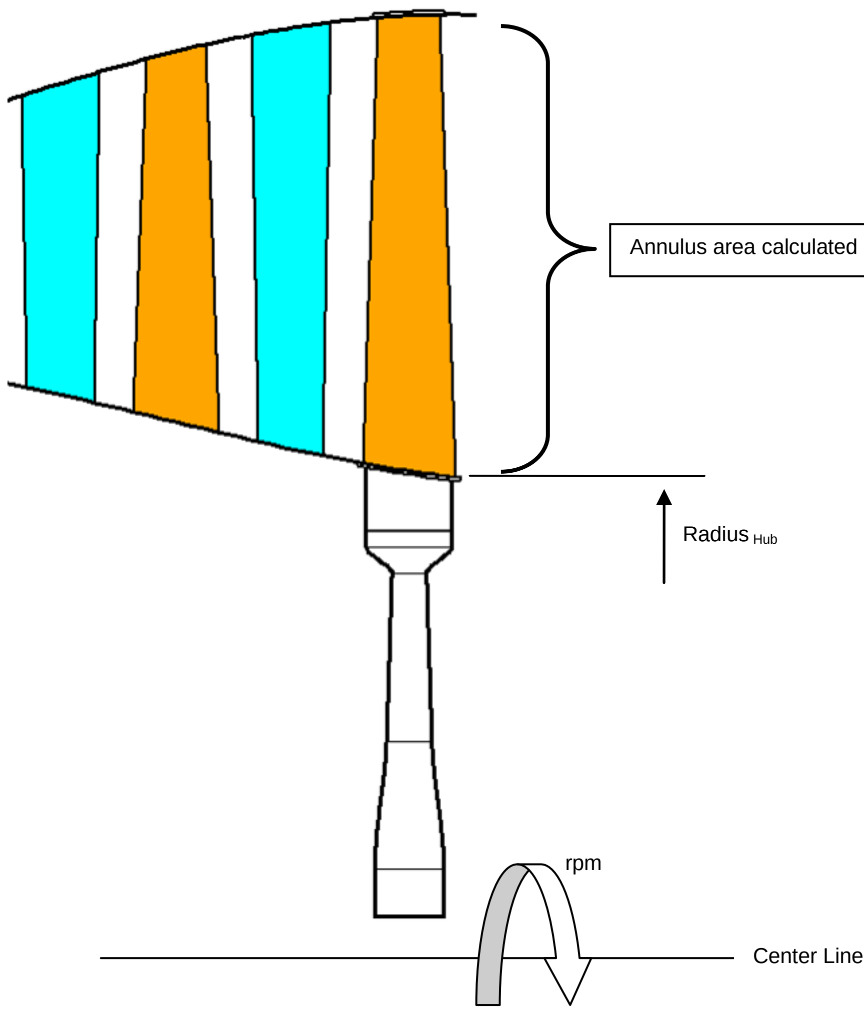
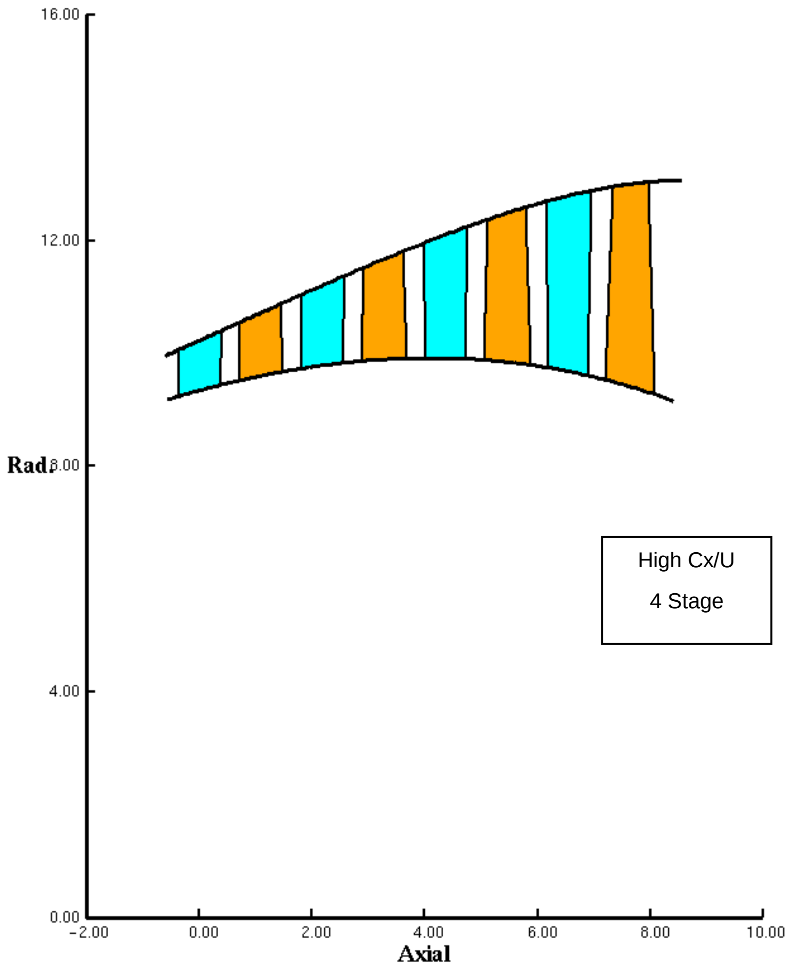


Figure B.1.—Turbine AN_2 and Rim Speed Definitions

Appendix C.—FlowPath Details

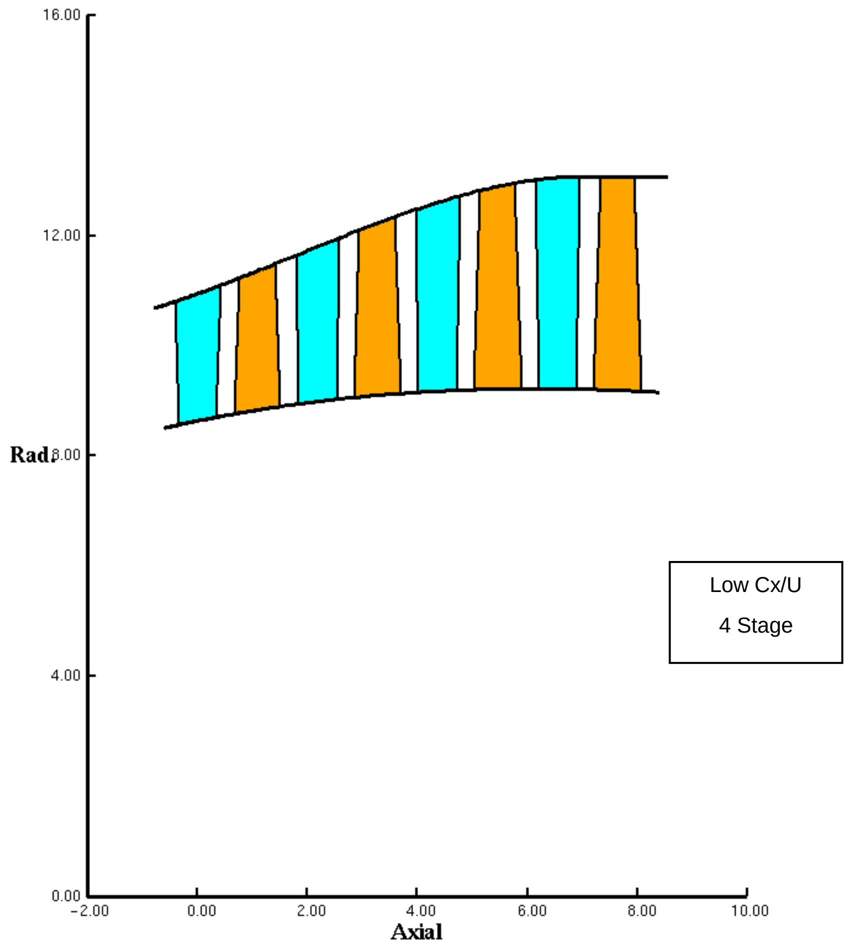


High CX/U

% Speed	Design RPM	Fuel Burn%	ETA 1	ETA 2	ETA 3	ETA 4
53.8	8045	-3.29	73.34	68.62	69.34	91.39
69.2	10343	-7.88	88.33	84.71	84.12	88.62
84.6	12642	1.41	92.95	90.84	90.63	74.87
100.0	14941	23.20	91.25	91.58	92.80	57.42

%Speed	Work Coeff.	Flow Coeff.
54	**1.68**	**0.813**
100	**0.5**	**0.448**

Figure C.1.—High Cx/U Four Stage

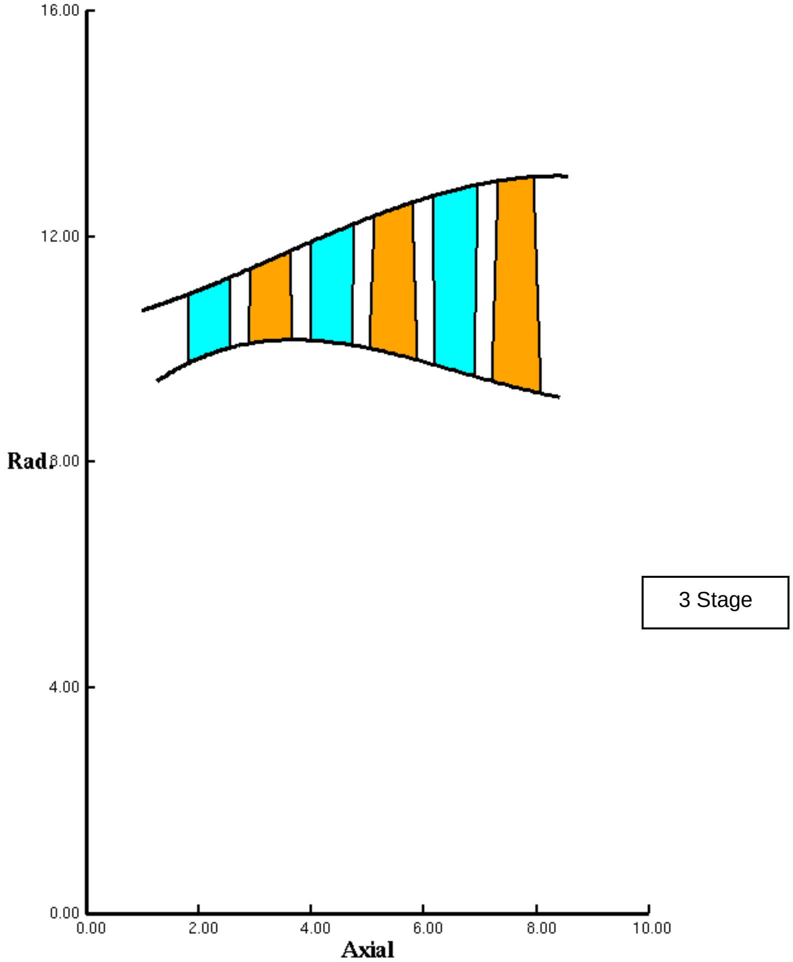


Low CX/U

% Speed	Design RPM	Fuel Burn%	ETA 1	ETA 2	ETA 3	ETA 4
53.8	8045	-2.22	69.98	66.62	69.30	90.20
69.2	10343	-7.80	87.58	83.60	82.85	89.14
84.6	12642	-1.84	92.00	89.60	89.44	78.75
100.0	14941	24.30	89.29	89.78	91.43	57.00

%Speed	Work Coeff.	Flow Coeff.
54	**1.66**	**0.532**
100	**0.49**	**0.3**

Figure C.2.—Low Cx/U Four Stage

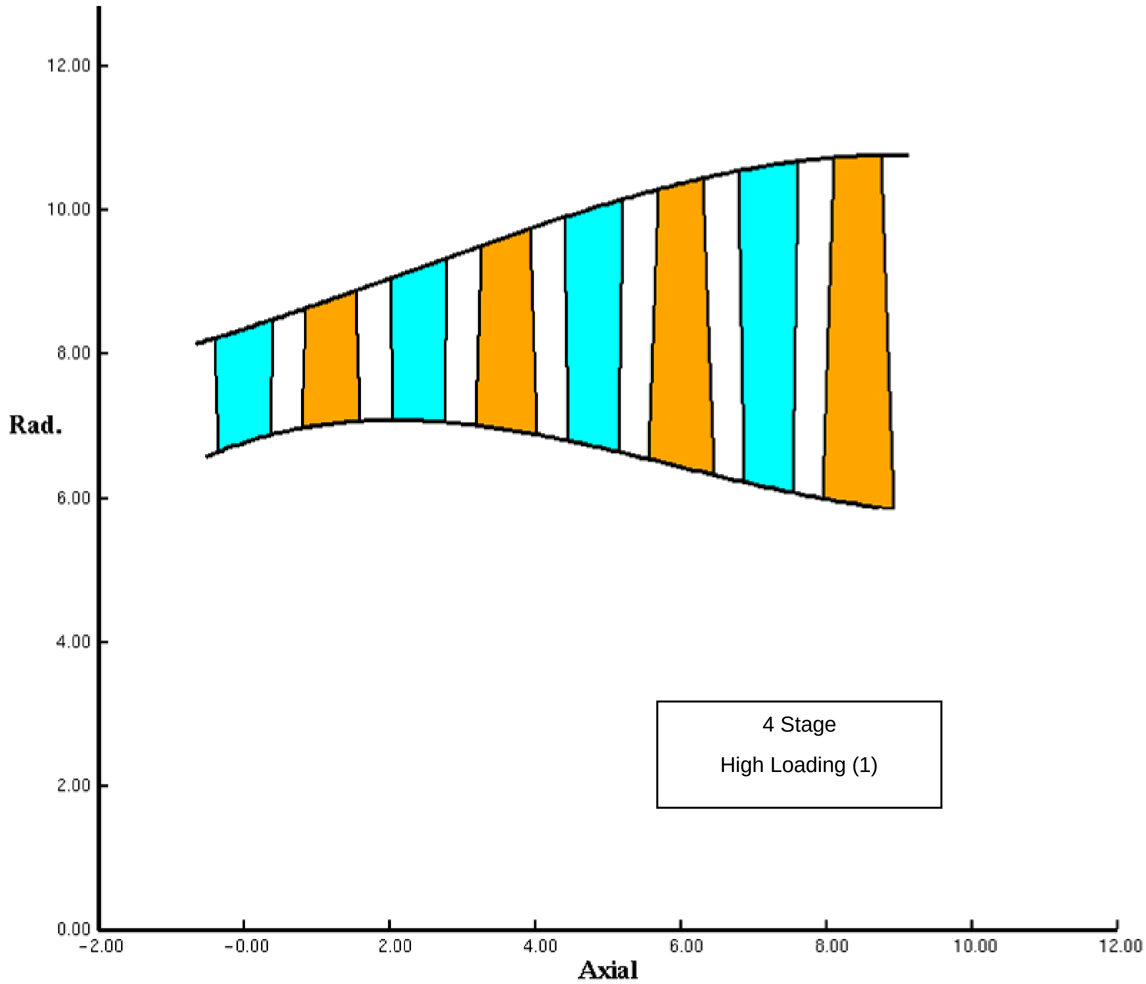


3 Stg

% Speed	Design RPM	Fuel Burn%	ETA 1	ETA 2	ETA 3	ETA 4
53.8	8045	-1.11	70.57	66.14	67.52	89.72
69.2	10343	-4.51	78.24	74.89	74.04	89.63
84.6	12642	-7.19	93.53	91.76	91.60	84.44
100.0	14941	-6.36	92.35	92.49	93.53	66.26

%Speed	Work Coeff.	Flow Coeff.
54	**2.11**	**0.722**
100	**0.63**	**0.368**

Figure C.3.—Three Stage

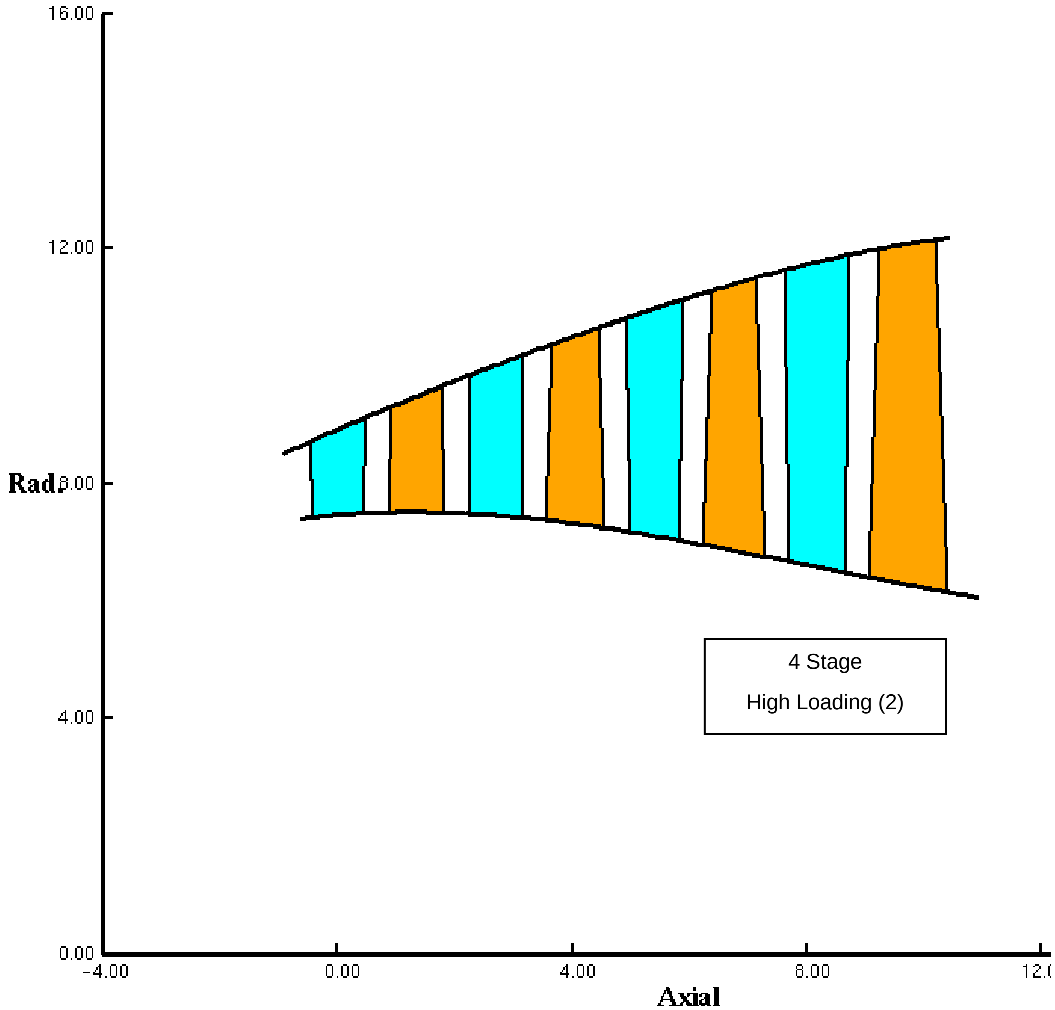


4 Stg Hi Loading (1)

% Speed	Design RPM	Fuel Burn%	ETA 1	ETA 2	ETA 3	ETA 4
53.8	8045	-0.84	78.77	71.42	69.10	87.45
69.2	10343	-7.98	90.15	87.28	87.13	87.37
84.6	12642	-8.31	93.67	92.32	92.37	85.64
100.0	14941	-3.68	93.96	93.59	94.26	79.31

%Speed	Work Coeff.	Flow Coeff.
54	**2.826**	**1.008**
100	**0.828**	**0.467**

Figure C.4.—Four Stage High Loading (1)

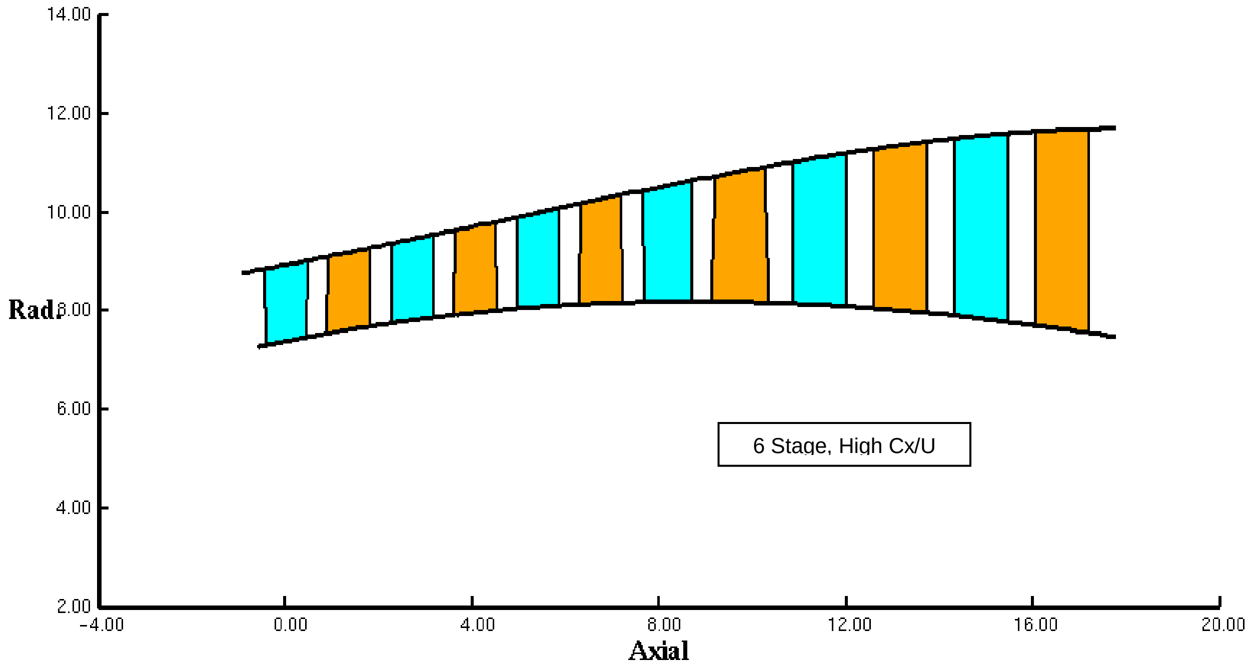


4 Stg Hi Loading (2)

% Speed	Design RPM	Fuel Burn%	ETA 1	ETA 2	ETA 3	ETA 4
54.0	7000	3.62	76.30	65.58	63.81	85.34
69.3	8988	-6.27	89.07	85.79	86.38	85.44
84.7	10975	-8.11	92.90	91.62	92.32	85.12
100.0	12963	-7.29	93.67	93.29	94.31	83.67

%Speed	Work Coeff.	Flow Coeff.
54	**3.116**	**0.832**
100	**0.919**	**0.377**

Figure C.5.—Four Stage High Loading (2)

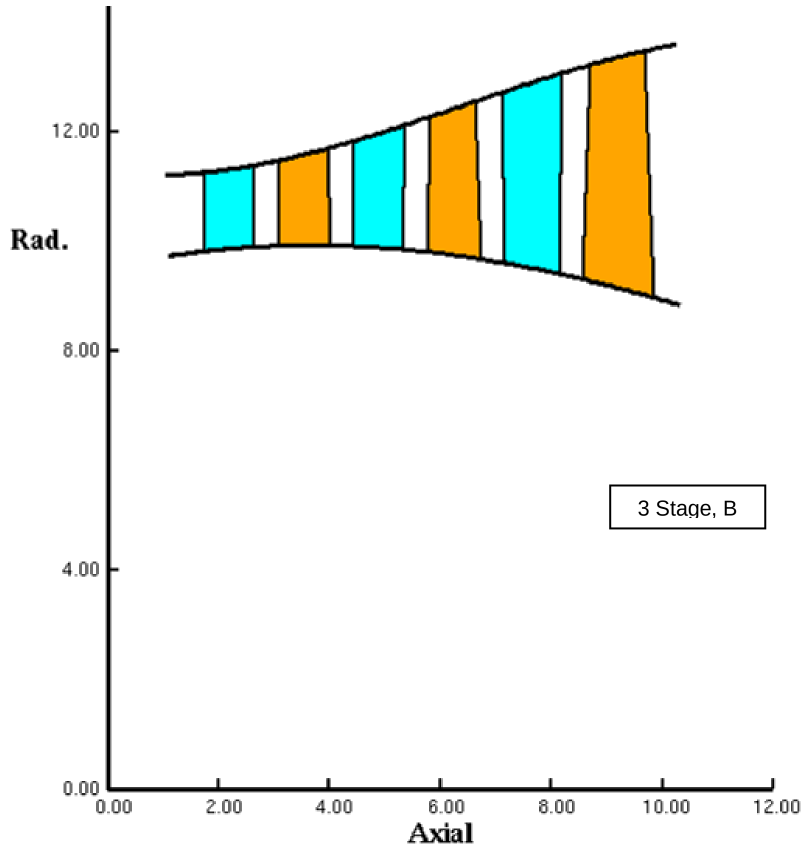


6 Stage A

% Speed	Design RPM	Fuel Burn%	ETA 1	ETA 2	ETA 3	ETA 4
54.0	7000	1.01	69.66	63.25	64.03	89.39
69.3	8988	-6.27	87.12	83.61	82.71	87.05
84.7	10975	0.50	92.74	90.47	90.61	75.84
100.0	12963	20.42	92.19	92.22	93.34	59.02

%Speed	Work Coeff.	Flow Coeff.
54	**2.031**	**1.037**
100	**0.611**	**0.541**

Figure C.6.—SixStage High Cx/U

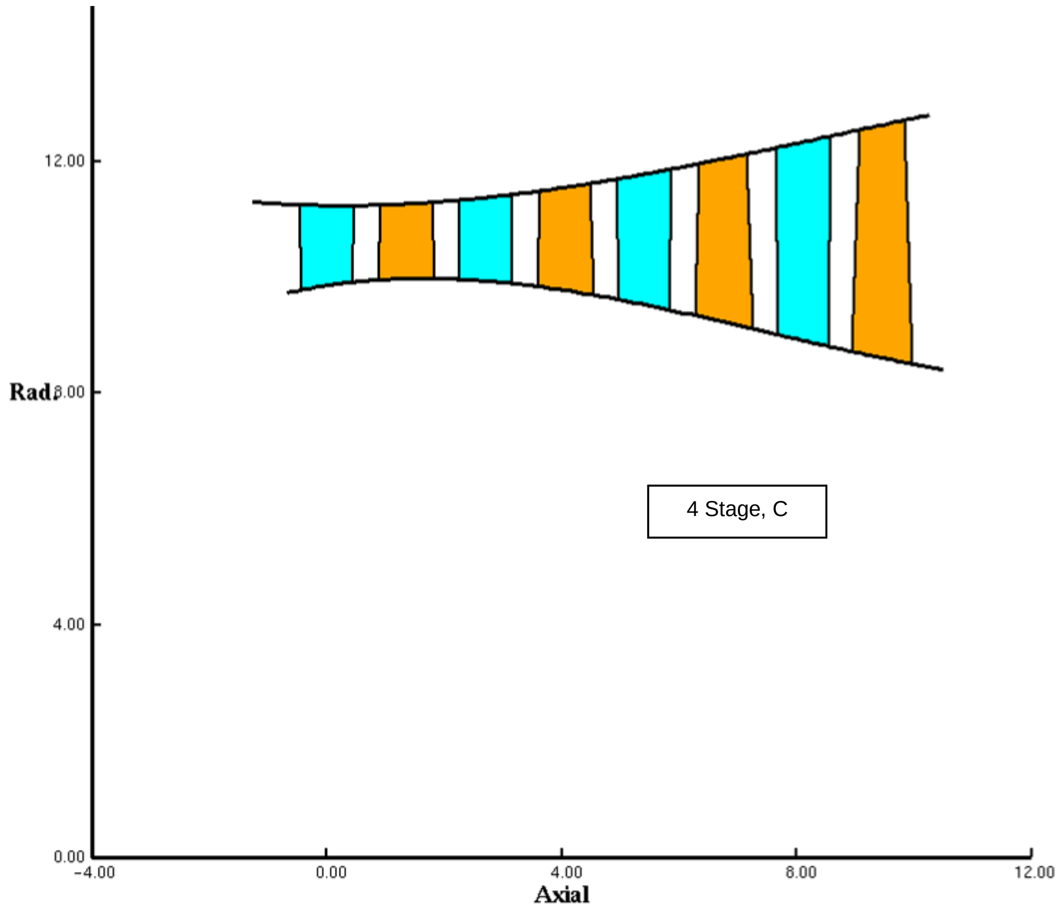


3 Stage B

% Speed	Design RPM	Fuel Burn%	ETA 1	ETA 2	ETA 3	ETA 4
54.0	6790	4.91	65.66	61.47	62.07	85.80
69.3	8718	-5.68	87.75	83.89	83.69	85.81
84.7	10646	-8.02	92.48	91.06	91.67	85.58
100.0	12574	-7.45	93.23	92.82	93.98	84.00

%Speed	Work Coeff.	Flow Coeff.
54	**2.991**	**0.8423**
100	**0.966**	**0.4147**

Figure C.7.—Three Stage B



4 Stage C

% Speed	Design RPM	Fuel Burn%	ETA 1	ETA 2	ETA 3	ETA 4
54.0	6200	4.41	68.91	60.48	62.16	86.31
69.3	7960	-5.84	87.29	83.39	83.22	86.26
84.7	9721	-6.21	92.48	90.80	91.14	83.40
100.0	11482	0.60	93.00	92.65	93.82	74.85

%Speed	Work Coeff.	Flow Coeff.
54	**2.925**	**1.09025**
100	**0.864**	**0.507**

Figure C.8.—Four Stage C

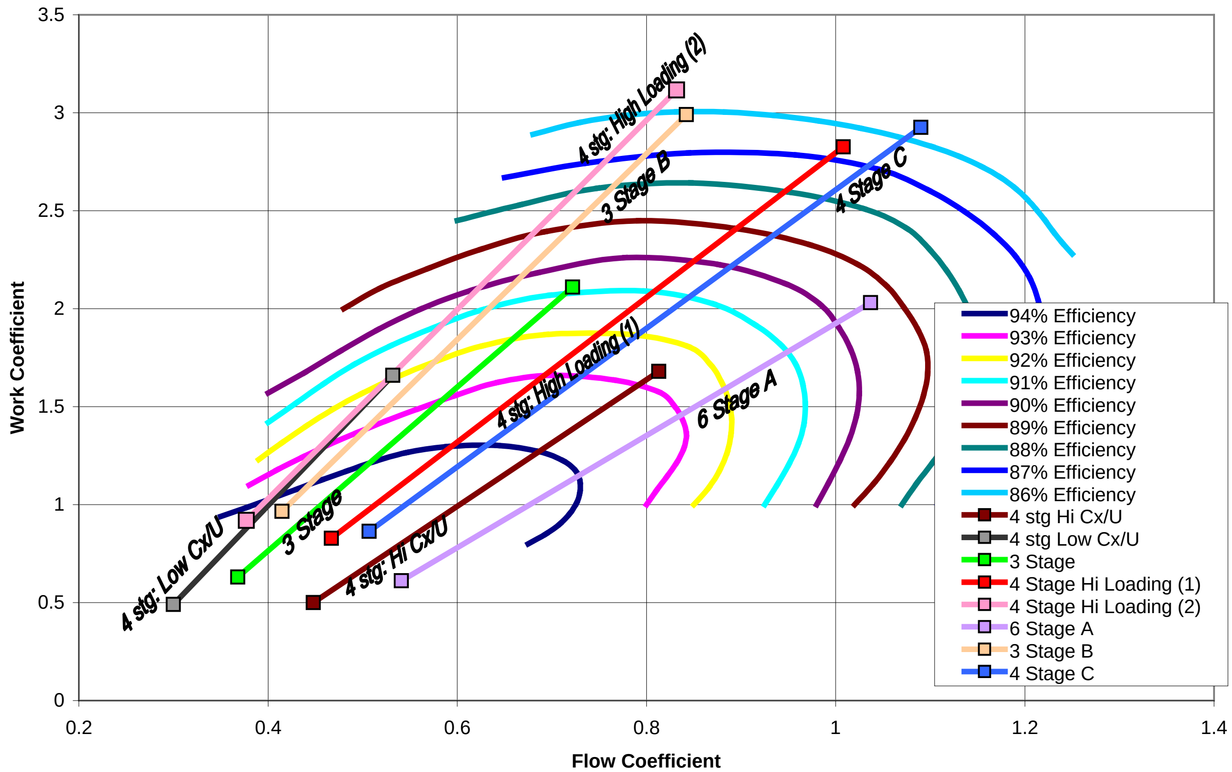


Figure C.9.—Smith Curve of All Turbines

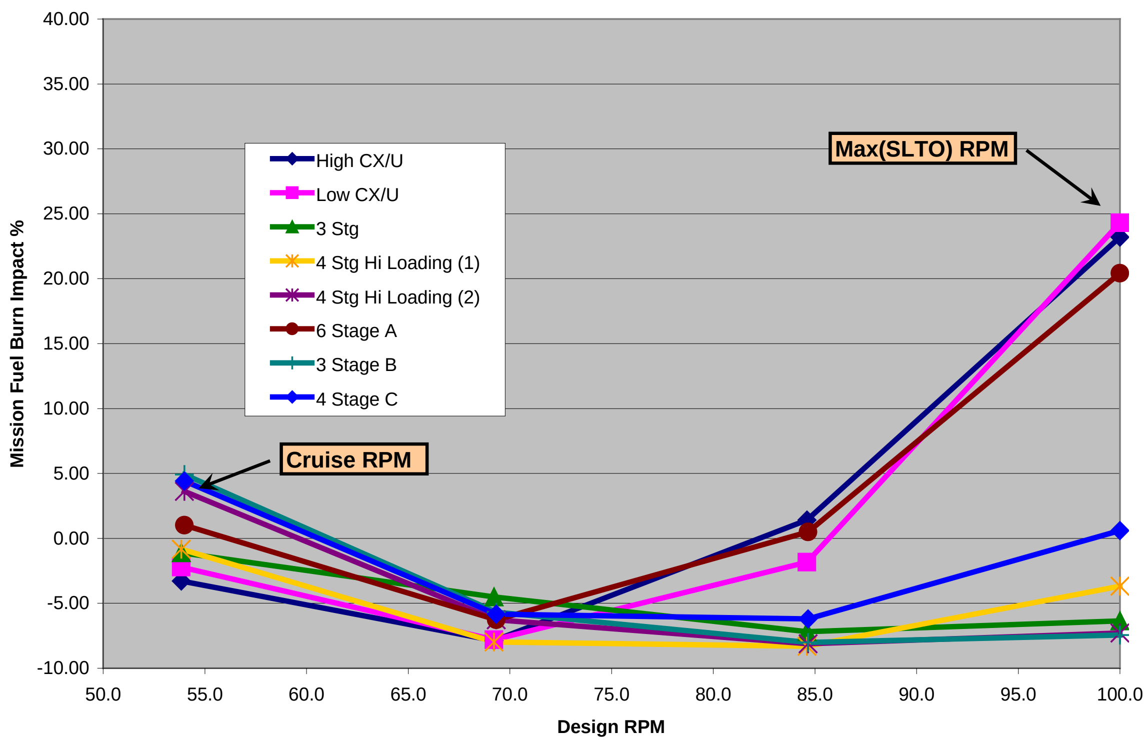


Figure C.10.—Design Speed Comparison: All Turbines

Appendix D.—Four Stage CFD Analysis

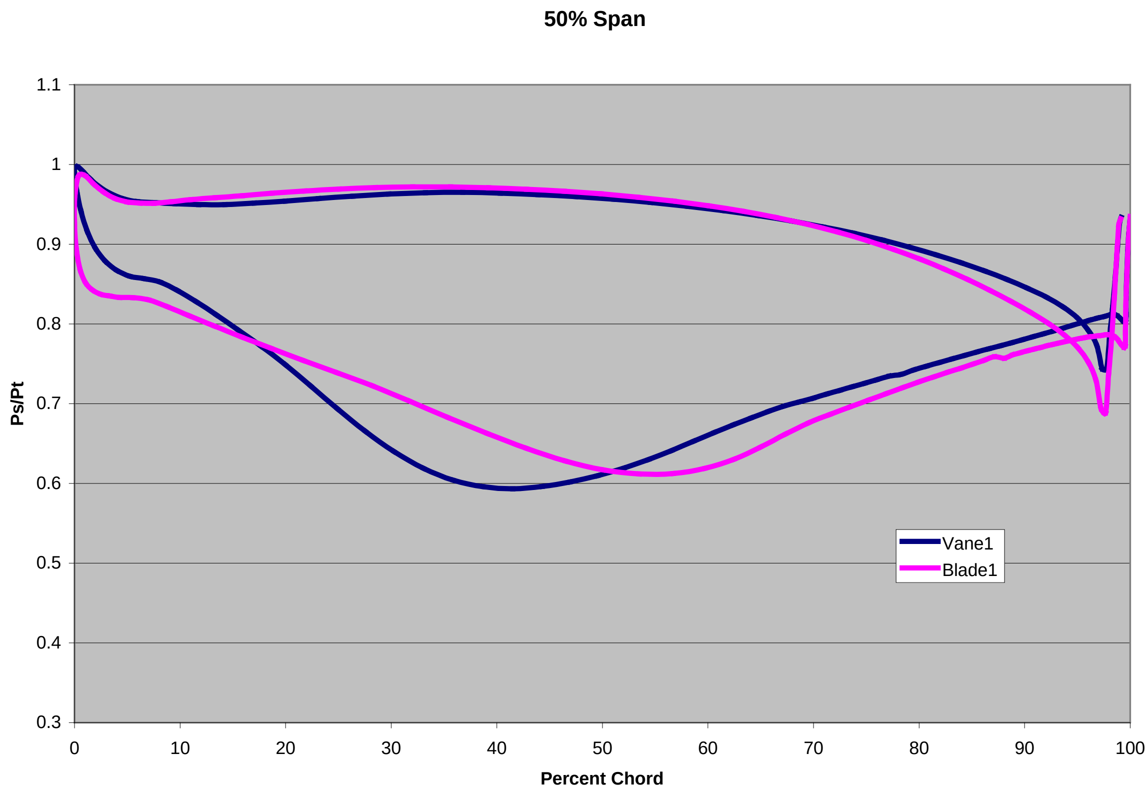
The Four Stage power turbine presented in this study was analyzed using a Williams International proprietary CFD code called VORTEX. VORTEX is a 3–D, finite volume, explicit time marching flow solver. The solution assumes steady-state, time averaged flow. Each blade row is analyzed in the relative frame using mixing planes to jump from rotating to stationary blade rows. The mixing planes assure conservation of mass, momentum and energy. The performance used to analyze the turbine was based on the mission point 4 (see Table 2.1 and Table A.4) with small modifications. Point 4 corresponds to a 54 percent speed cruise condition. The CFD uses a fictitious design point. To execute the design, point 4 is used for the thermodynamics, but the speed is increased to 75 percent. The pressure ratio was also modified. The NPSS model had an efficiency at point 4 of 78.6 percent and an efficiency at point 3 (100 percent speed) of 84.9 percent. The predicted efficiency of this four stage is 86.54 and 90.74 percent respectively which requires less PR in order to meet the power requirement. This would be a significant rematch to the engine and would require additional cycle work, possible including a reduction in engine core size. Below is a summary of the parameters used in the CFD as well as the cycle targets. The inlet temperature and pressures shown are mass averaged values taken from the converged solution and differ slightly from the targets. Typically the inlet profiles can be adjusted as the simulation/design matures to hone in on the target values. The inlet mass flow is approximately 2.7 percent high which would require closing airfoil throat areas to assure proper engine matching.

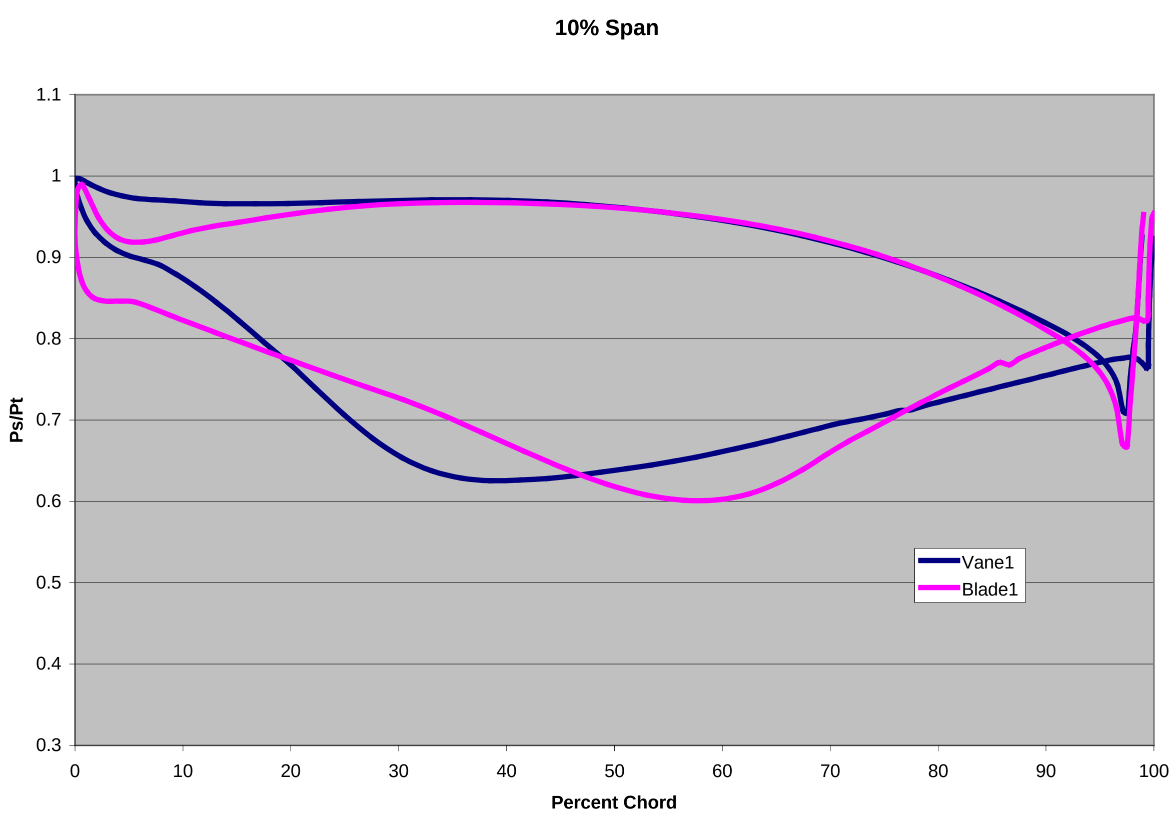
	Cycle	CFD
• PT	31.0 psia	30.93 psia
• TT	1749 °R	1696 °R
• Mdot	12.04 lbm/s	12.37 lbm/s
• rpm		11174 (75 percent speed)
• PR	6.18	5.6
• ETA	78.6 - 84.9 percent	92.9 percent [1]

[1] No leakage, cooling or tip clearance: MeanLine prediction = 93.55 percent @ PR = 5.78

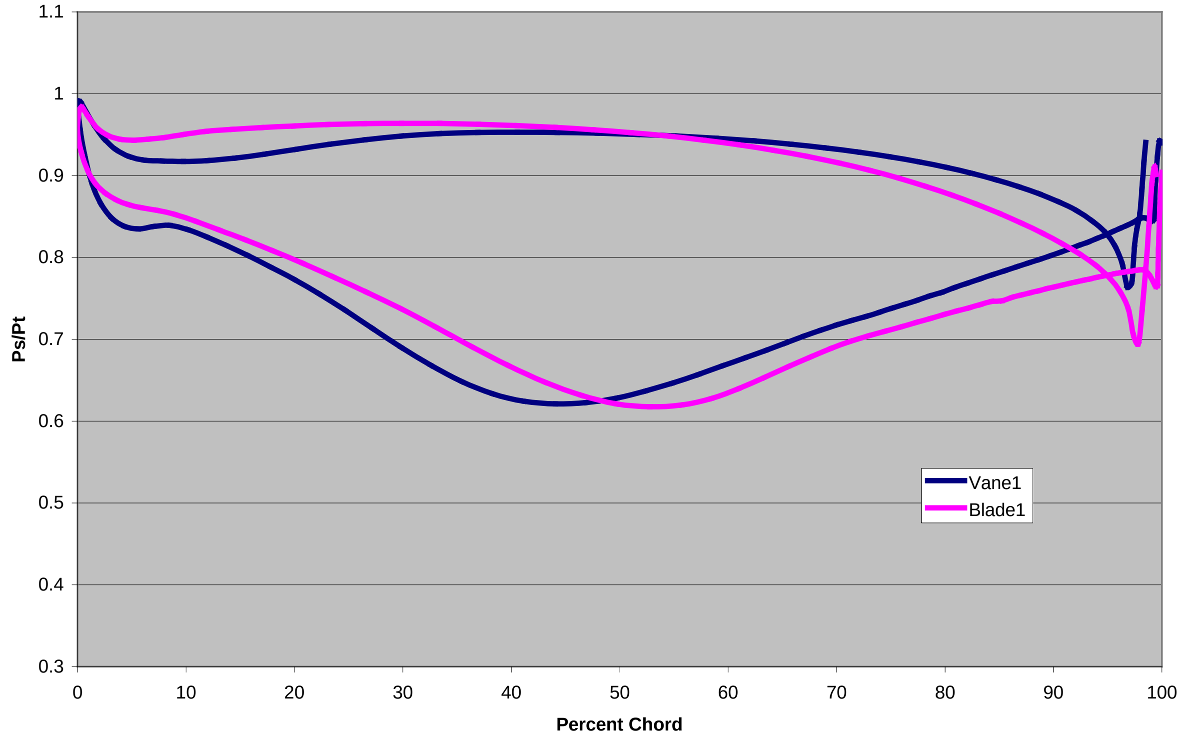
The geometry used in the CFD did not have fillets between the airfoil and endwall intersection. The following are surface static pressure loading plots of each stage. The vane and blade are plotted together: Hub, Mean and Tip.

D.1 Stage 1


50% Span
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
Ps/Pt
0
10
20
30
40
50
60
70
80
90
100
Percent Chord
Vane1
Blade1

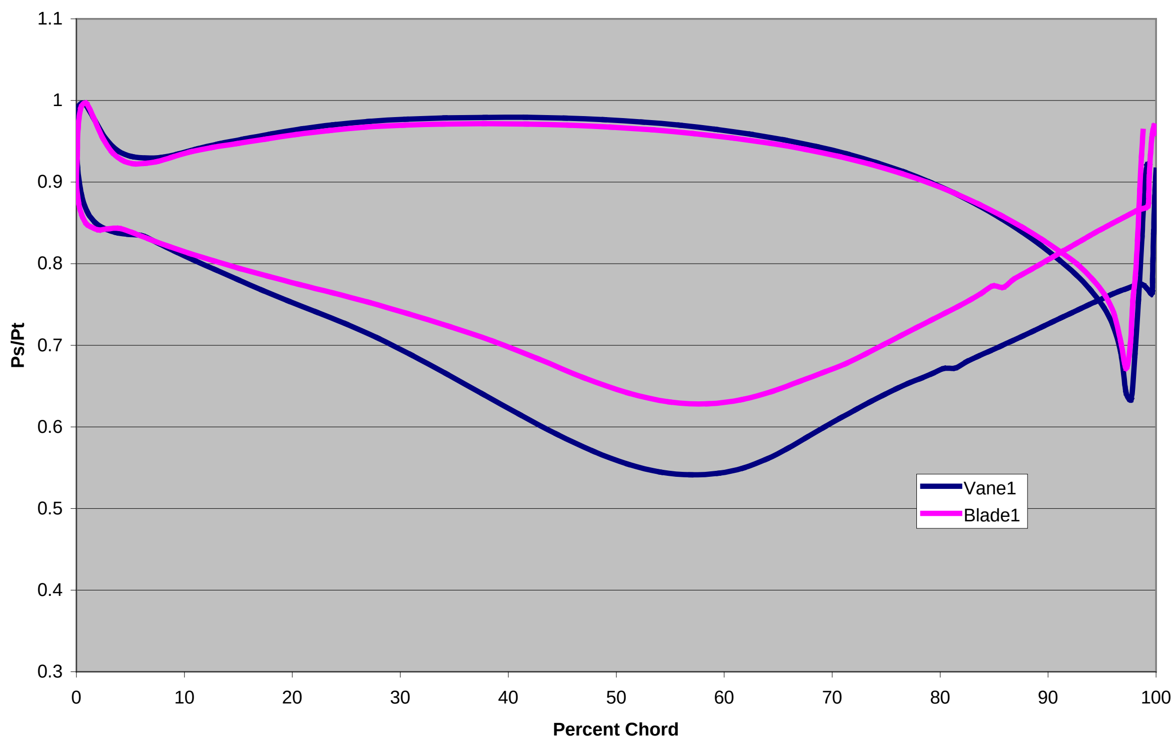

10% Span
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
Ps/Pt
0
10
20
30
40
50
60
70
80
90
100
Percent Chord
Vane1
Blade1

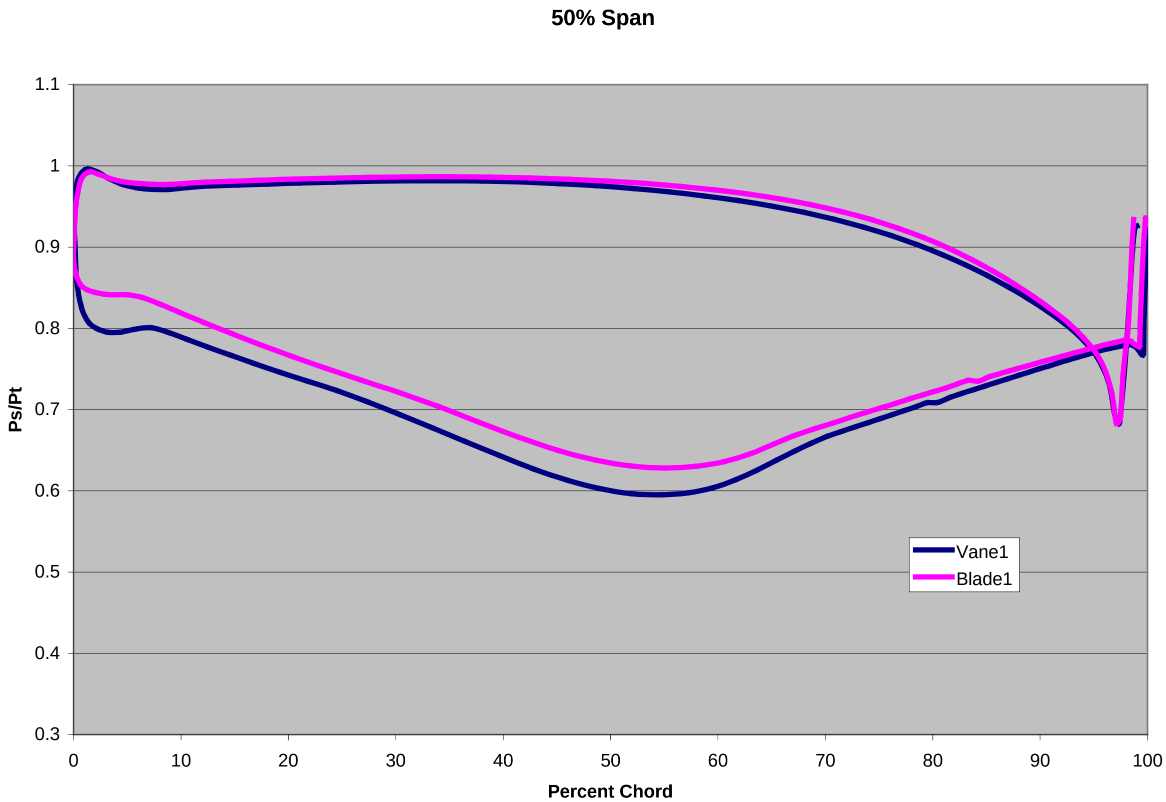
90% Span

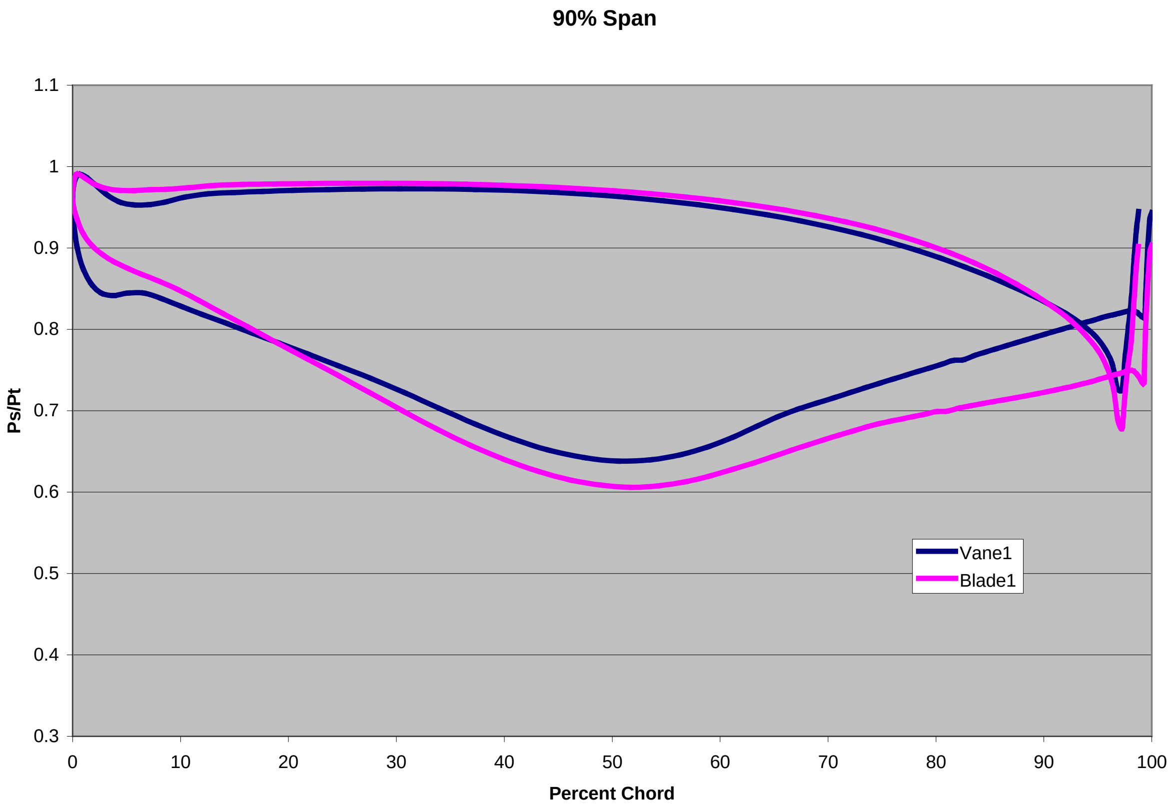


D.2 Stage 2

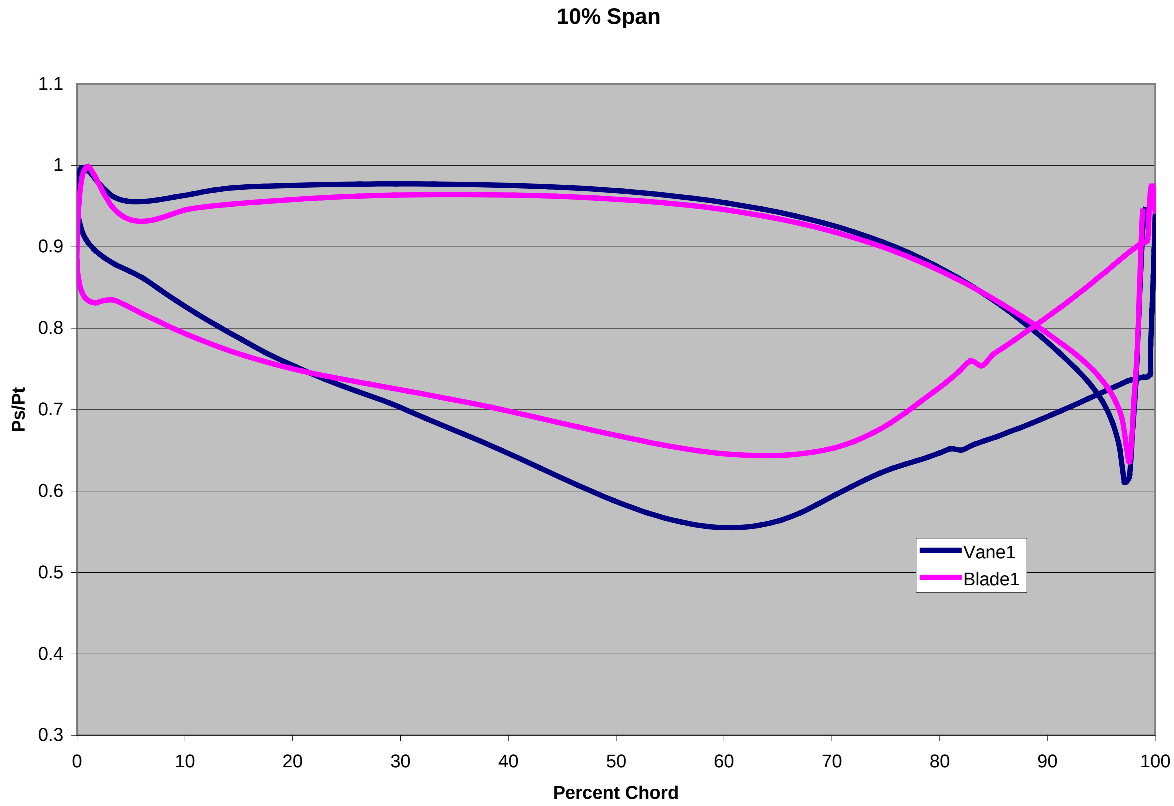
10% Span



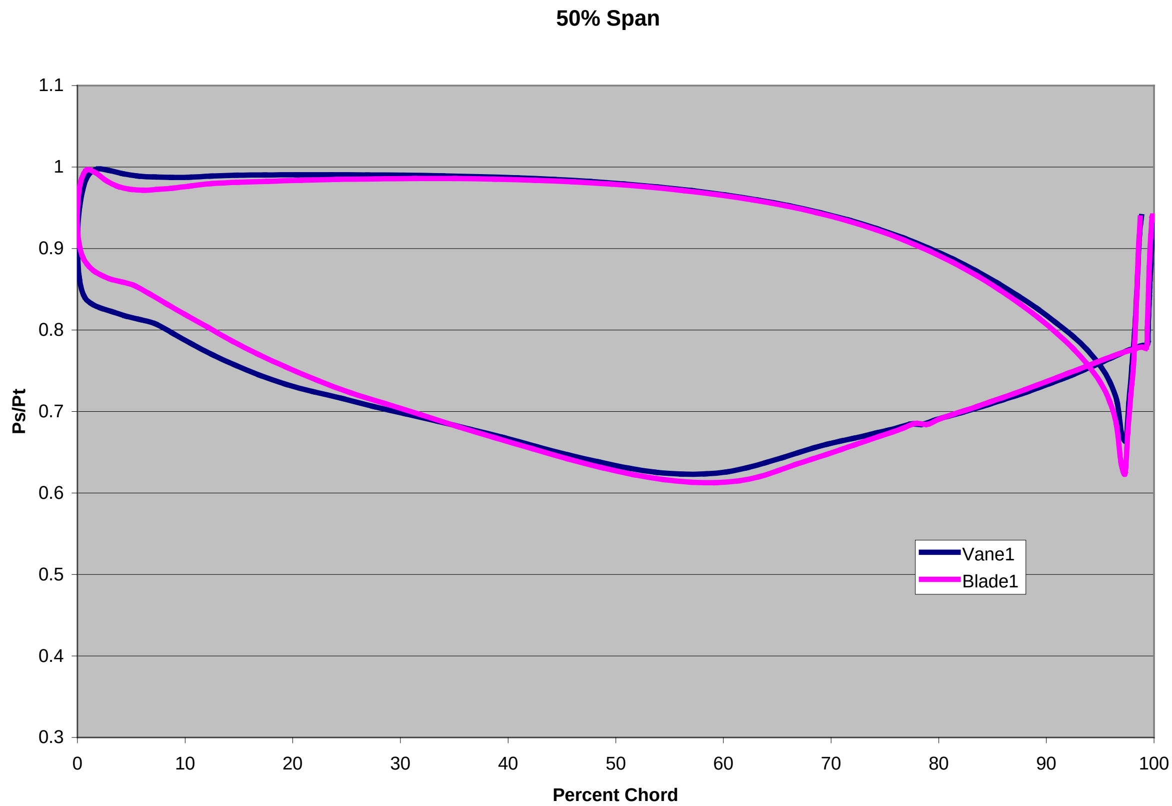

50% Span
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
Ps/Pt
0
10
20
30
40
50
60
70
80
90
100
Percent Chord
Vane1
Blade1


90% Span
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
Ps/Pt
0
10
20
30
40
50
60
70
80
90
100
Percent Chord
Vane1
Blade1

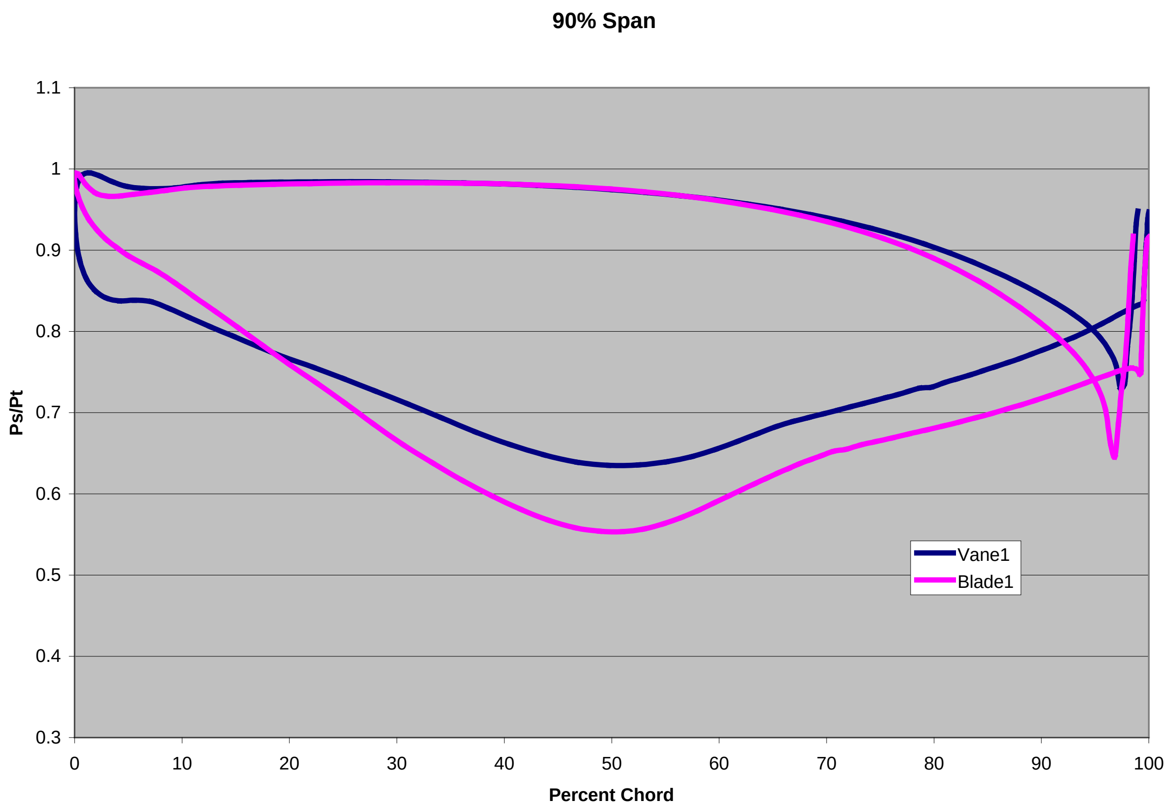
D.3 Stage 3



10% Span
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
Ps/Pt
0
10
20
30
40
50
60
70
80
90
100
Percent Chord
Vane1
Blade1

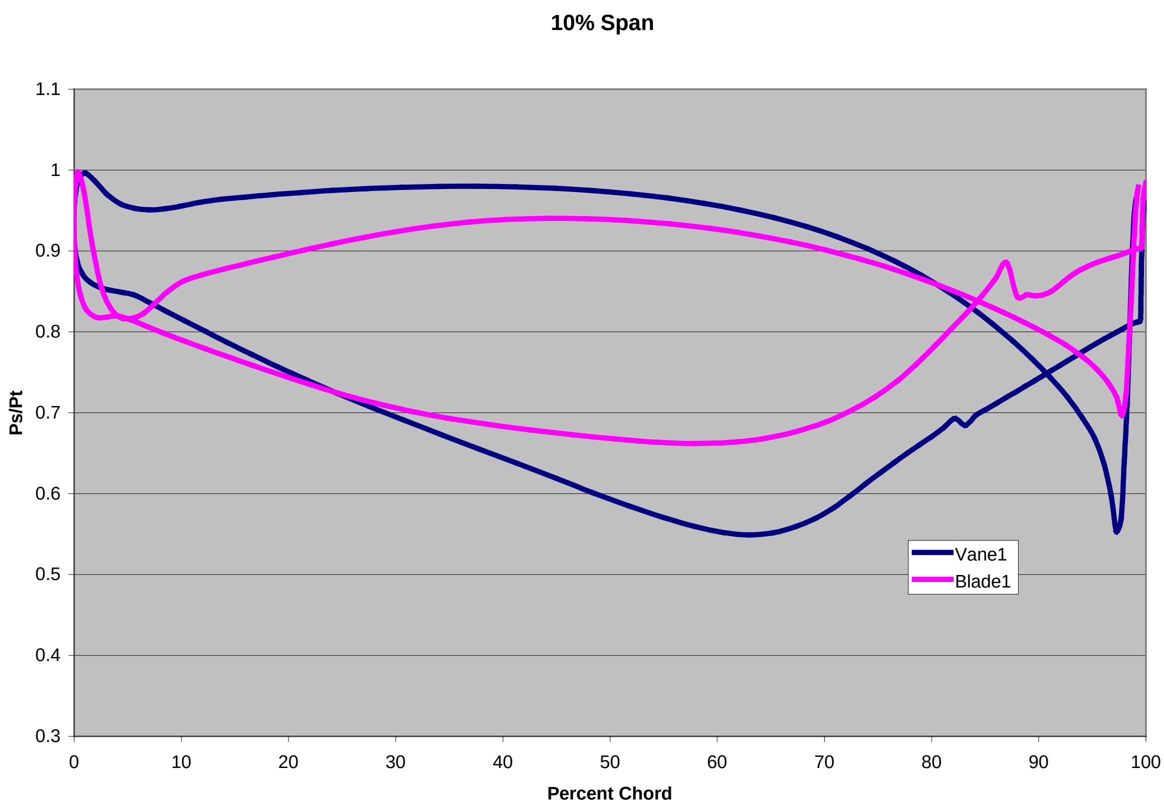


50% Span
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
Ps/Pt
0
10
20
30
40
50
60
70
80
90
100
Percent Chord
Vane1
Blade1

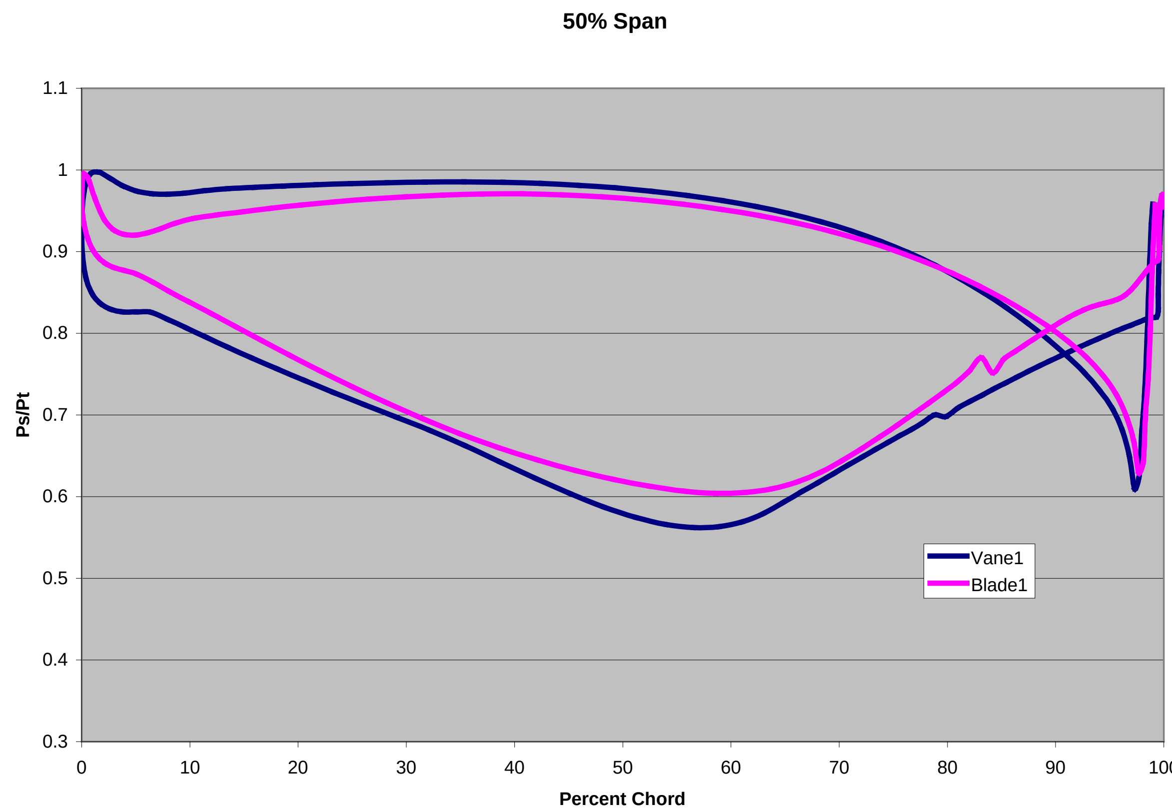


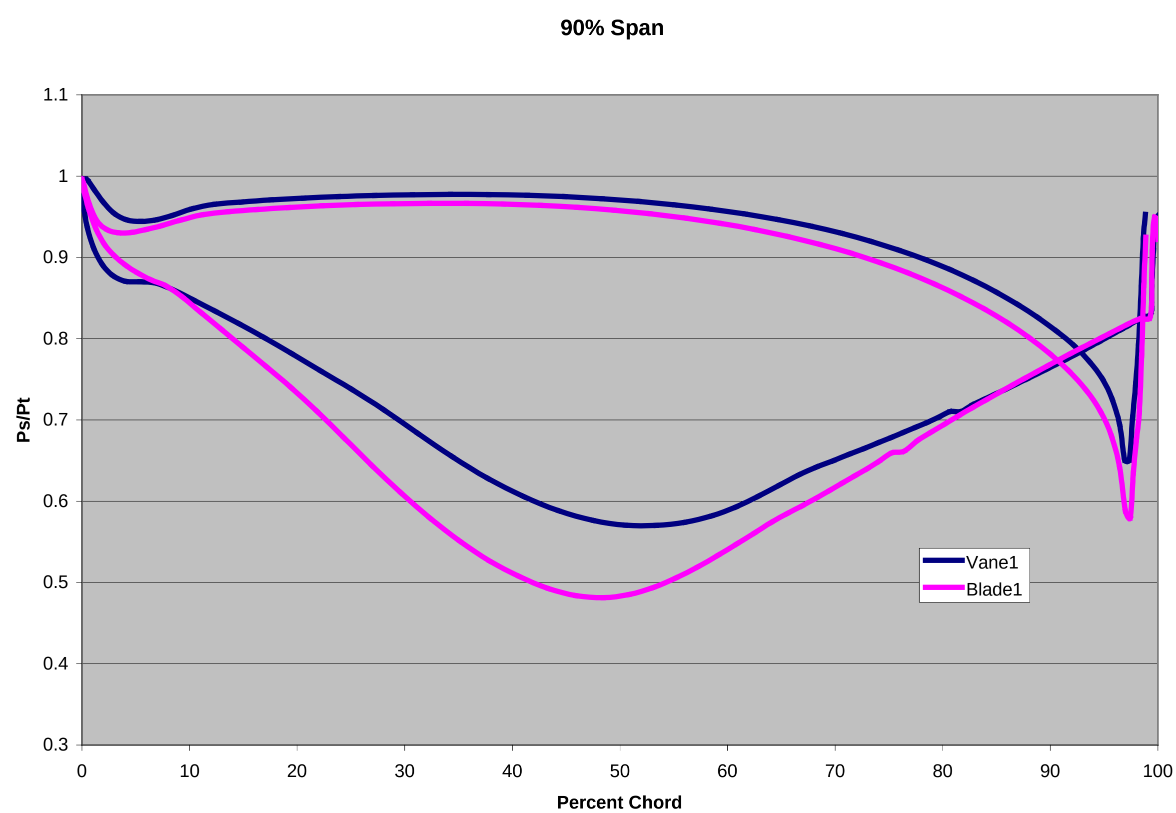
90% Span
Ps/Pt
Percent Chord
Vane1
Blade1
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0
10
20
30
40
50
60
70
80
90
100

D.4 Stage 4



10% Span
Ps/Pt
Percent Chord
Vane1
Blade1
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0
10
20
30
40
50
60
70
80
90
100


50% Span
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
Ps/Pt
0
10
20
30
40
50
60
70
80
90
100
Percent Chord
Vane1
Blade1


90% Span
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
Ps/Pt
0
10
20
30
40
50
60
70
80
90
100
Percent Chord
Vane1
Blade1

Meanline Analysis of Design Point
75% Speed (11174 rpm)

```
Flow Parm. (Inlet)            :     16.240
Mass Flow                     :     12.040
Efficiency                    :    92.8662%
Flow Parm. (Exit)             :     76.472
Power(hp)                     :   2684.958
Pressure Ratio (Total/Total)  :      5.769
Pressure Ratio (Total/Static) :      6.330
Inlet Temp. (degrees R / F)   :   1749.080 /   1289.410
TRIT (degrees R / F)          :   1749.080 /   1289.410
Exit TT    (degrees R / F)    :   1165.389 /    705.719
Enthalpy Drop   (BTU/lbm)     :     39.608
Ratio Specific Heats (Gamma)  :      1.340
Gas Constant (ft-lbf/degR/lbm):     53.374
Avg. Work Coefficient         :      1.459
Core Flow  (lbm/s)            :     12.040
Nozzle Cooling                :      0.000%
Rotor Cooling                 :      0.000%

Rotor Summary:
Title                 Reaction  WorkCoef     Cm/U      AN^2  RimSpeed
ROTOR: STAGE    1      48.000%     1.470     0.726    11.390   689.720
ROTOR: STAGE    2      47.000%     1.490     0.563    18.720   671.266
ROTOR: STAGE    3      45.000%     1.496     0.551    27.121   617.638
ROTOR: STAGE    4      40.000%     1.384     0.702    32.240   567.395

Corrected Speed (rpm)         :    6085.02
(based on TRIT & 1st rpm found)

======================================================================
                              Vane          Blade

Turning                     58.1564       78.4812
                            85.9121       90.6473
                            92.4592       93.8363
                            88.4801       81.7638

RVR                          2.0792        1.9532
                             2.0969        2.2366
                             2.4743        2.4077
                             2.4598        2.0300

Convergence Ratio            1.8046        1.6902
                             1.7790        1.8930
                             2.0383        1.9791
                             1.9660        1.6718

Reynolds #, SS/1000.       179.2235      152.0635
                           145.1666      126.1129
                           118.1032       93.2357
                            80.7626       59.2618

LE Mach # (relative)         0.2733        0.2985
                             0.2872        0.2673
                             0.2553        0.2647
                             0.2783        0.3262

TE Mach # (relative)         0.5824        0.5983
                             0.6181        0.6148
                             0.6509        0.6579
                             0.7092        0.6836

LE Swirl (relative)          0.0000       17.9747
                           -22.1197       24.7990
                           -25.4011       27.7528
                           -24.2202       23.9420

TE Swirl (relative)         58.1564      -60.3947
                            63.7159      -65.7272
```

	66.9995	-65.9808
	64.2247	-57.7576
Total Loss %	1.4064	1.9212
	2.0358	2.1632
	2.1774	2.3416
	2.1681	2.2357
Zweifel	1.0569	1.0284
	1.0437	1.0370
	1.0391	1.0437
	1.0225	1.0499
Throat Area	37.6309	-42.5160
	49.0312	-59.0217
	69.3542	-85.1203
	102.2492	-131.8714
Number of Airfoils	52	65
	62	62
	59	65
	67	76
Exit Mach/Swirl (Absolute)	0.3718	-9.3783

Appendix E.—Meanline Results for Four Stage: High Loading 1

Rotor Summary at Design Speed of 54 percent:

Title	Reaction	WorkCoef	Cm/U	AN^2	RimSpeed
ROTOR: STAGE 1	48.000%	2.826	1.072	5.902	496.707
ROTOR: STAGE 2	45.000%	2.840	0.857	9.700	483.381
ROTOR: STAGE 3	45.000%	2.863	0.880	14.081	444.190
ROTOR: STAGE 4	39.992%	2.774	1.224	16.650	410.626

Overall Efficiency = 87.5%

Rotor Summary @ Design Speed 100%:

Title	Reaction	WorkCoef	Cm/U	AN^2	RimSpeed
ROTOR: STAGE 1	48.000%	0.834	0.539	20.240	919.819
ROTOR: STAGE 2	45.000%	0.848	0.416	33.265	895.143
ROTOR: STAGE 3	45.000%	0.851	0.402	48.287	822.569
ROTOR: STAGE 4	40.000%	0.778	0.512	57.098	760.413

Overall Efficiency = 94%

Airfoil Summary

	54% Speed		**100% Speed**	
	Vane	**Blade**	**Vane**	**Blade**
Turning	59.3261	101.7896	57.7106	51.4604
	110.8252	114.7838	58.0856	58.7734
	115.4375	116.0826	53.8484	56.6190
	110.8802	100.6000	52.2701	50.9701
Vexit/Vinlet	2.2231	1.7296	2.0611	2.0179
	1.6517	1.6362	2.2851	2.4019
	1.8324	1.7477	2.6784	2.6977
	1.7983	1.5571	2.6875	2.2304
Reynolds #, SS/1000.	192.2316	162.2900	176.8202	166.8413
	147.8500	121.7398	160.8162	137.0289
	112.3183	87.5698	136.1440	106.9008
	73.1437	53.5719	94.8810	66.7247
LE Mach # (relative)	0.2730	0.3809	0.2730	0.2876
	0.4105	0.4037	0.2644	0.2426
	0.3843	0.4147	0.2332	0.2325
	0.4390	0.5105	0.2532	0.2931
	54% Speed		**100% Speed**	

	Vane	Blade	Vane	Blade
TE Mach # (relative)	0.6244	0.6770	0.5764	0.5956
	0.6956	0.6769	0.6213	0.5993
	0.7258	0.7479	0.6439	0.6480
	0.8204	0.8226	0.7056	0.6759
LE Swirl (relative)	0.0000	39.4746	0.0000	-9.0460
	-46.1872	48.9328	5.9468	-6.6781
	-48.6347	50.4989	13.3548	-9.6122
	-47.9455	44.9543	12.4835	-7.2519
TE Swirl (relative)	59.3261	-62.1228	57.7106	-60.5652
	64.5339	-65.7028	64.0554	-65.4882
	66.7344	-65.4703	67.2378	-66.2728
	62.8947	-55.5671	64.7740	-58.2441
Total Loss %	1.6196	3.4411	1.3734	1.4617
	3.8016	3.8811	1.5134	1.5536
	3.8187	4.4511	1.6540	1.6506
	4.1192	5.0666	1.6129	1.5247
Zweifel	1.0550	1.0259	1.0649	1.0237
	1.0657	1.0499	1.0140	1.0355
	1.0641	1.0576	1.0127	1.0284
	1.0377	1.0356	1.0124	1.0190
Number of Airfoils	51	76	52	50
	74	77	50	49
	72	82	45	49
	88	105	49	56
Exit Mach/Swirl (Absolute)	0.5549	-32.7647	0.3768	18.4055

Appendix F.—Disk Sizing

A 2–D disk sizing tool was used to approximate disk mass and structural feasibility. Below is a screen shot of disks that were designed based on achieving 25 percent over speed capability with typical disk alloys. The resulting weight and mass moment of inertia of each disk plus the blades is shown.

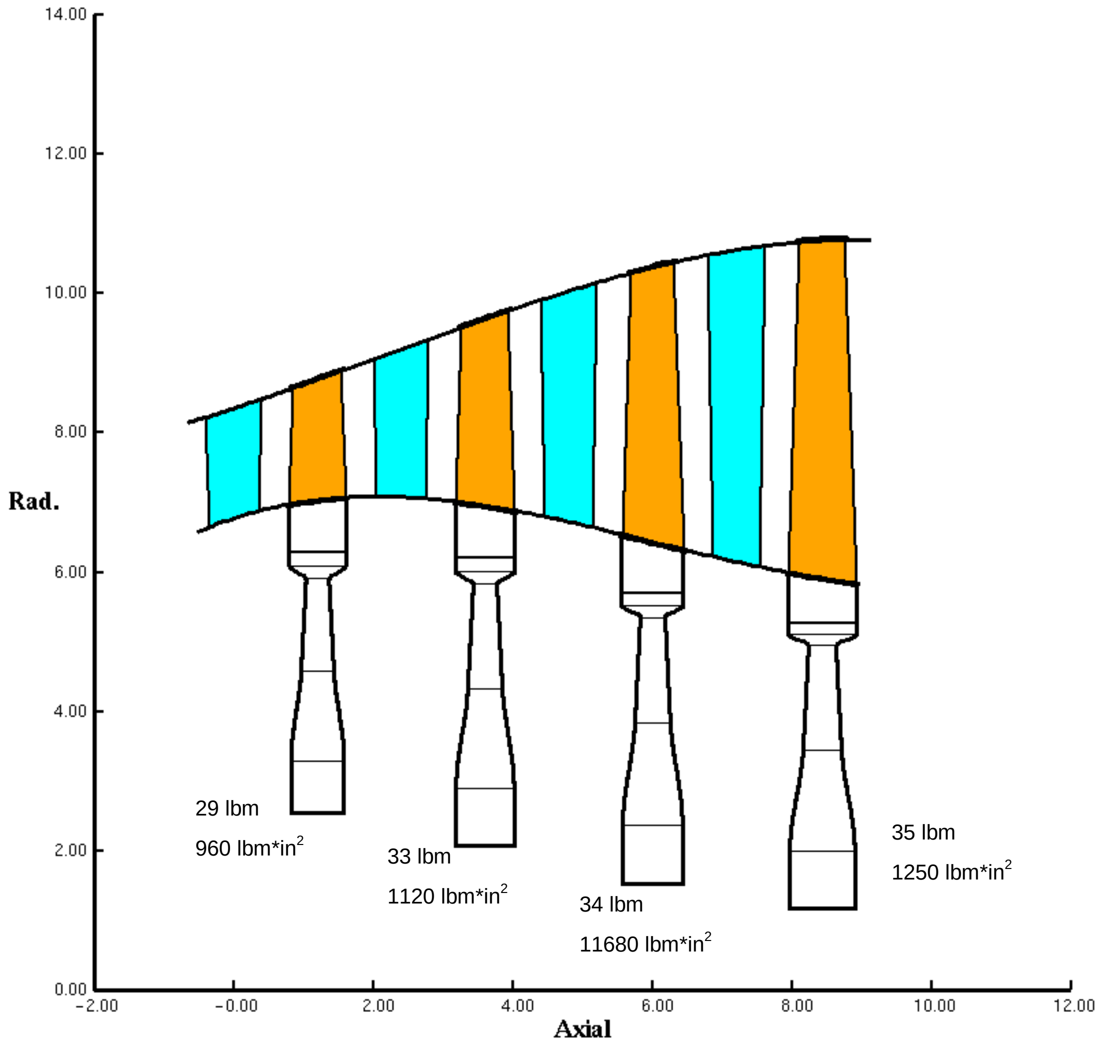


Figure F.1.—Approximate Disk Size

Appendix G.—Efficiency and Reaction Definitions

The scope of this work is concentrated on understanding speed variations and the impact to turbine efficiency. In order to simplify this understanding, the analysis presented in this report does not consider cooling flows. This simplifies the efficiency definition. The efficiency numbers presented in this report are calculated assuming ideal gas as follows.

$$\eta \equiv \frac{\text{ActualPower}}{\text{IdealPower}} = \frac{\Delta Tt}{Tin * \left(1 - Pr^{\frac{1-\gamma}{\gamma}}\right)}$$

where:

Pr = Total Pressure at inlet / Total Pressure at outlet
ΔTt = Total Temperature at inlet – Total Temperature at outlet
Tin = Total temperature at inlet
γ is the ratio of specific heats taken at the average of the inlet and exit Total Temperatures.

In this work, stage reaction refers to pressure reaction defined as the static pressure drop across the rotor normalized by the static pressure drop across the whole stage.

$$\text{Reaction} \equiv \left(\frac{Ps_{\text{RotorLE}} - Ps_{\text{RotorTE}}}{Ps_{\text{NozzleLE}} - Ps_{\text{RotorTE}}}\right)$$

Appendix H.—NPSS Output for Critical Mission Point

TABLE H.1.—65 PERCENT DESIGN SPEED TAKE OFF

```
*******************************************************************************************************************************
Date:05/24/11    Time:13:01:28    Model:   AHS 2010 Govt turboshaft engine - 65% speed turbine - Takeoff    converge = 1   CASE: 100
Version:            NPSS_2.3    Gas Package: Janaf    iter/pass/Jacb/Broy7=  7/ 18/ 1/ 5    Run by:              tm1862      PC:    50

                                               SUMMARY OUTPUT DATA
    MN        alt      dTs         W          Fn      Power      BSFC       Wfuel       VTAS      OPR       T4      T41       T47   Dyn P.
 0.000        0.0    45.00     28.17       464.6     7890.5    0.3305     2668.99       0.00   42.231   3769.2   3471.0    2884.2      0.0

                                                FLOW STATION DATA
                                W          Pt         Tt         ht      FAR        Wc         Ps         Ts      Aphy       MN     gamt     gams
FL1  InletStart.Fl_O        28.17      14.696     563.67       4.62   0.0000     29.36     14.696     563.67    -----.--   0.000   1.3995   1.3995
FL2  Inlet.Fl_O             28.17      14.696     563.67       4.62   0.0000     29.36     13.162     546.20    136.07   0.400   1.3995   1.3998
FL22 Duct1.Fl_O             28.17      14.696     563.67       4.62   0.0000     29.36     14.292     559.20    253.60   0.200   1.3995   1.3996
FL23 LPC.Fl_O               28.17     213.118    1302.21     187.46   0.0000      3.08    191.446    1265.56     14.45   0.399   1.3617   1.3640
FL24 ICduct.Fl_O            28.17     212.692    1302.21     187.46   0.0000      3.08    191.063    1265.56     14.48   0.399   1.3617   1.3640
FL25 HPC_axi.Fl_O           28.17     239.929    1349.79     199.78   0.0000      2.78    225.836    1328.37     16.76   0.300   1.3589   1.3602
FL26 Bld25.Fl_O             26.23     239.929    1349.79     199.78   0.0000      2.59    215.589    1312.11     12.18   0.399   1.3589   1.3611
FL27 HPC_centri.Fl_O        26.23     620.620    1786.31     315.94   0.0000      1.15    584.548    1759.54      6.98   0.300   1.3367   1.3379
FL28 Bld3.Fl_O              19.87     620.620    1786.31     315.94   0.0000      0.87    595.290    1767.65      6.24   0.250   1.3367   1.3375
FL3  Duct6.Fl_O             19.87     620.620    1786.31     315.94   0.0000      0.87    604.261    1774.33      7.70   0.200   1.3367   1.3372
FL4  Burner.Fl_O            20.61     608.208    3769.16     260.95   0.0373      1.34    552.163    3694.08      6.50   0.401   1.2520   1.2540
FL42 HPT.Fl_O               26.97     291.135    2956.47     148.09   0.0283      3.25    275.130    2919.73     20.07   0.300   1.2786   1.2796
FL43 Duct43.Fl_O            26.97     291.135    2956.47     148.09   0.0283      3.25    263.408    2891.67     15.65   0.400   1.2786   1.2804
FL44 LPT.Fl_O               28.91      84.443    2274.77     -26.60   0.0263     10.54     82.257    2260.99     93.61   0.202   1.2998   1.3002
FL45 ITduct.Fl_O            28.91      84.443    2274.82     -26.60   0.0263     10.54     76.075    2220.41     50.08   0.404   1.2998   1.3016
FL6  PowerT.Fl_O            28.91      15.430    1605.77    -219.51   0.0263     48.45     14.537    1582.30    293.77   0.301   1.3269   1.3281
FL7  Duct12.Fl_O            28.91      15.430    1605.82    -219.51   0.0263     48.45     14.537    1582.36    293.78   0.301   1.3269   1.3281
FL9  Nozzle.Fl_O            28.91      15.430    1605.88    -219.51   0.0263     48.45     14.696    1586.69    322.12   0.272   1.3269   1.3278

TURBOMACHINERY PERFORMANCE DATA
            Wc      PR       eff          Nc        TR     efPoly        pwr      SMN      SMW
LPC      29.36  14.502    0.8439   12000.000    2.3102    0.8889     -7286.8    19.91    19.50
HPC_axi   3.08   1.128    0.8875    9681.203    1.0365    0.8892      -490.9    19.92    12.44
HPC_cen>  2.59   2.587    0.8591    9509.053    1.3234    0.8748     -4311.1    20.24    18.65
HPT       1.34   2.089    0.8503     249.863    1.1353    0.8159      4802.0
LPT       3.25   3.448    0.8504     230.071    1.2582    0.8239      7286.7
PowerT   10.54   5.472    0.8835     314.498    1.4168    0.8587      7890.5

TURBOMACHINERY MAP DATA
         WcMap   PRmap    effMap       NcMap    R/Parm     s_WcDes    s_PRdes  s_effDes    s_NcDes
LPC      30.00   9.006    0.8510     100.000    1.9970    0.978860     1.6865    0.9916     0.8333
HPC_axi  29.90   1.200    0.8519       0.997    1.9839    0.103125     0.6398    1.0418     0.0001
HPC_cen> 29.89   3.182    0.8517       0.997    1.9961    0.086701     0.7273    1.0086     0.0001
HPT      30.15   5.972    0.9291     100.188    5.9722    0.044531     4.5654    0.9152     0.0176
LPT     149.72   6.032    0.9280     100.511    6.0322    0.021712     2.0559    0.9163     0.0192
PowerT   10.03   5.473    0.8835    7162.562    5.4727    1.050286     1.0001    1.0001     1.0000

===INLETS====    eRam       Afs       Fram
Inlet          1.0000   -----.--       0.0       BLEEDS - output     Wb/Win    hscale    Pscale          W        Tt       ht        Pt
                                                 C_LPTCharg   Bl>    0.0182    1.0000    1.0000     0.5126   1349.79   199.78   239.929
====DUCTS====  dPnorm        MN       Aphy       C_LPTUncharg Bl>    0.0506    1.0000    1.0000     1.4241   1349.79   199.78   239.929
Duct1          0.0000    0.4001     136.07       C_HPTCharg   Bl>    0.0823    1.0000    1.0000     2.1597   1786.31   315.94   620.620
ICduct         0.0020    0.3994      14.45       C_HPTUncharg Bl>    0.1602    1.0000    1.0000     4.2020   1786.31   315.94   620.620
Duct6          0.0000    0.2503       6.24
Duct43         0.0000    0.3004      20.07
ITduct         0.0000    0.2016      93.61
Duct12         0.0000    0.3009     293.77

===SHAFTS====   Nmech    trq_in     pwr_in
HP_Shaft      15340.0    1644.1     4802.0
IP_Shaft      12509.7    3059.3     7286.7
LP_Shaft      15000.0    2762.8     7890.5

===BURNERS===   TtOut       eff     dPnorm     Wfuel       FAR     EINOx      ppm
Burner        3769.16    1.0000     0.0200   0.74138   0.03731

===NOZZLES===      PR       Cfg       CdTh        Cv       Ath      MNth     Vact        Fg
Nozzle          1.050    1.0000     1.0000    1.0000    321.89     0.272    517.0     464.6
```

TABLE H.2.—65 PERCENT DESIGN SPEED CLIMB

```
*******************************************************************************************************************************
Date:05/24/11     Time:13:01:28    Model:     AHS 2010 Govt turboshaft engine - 65% speed turbine - Climb      converge = 1   CASE: 100
Version:            NPSS_2.3    Gas Package: Janaf     iter/pass/Jacb/Broy= 20/ 31/ 1/18    Run by:             tm1862       PC:    50

                                                SUMMARY OUTPUT DATA
    MN        alt      dTs          W          Fn       Power       BSFC       Wfuel       VTAS      OPR       T4       T41       T47   Dyn P.
 0.000        0.0     0.00      19.98       304.1      2646.3     0.4551     1259.82       0.00   25.976   2903.4   2674.3    2203.1      0.0

                                                 FLOW STATION DATA
                                       W        Pt        Tt        ht      FAR       Wc        Ps        Ts      Aphy     MN    gamt    gams
FL1  InletStart.Fl_O               19.98    14.696    518.67     -6.18   0.0000    19.98    14.696    518.67   -----.--  0.000  1.4002  1.4002
FL2  Inlet.Fl_O                    19.98    14.696    518.67     -6.18   0.0000    19.98    14.033    511.87    136.07  0.258  1.4002  1.4003
FL22 Duct1.Fl_O                    19.98    14.696    518.67     -6.18   0.0000    19.98    14.512    516.80    253.60  0.134  1.4002  1.4003
FL23 LPC.Fl_O                      19.98   139.757   1062.08    126.40   0.0000     3.01   126.302   1033.00     14.45  0.386  1.3769  1.3787
FL24 ICduct.Fl_O                   19.98   139.478   1062.08    126.40   0.0000     3.01   126.049   1033.00     14.48  0.386  1.3769  1.3787
FL25 HPC_axi.Fl_O                  19.98   157.365   1101.89    136.40   0.0000     2.72   148.577   1084.76     16.76  0.290  1.3743  1.3754
FL26 Bld25.Fl_O                    18.61   157.365   1101.89    136.40   0.0000     2.53   142.244   1071.93     12.18  0.386  1.3743  1.3762
FL27 HPC_centri.Fl_O               18.61   381.746   1444.24    224.44   0.0000     1.20   357.780   1419.95      6.98  0.311  1.3535  1.3548
FL28 Bld3.Fl_O                     14.09   381.746   1444.24    224.44   0.0000     0.91   364.944   1427.34      6.24  0.259  1.3535  1.3544
FL3  Duct6.Fl_O                    14.09   381.746   1444.24    224.44   0.0000     0.91   370.907   1433.41      7.70  0.207  1.3535  1.3541
FL4  Burner.Fl_O                   14.44   374.111   2903.39    191.13   0.0248     1.34   338.989   2840.14      6.50  0.397  1.2820  1.2838
FL42 HPT.Fl_O                      18.96   178.418   2256.84    102.11   0.0188     3.26   168.470   2226.61     20.07  0.298  1.3052  1.3062
FL43 Duct43.Fl_O                   18.96   178.418   2256.89    102.11   0.0188     3.26   161.186   2203.61     15.65  0.397  1.3052  1.3070
FL44 LPT.Fl_O                      20.33    54.478   1727.90    -25.88   0.0175    10.01    53.204   1717.84     93.61  0.189  1.3266  1.3271
FL45 ITduct.Fl_O                   20.33    54.478   1727.95    -25.88   0.0175    10.01    49.665   1688.94     50.08  0.375  1.3266  1.3284
FL6  PowerT.Fl_O                   20.33    15.431   1391.41   -117.88   0.0175    31.71    15.063   1382.83    293.77  0.190  1.3443  1.3448
FL7  Duct12.Fl_O                   20.33    15.431   1391.47   -117.88   0.0175    31.71    15.063   1382.90    293.78  0.190  1.3443  1.3448
FL9  Nozzle.Fl_O                   20.33    15.431   1391.54   -117.88   0.0175    31.71    14.696   1374.25    210.76  0.270  1.3443  1.3453

TURBOMACHINERY PERFORMANCE DATA
              Wc       PR      eff         Nc        TR    efPoly        pwr     SMN      SMW
LPC        19.98    9.510   0.8460  10818.559    2.0477    0.8853    -3747.7   17.84    19.09
HPC_axi     3.01    1.128   0.8936   9456.518    1.0375    0.8953     -282.6   19.37    11.28
HPC_cen>    2.53    2.426   0.8588   9284.124    1.3107    0.8741    -2317.5   26.03    25.07
HPT         1.34    2.097   0.8502    251.138    1.1488    0.8303     2599.9
LPT         3.26    3.275   0.8520    227.727    1.2662    0.8307     3748.0
PowerT     10.01    3.531   0.7181    360.849    1.2420    0.6839     2646.2

TURBOMACHINERY MAP DATA
           WcMap    PRmap   effMap      NcMap    R/Parm     s_WcDes   s_PRdes  s_effDes   s_NcDes
LPC        20.41    6.046   0.8532     90.155    1.6982    0.978860    1.6865    0.9916    0.8333
HPC_axi    29.21    1.200   0.8577      0.974    1.8760    0.103125    0.6398    1.0418    0.0001
HPC_cen>   29.21    2.961   0.8514      0.973    2.0487    0.086701    0.7273    1.0086    0.0001
HPT        30.14    6.007   0.9290    100.699    6.0075    0.044531    4.5654    0.9152    0.0176
LPT       149.99    5.677   0.9298     99.487    5.6772    0.021712    2.0559    0.9163    0.0192
PowerT      9.53    3.531   0.7181   8218.192    3.5307    1.050286    1.0001    1.0001    1.0000

===INLETS====    eRam      Afs      Fram
Inlet          1.0000   -----.--      0.0      BLEEDS - output    Wb/Win   hscale   Pscale         W        Tt       ht        Pt
                                               C_LPTCharg   Bl>   0.0182   1.0000   1.0000    0.3636   1101.89   136.40   157.365
====DUCTS====   dPnorm       MN      Aphy      C_LPTUncharg Bl>   0.0506   1.0000   1.0000    1.0101   1101.89   136.40   157.365
Duct1           0.0000   0.2576    136.07      C_HPTCharg   Bl>   0.0823   1.0000   1.0000    1.5318   1444.24   224.44   381.746
ICduct          0.0020   0.3859     14.45      C_HPTUncharg Bl>   0.1602   1.0000   1.0000    2.9804   1444.24   224.44   381.746
Duct6           0.0000   0.2586      6.24
Duct43          0.0000   0.2980     20.07
ITduct          0.0000   0.1891     93.61
Duct12          0.0000   0.1897    293.77

===SHAFTS====    Nmech   trq_in    pwr_in
HP_Shaft       13532.1   1009.1    2599.9
IP_Shaft       10818.6   1819.5    3748.0
LP_Shaft       15000.0    926.5    2646.2

===BURNERS===    TtOut      eff    dPnorm     Wfuel       FAR     EINOx      ppm
Burner         2903.39   1.0000    0.0200   0.34995   0.02483

===NOZZLES===       PR      Cfg      CdTh        Cv       Ath      MNth     Vact       Fg
Nozzle           1.050   1.0000    1.0000    1.0000    321.89     0.270    481.3    304.1
```

TABLE H.3.—65 PERCENT DESIGN SPEED CRUISE

****

Date:05/24/11 Time:13:01:29 Model: AHS 2010 Govt turboshaft engine - 65% speed turbine - Cruise converge = 1 CASE: 101
Version: NPSS_2.3 Gas Package: Janaf iter/pass/Jacb/Broy= 28/ 50/ 2/25 Run by: tm1862 PC: 50

SUMMARY OUTPUT DATA

MN	alt	dTs	W	Fn	Power	BSFC	Wfuel	VTAS	OPR	T4	T41	T47	Dyn P.
0.510	28000.0	0.00	11.80	-25.9	2351.0	0.3141	735.13	511.85	39.130	2847.0	2619.0	2155.0	0.0

FLOW STATION DATA

	W	Pt	Tt	ht	FAR	Wc	Ps	Ts	Aphy	MN	gamt	gams
FL1 InletStart.Fl_O	11.80	5.705	440.66	-24.88	0.0000	28.03	4.776	418.82	107.88	0.510	1.4010	1.4011
FL2 Inlet.Fl_O	11.80	5.705	440.66	-24.88	0.0000	28.03	5.169	428.40	136.07	0.378	1.4010	1.4010
FL22 Duct1.Fl_O	11.80	5.705	440.66	-24.88	0.0000	28.03	5.562	437.48	253.60	0.190	1.4010	1.4010
FL23 LPC.Fl_O	11.80	80.640	1019.99	115.89	0.0000	3.02	72.819	991.72	14.45	0.387	1.3795	1.3812
FL24 ICduct.Fl_O	11.80	80.479	1019.99	115.89	0.0000	3.02	72.673	991.72	14.48	0.387	1.3795	1.3812
FL25 HPC_axi.Fl_O	11.80	90.847	1058.62	125.54	0.0000	2.73	85.741	1041.97	16.76	0.291	1.3771	1.3781
FL26 Bld25.Fl_O	10.99	90.847	1058.62	125.54	0.0000	2.54	82.059	1029.49	12.18	0.387	1.3771	1.3789
FL27 HPC_centri.Fl_O	10.99	223.217	1394.60	211.44	0.0000	1.19	209.421	1371.40	6.98	0.308	1.3563	1.3576
FL28 Bld3.Fl_O	8.33	223.217	1394.60	211.44	0.0000	0.90	213.541	1378.44	6.24	0.256	1.3563	1.3572
FL3 Duct6.Fl_O	8.33	223.217	1394.60	211.44	0.0000	0.90	216.973	1384.23	7.70	0.205	1.3563	1.3569
FL4 Burner.Fl_O	8.53	218.753	2847.03	178.94	0.0245	1.34	198.185	2784.66	6.50	0.397	1.2837	1.2855
FL42 HPT.Fl_O	11.20	104.659	2208.49	92.17	0.0186	3.24	98.870	2179.03	20.07	0.296	1.3070	1.3080
FL43 Duct43.Fl_O	11.20	104.659	2208.54	92.17	0.0186	3.24	94.637	2156.67	15.65	0.395	1.3070	1.3087
FL44 LPT.Fl_O	12.01	28.056	1648.42	-43.94	0.0173	11.21	27.227	1636.16	93.61	0.213	1.3306	1.3312
FL45 ITduct.Fl_O	12.01	28.056	1648.48	-43.94	0.0173	11.21	24.842	1599.24	50.08	0.431	1.3306	1.3330
FL6 PowerT.Fl_O	12.01	5.015	1131.40	-182.32	0.0173	51.97	4.677	1110.67	293.77	0.321	1.3606	1.3620
FL7 Duct12.Fl_O	12.01	5.015	1131.47	-182.32	0.0173	51.97	4.677	1110.73	293.78	0.321	1.3606	1.3620
FL9 Nozzle.Fl_O	12.01	5.015	1131.53	-182.32	0.0173	51.98	4.776	1117.01	345.52	0.268	1.3606	1.3616

TURBOMACHINERY PERFORMANCE DATA

	Wc	PR	eff	Nc	TR	efPoly	pwr	SMN	SMW
LPC	28.03	14.136	0.8489	11830.394	2.3147	0.8929	-2350.7	17.22	17.26
HPC_axi	3.02	1.129	0.8930	9493.110	1.0379	0.8947	-161.2	19.31	11.36
HPC_cen>	2.54	2.457	0.8599	9318.289	1.3174	0.8753	-1336.0	24.66	23.60
HPT	1.34	2.090	0.8502	249.497	1.1488	0.8311	1497.1		
LPT	3.24	3.730	0.8467	232.035	1.2982	0.8226	2350.7		
PowerT	11.21	5.595	0.8783	198.934	1.4572	0.8513	2350.9		

TURBOMACHINERY MAP DATA

	WcMap	PRmap	effMap	NcMap	R/Parm	s_WcDes	s_PRdes	s_effDes	s_NcDes
LPC	28.63	8.789	0.8560	98.587	1.8497	0.978860	1.6865	0.9916	0.8333
HPC_axi	29.31	1.201	0.8571	0.977	1.8849	0.103125	0.6398	1.0418	0.0001
HPC_cen>	29.30	3.003	0.8525	0.977	2.0338	0.086701	0.7273	1.0086	0.0001
HPT	30.15	5.977	0.9290	100.041	5.9770	0.044531	4.5654	0.9152	0.0176
LPT	149.41	6.613	0.9240	101.369	6.6132	0.021712	2.0559	0.9163	0.0192
PowerT	10.68	5.595	0.8783	4530.633	5.5951	1.050286	1.0001	1.0001	1.0000

===INLETS====	eRam	Afs	Fram
Inlet	1.0000	107.88	187.8

BLEEDS - output	Wb/Win	hscale	Pscale	W	Tt	ht	Pt
C_LPTCharg Bl>	0.0182	1.0000	1.0000	0.2148	1058.62	125.54	90.847
C_LPTUncharg Bl>	0.0506	1.0000	1.0000	0.5968	1058.62	125.54	90.847
C_HPTCharg Bl>	0.0823	1.0000	1.0000	0.9050	1394.60	211.44	223.217
C_HPTUncharg Bl>	0.1602	1.0000	1.0000	1.7608	1394.60	211.44	223.217

====DUCTS====	dPnorm	MN	Aphy
Duct1	0.0000	0.3779	136.07
ICduct	0.0020	0.3871	14.45
Duct6	0.0000	0.2563	6.24
Duct43	0.0000	0.2965	20.07
ITduct	0.0000	0.2127	93.61
Duct12	0.0000	0.3214	293.77

===SHAFTS====	Nmech	trq in	pwr in
HP_Shaft	13312.5	590.7	1497.1
IP_Shaft	10904.5	1132.2	2350.7
LP_Shaft	8077.0	1528.7	2350.9

===BURNERS===	TtOut	eff	dPnorm	Wfuel	FAR	EINOx	ppm
Burner	2847.03	1.0000	0.0200	0.20420	0.02453		

===NOZZLES===	PR	Cfg	CdTh	Cv	Ath	MNth	Vact	Fg
Nozzle	1.050	1.0000	1.0000	1.0000	321.89	0.268	433.7	161.8

TABLE H.4.—75 PERCENT DESIGN SPEED TAKE OFF

```
*******************************************************************************************************************************
Date:05/24/11    Time:12:57:33    Model:   AHS 2010 Govt turboshaft engine - 75% speed turbine - Takeoff     converge = 1   CASE: 100
Version:              NPSS_2.3    Gas Package: Janaf    iter/pass/Jacb/Broy=  7/ 18/ 1/ 5    Run by:                tm1862      PC:    50

                                               SUMMARY OUTPUT DATA
    MN        alt      dTs          W           Fn        Power       BSFC       Wfuel       VTAS       OPR        T4       T41       T47  Dyn P.
 0.000        0.0    45.00      27.02        441.8       7866.9     0.3182     2559.60       0.00    42.270    3766.5    3470.5    2884.1     0.0

                                                FLOW STATION DATA
                                W         Pt         Tt         ht      FAR        Wc         Ps          Ts       Aphy      MN     gamt      gams
FL1  InletStart.Fl_O        27.02     14.696     563.67       4.62   0.0000     28.16     14.696      563.67    -----.--   0.000  1.3995   1.3995
FL2  Inlet.Fl_O             27.02     14.696     563.67       4.62   0.0000     28.16     13.161      546.20     130.50   0.400  1.3995   1.3998
FL22 Duct1.Fl_O             27.02     14.696     563.67       4.62   0.0000     28.16     14.292      559.20     243.22   0.200  1.3995   1.3996
FL23 LPC.Fl_O               27.02    213.138    1302.67     187.58   0.0000      2.95    191.426     1265.94      13.85   0.400  1.3617   1.3640
FL24 ICduct.Fl_O            27.02    212.712    1302.67     187.58   0.0000      2.96    191.044     1265.94      13.88   0.400  1.3617   1.3640
FL25 HPC_axi.Fl_O           27.02    239.729    1349.92     199.81   0.0000      2.67    225.624     1328.46      16.07   0.300  1.3589   1.3602
FL26 Bld25.Fl_O             25.17    239.729    1349.92     199.81   0.0000      2.49    215.366     1312.16      11.69   0.400  1.3589   1.3611
FL27 HPC_centri.Fl_O        25.17    621.191    1787.86     316.36   0.0000      1.11    585.141     1761.11       6.70   0.300  1.3367   1.3378
FL28 Bld3.Fl_O              19.10    621.191    1787.86     316.36   0.0000      0.84    595.875     1769.21       6.00   0.250  1.3367   1.3375
FL3  Duct6.Fl_O             19.10    621.191    1787.86     316.36   0.0000      0.84    604.840     1775.88       7.41   0.200  1.3367   1.3372
FL4  Burner.Fl_O            19.81    608.767    3766.50     261.47   0.0372      1.29    552.655     3691.42       6.24   0.401  1.2521   1.2541
FL42 HPT.Fl_O               25.89    290.964    2955.80     148.24   0.0282      3.12    274.959     2919.04      19.27   0.301  1.2786   1.2796
FL43 Duct43.Fl_O            25.89    290.964    2955.80     148.24   0.0282      3.12    263.238     2890.96      15.02   0.401  1.2786   1.2804
FL44 LPT.Fl_O               27.73     84.350    2274.58     -26.60   0.0263     10.12     82.177     2260.87      90.09   0.201  1.2998   1.3003
FL45 ITduct.Fl_O            27.73     84.350    2274.63     -26.60   0.0263     10.12     76.035     2220.53      48.19   0.402  1.2998   1.3016
FL6  PowerT.Fl_O            27.73     15.431    1578.15    -227.13   0.0263     46.06     14.531     1554.84     278.41   0.302  1.3283   1.3295
FL7  Duct12.Fl_O            27.73     15.431    1578.21    -227.13   0.0263     46.06     14.531     1554.90     278.42   0.302  1.3283   1.3295
FL9  Nozzle.Fl_O            27.73     15.431    1578.27    -227.13   0.0263     46.06     14.696     1559.32     306.20   0.272  1.3283   1.3293

TURBOMACHINERY PERFORMANCE DATA
             Wc       PR       eff          Nc         TR     efPoly        pwr      SMN      SMW
LPC       28.16   14.503    0.8434   12000.000     2.3110     0.8886    -6993.4    20.01    19.60
HPC_axi    2.96    1.127    0.8869    9686.004     1.0363     0.8887     -467.6    19.94    12.48
HPC_cen>   2.49    2.591    0.8581    9514.980     1.3244     0.8740    -4151.3    20.11    18.46
HPT        1.29    2.092    0.8503     250.119     1.1356     0.8159     4618.9
LPT        3.12    3.450    0.8505     230.097     1.2584     0.8240     6993.4
PowerT    10.12    5.466    0.9190     314.511     1.4414     0.9005     7866.9

TURBOMACHINERY MAP DATA
          WcMap    PRmap    effMap       NcMap     R/Parm     s_WcDes    s_PRdes   s_effDes    s_NcDes
LPC       30.00    8.999    0.8510     100.000     2.0005    0.938796     1.6881     0.9911     0.8333
HPC_axi   29.93    1.200    0.8517       0.997     1.9877    0.098842     0.6347     1.0414     0.0001
HPC_cen>  29.92    3.188    0.8515       0.998     1.9949    0.083218     0.7273     1.0077     0.0001
HPT       30.15    5.974    0.9291     100.177     5.9744    0.042746     4.5543     0.9152     0.0176
LPT      149.74    6.012    0.9281     100.436     6.0116    0.020843     2.0460     0.9163     0.0192
PowerT    10.32    5.466    0.9190    7162.784     5.4664    0.980704     1.0000     1.0000     1.0000

===INLETS====    eRam       Afs       Fram
Inlet          1.0000   -----.--       0.0       BLEEDS - output     Wb/Win    hscale    Pscale          W        Tt        ht         Pt
                                                  C_LPTCharg   Bl>    0.0180    1.0000    1.0000     0.4859   1349.92    199.81    239.729
====DUCTS====  dPnorm        MN       Aphy       C_LPTUncharg Bl>    0.0502    1.0000    1.0000     1.3558   1349.92    199.81    239.729
Duct1          0.0000    0.4001     130.50       C_HPTCharg   Bl>    0.0819    1.0000    1.0000     2.0613   1787.86    316.36    621.191
ICduct         0.0020    0.3998      13.85       C_HPTUncharg Bl>    0.1595    1.0000    1.0000     4.0143   1787.86    316.36    621.191
Duct6          0.0000    0.2501       6.00
Duct43         0.0000    0.3005      19.27
ITduct         0.0000    0.2011      90.09
Duct12         0.0000    0.3018     278.41

===SHAFTS====   Nmech    trq_in    pwr_in
HP_Shaft      15350.3    1580.4    4618.9
IP_Shaft      12509.7    2936.1    6993.4
LP_Shaft      15000.0    2754.5    7866.9

===BURNERS===  TtOut        eff    dPnorm     Wfuel       FAR     EINOx      ppm
Burner       3766.50     1.0000    0.0200   0.71100   0.03723

===NOZZLES===     PR        Cfg      CdTh        Cv       Ath      MNth     Vact        Fg
Nozzle         1.050     1.0000    1.0000    1.0000    305.32     0.272    512.7     441.8
```

TABLE H.5.—75 PERCENT DESIGN SPEED CLIMB

```
*******************************************************************************************************************
Date:05/24/11    Time:12:57:33    Model:     AHS 2010 Govt turboshaft engine - 75% speed turbine - Climb    converge = 1   CASE: 100
Version:             NPSS_2.3    Gas Package: Janaf    iter/pass/Jacb/Broy= 18/ 29/ 1/16    Run by:             tm1862      PC:    50

                                        SUMMARY OUTPUT DATA
    MN        alt      dTs          W           Fn       Power      BSFC       Wfuel       VTAS      OPR       T4      T41      T47  Dyn P.
 0.000        0.0     0.00      18.92        281.5      2646.3    0.4171     1150.64       0.00   25.419   2849.1   2627.8   2165.6     0.0

                                         FLOW STATION DATA
                                W         Pt          Tt        ht     FAR        Wc          Ps          Ts      Aphy      MN     gamt     gams
FL1  InletStart.Fl_O        18.92     14.696      518.67     -6.18  0.0000     18.92      14.696      518.67   -----.--  0.000  1.4002  1.4002
FL2  Inlet.Fl_O             18.92     14.696      518.67     -6.18  0.0000     18.92      14.051      512.05    130.50  0.254  1.4002  1.4003
FL22 Duct1.Fl_O             18.92     14.696      518.67     -6.18  0.0000     18.92      14.517      516.85    243.22  0.133  1.4002  1.4003
FL23 LPC.Fl_O               18.92    138.843     1061.32    126.21  0.0000      2.86     125.656     1032.67     13.85  0.383  1.3769  1.3787
FL24 ICduct.Fl_O            18.92    138.566     1061.32    126.21  0.0000      2.87     125.404     1032.67     13.88  0.383  1.3769  1.3787
FL25 HPC_axi.Fl_O           18.92    156.159     1100.69    136.09  0.0000      2.59     147.546     1083.79     16.07  0.288  1.3744  1.3755
FL26 Bld25.Fl_O             17.63    156.159     1100.69    136.09  0.0000      2.42     141.350     1071.15     11.69  0.383  1.3744  1.3763
FL27 HPC_centri.Fl_O        17.63    373.551     1437.05    222.55  0.0000      1.15     349.784     1412.53      6.70  0.313  1.3539  1.3552
FL28 Bld3.Fl_O              13.37    373.551     1437.05    222.55  0.0000      0.88     356.894     1419.99      6.00  0.260  1.3539  1.3548
FL3  Duct6.Fl_O             13.37    373.551     1437.05    222.55  0.0000      0.88     362.809     1426.12      7.41  0.208  1.3539  1.3545
FL4  Burner.Fl_O            13.69    366.080     2849.07    190.55  0.0239      1.29     331.678     2786.62      6.24  0.396  1.2841  1.2859
FL42 HPT.Fl_O               17.95    174.554     2217.28    102.80  0.0181      3.12     164.832     2187.48     19.27  0.298  1.3070  1.3080
FL43 Duct43.Fl_O            17.95    174.554     2217.33    102.80  0.0181      3.12     157.716     2164.84     15.02  0.397  1.3070  1.3088
FL44 LPT.Fl_O               19.24     52.057     1689.29    -25.16  0.0169      9.80      50.796     1679.04     90.09  0.192  1.3289  1.3293
FL45 ITduct.Fl_O            19.24     52.057     1689.35    -25.16  0.0169      9.80      47.276     1649.44     48.19  0.383  1.3289  1.3307
FL6  PowerT.Fl_O            19.24     15.430     1331.28   -122.38  0.0169     29.35      15.080     1323.39    278.41  0.185  1.3483  1.3487
FL7  Duct12.Fl_O            19.24     15.430     1331.35   -122.38  0.0169     29.35      15.080     1323.46    278.42  0.185  1.3483  1.3487
FL9  Nozzle.Fl_O            19.24     15.430     1331.41   -122.38  0.0169     29.36      14.696     1314.71    195.08  0.270  1.3483  1.3493

TURBOMACHINERY PERFORMANCE DATA
            Wc       PR      eff          Nc        TR    efPoly        pwr      SMN      SMW
LPC      18.92    9.448   0.8439   10789.426    2.0462    0.8837    -3543.7    16.97    18.19
HPC_axi   2.87    1.127   0.8946    9399.682    1.0371    0.8963     -264.5    19.28    11.03
HPC_cen>  2.42    2.392   0.8581    9230.074    1.3056    0.8733    -2156.3    27.26    26.47
HPT       1.29    2.097   0.8504     251.907    1.1497    0.8311     2420.8
LPT       3.12    3.353   0.8517     229.131    1.2734    0.8304     3543.8
PowerT    9.80    3.374   0.8014     364.949    1.2691    0.7748     2646.4

TURBOMACHINERY MAP DATA
         WcMap    PRmap   effMap       NcMap    R/Parm     s_WcDes   s_PRdes  s_effDes   s_NcDes
LPC      20.15    6.004   0.8515      89.912    1.6735    0.938796    1.6881    0.9911    0.8333
HPC_axi  29.04    1.200   0.8590       0.968    1.8534    0.098842    0.6347    1.0414    0.0001
HPC_cen> 29.04    2.914   0.8516       0.968    2.0536    0.083218    0.7273    1.0077    0.0001
HPT      30.14    5.997   0.9292     100.892    5.9971    0.042746    4.5543    0.9152    0.0176
LPT     149.89    5.814   0.9295     100.014    5.8144    0.020843    2.0460    0.9163    0.0192
PowerT    9.99    3.374   0.8014    8311.469    3.3737    0.980704    1.0000    1.0000    1.0000

===INLETS====    eRam      Afs      Fram
Inlet          1.0000   -----.--     0.0      BLEEDS - output     Wb/Win   hscale   Pscale        W        Tt       ht        Pt
                                               C_LPTCharg   Bl>   0.0180   1.0000   1.0000   0.3403   1100.69   136.09   156.159
====DUCTS====  dPnorm       MN      Aphy      C_LPTUncharg Bl>   0.0502   1.0000   1.0000   0.9494   1100.69   136.09   156.159
Duct1          0.0000   0.2541    130.50      C_HPTCharg   Bl>   0.0819   1.0000   1.0000   1.4434   1437.05   222.55   373.551
ICduct         0.0020   0.3831     13.85      C_HPTUncharg Bl>   0.1595   1.0000   1.0000   2.8110   1437.05   222.55   373.551
Duct6          0.0000   0.2603      6.00
Duct43         0.0000   0.2976     19.27
ITduct         0.0000   0.1924     90.09
Duct12         0.0000   0.1848    278.41

===SHAFTS====   Nmech    trq_in    pwr_in
HP_Shaft      13445.9     945.6    2420.8
IP_Shaft      10789.4    1725.1    3543.8
LP_Shaft      15000.0     926.6    2646.4

===BURNERS===   TtOut       eff    dPnorm     Wfuel       FAR     EINOx      ppm
Burner        2849.06    1.0000    0.0200   0.31962   0.02390

===NOZZLES===      PR       Cfg      CdTh        Cv       Ath      MNth     Vact        Fg
Nozzle          1.050    1.0000    1.0000    1.0000    305.32     0.270    470.7     281.5
```

TABLE H.6.—75 PERCENT DESIGN SPEED CRUISE

```
*******************************************************************************************************************************
Date:05/24/11    Time:12:57:35    Model:    AHS 2010 Govt turboshaft engine - 75% speed turbine - Cruise    converge = 1   CASE: 101
Version:            NPSS_2.3    Gas Package: Janaf    iter/pass/Jacb/Broy= 53/ 75/ 2/50    Run by:              tm1862      PC:    50

                                               SUMMARY OUTPUT DATA
    MN        alt      dTs          W           Fn       Power      BSFC       Wfuel      VTAS       OPR        T4       T41       T47   Dyn P.
 0.510    28000.0     0.00      11.45         -23.4     2351.3    0.3147      736.90    511.85    39.986    2895.8    2663.6    2191.6     0.0

                                                FLOW STATION DATA
                                 W         Pt         Tt          ht     FAR        Wc          Ps          Ts       Aphy      MN      gamt      gams
FL1  InletStart.Fl_O         11.45      5.705     440.66      -24.88  0.0000     27.18       4.776      418.82     104.63   0.510  1.4010   1.4011
FL2  Inlet.Fl_O              11.45      5.705     440.66      -24.88  0.0000     27.18       5.155      428.07     130.50   0.383  1.4010   1.4010
FL22 Duct1.Fl_O              11.45      5.705     440.66      -24.88  0.0000     27.18       5.559      437.41     243.22   0.193  1.4010   1.4010
FL23 LPC.Fl_O                11.45     81.120    1022.86      116.60  0.0000      2.91      73.121      994.03      13.85   0.391  1.3793   1.3811
FL24 ICduct.Fl_O             11.45     80.957    1022.86      116.60  0.0000      2.92      72.975      994.03      13.88   0.391  1.3793   1.3811
FL25 HPC_axi.Fl_O            11.45     91.306    1061.40      126.23  0.0000      2.64      86.095     1044.44      16.07   0.293  1.3769   1.3780
FL26 Bld25.Fl_O              10.67     91.306    1061.40      126.23  0.0000      2.46      82.327     1031.69      11.69   0.390  1.3769   1.3788
FL27 HPC_centri.Fl_O         10.67    228.102    1405.52      214.29  0.0000      1.13     214.211     1382.50       6.70   0.306  1.3556   1.3570
FL28 Bld3.Fl_O                8.09    228.102    1405.52      214.29  0.0000      0.86     218.356     1389.48       6.00   0.254  1.3556   1.3566
FL3  Duct6.Fl_O               8.09    228.102    1405.52      214.29  0.0000      0.86     221.811     1395.23       7.41   0.203  1.3556   1.3562
FL4  Burner.Fl_O              8.30    223.540    2895.77      180.69  0.0253      1.29     202.534     2832.65       6.24   0.397  1.2819   1.2837
FL42 HPT.Fl_O                10.87    106.607    2246.15       92.10  0.0192      3.12     100.693     2216.24      19.27   0.297  1.3053   1.3063
FL43 Duct43.Fl_O             10.87    106.607    2246.20       92.10  0.0192      3.12      96.367     2193.47      15.02   0.396  1.3053   1.3071
FL44 LPT.Fl_O                11.65     29.200    1684.67      -44.60  0.0179     10.57      28.373     1672.74      90.09   0.208  1.3284   1.3290
FL45 ITduct.Fl_O             11.65     29.200    1684.74      -44.60  0.0179     10.57      26.013     1637.12      48.19   0.420  1.3284   1.3307
FL6  PowerT.Fl_O             11.65      5.015    1154.21     -187.21  0.0179     50.93       4.652     1131.49     278.41   0.334  1.3588   1.3603
FL7  Duct12.Fl_O             11.65      5.015    1154.28     -187.21  0.0179     50.94       4.652     1131.56     278.42   0.334  1.3588   1.3603
FL9  Nozzle.Fl_O             11.65      5.015    1154.35     -187.21  0.0179     50.94       4.776     1139.55     338.39   0.269  1.3588   1.3597

TURBOMACHINERY PERFORMANCE DATA
             Wc       PR      eff          Nc        TR    efPoly        pwr      SMN      SMW
LPC       27.18   14.220   0.8472   11869.667    2.3212    0.8918    -2291.4    17.98    18.02
HPC_axi    2.92    1.128   0.8908    9558.476    1.0377    0.8926     -155.9    19.48    11.70
HPC_cen>   2.46    2.498   0.8585    9383.356    1.3242    0.8744    -1329.0    23.31    22.04
HPT        1.29    2.097   0.8499     249.442    1.1487    0.8301     1485.0
LPT        3.12    3.651   0.8474     230.845    1.2917    0.8238     2291.3
PowerT    10.57    5.823   0.8690     196.781    1.4598    0.8397     2351.1

TURBOMACHINERY MAP DATA
          WcMap    PRmap   effMap       NcMap     R/Parm      s_WcDes    s_PRdes  s_effDes    s_NcDes
LPC       28.95    8.831   0.8549      98.914     1.8864     0.938796     1.6881    0.9911     0.8333
HPC_axi   29.52    1.201   0.8554       0.984     1.9166     0.098842     0.6347    1.0414     0.0001
HPC_cen>  29.51    3.060   0.8520       0.984     2.0277     0.083218     0.7273    1.0077     0.0001
HPT       30.15    5.995   0.9287      99.905     5.9954     0.042746     4.5543    0.9152     0.0176
LPT      149.63    6.424   0.9247     100.763     6.4237     0.020843     2.0460    0.9163     0.0192
PowerT    10.78    5.823   0.8690    4481.571     5.8226     0.980704     1.0000    1.0000     1.0000

===INLETS====     eRam       Afs      Fram
Inlet           1.0000    104.63     182.1        BLEEDS - output     Wb/Win    hscale    Pscale          W        Tt        ht         Pt
                                                  C_LPTCharg   Bl>    0.0180    1.0000    1.0000     0.2059   1061.40    126.23     91.306
====DUCTS====   dPnorm        MN      Aphy        C_LPTUncharg Bl>    0.0502    1.0000    1.0000     0.5744   1061.40    126.23     91.306
Duct1           0.0000    0.3830    130.50        C_HPTCharg   Bl>    0.0819    1.0000    1.0000     0.8734   1405.52    214.29    228.102
ICduct          0.0020    0.3905     13.85        C_HPTUncharg Bl>    0.1595    1.0000    1.0000     1.7009   1405.52    214.29    228.102
Duct6           0.0000    0.2545      6.00
Duct43          0.0000    0.2972     19.27
ITduct          0.0000    0.2083     90.09
Duct12          0.0000    0.3341    278.41

===SHAFTS====    Nmech    trq_in    pwr_in
HP_Shaft       13423.1     581.1    1485.0
IP_Shaft       10940.7    1099.9    2291.3
LP_Shaft        8077.0    1528.8    2351.1

===BURNERS===    TtOut       eff    dPnorm      Wfuel        FAR     EINOx       ppm
Burner         2895.77    1.0000    0.0200    0.20469    0.02529

===NOZZLES===       PR       Cfg      CdTh       Cv        Ath      MNth      Vact        Fg
Nozzle           1.050    1.0000    1.0000   1.0000     305.32     0.269     438.3     158.7
```

TABLE H.7.—85 PERCENT DESIGN SPEED TAKE OFF

```
*******************************************************************************************************************************
Date:05/24/11    Time:13:47:18    Model:   AHS 2010 Govt turboshaft engine - 65% speed turbine - Takeoff    converge = 1   CASE: 100
Version:           NPSS_2.3    Gas Package: Janaf    iter/pass/Jacb/Broy=  7/ 29/ 2/ 4    Run by:             tm1862      PC:    50

                                           SUMMARY OUTPUT DATA
     MN       alt      dTs          W          Fn       Power       BSFC       Wfuel       VTAS       OPR        T4       T41       T47  Dyn P.
  0.000       0.0     45.00     26.67       433.8      7859.4     0.3130     2513.91       0.00    42.293    3748.4    3459.4    2876.7     0.0

                                            FLOW STATION DATA
                                 W         Pt         Tt         ht      FAR        Wc         Ps         Ts      Aphy       MN     gamt     gams
FL1  InletStart.Fl_O         26.67     14.696     563.67       4.62   0.0000     27.80     14.696     563.67    -----.--   0.000   1.3995   1.3995
FL2  Inlet.Fl_O              26.67     14.696     563.67       4.62   0.0000     27.80     13.161     546.19    128.83   0.400   1.3995   1.3998
FL22 Duct1.Fl_O              26.67     14.696     563.67       4.62   0.0000     27.80     14.292     559.20    240.10   0.200   1.3995   1.3996
FL23 LPC.Fl_O                26.67    213.240    1303.06     187.68   0.0000      2.91    191.489    1266.28     13.66   0.400   1.3617   1.3640
FL24 ICduct.Fl_O             26.67    212.813    1303.06     187.68   0.0000      2.92    191.106    1266.28     13.69   0.400   1.3617   1.3640
FL25 HPC_axi.Fl_O            26.67    239.578    1349.89     199.81   0.0000      2.64    225.463    1328.41     15.87   0.300   1.3589   1.3602
FL26 Bld25.Fl_O              24.89    239.578    1349.89     199.81   0.0000      2.46    215.196    1312.09     11.56   0.400   1.3589   1.3611
FL27 HPC_centri.Fl_O         24.89    621.533    1788.60     316.56   0.0000      1.09    585.493    1761.87      6.62   0.300   1.3366   1.3378
FL28 Bld3.Fl_O               18.97    621.533    1788.60     316.56   0.0000      0.83    596.224    1769.96      5.96   0.250   1.3366   1.3374
FL3  Duct6.Fl_O              18.97    621.533    1788.60     316.56   0.0000      0.83    605.186    1776.63      7.36   0.200   1.3366   1.3372
FL4  Burner.Fl_O             19.67    609.102    3748.43     262.28   0.0368      1.28    552.900    3673.49      6.18   0.401   1.2528   1.2548
FL42 HPT.Fl_O                25.59    290.574    2946.75     148.62   0.0281      3.08    274.578    2910.05     19.04   0.301   1.2789   1.2800
FL43 Duct43.Fl_O             25.59    290.574    2946.75     148.62   0.0281      3.08    262.861    2882.00     14.84   0.401   1.2789   1.2808
FL44 LPT.Fl_O                27.37     83.903    2267.24     -26.44   0.0262     10.02     81.746    2253.58     89.36   0.201   1.3001   1.3006
FL45 ITduct.Fl_O             27.37     83.903    2267.29     -26.44   0.0262     10.02     75.655    2213.48     47.81   0.402   1.3001   1.3019
FL6  PowerT.Fl_O             27.37     15.431    1561.57    -229.40   0.0262     45.23     14.527    1538.35    272.81   0.302   1.3292   1.3305
FL7  Duct12.Fl_O             27.37     15.431    1561.63    -229.40   0.0262     45.23     14.527    1538.41    272.82   0.302   1.3292   1.3304
FL9  Nozzle.Fl_O             27.37     15.431    1561.69    -229.40   0.0262     45.23     14.696    1542.91    300.63   0.272   1.3292   1.3302

TURBOMACHINERY PERFORMANCE DATA
              Wc      PR       eff          Nc        TR    efPoly        pwr      SMN      SMW
LPC        27.80  14.510    0.8431   12000.000    2.3118    0.8884    -6907.8    20.09    19.67
HPC_axi     2.92   1.126    0.8867    9689.199    1.0359    0.8884     -457.5    19.95    12.51
HPC_cen>    2.46   2.594    0.8577    9519.646    1.3250    0.8737    -4111.6    20.02    18.35
HPT         1.28   2.096    0.8503     250.842    1.1363    0.8162     4569.1
LPT         3.08   3.463    0.8505     230.450    1.2595    0.8238     6908.0
PowerT     10.02   5.437    0.9357     315.020    1.4520    0.9200     7859.2

TURBOMACHINERY MAP DATA
           WcMap   PRmap    effMap       NcMap     R/Parm     s_WcDes    s_PRdes  s_effDes    s_NcDes
LPC        30.00   8.994    0.8509     100.000     2.0028    0.926742     1.6901    0.9909     0.8333
HPC_axi    29.94   1.200    0.8515       0.998     1.9904    0.097488     0.6285    1.0413     0.0001
HPC_cen>   29.93   3.192    0.8514       0.998     1.9942    0.082277     0.7273    1.0074     0.0001
HPT        30.15   5.976    0.9291     100.172     5.9760    0.042317     4.5393    0.9152     0.0175
LPT       149.76   5.999    0.9281     100.389     5.9991    0.020596     2.0295    0.9163     0.0191
PowerT     10.44   5.437    0.9357    7174.453     5.4374    0.959975     1.0000    1.0000     1.0000

===INLETS====    eRam       Afs      Fram
Inlet          1.0000   -----.--      0.0        BLEEDS - output     Wb/Win    hscale    Pscale          W        Tt        ht        Pt
                                                 C_LPTCharg   Bl>    0.0175    1.0000    1.0000     0.4665   1349.89    199.81   239.578
====DUCTS====  dPnorm        MN      Aphy        C_LPTUncharg Bl>    0.0493    1.0000    1.0000     1.3145   1349.89    199.81   239.578
Duct1          0.0000    0.4001    128.83        C_HPTCharg   Bl>    0.0805    1.0000    1.0000     2.0039   1788.60    316.56   621.533
ICduct         0.0020    0.4001     13.66        C_HPTUncharg Bl>    0.1572    1.0000    1.0000     3.9136   1788.60    316.56   621.533
Duct6          0.0000    0.2500      5.96
Duct43         0.0000    0.3006     19.04
ITduct         0.0000    0.2008     89.36
Duct12         0.0000    0.3024    272.81

===SHAFTS====   Nmech    trq_in    pwr_in
HP_Shaft      15357.7    1562.6    4569.1
IP_Shaft      12509.7    2900.2    6908.0
LP_Shaft      15000.0    2751.8    7859.2

===BURNERS===   TtOut       eff    dPnorm     Wfuel       FAR     EINOx      ppm
Burner        3748.43    1.0000    0.0200   0.69831   0.03681

===NOZZLES===      PR       Cfg      CdTh        Cv       Ath      MNth     Vact       Fg
Nozzle          1.050    1.0000    1.0000    1.0000    299.10     0.272    510.0    433.8
```

TABLE H.8.—85 PERCENT DESIGN SPEED CLIMB

```
****************************************************************************************************************************************
Date:05/24/11     Time:13:47:19     Model:     AHS 2010 Govt turboshaft engine - 65% speed turbine - Climb     converge = 1   CASE: 100
Version:             NPSS_2.3     Gas Package: Janaf     iter/pass/Jacb/Broy= 19/ 30/ 1/17     Run by:              tm1862      PC:    50

                                          SUMMARY OUTPUT DATA
     MN        alt      dTs          W          Fn       Power      BSFC       Wfuel       VTAS      OPR        T4       T41       T47   Dyn P.
  0.000        0.0     0.00      18.51       271.5      2646.3    0.3984     1097.54       0.00   25.069    2806.6    2594.1    2139.6      0.0

                                           FLOW STATION DATA
                                W        Pt         Tt         ht      FAR        Wc         Ps         Ts      Aphy      MN     gamt     gams
FL1  InletStart.Fl_O        18.51    14.696     518.67      -6.18   0.0000     18.51     14.696     518.67   -----.--   0.000  1.4002   1.4002
FL2  Inlet.Fl_O             18.51    14.696     518.67      -6.18   0.0000     18.51     14.063     512.18     128.83   0.252  1.4002   1.4003
FL22 Duct1.Fl_O             18.51    14.696     518.67      -6.18   0.0000     18.51     14.520     516.89     240.10   0.131  1.4002   1.4003
FL23 LPC.Fl_O               18.51   138.096    1060.67     126.05   0.0000      2.82    125.070    1032.24      13.66   0.382  1.3769   1.3787
FL24 ICduct.Fl_O            18.51   137.820    1060.67     126.05   0.0000      2.82    124.820    1032.24      13.69   0.382  1.3769   1.3787
FL25 HPC_axi.Fl_O           18.51   155.129    1099.58     135.82   0.0000      2.55    146.627    1082.81      15.87   0.287  1.3745   1.3756
FL26 Bld25.Fl_O             17.27   155.129    1099.58     135.82   0.0000      2.38    140.516    1070.28      11.56   0.382  1.3745   1.3763
FL27 HPC_centri.Fl_O        17.27   368.418    1432.65     221.40   0.0000      1.15    344.817    1408.03       6.62   0.314  1.3541   1.3555
FL28 Bld3.Fl_O              13.17   368.418    1432.65     221.40   0.0000      0.87    351.880    1415.53       5.96   0.261  1.3541   1.3551
FL3  Duct6.Fl_O             13.17   368.418    1432.65     221.40   0.0000      0.87    357.754    1421.68       7.36   0.209  1.3541   1.3547
FL4  Burner.Fl_O            13.47   361.050    2806.62     190.42   0.0232      1.28    327.083    2744.81       6.18   0.396  1.2857   1.2875
FL42 HPT.Fl_O               17.58   171.977    2189.18     103.28   0.0177      3.09    162.404    2159.73      19.04   0.297  1.3082   1.3093
FL43 Duct43.Fl_O            17.58   171.977    2189.23     103.28   0.0177      3.09    155.399    2137.29      14.84   0.396  1.3082   1.3101
FL44 LPT.Fl_O               18.81    50.451    1663.08     -24.67   0.0165      9.81     49.206    1652.78      89.36   0.194  1.3304   1.3309
FL45 ITduct.Fl_O            18.81    50.451    1663.15     -24.67   0.0165      9.81     45.721    1622.87      47.81   0.387  1.3304   1.3323
FL6  PowerT.Fl_O            18.81    15.430    1295.39    -124.09   0.0165     28.32     15.091    1287.93     272.81   0.182  1.3508   1.3512
FL7  Duct12.Fl_O            18.81    15.430    1295.46    -124.09   0.0165     28.32     15.091    1287.99     272.82   0.182  1.3507   1.3512
FL9  Nozzle.Fl_O            18.81    15.430    1295.52    -124.09   0.0165     28.32     14.696    1279.21     188.20   0.269  1.3507   1.3518

TURBOMACHINERY PERFORMANCE DATA
              Wc      PR      eff          Nc        TR    efPoly        pwr      SMN      SMW
LPC        18.51   9.397   0.8422   10765.075    2.0450    0.8823    -3462.5    16.53    17.69
HPC_axi     2.82   1.126   0.8952    9369.305    1.0367    0.8968     -255.8    19.23    10.91
HPC_cen>    2.38   2.375   0.8580    9202.035    1.3029    0.8731    -2091.3    27.88    27.19
HPT         1.28   2.099   0.8505     252.907    1.1507    0.8317     2347.0
LPT         3.09   3.409   0.8513     230.076    1.2783    0.8295     3462.6
PowerT      9.81   3.270   0.8516     367.812    1.2840    0.8307     2646.3

TURBOMACHINERY MAP DATA
           WcMap   PRmap   effMap       NcMap    R/Parm     s_WcDes    s_PRdes  s_effDes    s_NcDes
LPC        19.97   5.968   0.8500      89.709    1.6619    0.926742     1.6901    0.9909     0.8333
HPC_axi    28.95   1.200   0.8597       0.965    1.8417    0.097488     0.6285    1.0413     0.0001
HPC_cen>   28.95   2.891   0.8517       0.965    2.0555    0.082277     0.7273    1.0074     0.0001
HPT        30.14   5.991   0.9293     100.996    5.9905    0.042317     4.5393    0.9152     0.0175
LPT       149.82   5.889   0.9290     100.226    5.8886    0.020596     2.0295    0.9163     0.0191
PowerT     10.22   3.270   0.8516    8376.780    3.2697    0.959975     1.0000    1.0000     1.0000

===INLETS====    eRam       Afs      Fram
Inlet          1.0000   -----.--      0.0       BLEEDS - output     Wb/Win    hscale    Pscale         W        Tt        ht        Pt
                                                C_LPTCharg   Bl>    0.0175    1.0000    1.0000    0.3237   1099.58    135.82   155.129
====DUCTS====  dPnorm        MN      Aphy       C_LPTUncharg Bl>    0.0493    1.0000    1.0000    0.9122   1099.58    135.82   155.129
Duct1          0.0000    0.2516    128.83       C_HPTCharg   Bl>    0.0805    1.0000    1.0000    1.3906   1432.65    221.40   368.418
ICduct         0.0020    0.3817     13.66       C_HPTUncharg Bl>    0.1572    1.0000    1.0000    2.7158   1432.65    221.40   368.418
Duct6          0.0000    0.2611      5.96
Duct43         0.0000    0.2973     19.04
ITduct         0.0000    0.1942     89.36
Duct12         0.0000    0.1817    272.81

===SHAFTS====   Nmech    trq_in    pwr_in
HP_Shaft      13398.4     920.0    2347.0
IP_Shaft      10765.1    1689.3    3462.6
LP_Shaft      15000.0     926.6    2646.3

===BURNERS===   TtOut       eff    dPnorm     Wfuel       FAR     EINOx       ppm
Burner        2806.61    1.0000    0.0200   0.30487   0.02316

===NOZZLES===      PR       Cfg      CdTh        Cv       Ath      MNth      Vact        Fg
Nozzle          1.050    1.0000    1.0000    1.0000    299.10     0.269     464.2     271.5
```

TABLE H.9.—85 PERCENT DESIGN SPEED CRUISE

```
*******************************************************************************************************
Date:05/24/11    Time:13:47:20    Model:    AHS 2010 Govt turboshaft engine - 65% speed turbine - Cruise    converge = 1   CASE: 101
Version:           NPSS_2.3    Gas Package: Janaf    iter/pass/Jacb/Broy= 41/ 74/ 3/37    Run by:           tm1862      PC:    50

                                      SUMMARY OUTPUT DATA
    MN       alt      dTs        W         Fn      Power      BSFC      Wfuel      VTAS      OPR       T4       T41       T47   Dyn P.
 0.510   28000.0     0.00     11.38      -21.3     2351.0    0.3207    751.16    511.85   40.624   2927.6   2695.8    2218.6      0.0

                                       FLOW STATION DATA
                               W        Pt        Tt         ht      FAR       Wc         Ps        Ts      Aphy     MN    gamt    gams
FL1  InletStart.Fl_O       11.38     5.705    440.66     -24.88   0.0000    27.01      4.776    418.82    103.97  0.510  1.4010  1.4011
FL2  Inlet.Fl_O            11.38     5.705    440.66     -24.88   0.0000    27.01      5.147    427.87    128.83  0.386  1.4010  1.4010
FL22 Duct1.Fl_O            11.38     5.705    440.66     -24.88   0.0000    27.01      5.557    437.36    240.10  0.194  1.4010  1.4010
FL23 LPC.Fl_O              11.38    81.168   1023.71     116.81   0.0000     2.89     73.031    994.35     13.66  0.394  1.3793  1.3811
FL24 ICduct.Fl_O           11.38    81.005   1023.71     116.81   0.0000     2.90     72.885    994.35     13.69  0.394  1.3793  1.3811
FL25 HPC_axi.Fl_O          11.38    91.249   1061.96     126.37   0.0000     2.62     85.957   1044.72     15.87  0.296  1.3769  1.3779
FL26 Bld25.Fl_O            10.62    91.249   1061.96     126.37   0.0000     2.45     82.122   1031.71     11.56  0.394  1.3769  1.3788
FL27 HPC_centri.Fl_O       10.62   231.744   1413.48     216.37   0.0000     1.11    217.828   1390.69      6.62  0.303  1.3552  1.3565
FL28 Bld3.Fl_O              8.09   231.744   1413.48     216.37   0.0000     0.85    221.977   1397.60      5.96  0.253  1.3552  1.3561
FL3  Duct6.Fl_O             8.09   231.744   1413.48     216.37   0.0000     0.85    225.438   1403.30      7.36  0.202  1.3552  1.3558
FL4  Burner.Fl_O            8.30   227.109   2927.61     182.05   0.0258     1.28    205.767   2863.94      6.18  0.397  1.2807  1.2825
FL42 HPT.Fl_O              10.82   107.897   2273.17      91.74   0.0197     3.09    101.892   2242.85     19.04  0.298  1.3041  1.3051
FL43 Duct43.Fl_O           10.82   107.897   2273.22      91.74   0.0197     3.09     97.496   2219.80     14.84  0.397  1.3041  1.3059
FL44 LPT.Fl_O              11.58    30.139   1712.78     -45.12   0.0183    10.26     29.322   1701.22     89.36  0.204  1.3268  1.3273
FL45 ITduct.Fl_O           11.58    30.139   1712.83     -45.12   0.0183    10.26     27.005   1667.01     47.81  0.409  1.3268  1.3289
FL6  PowerT.Fl_O           11.58     5.015   1181.37    -188.56   0.0183    51.23      4.630   1156.80    272.81  0.345  1.3567  1.3583
FL7  Duct12.Fl_O           11.58     5.015   1181.43    -188.56   0.0183    51.23      4.630   1156.86    272.82  0.345  1.3567  1.3583
FL9  Nozzle.Fl_O           11.58     5.015   1181.50    -188.56   0.0183    51.23      4.776   1166.42    340.30  0.269  1.3567  1.3577

TURBOMACHINERY PERFORMANCE DATA
            Wc      PR      eff         Nc       TR   efPoly        pwr     SMN     SMW
LPC      27.01  14.229   0.8463  11892.165   2.3231   0.8911    -2280.3   18.83   18.78
HPC_axi   2.90   1.126   0.8888   9626.512   1.0374   0.8906     -153.8   19.67   12.08
HPC_cen>  2.45   2.540   0.8575   9451.543   1.3310   0.8737    -1351.8   22.03   20.55
HPT       1.28   2.105   0.8497    249.951   1.1489   0.8294     1505.6
LPT       3.09   3.580   0.8481    229.904   1.2862   0.8251     2280.3
PowerT   10.26   6.010   0.8471    195.161   1.4500   0.8136     2351.0

TURBOMACHINERY MAP DATA
         WcMap   PRmap   effMap      NcMap   R/Parm    s_WcDes   s_PRdes  s_effDes   s_NcDes
LPC      29.15   8.827   0.8540     99.101   1.9218   0.926742    1.6901    0.9909    0.8333
HPC_axi  29.74   1.201   0.8535      0.992   1.9515   0.097488    0.6285    1.0413    0.0001
HPC_cen> 29.74   3.117   0.8512      0.991   2.0221   0.082277    0.7273    1.0074    0.0001
HPT      30.15   6.015   0.9284     99.816   6.0153   0.042317    4.5393    0.9152    0.0175
LPT     149.85   6.236   0.9256    100.151   6.2361   0.020596    2.0295    0.9163    0.0191
PowerT   10.69   6.010   0.8471   4444.712   6.0097   0.959975    1.0000    1.0000    1.0000

===INLETS====    eRam      Afs      Fram
Inlet          1.0000   103.97     181.0      BLEEDS - output    Wb/Win   hscale   Pscale         W        Tt        ht        Pt
                                              C_LPTCharg   Bl>   0.0175   1.0000   1.0000    0.1990   1061.96    126.37    91.249
====DUCTS====  dPnorm       MN      Aphy      C_LPTUncharg Bl>   0.0493   1.0000   1.0000    0.5606   1061.96    126.37    91.249
Duct1          0.0000   0.3861    128.83      C_HPTCharg   Bl>   0.0805   1.0000   1.0000    0.8547   1413.48    216.37   231.744
ICduct         0.0020   0.3940     13.66      C_HPTUncharg Bl>   0.1572   1.0000   1.0000    1.6692   1413.48    216.37   231.744
Duct6          0.0000   0.2527      5.96
Duct43         0.0000   0.2979     19.04
ITduct         0.0000   0.2038     89.36
Duct12         0.0000   0.3446    272.81

===SHAFTS====   Nmech   trq in    pwr in
HP_Shaft      13524.2    584.7    1505.6
IP_Shaft      10961.4   1092.6    2280.3
LP_Shaft       8077.0   1528.8    2351.0

===BURNERS===   TtOut      eff    dPnorm     Wfuel      FAR    EINOx      ppm
Burner        2927.61   1.0000    0.0200   0.20866  0.02579

===NOZZLES===      PR      Cfg      CdTh       Cv       Ath     MNth     Vact       Fg
Nozzle          1.050   1.0000    1.0000   1.0000    299.10    0.269    443.6    159.7
```

References

1. Snyder, C. A. and Thurman, D. R., "Gas Turbine Characteristics for a Large Civil Tilt-Rotor (LCTR)," NASA/TM—2010-216089, February 2010.
2. D'Angelo, M., "Wide Speed Range Turboshaft Study," NASA CR-198380, August 1995.
3. Welch, G.E., "Assessment of Aerodynamic Challenges of a Variable-Speed Power Turbine for Large Civil Tilt-Rotor Application," *Proc. American Helicopter Society 66th Annual Forum*, Phoenix, AZ, May 11-13, 2010.
4. Kacker, S. C., and Okapuu, U., "A Mean Line Prediction Method for Axial Flow Turbine Efficiency," ASME 81-GT-58, 1981.
5. Moustapha, S.H., Kacker, S. C., and Tremblay, B., "Improved Incidence Losses Prediction Method for Turbine Airfoils," ASME 89-GT284, 1989.
6. Smith, S. F., "A Simple Correlation of Turbine Efficiency," J. Royal Aero. Soc., 69, 1965, p. 467–470.

REPORT DOCUMENTATION PAGE						*Form Approved* *OMB No. 0704-0188*
The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.						
1. REPORT DATE *(DD-MM-YYYY)* 01-02-2012		**2. REPORT TYPE** Final Contractor Report				**3. DATES COVERED** *(From - To)* October 2010 to March 2011
4. TITLE AND SUBTITLE Variable-Speed Power-Turbine for the Large Civil Tilt Rotor						**5a. CONTRACT NUMBER** NNC10BA15B
						5b. GRANT NUMBER
						5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Suchezky, Mark; Cruzen, G., Scott						**5d. PROJECT NUMBER**
						5e. TASK NUMBER NNC10TA76T
						5f. WORK UNIT NUMBER WBS 877868.02.07.03.01.02.01
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Williams International Co. LLC 2280 E. West Maple Road Walled Lake, Michigan 48390-0200						**8. PERFORMING ORGANIZATION REPORT NUMBER** E-18111
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001						**10. SPONSORING/MONITOR'S ACRONYM(S)** NASA
						11. SPONSORING/MONITORING REPORT NUMBER NASA/CR-2012-217424
12. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified-Unlimited Subject Categories: 01, 02, 03, and 07 Available electronically at http://www.sti.nasa.gov This publication is available from the NASA Center for AeroSpace Information, 443-757-5802						
13. SUPPLEMENTARY NOTES						
14. ABSTRACT Turbine design concepts were studied for application to a large civil tiltrotor transport aircraft. The concepts addressed the need for high turbine efficiency across the broad 2:1 turbine operating speed range representative of the notional mission for the aircraft. The study focused on tailoring basic turbine aerodynamic design design parameters to avoid the need for complex, heavy, and expensive variable geometry features. The results of the study showed that good turbine performance can be achieved across the design speed range if the design focuses on tailoring the aerodynamics for good tolerance to large swings in incidence, as opposed to optimizing for best performance at the long range cruise design point. A rig design configuration and program plan are suggested for a dedicated experiment to validate the proposed approach.						
15. SUBJECT TERMS Variable-speed power turbine; Turbine aerodynamics; Low pressure turbines; turbomachinery design; Rotordynamics; Turbine performance; Large civil tilt-rotor						
16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**		**19a. NAME OF RESPONSIBLE PERSON** STI Help Desk (email:help@sti.nasa.gov)
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U	UU	100		**19b. TELEPHONE NUMBER** ***(include area code)*** 443-757-5802

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18